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The use of UV LED technology for industrial curing applications has been steadily gaining traction since its introduction in 2002. Most of the early adoption occurred in the areas of UV digital inkjet, screen printing, structural bonding adhesives, and coatings and sealants for electronic assemblies. With regard to flexographic printing, the first UV LED equipped press was formally introduced to the world at Label Expo 2009 by Gallus Group, Siegwerk, and Phoseon Technology. It utilized the best UV LED lamp and flexo ink technology that was available at the time. This was a significant event in the converting industry and one which generated curiosity and market buzz but unfortunately no real commercial adoption. The tag and label industry simply did not believe that the technology was sufficiently proven to move forward with integration in 2009. A few years later at Label Expo 2012, Mark Andy, Phoseon Technology, and Flint Group launched the first fully integrated commercial UV LED press offering. It too generated curiosity and market buzz but with the more positive outcome of actual UV LED press sales.

It has been ten years since the Gallus UV LED flexo unveiling and six years since Mark Andy's. While the market adoption has not been as rapid as originally anticipated, it has certainly been steady in its growth. In fact, there are now over 250 narrow-web presses and over 10 mid-web and wide-web presses installed globally. In total, these 260 plus lines are equipped with more than 1,200 UV LED stations and include new press purchases with UV LED technology as well as field retrofits of previously installed machines. These flexo presses include anywhere from 1 to 13 UV LED curing stations each and represent over 5 years of continuous converter utilization.

North America has clearly led in UV LED flexo adoption, but there is growing activity today in both EMEA and APAC. In fact, considering all of the formulation, press, and LED capabilities now available to the market; an increasing number of formulation and UV LED suppliers; growing interest and activity within both independent and multi-national converters, and downward price pressure on equipment and formulations, it is a reasonable expectation that UV LED will be mainstream within the narrow-web flexo market by 2020. Mid-web and wide-web conversions are also poised to grow significantly but will lag narrow-web slightly in growth rate since the majority of wider web presses predominantly run aqueous and solvent based formulations today. That said, there is growing interest in the central impression and stack press world for single, dual, and fully equipped UV LED printers.

Market Factors Affecting Web Converters

Various global market factors are placing increasing pressure on converters as well as the traditional print process as illustrated in Figure 1. Brand owners are increasingly demanding while simultaneously insisting on price reductions. Just in time production as well as the trend toward locally directed packaging and shorter run lengths are pushing logistics, operating costs, and press performance to the limits at a time when press operators are already in short supply and margins are razor thin. The industry is trying to understand, navigate, and optimize the convergence of analog and digital print technology. Environmental and sustainability initiatives are increasingly rooted in all aspects of the supply chain, and the desire to expand market share is driving both narrow-web and wide-web converters into the mid-web flexible packaging space. All of these factors present a tremendous opportunity for innovative technologies such as UV LED curing to provide relief and performance optimization as converters seek to improve yield, efficiency, reliability, operating costs, and overall process control as well as develop new label and packaging offerings that cannot currently be produced with conventional UV curing systems.

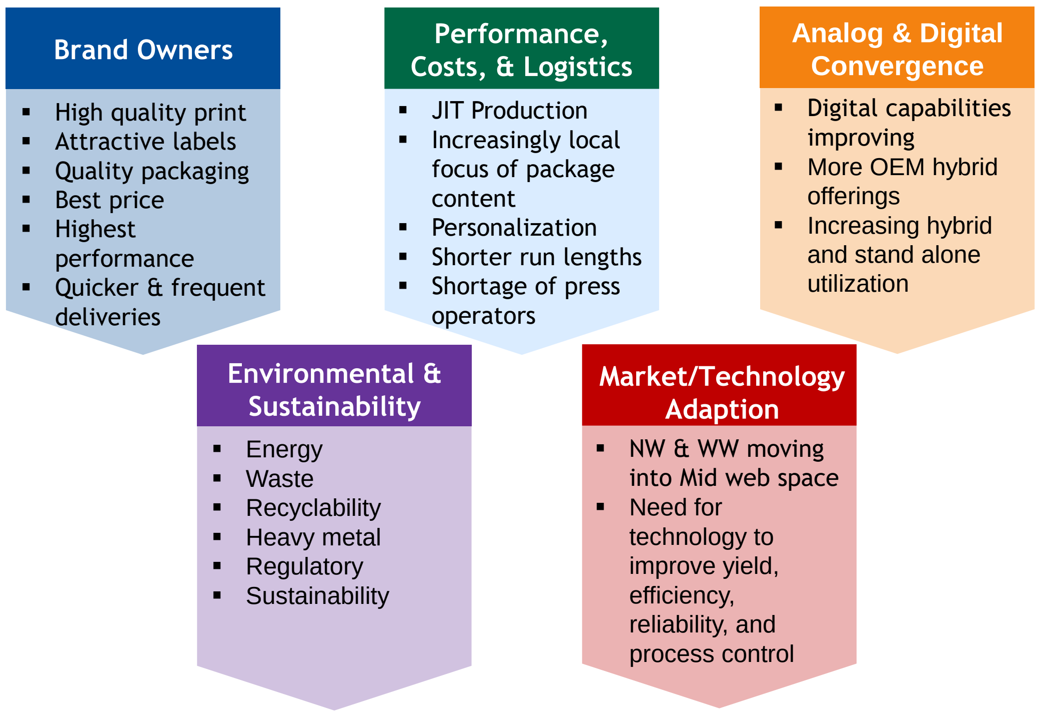

Figure 1: Market Factors Affecting Web Converters

UV LED Technology Positively Impacts Converters

Fortunately, UV LED curing technology positively addresses current converter issues due to its more productive, more reliable, and more repeatable performance characteristics along with its ability to generate high quality print more economically. Refer to Figure 2. From a production perspective, UV LED curing eliminates unplanned line stoppages associated with conventional mercury lamps which require frequent bulb and reflector replacements and shutter repairs. UV LED technology is instant ON/OFF which means it's always ready to cure. Lower production speeds for bottleneck curing stations such as white inks can typically be increased 10 to 30% with less overall waste and scrap. Dual station whites can often be replaced with a single hit of white. The combined result is more total press up time and a production machine that is better suited for just in time deliveries, both short and long run lengths, and more frequent job changes.

In general, Phoseon UV LED technology is more reliable, more stable, and more consistent in its output, lasting well in excess of 20K hours with minimal degradation. By comparison, conventional mercury lamps begin degrading from the first second they are turned ON. This is due to the fact that the quartz material that forms the mercury bulb is opaque in its natural state and does not optimally transmit UV light. The bulb manufacturing process transforms the quartz into a translucent material conducive to UV transmission. The conditions of UV lamp operation continuously expose the quartz to damaging short wavelength UVC and UVB rays as well as heat which immediately begins to revert the quartz back to its natural opaque state blocking a large portion of the UV output. As a result, conventional UV lamps used in flexographic presses only last between 500 and 1,500 hours typically.

Figure 2: UV LED Positively Affects Converters

UV LED curing systems are solid state digital devices that can be infinitely adjusted from as low as 1 to 10% up to 100% of the maximum UV output. The response time in UV LED adjustment is immediate allowing for the UV output to be scaled real time with press speed. Predictable and controllable curing enables repeatability of jobs and essential process control for low migration printing on food packaging. Mercury lamps, on the other hand, typically have stepped power levels as well as a lower power level limit. The lower limit is due to the fact that forced cooling air from the blower will over cool the bulb when insufficient wattage is applied and consequently extinguish the light. Overcooling is not an issue with UV LED technology.

UV LED technology is more economical than conventional UV in that it can reduce energy consumption up to 50%. It also reduces necessary support infrastructure such as exhaust blowers which typically require roof penetration, make-up air exchange systems which are often climate controlled, and larger power delivery systems. Added benefits include improved safety and environmental conditions due to the lack of mercury, UVB, UVC, and ozone as well as cooler lamp operating temperatures. From a high quality print perspective, UV LED offers full color gamut curing, better through cure and adhesion, reduced heat transfer to the substrate, more opaque whites, brighter fluorescents, truer metallics, and laminating adhesives with desirable destruct bonds.

Commercial State of UV LED Formulations

There is currently a full range of narrow-web UV LED process solutions available with more targeted and specialty formulations in development. The previous six months have seen the introduction of gloss and matte OPVs that cure at press speeds between 900 and 1,000 fpm with little to no yellowing as well as the first UV LED silicone release coating that cures at press speeds of 400 fpm. Many in the industry still believe it is not possible to cure coatings with UV LED at these speeds, but it is! Additional UV LED market offerings include laminating adhesives, fluorescents, metallics, cold foil adhesives, primers, and low migration inks. Refer to Table 1 for press speed ranges achievable with the various formulations.

Table 1: State of UV LED Formulations

UV LED Type	Max Press Speed (mpm)	Max Press Speed (fpm)	Notes
Inks	300	1,000	Line, Process, and High Density
OPVs	300	1,000	Matte and Gloss
Metallics	210	700	Truer and better with LED
Fluorescents	300	1,000	Brighter
Low Migration	120 to 210	400 to 700	Similar speeds to conventional UV and driven by extraction targets
Laminating Adhesives	>300	>1,000	Can cure as fast as press can run. Restricted by other process variables.
Cold Foil Adhesives	60 to 75	200 to 250	Can cure as fast as press can run. Restricted by other process variables.
PSA's	75	250	Similar speeds to conventional UV
Primers	300	1,000	Similar speeds to conventional UV
Release Coatings	120	400	Need surface cure
Specialty	Varies	Varies	Developed as needed by market and driven by volume and interest of formulator

In order to address converter preferences of not stocking two formulation sets (conventional and UV LED), most formulators are moving toward dual cure formulations. While conventional formulations are only optimized for mercury lamps, dual cure formulations are designed to work equally well with both UV LED and mercury. It won't be long before most of what converters are purchasing for their conventional UV lines is in fact fully formulated for the UV LED lines that they may not have even yet adopted.

Some converters have reported some issues with insufficient adhesion to some media or construction materials when using UV LED technology. Others have experienced viscosities that build over time and then lead to spitting and slinging issues at high speed. In the vast majority of cases, these issues are mostly caused by 1) a mis-matched UV formulation with the process or substrate, 2) the use of lower grade or aged constructions where certain components of the material bloom to the surface and decrease the surface energy resulting in poor adhesion, 3) less than optimal doctor blade selection or pressure, or 4) insufficient system maintenance and formulation handling. None of these application issues should be viewed as a detraction against UV LED technology itself as most can be resolved on press through mechanical adjustment and GMPs. These issues are similarly experienced with conventional UV technology and have been sufficiently remedied when they occur.

There is great satisfaction amongst those who have converted and properly "matched" LED to their application needs; however, fear of the unknown and risk aversion lingers amongst those who haven't converted or taken the time to properly evaluate market offerings. There is a general lack of understanding of UV LED technology in the label and packaging markets which makes it difficult for converters and press OEMs to adequately assess the differences in product offerings. The industry as a whole is working to improve its messaging and demonstrate the proven UV LED solutions that exist today. Refer to the paper *Characterizing UV LED Curing Systems* by Jennifer Heathcote, Phoseon Technology, for a detailed explanation of the differences in commercial UV LED curing systems and how to navigate the selection process.

Commercial State of UV LED Dryers

The designs of UV LED curing systems have advanced steadily over the previous 15 years, and the number of suppliers and product offerings has recently exploded. Web width is no longer an issue for UV LED with narrow, mid, and wide-web solutions installed globally today. Mid and wide-web UV LED assemblies can be designed as long, single UV LED heads or shorter, modular configurations with heads mated end-to-end to span any web width. While most systems currently sold into the flexo market are liquid-cooled, there is a major trend toward air-cooling which eliminates the need for a chiller. In terms of UV output, all UV curing sources including LED, arc, and microwave can be characterized according to spectral wavelength (nm), peak irradiance or intensity (Watts/cm2), and energy density or dose (Joules/cm2). These three characteristics should be matched to the needs of the press and intended converter production portfolio in order to deliver the most effective solution and meet performance targets.

While commercial UV LED systems are marketed at peak irradiances of up to 16 Watts/cm^2 for air-cooled and up to 50 Watts/cm^2 for liquid-cooled, the viable flexo irradiance range is actually 12 to 20 Watts/cm^2 with press speed actually driven by the delivered energy density (J/cm^2) and not the irradiance. It should be emphasized that a specified peak irradiance (W/cm^2) provides absolutely NO insight into delivered energy density (J/cm^2). In other words, not all 16 Watts/cm^2 UV LED systems deliver the same energy density, and in many cases, the emitted values are not even close. Furthermore, a high peak irradiance does NOT guarantee a high energy density.

What is not commonly understood is that a higher energy density is the necessary component to achieve faster press speeds and more thorough cure. Insufficient energy density contributes to tracking, offsetting, poor adhesion, odor, and uncured print particularly at speeds greater than 400 fpm. There are major energy density differences across UV LED products and vendors. Systems that supply sufficient energy density are capable of delivering quality cure at press speeds of 1,000 fpm and beyond.

Commercial UV LED wavelengths include 365, 385, 395, and 405 nm; however, the vast majority of flexo installations are equipped solely with 395 nm. Lab and field testing does not presently show any significant benefit to blending one or more of these longer wavelengths inside a single UV LED head; although, blended products sold on the market mistakenly claim otherwise. For most formulations, the chemistry really doesn't notice any significant difference across a span of 365 to 405 billionths of a meter; however, formulators generally prefer shorter wavelengths whenever possible due to the absorption characteristics of photoinitiators which logically drives them to recommend blended or shorter wavelengths. The benefit of blending just doesn't show up in practice, and 395 nm wins the real world application battle in most cases. It should be noted that of the four wavelengths, 395 nm is the most efficient and cost effective which is why the industry has generally standardized on this output.

Energy Density Insights

By definition, peak irradiance (Watts/cm^2) is the *radiant power* arriving at a surface per unit area. It is instrumental in penetration through the ink, coating, or adhesive. For UV LEDs, higher irradiances have also been shown to aide surface cure. Energy density (Joules/cm^2) is the *radiant energy* arriving at a surface per unit area, and a sufficient amount is absolutely necessary for full cure. In other words, peak irradiance is the delivered power, and energy density is the total delivered energy. In mathematical terms, energy density is the integral of irradiance over time. It is important to emphasize that for a given lamp output, peak irradiance remains constant with changes in press speed while the delivered energy density to the media decreases as press speeds are increased due to the media's shortened exposure time to the UV LED source. Refer to figure 3. Equally important to understand is that a percentage increase or decrease in peak irradiance of the UV LED head results in the same percentage change in energy density.

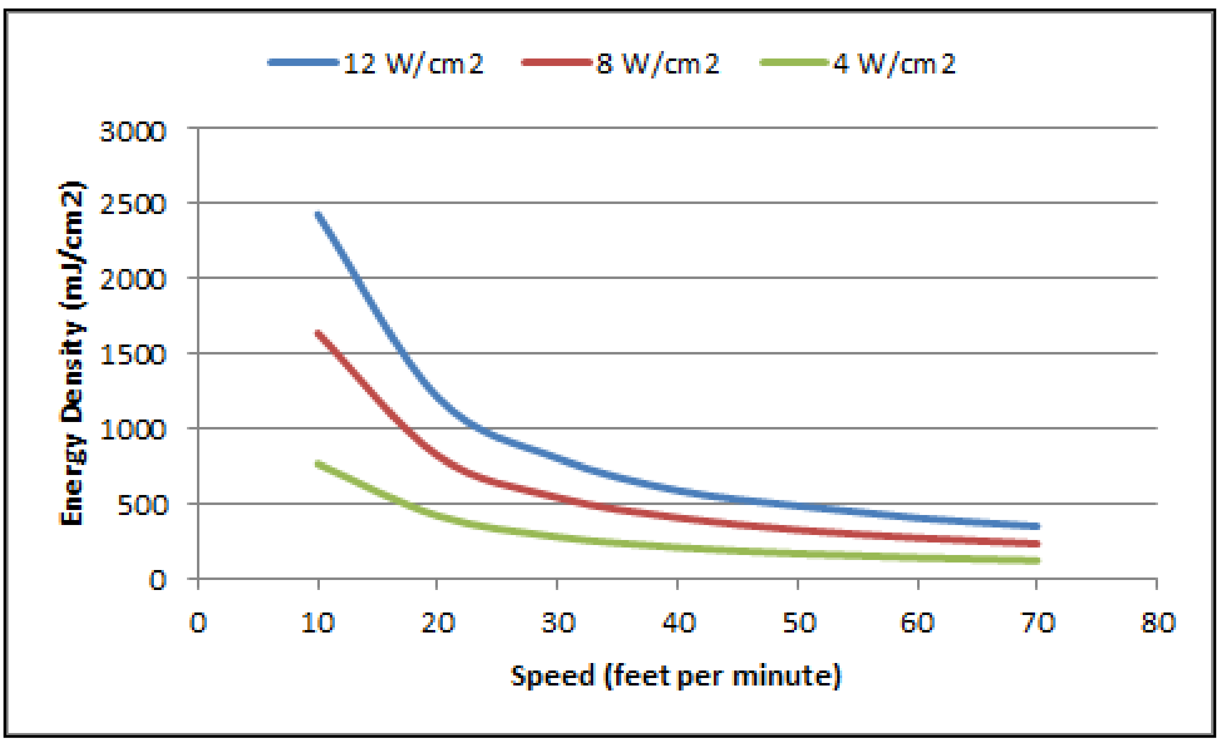

Figure 3: Energy Density vs Speed for Different Peak Irradiance Values.

Inks, coatings, and adhesives require a minimum threshold of irradiance for optimal cross-linking. The industry has really never studied whether maximum threshold irradiance is something that matters. Consequently, conventional UV curing systems are almost always run at 100% regardless of whether full power is needed.

Today, UV LED systems can be designed with irradiance levels over 10 times that of the highest irradiance levels for conventional UV systems. New research is revealing that in some cases, too high of an irradiance can result in diminishing cure as too many polymeric chains start reacting at the same time and ultimately terminate prematurely. There is an irradiance process window that should be defined for each application. It's not narrow, but there is likely both a minimum and a maximum limit for most formulations.

Over the past 15 years, the reaction in the chemistry has generally improved as the peak irradiance has increased. This has led to suppliers pushing increasingly higher irradiance products, formulators recommending increasingly higher irradiances for their chemistry, and integrators and end users making UV LED purchasing decisions solely based on this single specification of peak irradiance. It has been generally assumed by most of the industry that the improvements in cure had everything to do with the increasing irradiance alone; however, it was actually the proportional increase in energy density that was improving the cure. In reality, if the selected UV LED system is having trouble curing at the desired process speed, increasing the irradiance will often help but only to a point. After that, the focus should be on delivering more energy density (Joules/cm^2) through a different higher energy density UV LED source or through multiple lamps. Don't fall into the trap that a higher irradiance is always the answer. Sometimes turning the irradiance down and providing more energy density is the way to actually improve cure and line speed.

It must be emphasized that while energy density increases proportionally with increases in irradiance for *a given UV LED source* (i.e. doubling the irradiance for a given source will double the original energy density), a high irradiance does not necessarily guarantee a high energy density if it's not built into the source design. Sources with the same irradiance but dissimilar energy densities will actually diverge quite rapidly from each other in terms of energy density as irradiance is similarly increased. Refer to Figure 4 which shows 4 different products emitting drastically different energy density values for the same peak irradiance levels. Product D in the graph illustrates that it is entirely possible to generate greater energy density at lower peak irradiance as compared with products B and C. Energy density is one of the biggest reasons that not all products cure equally on high speed presses. The systems may emit the same peak irradiance, but they do NOT emit the same energy density.

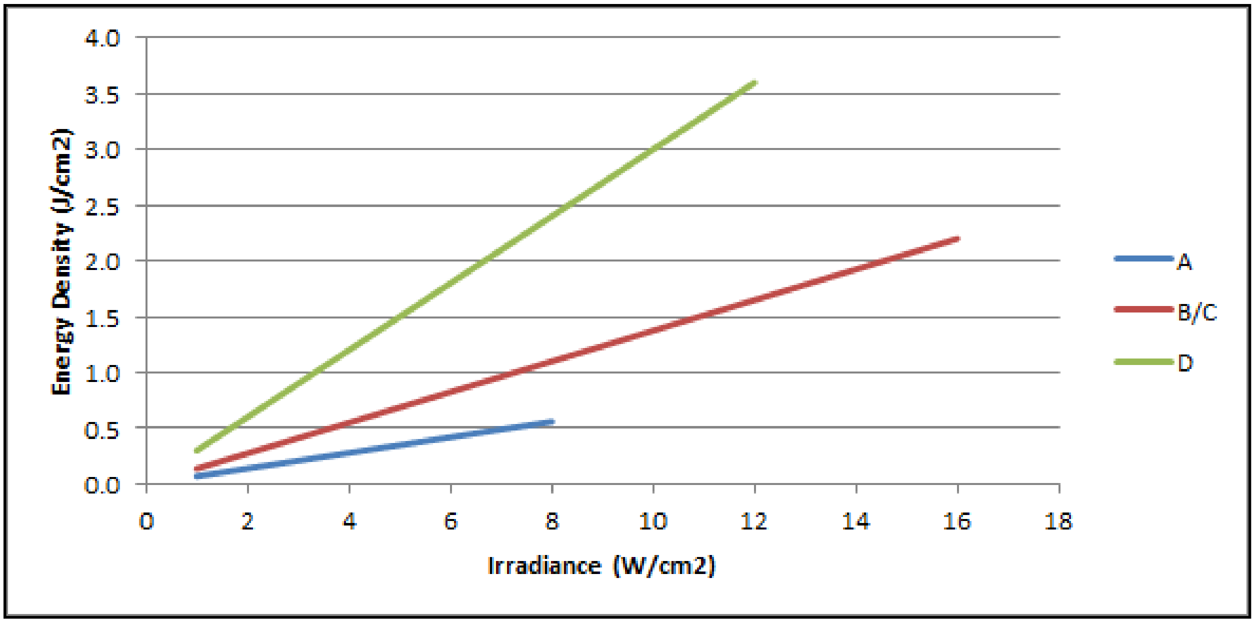

Figure 4: Irradiance vs Energy Density for Four Different UV LED Models.

Safety
UV LED curing technology is generally as safe and in many cases safer than conventional UV curing. The UV LED assemblies contain no mercury, emit no ozone, and operate at lower temperatures than mercury lamps. UVA is a relatively non-harmful wavelength range compared to UVC and UVB. The high peak irradiance of UV LEDs, however, make them incredibly bright. As a result, eye and machine shielding is recommended to protect the operator from long-term, direct exposure which could cause eye strain or discomfort. Typical shielding materials are tinted acrylic, polycarbonate, and sheet metal. It is always recommend that operators and maintenance staff wear long-sleeve clothing and safety glasses when working on the press, and they should always use protective gloves when handling any UV formulations.

Maintenance
UV LED technology is generally touted as low maintenance, but that does not mean NO maintenance. It is important to keep the emitting window of the light source clean and free from inks, coatings, and adhesives. Air filters should be regularly inspected and cleaned when needed. The chiller reservoir for liquid-cooled systems should be properly maintained with distilled water and corrosion inhibitor at the correction proportions. Chiller reservoir temperature should be set to factory recommendations; however, recommendations of coolant temperatures below 25°C can result in condensation in hot and humid environments. Better engineered systems will properly operate in the range of 25 to 35°C. Process variables should be defined at time of installation or set-up and periodically monitored to ensure nothing has drifted out of control. This includes periodic measurement of UV LED output.

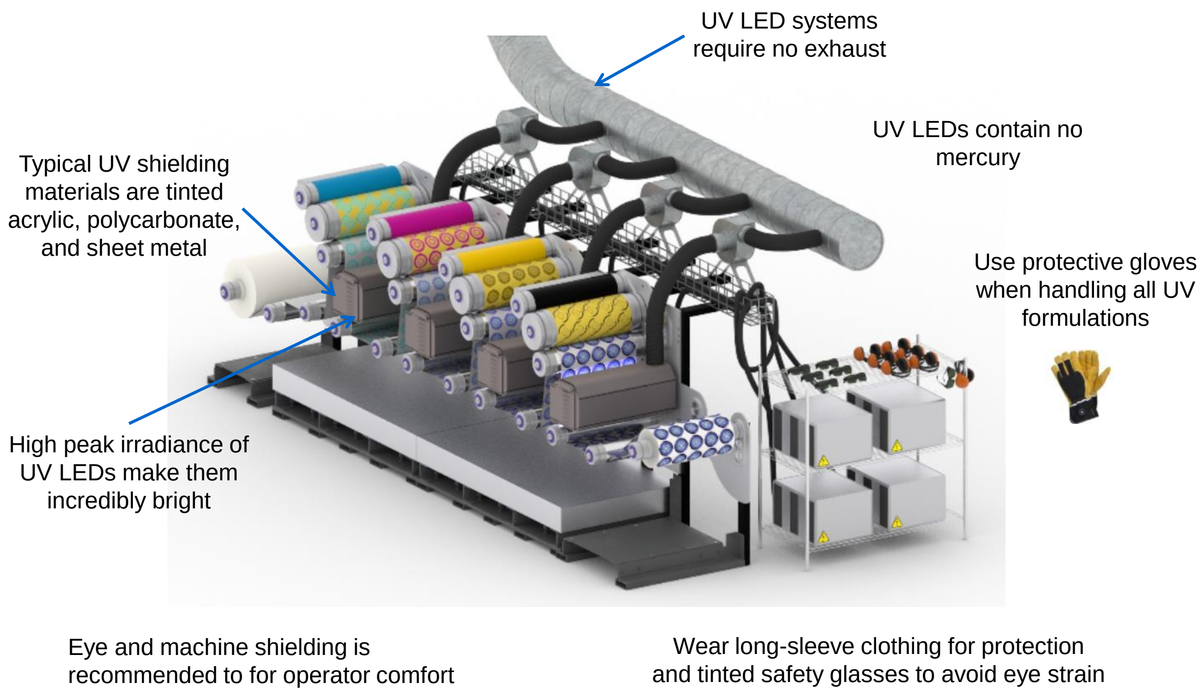

Figure 5: UV LED Systems are Safer Installations and Result in Safer Operation.

UV LED Flexo Market Challenges

Most of the market adoption challenges reside in that fact that UV LED technology is new, unfamiliar, and at times confusing to converters who are often looking for a proven, no-risk, drop-in solution; decisions are made using insufficiently crafted ROIs that fail to capture the true benefits and payback of UV LED technology; and the numerous converters who simply don't want to be first movers. In order to address this, suppliers in the market are working more closely with each other in order to better match the UV LED technology to the formulations, substrates, and press configurations. Proving these "matched" solutions to the market through reference sights and field testing will build trust and confidence in the technology.

Unfortunately, there have been a few mis-matched solutions sold into the market place that promised press speeds that were never realized, performance characteristics that fell short, or included inferior and untested UV LED curing systems that misleadingly touted the same performance benefits as the leaders in the industry but failed miserably and prematurely. Had better due diligence of ink, UV system, and press vendors as well as the applications been done prior to purchase, these "mis-matched" installations would not have occurred. These isolated installations are not representative of the majority of UV LED flexo installations and caution is advised in using them to disparage all UV LED curing technology.

When it comes to UV LED flexo for food packaging, the industry is joining forces to develop educational programs and good manufacturing practice guidelines. This is being spearheaded by the UVFood Safe consortium organized by Tarsus (Labels & Labeling magazine and Label Expo) with additional support from FINAT, RadTech, and leading component and chemistry suppliers. There is an immediate need for established low migration guidelines for flexible packaging. Converters need assistance understanding proper UV LED press set-up and cleaning as well a better understanding of what should be measured as well as how to measure how frequently to measure. The reliability, repeatability, and process control that UV LED technology offers makes it a perfect and superior choice for flexible food packaging, and this segment of the market is likely to grow rapidly in the coming years.

Projected Market Growth

UV LED technology for flexo printing is viable technology today. This includes both new OEM press purchases as well as field retrofits for tags, labels, and flexible packaging. The majority of ink, coating, and adhesive formulations cure incredibly well at speeds of up to 500 fpm and many are pushing speeds of over 1,000 fpm provided sufficient energy density is supplied by the UV LED system.

UV LED technology positively impacts converters and enables them to address and alleviate many of the factors affecting their operation today. What was said could never be done with UV LED, such as non-yellowing, high speed coatings, is already being done today. With all the building blocks now in place, UV LED flexo is poised to explode. It is expected to be mainstream for narrow-web by 2020 and will also experience increasing utilization in mid and wide-web over the coming years.

If your organization is not currently evaluating UV LED technology, you will soon find yourself desperately trying to play catch-up. Don't wait any longer. For converters, at the minimum, install a few UV LED stations on an existing press, and if you are in the market for a new press, you should absolutely equip it with UV LED on each and every station. Going UV LED allows press operators to concentrate on printing and owners and managers to focus on growing their print business!