Key Factors of UV Curing of Ink Jet Printing

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Abstract

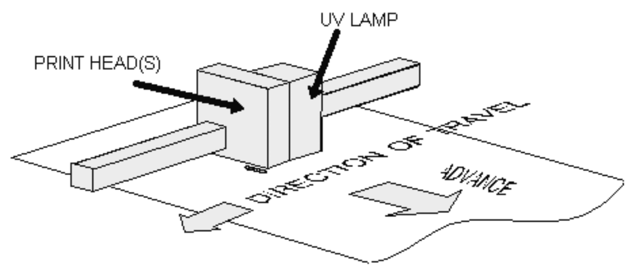
The physical properties of UV-cured materials are substantially affected by the lamp systems used to cure them. The development of the intended physical properties, whether an ink-jet printed process colors or solid colors can depend on how well these lamp systems are designed and managed.

Four key variables of a UV curing exposure system, which can be designed or selected to produce the most efficient result, are discussed. Variables include UV irradiance (or intensity), spectral distribution (wavelengths) of UV, total UV energy, and infra-red radiation. The interaction with the optical and physical characteristics of materials such as spectral absorptivity, optical thickness, and diffusivity, result in limitations of the cure "window." Typically, this cure "window" is limited by loss of key physical properties, including adhesion, solvent resistance and scratch resistance. The ability to match all of these lamp characteristics to the optical and physical properties of a UV curable material yields more efficient and stable UV curing processes in production.

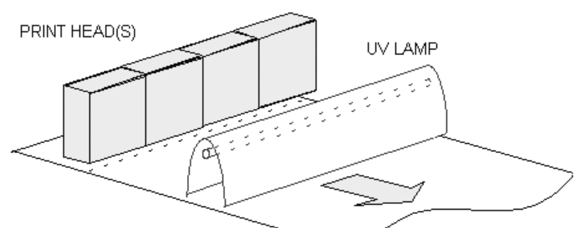
Introduction

UV inks have been developed for ink jet printing and for use in the variety of ink jet configurations and applications. The industrial applications of UV ink jet range from large-format multi-color graphics to small, single-color marking and identification. These applications can be divided into two general categories – distinguished by the configuration of UV lamps required to cure the inks.

• **Moving head, wide graphics** systems are characterized by print heads that move across the print area. The printing may be unidirectional or bi-directional. Because the UV cure follows the print head, unidirectional travel requires one UV lamp, while bi-directional travel typically requires two. The substrate sheet or roll advances, usually intermittently, to provide the travel in the perpendicular direction. Two-axis motion, similar to an X-Y plotter, may also carry one or two UV lamps. Because the lamps move with the print heads in moving-head systems, it is desirable that the UV lamps be small and lightweight.



• **Fixed head, high speed** systems are characterized by head arrays that span the print width. They are referred to as "one-pass" systems. The UV lamps are situated downstream, before sheet or roll stacking or rewind, and also span the print width.



Fixed-head systems are typically found where higher throughput and speed are required, and some of the applications include:

- Product Labels (short run), tags and tickets
- Addressing (variable information)/mailing
- Web Printing (variable data stations)
- Marking (barcodes, date codes - including 2D, part numbers)
- Wire, Cable, and Connector Marking
- PC Board graphics
- Sequential Numbering
- Gaming pieces and cards
- Statements and forms
- Plastic cards

A UV curable system achieves the transition from liquid to solid by means of either chain addition polymerization or an epoxy reaction, triggered by a photochemical interaction. A *photoinitiator* is the active component of the material formulation. The photoinitiator absorbs energy when exposed to ultraviolet energy, which starts the reaction. In UV curable material, the resin binder is replaced by a formulation of liquid monomers and oligomers, into which a pigment can be dispersed. The coating is completely reactive and because there is no mass transfer (evaporation) in the reaction, the ink film is essentially the same thickness after curing as it was when laid down wet. These systems are often referred to as "100% solids."

A UV Curing system should be thought of as consisting of *three* component parts, all integrally related:

- **The application**, particularly the end product it produces, will determine the requirements of the physical properties of the cured photochemistry. *Target properties*, such as opacity or hiding, film thickness, hardness or flexibility, resistance to abrasion or scratching, and adhesion are only a few that are determined by the end product and the coating, decorating or bonding process used.
- **The photochemistry** is designed to achieve the *target properties* upon exposure to the appropriate energy of radiation. Formulation variables include seemingly infinite choices and combinations of monomers, oligomers, photoinitators and functional additives. Identifying the *optical properties* (spectral absorption, spectral response, and "optical thickness") of the formulation is critical to achieving successful cure.
- **The UV lamp system** will have a number of key exposure variables, which will also have a significant effect on the target properties. These key variables are spectral radiance (emitted wavelengths), irradiance (the "intensity" of UV arriving at the work surface), time of exposure, and the infrared energy directed toward the work surface. All of these must be optimized to achieve an efficient UV curing process with a sufficiently wide operating "window."

The principal ingredients of a UV-curable ink are:
Oligomers - Larger molecules; primarily determine ultimate physical properties.
Monomers - Smaller molecules; affect (wet) viscosity and rate of crosslinking reaction.
Photoinitiators - Respond to UV and initiate reaction; low concentration (1% - 2%).
Additives - Pigments, surfactants, de-foamers, etc. - these do not enter into the cross-linking reaction.

In addition to the chemistry of the UV-curable ink or coating, an important part of the UV system is the lamp system used to expose the materials to UV. UV curing begins with a photon-molecule collision. The effectiveness of the curing process is dependent on the ease or difficulty of projecting photons into a curable material to activate photoinitiator molecules.

The optical properties of the ink, such as optical density (opacity) and the optical characteristics of the curing lamp must be "matched" to produce an effective UV curing system.

A variety of photoinitiators is available to the formulators of inks and coatings. Each type of photoinitiator responds to a different but very specific wavelength range of UV.

In examining the interaction of photons with photoinitiator molecules, we note an interesting and fundamental fact: *Photoinitiator molecules are dispersed uniformly throughout the material -- but photons are not.*

Optically Thick Coatings and Inks

Inks and pigmented coatings pose special problems, owing to the fact that <u>opacity</u> or <u>color strength</u> are desirable properties. Distinct from the *physical* thickness of a film, its *optical* thickness is important.

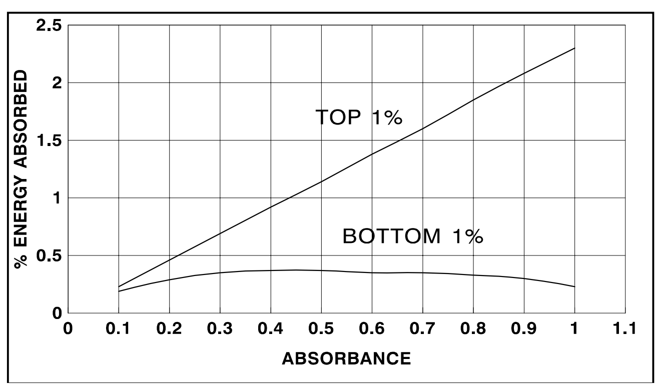
The reduction of UV energy as it passes into or through any material is described by the Beer-Lambert law. Energy that is not absorbed in an upper layer of the film and not reflected is transmitted and available to lower layers.

$$I_{a\lambda} = \frac{I_{o\lambda}(1 - 10^{-A_\lambda})}{d}$$

where $\boldsymbol{I_o}$ is the incident energy at wavelength λ, $\boldsymbol{I_a}$ is the energy absorbed, ***A*.** is absorbance at wavelength λ, and ***d*** is the depth from the surface or film thickness

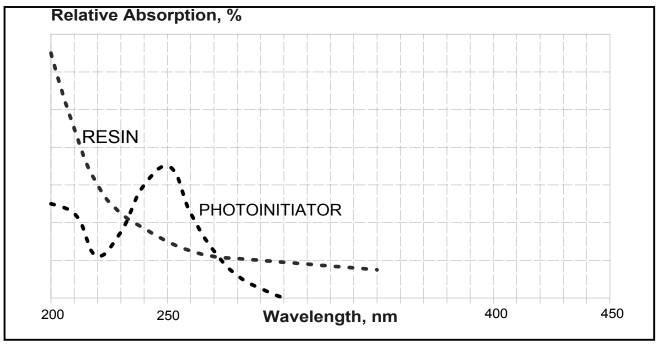
Significance of Absorbance

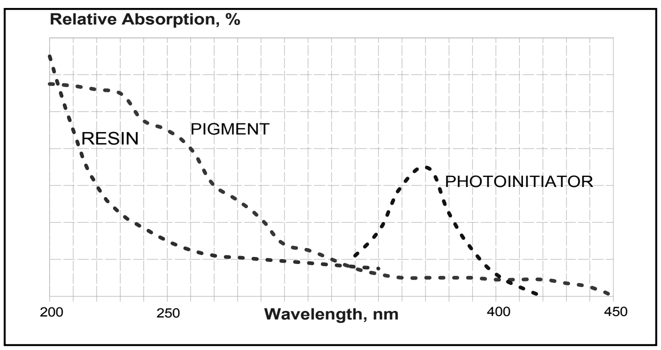
An examination of this equation reveals the relative energy absorbed in the top surface (1% layer) and the extreme bottom (1% layer) of a film, as a function of absorbance. There is a great difference in the UV energy in these two zones.



Significance of Spectral Absorbance

In examining 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. Typically, film thickness is limited, and adhesion to a substrate is often the first property to suffer. Even the photoinitiator absorbs energy in the wavelengths it is sensitive to, and blocks that same wavelength from deeper photoinitiator molecules. The graphs also illustrate that a photoinitiator that may be appropriate for a clear coating of for a thin film, may not be an appropriate selection for an ink. For ink, a photoinitiator with a longer wavelength response would be a better choice.

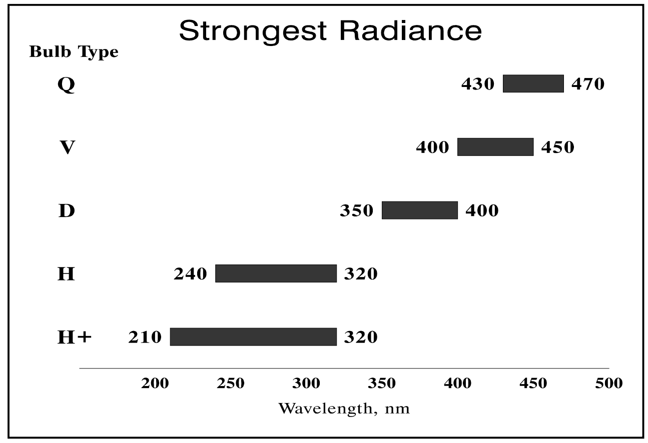




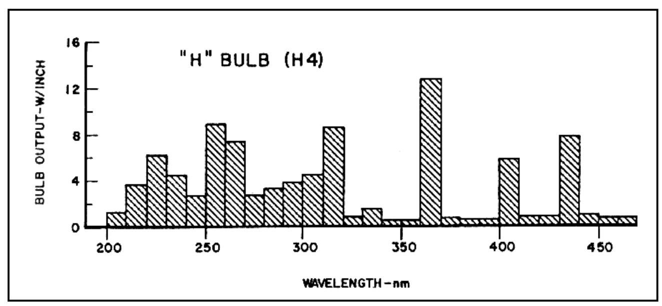
Significance of Wavelength

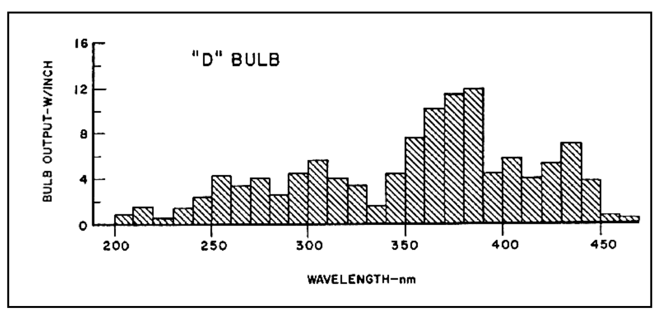
Most UV curing involves *two* UV wavelength ranges at work simultaneously (*three*, if we include infra-red). Short wavelengths work on the surface; longer waves work more deeply in the ink or coating. This is principally the result of the fact that short wavelength energy is absorbed at the surface and is not available to deeper layers. Insufficient short-wave exposure may result in a tacky surface; insufficient long wavelength energy may result in adhesion failure. Each formulation and film thickness benefits from an appropriate ratio of short and long wavelength energy.

The most basic mercury bulb emits energy in both ranges, but its strong emission in the short wavelengths make it particularly useful for coatings and thin ink layers. Higher absorptivity materials, such as adhesives and screen inks are often formulated for longer wave cure, using long wave photoinitiators. These materials are cured with bulbs containing additives, along with mercury, that emit UV that is much richer in the long-wave UV. These longer-wave bulbs also emit some short-wavelength energy, which is often sufficient to assist with surface cure.



Additive materials such as metal halides can be included in the UV bulb in small, precisely measured quantities, and the spectral distribution of its output modified. (By summarizing the spectral output power distribution in bands of 10 nm wavelength and plotting using the center wavelength of each band, a very reproducible and easy to analyze spectral output chart can be made.)





Optical Factors Which Characterize the Process

There are a number of factors (outside of the formulation itself) which affect the curing and the consequent performance of the UV curable material. These factors are the optical and physical characteristics of the curing *system*. Among them are the key elements of the UV exposure:

A. ***UV Irradiance*** is the radiant power, within a stated wavelength range, arriving at a surface per unit area. It is photon flux, and is expressed in watts or milliwatts per square centimeter. Irradiance varies with lamp output power, efficiency and focus of its reflector system, and distance to the surface. (It is a characteristic of the lamp geometry and power, so does not vary with speed). The intense, peak of focused power directly under a lamp is referred to as *"peak irradiance." Irradiance* incorporates ***all*** of the individual effects of electrical power, efficiency, radiant output, reflectance, focus, bulb size, and lamp geometry.

When Irradiance is measured in any specific range of wavelengths, it is called "*Effective Irradiance*"

Higher irradiance at the surface will provide correspondingly higher UV energy within the ink or coating. Depth of cure is more affected by irradiance than by length (time) of exposure (energy). The effects of irradiance are more important for higher absorbance (more opaque) films and inks.

B. ***Spectral Distribution*** describes the relative radiant energy as a function of wavelength emitted by a bulb or the wavelength distribution of radiant energy arriving at a surface. In order to display the distribution of UV energy, it is convenient to combine spectral energy into 10-nanometer bands to produce a distribution plot (or table). This permits comparison of various bulbs and is more easily applied to spectral power and energy calculations. Lamp manufacturers publish spectral distribution data for their bulbs.

C. ***UV Effective Energy*** is the radiant energy, within a stated wavelength range, arriving at a surface per unit area. Sometimes loosely (and incorrectly) referred to as "dose," it is the total accumulated photon quantity arriving at a surface. Energy is inversely proportional to speed under any given exposure source, and proportional to the number of exposures (number of 'passes' or rows of lamps). It is the time-integral of irradiance to which a surface is exposed as it travels past a lamp or a sequence of lamps, usually expressed in joules or millijoules per square centimeter.

D. ***Infrared Radiance*** is the amount of infrared energy primarily emitted by the quartz envelope of the UV source. This energy is collected and focused with the UV energy on the work surface, depending on the IR reflectivity and efficiency of the reflector. IR can be evaluated in energy or irradiance units, but usually the surface temperature it produces is of prime interest. The heat that it produces may be a benefit or a nuisance.

Benefits of Utilizing UV for Digital Printing

The benefits available to digital printing are many of the same benefits that have been proven in a number of other types of printing systems. The use of UV inks is common in offset, letterpress, flexographic, screen and ink-jet printing owing to the high effective speed of "drying." It is also effectively used in printing where thick, rich laydowns of ink provide the opacity and richness to process as well as solid color decoration.

Specific potential benefits to digital printing are:

- No solvents - No VOC's;
- High opacity and coverage because inks are 100% solids;
- Inks do not dry in the printing equipment;
- Inks maintain consistency - do not require adjustment;
- Ink strength remains constant;
- Dot gain is less than with solvent-based inks;
- Higher scratch and chemical resistance.

Conclusion

Most UV curable films are "optically thick," and much more radiant energy is absorbed near the surface of the material, and absorbance varies wildly with wavelength. Spectral absorbance a critical factor in achieving a sufficiently wide process window. UV absorbance affects the depth of cure, and IR absorbance affects the observed temperature.

The effectiveness of a UV curing system is the practical result of a process design that combines the method of application on ink or coating, the photochemistry of UV-curable inks, and the UV lamp designs into an integrated system. Careful attention to the optical factors and the interaction of inks and lamps can provide a successful UV system with wide operating limits.

Optical characteristics of lamp systems and their interaction with the optical properties of curable materials are an integral part of performance. Lamp characteristics, such as spectral distribution, peak irradiance, and controlled infrared energy can be effectively used, along with formulation strategies, to design UV systems with acceptably wide process windows.