Comparison of UV and EB Technology for Printing and Packaging Applications

By Stephen C. Lapin

UV/EB curing technology for inks, coatings and laminating adhesives has become well established in certain segments of the packaging industry—including folding cartons, labels and multiwall bags. There is also growing interest in UV/EB technology for flexible packaging.[1] The growth in UV/EB applications is due, in part, from the inherent advantages over solvent- and water-based materials.

The solvent in conventional inks, coatings and adhesives functions simply as the "carrier" for the "solids" portion of the material. In most cases, solvent emissions are handled by thermal oxidation which produces greenhouse gas (CO_2). Solvents are highly refined materials derived from fossil hydrocarbon sources. It is quite wasteful to use such a high-value material for such a low-value temporary function. Solvent-based materials are old technology that is clearly out of step with a sustainable future.

A clear understanding of the differences between UV and EB can facilitate a selection of which technology is best suited to the end-use application.

At first glance, water-based inks, coatings and adhesives would appear to be an excellent choice from an environmental perspective. Water is a relatively plentiful, low-cost and environmentally friendly carrier. The main disadvantage with water is the high energy required to remove water from the solids portion of the formula. This high-energy requirement for water is illustrated by comparing the heat of vaporization to some common solvents[2]:

water = 540 calories/gram
toluene = 88
heptane = 76

The generation of energy needed to operate the driers to remove water results in significant CO_2 emissions. In addition, most water-based materials do contain some solvents to aid the formation of the polymer film upon drying the ink, coating or adhesive. Also, in many cases, water-based materials do not have the resistance or appearance properties to match higher performance solvent- or UV/EB-based materials.

In spite of the clear advantages of UV/EB technology over solvent and water-based technology, there is often some confusion as to whether UV or EB is a better choice. A clear understanding of the differences between UV and EB can facilitate a selection of which technology is best suited to the end-use application.

UV and EB Energy Considerations

There are some fundamental differences between UV and EB energy that provide the foundation for understanding the technologies. The smallest "bit" of UV energy is the photon that is known to have both particle and wave-like characteristics.

The energy for photons is determined by the wavelength. The range of wavelengths for UV curing applications is typically about 250 to 450 nm. The shorter the wavelength, the higher the energy. Wavelength units may be converted to other energy units for comparison. For example, a 350 nm photon is equivalent to 3.5 electron volts (eV). UVcuring processes are often characterized by the total amount of applied UV energy impinging per unit surface area (also known as the irradiance). The UV energy needed for a curing process depends on the material and the application. For an ink, coating or adhesive for a packaging application, the UV energy typically ranges from about 0.1 to 0.5 J/cm.[2]

The smallest "bit" of EB energy is the electron. The energy of the electrons is determined by the accelerating potential of the EB equipment. The range of accelerating potential used for typical packaging applications is about 80 to 180 kV. The electrons lose some energy when passing through the foil window and the air space between the window and the substrate. For example, the electrons from an EB unit operating at 100 kV have an average energy of about 70 keV when they reach the substrate. EB curing processes are often characterized by the total amount of energy absorbed per unit mass of the substrate (also known as the cure dose). The dose for EB curing depends on the material and the application. For an ink, coating or adhesive for a packaging application, the cure dose typically ranges from about 20 to 40 kGy (2 to 4 Mrads).

It is interesting to compare the energy of a typical UV photon (3.5 eV) to an EB electron (70,000 eV). Clearly, EB electrons are much more energetic than UV photons. This has a significant impact on how this energy interacts with the media to be cured. The typical chemical bond energy in an organic material that is the basis of an ink, coating or adhesive is on the order of 5 eV. Curing reactions are initiated with the breaking of a chemical bond. Since UV photons have less energy than the bond energy, they cannot initiate curing on their own. A photoinitiator is needed which can be activated by the lower energy photons. The energy of the EB electrons easily exceeds the bond energy of the curable materials; thus they will initiate curing without an added photoinitiator. EB is also known as ionizing radiation because of its ability to break chemical bonds. UV is non-ionizing radiation.

In addition to considering the energy of the individual photons and electrons, it is useful to compare the total energy applied in the curing process. As can be seen from the discussion above, UV curing is characterized by the energy absorbed per unit area (irradiance), while EB curing is characterized by the energy per unit mass (dose). If one considers a given thickness and density of the substrate, it is possible to make a direct comparison of the total applied energy in UV- and EB-curing processes. A typical modern low-voltage EB unit operating at 125 kV will penetrate into a 50 g/m² layer.

Thus, given 1 kGy = 1 J/gram, and assuming a 50 gram/m² substrate, then; 20 to 40 kGy = 0.1 to 0.2 J/cm² for typical EB curing compared to: 0.1 to 0.5 J/cm² for typical UV curing.

The lesson from this exercise in energy unit conversions is that although EB electrons are much more energetic than UV photons, the total amount of energy applied in a typical curing process is not all that different.

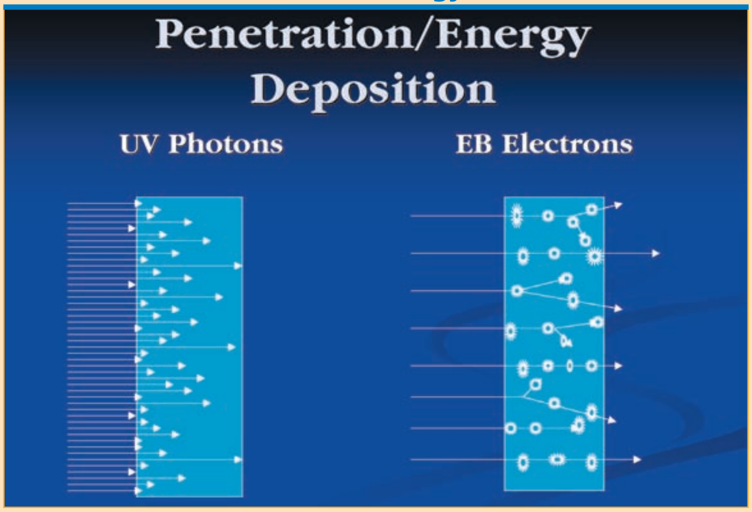
UV and EB Penetration

The nature of the energy determines how it penetrates into a material. Curing can only occur in areas that are effectively exposed. Figure 1 provides a cross-sectional illustration of the differences between UV and EB penetration.

Penetration of UV energy depends on the optical density (OD) of the

Figure 1

Penetration of UV and EB energy



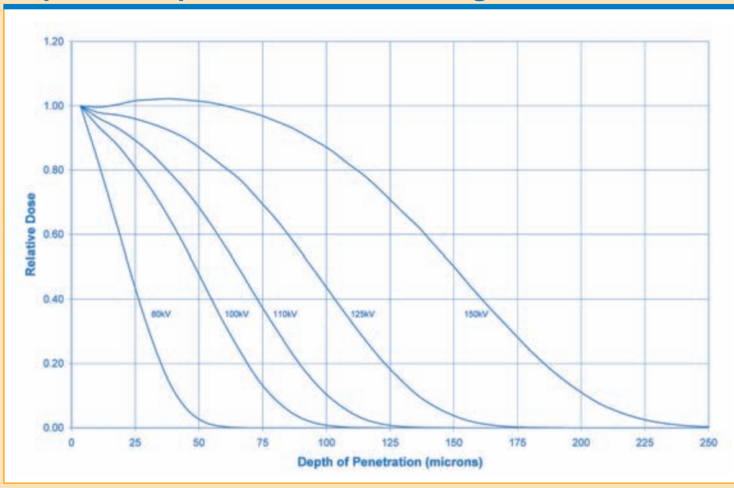
material. Clear materials are "optically thin." In general, UV energy can easily penetrate clear materials such as overprint coatings and clear films. Even if a portion of the UV spectrum is blocked by a clear layer (such as a PET film), effective curing can usually be achieved throughout the thickness of the layer by selecting the proper photoinitiator package. Penetration of UV energy becomes a significant challenge when curing "optically thick" pigmented materials. Many pigmented printing inks can be UV cured as long as the pigment loading and/or ink thicknesses remain relatively low. It is typically difficult to UV cure through printed, white opaque, heavy black or metallic inks.[3]

Penetration of UV energy can be controlled, to a degree, by the peak irradiance of the lamp. The peak irradiance depends on the power and the focus of the lamp system. High-power, tightly focused lamps can improve curing of some higher OD ink layers[4]; however, the OD can reach a point in which curing is not possible with any commercial lamp system.

EB penetration depends upon the mass density and thickness of the material. Electrons penetrate more deeply through lower density materials (such as polyolefin films and paper) compared to high-density materials such as metal foils. Mass density and thickness taken together may be expressed as the basis weight of the material. For most printing and packaging applications, the basis weight is expressed in units of grams/meter^2 or pounds/3000 ft^2. Electrons are "color blind" and penetration is not affected by pigments and opaque substrates. EB is ideal for curing high-opacity white, black and metallic ink layers. EB can also penetrate reverse printed, metalized and white films as well as papers to instantly cure adhesive layers for laminating applications.[5]

Figure 2

Depth/dose profiles for low-voltage EB



EB penetration is controlled by the accelerating potential (voltage) of the EB equipment. Figure 2 shows EB penetration as a function of voltage. Low-voltage EB equipment operating from about 70 to 125 kV is ideal for curing thin inks, coatings and film layers used in most printing and packaging applications.[6]

UV and EB Equipment

The most common UV equipment for printing and packaging applications is based on medium-pressure mercury lamps. These lamps may be energized through electrodes (arc type) or by microwaves (electrodeless). Medium-pressure mercury lamps produce a characteristic UV-emission spectrum with multiple peaks between 250 nm to 450 nm. Mercury lamps may also be doped with various elements to shift the spectral output to better match the inks, coating or adhesive that is being cured.

Other types of lamps, such as xenon lamps, are available but are not commonly used for printing and packaging applications. UV-light emitting diodes (LEDs) are now available with higher powers, but their use is still quite limited in printing and packaging materials.[7]

EB equipment is based on electrically operated filaments and grids contained within a vacuum chamber. The electrons are accelerated through a window/foil structure to reach the substrate at atmospheric pressure. EB equipment includes "curtain" and scanning type units. The curtain type is used almost exclusively for printing and packaging applications. Most EB equipment includes an active pumping system to maintain a vacuum in the electron gun chamber. A new generation of modular 10- and 16-inch wide EB equipment based on permanent vacuum emitters is also now available. There have been some initial investigations incorporating these modular emitters in printing applications.[8]

UV and EB Equipment Safety

UV lamps used in printing and packaging applications produce significant short wavelength UV output. This intense UV energy can cause skin and eye damage. Commercial UV lamp equipment used for printing and packaging applications is completely shielded and interlocked to contain the damaging UV energy. In most cases, no special personal protective equipment (PPE) is required other than the PPE normally recommended in the printing and packing production plant environment. In addition to UV energy hazards, mercury lamps also operate at very high temperatures. Hazards from thermal skin burns are minimized by the lamp housing which surrounds the bulb.

Electrons from EB equipment present limited hazards because of their limited ability to penetrate. The main hazard of EB is the secondary X-rays that are generated when electrons interact with matter, including metal components within the EB reaction chamber. Modern EB equipment is completely self-shielded. The shielding is interlocked and monitors are present which will shut down the EB unit if X-rays are detected. Radiation is not present if the machine is not energized. Most EB installations will include a person trained as a Radiation Safety Officer (RSO). Periodic radiation surveys are typically conducted to supplement the continuous monitoring of the equipment. Worker exposures above normal environmental background levels are extremely rare.

Both UV and EB equipment are very safe to operate and there are no significant drivers for selection of one technology over the other based on safety.

Equipment Size

The components of typical UV curing systems include the lamp, power supply, air handling equipment (blowers) and control panels. These components are pictured in Figure 3. The lamp (which includes the bulb, reflectors, shielding and heat management components) is relatively compact and lends itself well to interstation installation between printing decks (Figure 4). Interstation installation allows curing of each ink color. Multiple colors are combined in a "dry trapping" process to create the graphic image. Interstation curing also allows press designs in which the printed side of the web may be turned up against an idler roll between stations.

Original industrial EB equipment was quite large (Figure 5). Modern low-voltage EB equipment can be less than one-half the size of original industrial EB equipment. In spite of the size reduction, it is still not practical to use this equipment for interstation curing; though the smaller footprint is still very attractive for end-of-press installations.[9] The most common installation of this type of equipment is at the end of a web offset press used for the production of folding cartons (Figure 6). Offset (lithographic) printing uses paste inks which are designed to be "wet trapped" without any interstation drying. This lends itself well to EB curing at the end of the press with a single EB unit. The development of modern low-voltage EB equipment coincides nicely with the development of web offset presses incorporating variable repeat length technology. This has facilitated expansion of web-offset printing technology beyond folding cartons to flexible packaging and labels.[10]

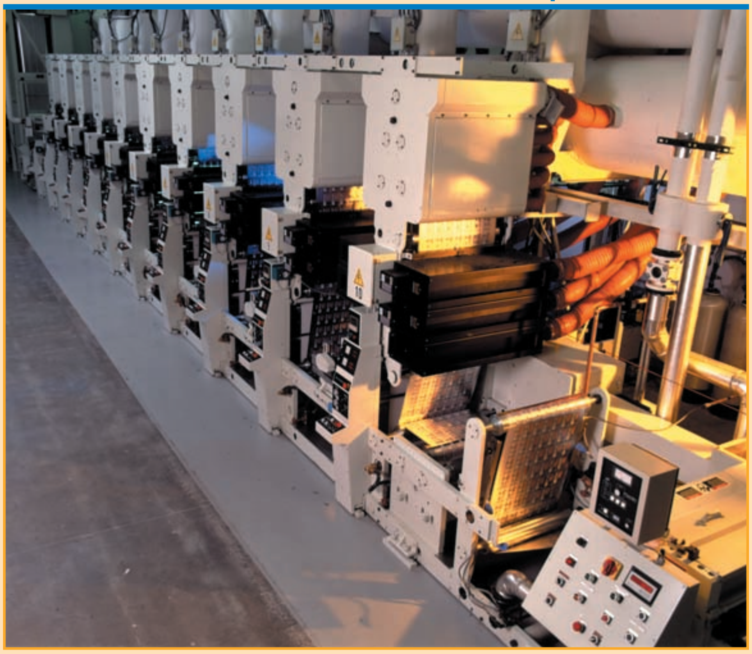
Flexographic printing utilizes liquid inks so, historically, it has been necessary to use interstation curing to dry trap inks. This interstation curing has been achieved by thermal or UV curing technology. Recently new technology (Wetflex™) has been developed to wet trap flexographic inks.[11] Wet trapping allows interstation curing to be eliminated and replaced with a single EB curing station at the end of the press (Figure 7). This technology has also been shown to give extremely low dot gain which results in superior quality printing. It should be noted that Wetflex is limited to central impression (CI) flexo press configurations in which the printed side of the web does not contact idler rolls until after EB curing. Flexographic CI printing is often the preferred

Figure 3

UV Lamp system components

Figure 4

Interstation UV installation on a flexo press



method for flexible packaging since it provides superior handling of extensible film substrates.

New permanent vacuum modular low-voltage equipment makes it possible to consider interstation EB curing. So far this does not appear to be a commercial reality, but it is an area for potential future development.

Capital Costs

The cost of a UV lamp for a narrow application is relatively low. For many printing and packing applications, a single lamp operating at input powers up to 600 w/in will cure a single ink or topcoat up to about 300 to 400 feet/minute. Installation of six or more press stations running at 800 to 1,000 ft/minute could require 12 or more lamps.

Original industrial EB curing units typically cost more than $1 million. Modern low-voltage equipment has reduced the cost by at least half. A single EB unit is capable of delivering 30 kGy (3 Mrad) cure dose at greater than 1,000 ft/min. As discussed above, multiple wet-trapped ink and coating layers may be cured with this single unit. EB curing units are easily sized for wide-web (>60 inches) printing applications.

Even though a single UV lamp is significantly lower in cost than an EB unit, when one considers the total capital cost of a wide, high-speed line, EB may be comparable or lower in cost than a multilamp UV installation.

Operating Costs

One of the primary advantages of UV and EB curing is the reduced energy costs compared to thermal drying ovens.[12] Another major component of the operating expense is the cost of the inks, coatings and adhesives. When comparisons are made based on the "solids" that are applied, it may be seen that the cost of UV/EB materials (which are near 100% solids) may not command a significant premium.

In general, there does not tend to be a significant difference in cost between UV and EB inks, coatings and

Figure 5

Industrial EB processing equipment

Figure 6

Low-voltage EB equipment on web offset press

adhesives for printing and packaging applications. This may be due in part to a declining cost of photoinitiators following the expiration of some key patents. Comparison of UV and EB operating costs is, therefore, more related to the equipment itself.

With mercury-based UV lamps, about one-half of the electrical energy input is converted to UV energy. The remaining energy is lost as heat. Some additional electrical energy is consumed in the operation of blowers for air cooling which is most common for printing and packaging applications.

EB equipment is more efficient at converting electrical energy into curing energy compared to UV equipment. Some additional electrical energy is needed for vacuum pumps and water cooling of the emitter. Another operating cost of EB is nitrogen, which is needed to inert the curing zone for most ink and coating applications.

A detailed comparison of operating costs for UV and EB can be made for a specific application. Often, this analysis will show similar costs for UV and EB and significant savings compared to thermal curing.

Inerting

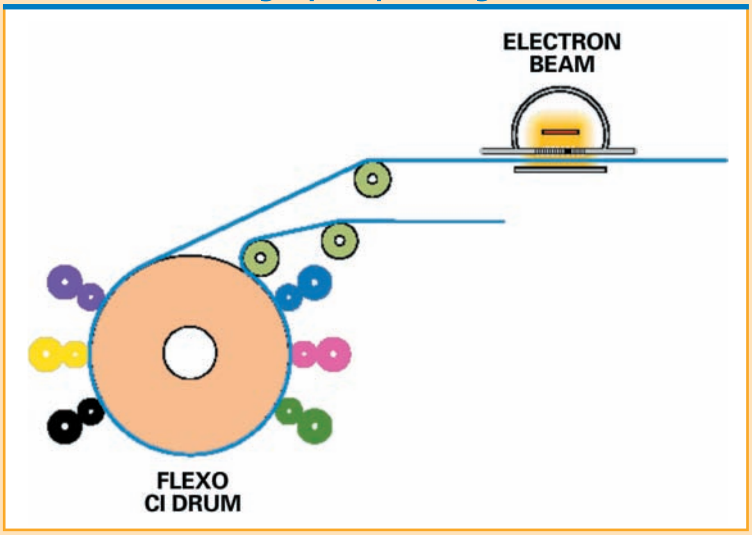
Free radical curing—commonly used in both UV and EB applications—is inhibited by atmospheric oxygen. Oxygen itself exists in a biradical (triplet) state and will rapidly diffuse into the surface of an ink or coating and terminate the polymerization (curing) reaction.

UV formulations can be designed to cure in an air atmosphere. In air curing systems, the radical initiation essentially outcompetes the oxygen termination. This is possible because of the high surface irradiance illustrated in Figure 1. The ability to UV cure in air can be advantageous for some printing and packaging applications. In particular, air curing is very important in sheet-fed printing. Sheet-fed equipment is very difficult to inert because of the mechanisms present to transport the sheet through the press.

In some cases, it may be advantageous to inert UV-cured systems. Inerting can greatly accelerate UV curing which can increase line speed, reduce the number of lamps, and/or reduce the amount of photoinitiator needed for curing. Inerting may be an attractive option for food packing applications in which

Figure 7

WetFlex™ EB flexographic printing



migration of the photoinitiator and their fragments may be a concern.

EB curing of free-radical inks and coatings requires inerting to displace the atmospheric oxygen in the reaction chamber of the cure unit. EB energy is deposited more evenly throughout the thickness of the ink and coating. The absence of excess energy at the surface does not allow curing reactions to compete with oxygen termination (Figure 1).

EB laminating involves irradiation of the adhesive that is contained between two layers of substrate. EB laminating does not require inerting because the substrates are generally effective at preventing the diffusion of oxygen into the adhesive layer.

Inerting is most commonly achieved with nitrogen gas. Nitrogen serves to displace oxygen from the reaction chamber. The most common source of the nitrogen gas is a tank of liquid nitrogen. The liquid offers the high-purity nitrogen and volume needed for the curing process. Most modern EB equipment is designed with nitrogen knives to remove the surface boundary layer of air. Optimized inerting systems can reduce the amount of nitrogen that is used.[13]

Effect on Substrates

Since EB is ionizing radiation, it may affect the thermal and mechanical properties of substrates. EB affects different polymer films in different ways. References are available which describe the effects. Fortunately, with the relatively low dose (20 to 40 kGy) used in most curing applications, the effects are minimal and the films are still fully functional for the intended application. Another strategy to minimize film damage is to use low voltage in the range of 70 to 110 kV. These voltages allow the beam to easily penetrate the coating and ink layer while minimizing the energy at the inner (food contact) layer. This is particularly important when the inner layer is designed to be heat sealed when the packaged is filled and sealed.[14]

In some cases where porous substrates (such as paper or cavitiated films) are used, it can be advantageous to use EB to cure materials which have penetrated into the substrate.

EB's effect on the substrate can be beneficial. Cross-linking may enhance the properties of some polyethylene-based films. EB-induced ionization of the film surface may result in enhanced adhesion by grafting of the ink or coating layer. EB can also potentially be used for simultaneous curing and surface sterilization of the food contact layer.

Since UV is non-ionizing radiation, effects on the substrates are minimal. Since grafting is not expected, a primer layer may be needed for adhesion to some films.

Heat Control

Mercury lamps used for UV curing produce significant heat. This is due to high temperatures needed to create and maintain a plasma within the quartz bulb. Approximately one-half of the electrical energy input into the lamp is converted to heat (IR) energy. UV systems for printing and packing applications are commonly cooled by moving high volumes of air over the lamp. Water-cooled lamps are also available.

Many packaging films may be adversely affected by heat from the lamps. High-speed transport of the substrate under the lamp minimizes heat exposure. Most arc lamp-based web systems include shutters to prevent the web from burning when it is stopped. Other strategies used to minimize lamp heat effects on the substrates include dichroic reflectors, hot mirrors and chill drums.[15]

EB is a cooler process compared to UV. Some internal components of the EB emitter (including the window) utilize water cooling. Little heat is transferred to the substrate which allows most packaging films to run without any effect on the dimensional stability of the film. A chill drum may be integrated into the EB unit for applications that are very sensitive to heat. In this configuration the substrate is in direct contact with the chill drum during irradiation.

In general, there does not tend to be a significant difference in cost between UV and EB inks, coatings and adhesives for printing and packaging applications.

Food Packaging

UV-curable coatings and inks have been used in food packaging applications for many years. These applications are possible with packaging designs that include a functional barrier between the ink or coating and the food. Taint and odor problems can usually be prevented by using properly formulated UV-curable inks and coatings. Photoinitiators and photoinitiator fragments can be a source of concern for migration, odor and taint. New systems have been developed that include polymeric photointiators, reactive photointiators,[16] and oligomers that contain a "built-in" photoinitiator moiety.[17] Some of these systems have been effective but may still lack cost/performance properties needed for practical applications.

Since EB does not require an initiator, it is often considered to be more "food friendly." EB-induced breakdown of components of inks, coatings, adhesives and substrates may be a source of other taint, odor and migration issues that merit investigation for a given application.

In many packaging constructions, the functional barrier is obvious and there is no reasonable expectation of adulterating the food. Examples include labels on rigid containers and folding cartons that have an additional inner layer of packaging around the food. There are many constructions in which the barrier is less obvious. This may include cases in which a relatively thin polyolefin film is the only layer between the UV/EB material and the food. It may also include applications in which the UV/EB printed/coated surface is in contact with the food contact surface during roll-to-roll or cut-and-stack processing of the packaging allowing off-setting to occur prior to filling. Migration testing or calculations can often be used to establish food law compliance in these cases.[18] The recent successful Food Contact Notification (FCN) can also help assure food law compliance and provide additional assurances for end-users.[19]

Consistency/Maintenance

Process consistency and maintenance required to assure product quality may also merit consideration when comparing UV and EB technology. The output of UV lamps will decrease as the lamps age. This decrease may not be uniform across the spectral output with short wavelengths output degrading before longer wavelengths. This can affect the surface versus throughcure characteristics of the process. The aging may also not be uniform across the width of the lamp causing inconsistent curing at the edges of the sheet or web relative to the center. The process itself may be able to tolerate this variability in lamp output. The most common way to minimize the variability is by preventive maintenance which consists primarily of bulb replacement and reflector cleaning or replacement. The typical lamp maintenance interval is about 1,000 to 3,000 hours. The cleanliness of the process can have a major effect on the need for maintenance. Ink mist, paper dust and other sources of contamination will shorten the useful life of the lamp. Lamp temperature control is also critical for maximum life.

EB output tends to be very consistent with time. No significant change is expected with age. Variability in cross-web uniformity is typically less than 10%. Essentially, all EB systems are directly linked to line speed. Beam current automatically ramps to maintain a constant cure dose at all speeds. The typical preventive maintenance interval is 4,000 to 8,000 hours and mainly involves changing window foils and filaments. Factors affecting the EB maintenance cycle are process cleanliness and window temperature control.

One factor to consider is that when an EB unit is down for maintenance the process must stop. With a multilamp UV system, it may be possible to slow but not stop the process while waiting for repairs on one of the lamps.

Measurement

Measurement is critical for maintaining a constant process for UV and EB. There is a wide range of radiometers available to measure the output of UV lamp systems. These include electronic probes which may be temporality inserted or fixed in the lamp housing. Radiometers are also available which can be attached to the moving substrate.[20] UV-sensitive films are available that can attach to a substrate and not interfere as they pass through press stations or rollers. The films may produce a visible color change or require a subsequent optical reading which is related to the UV exposure.[21] The limits of each type of radiometer must be understood in order to be used effectively.

The most common type of EB measurement involves exposure of thin films containing radiochromic indicators. The optical changes in the films are subsequently measured against calibration cures which are generated from films traceable to NIST standards.[22]

Conclusions

UV and EB are environmentally sound technologies well suited for printing and packaging applications. The selection of UV or EB should be based on the best fit for the selected application. For some applications the choice is obvious. Others may require a cost/benefit analysis in order to make the best choice. ◗

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