

Title: Characterizing UV LED Curing Systems
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Try to recall the very first time you went into the hardware store to purchase LED light bulbs for your home, office, or other space. Do you remember what it was like to stand in the aisle in search of something as common as a light bulb only to be confronted with all the unfamiliar and confusing language printed on the LED packaging? Were you slightly overwhelmed with an inability to make a decision? Were you a bit fearful that you would make the wrong choice?

For decades, purchasing a routine commodity like a light bulb required almost no thought and could even be pulled off the shelf correctly by a young child with the most minimal instructions. Due to the technical differences in the way the lighting industry specifies an incandescent bulb and an LED bulb, general lighting LEDs seem to require that buyers have an advanced technical degree just to understand the information on the packaging.

Depending on your personality, when purchasing a product for the first time, you probably fall into four buyer categories. These include brand familiarity, price vs quality, the educated guess, and the researcher. The brand purchaser transfers all positive and negative thoughts and feelings associated with a brand for one product directly to another. If GE or Phillips makes a great incandescent or fluorescent bulb, then they absolutely must make a great LED bulb, right? So you scan the bulbs made

by your brand of choice, passing over the brands you do not recognize, and select the desired room type or color temperature listed on the box – kitchen, bedroom, office, soft, bright, daylight. There it is, and off you go. The price buyer either assumes that price is directly correlated with quality and buys the most expensive item on the shelf, or he or she assumes that all the products are essentially the same and, therefore, buys the cheapest. Why spend any more hard earned money than necessary, right? The educated guess buyer stands in the aisle for as long as needed in order to read and compare



every bit of technical information listed on every single product package. They may or may not fully understand what they are reading, but through the process of comparison, they ultimately arrive at an educated guess that makes them feel comfortable with their selection. The final buyer type confidently arrives at the store having already logged hours on product websites and having watched numerous online video testimonials from people having already gone through the a similar exercise. He or she

quickly scans the shelf for the exact product previously selected through research and quickly heads to the cashier.

Job well done? Maybe, but then again, maybe not. In the end, it doesn't really matter how you made your decision. It all comes down to the moment of truth when you actually plugged your LED into the lighting socket in the desired room or space. Your selection either provided the desired brightness, color temperature, and lighting as you intended, or it simply did not. Were you thrilled with your choice or disappointed?

The desired goal at the time you entered the store was to select an LED that matched your unique lighting needs and preferences for your intended use; however, the necessary evaluation and decision making process that would have successfully delivered that goal was not necessarily achieved with the four buyer scenarios described. Some of us may have gotten lucky with our choice, but how many of us have bought an LED bulb for one room only to regret our choice and move it to another room where it seemed to work better? Others may have just removed their disappointing choice and reinstalled the incandescent or fluorescent bulb. In hindsight, you might have had the exact same chance of success if you had just stood in the store aisle and blindly thrown a dart at all the boxes on the shelf.

With respect to curing technology, how many of you are simply throwing hypothetical darts at your UV selection? The decision process that many manufacturers are using to select a UV LED curing system for their printer or production line is very similar to a first trip to the hardware store to purchase LED light bulbs. When we aren't intimately familiar with features and performance within a new product category, we often rely on quick rudimentary decision making processes that often work well in other situations yet give us a false sense of security that we did everything we could to make the right choice in this new situation. Also known as heuristics, these are mental shortcuts that help us make decisions quickly but come with the tradeoff that the decision may not be optimal and is quite often flawed or biased.

Time and time again, UV LED technology has been proven successful in a wide range of industrial and printing applications including ones that were once thought impossible. UV LED curing systems, however, vary drastically from one another and are fundamentally different than medium pressure microwave and arc lamps. As a result, using any of the four decision making processes previously presented is likely to leave you disappointed and with a solution that is not matched to the particular application needs. It isn't the LED technology; it's simply a mismatch with the application.

The optimal way to select a UV LED curing system is to understand what drives the differences in the products available on the market as well as what the intended application truly requires. For a first time purchase, this can be a bit more time consuming than the use of heuristics, but it will ultimately lead the buyer to a better purchase. Subsequent UV LED purchase decisions will then move more quickly and confidently.

In order to properly evaluate and compare UV LED curing systems, one should start with an assessment of the following product characteristics for each model being considered.

- UV output
- electrical input
- use of optics
- life
- uniformity
- thermal management and cooling
- ruggedness and reliability
- intended use or application

The purpose of this paper is to explain these eight key elements of UV LED curing systems and equip the reader with the tools necessary to characterize and select the optimal UV curing systems for a given application or process the very first time. In other words, this paper intends to move the reader from newbie to an enlightened UV LED curing system buyer.

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). As with all spectral emissions, UV light exhibits properties of both particles (photons) and waves and is defined according to the magnitude of its wavelength. For ultraviolet wavelengths, this distance is on the order of a billionth of a meter and is typically categorized into bands of UVC (100 to 280 nm), UVB (280 to 315 nm), UVA (315 to 400 nm), and UVV (400 to 700 nm).

While arc and microwave lamps are considered broadband sources in that they include wavelengths across the UVC, UVB, UVA, UVV, and infrared bands; UV LEDs are relatively monochromatic, capable of producing much greater intensities, and commercially limited to longer UVA wavelengths (365, 385, 395, and 405 nm) today. See chart in Figure 1. Lab and field testing does not presently show any detectable benefit to blending one or more of these four 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.

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. There is ongoing research and development in the UVC and UVB bands; however, for the purposes of industrial curing, the diodes are continue to be very low power, relatively inefficient, offer very short lifetimes, cost hundreds of times that of UVA diodes, and haven't yet been proven to deliver the speculated cure performance in actual testing.

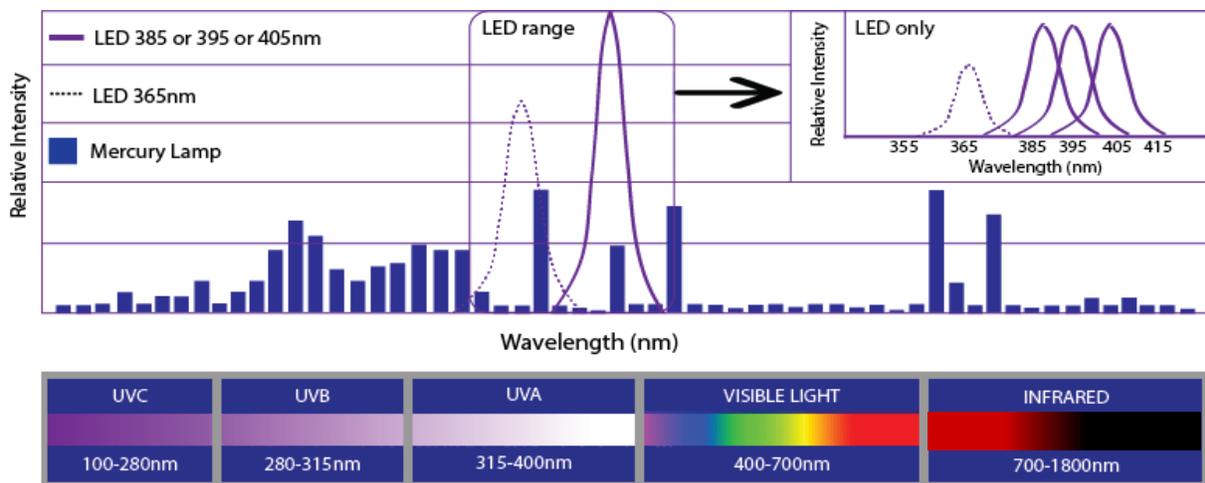


Figure 1: Wavelength vs Irradiance for Conventional Mercury Lamps and UV LED Systems.

By definition, peak irradiance (Watts/cm²) 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 aid surface cure. Energy density (Joules/cm²) 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 decreases as press speeds are increased due to the media's shortened exposure time to the UV LED source. Equally important to understand is that a percentage increase or decrease in peak irradiance results in the same percentage change in energy density.

Peak irradiance is affected by the driven output of the engineered light source, the use of reflectors or optics to concentrate or contain the rays in a tighter surface impact area (discussed later in the paper), and the distance of the source from the cure surface. As with conventional UV sources, the irradiance for flat glass UV LEDs at the cure surface decreases quickly as the distance between the source and the cure surface increases. With UV LEDs, the UV rays emit 180 degrees from each discrete diode. By comparison, UV lamps emit 360 degrees with most of the energy captured and re-directed by a reflector. In both cases, the rays quickly diverge from one another and spread out over a greater surface area when the source is located further away from the media or part.

Energy density is a factor of the output of the engineered light source, the number of UV sources, and the exposure time or press speed. In other words, increasing the irradiance, slowing the line speed, or adding more lamps or wider lamps will all increase energy density for a given UV LED source. It is important to understand that not all UV LED products with the same irradiance deliver the same energy density (discussed later in paper).

Conventional arc lamps typically emit in the range of 1 to 3 Watts/cm² while microwave lamps generally emit as much as 5 Watts/cm². Phoseon's UV LED curing systems currently emit up to 16 Watts/cm² for air-cooled heads and 24 Watts/cm² for liquid-cooled heads. Products supplied by other UV LED manufacturers promote irradiance levels as high as 30 and even 50 Watts/cm². Inks, coatings, and adhesives require a minimum threshold of irradiance for optimal cross-linking. The industry has really never studied whether maximum threshold irradiance was something that mattered. Consequently, UV curing systems have almost always been run at 100% regardless of whether full power was 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 irradiance products, and integrators and end users making UV LED purchasing decisions 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 irradiance itself; 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/cm²) through a different 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 2 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.

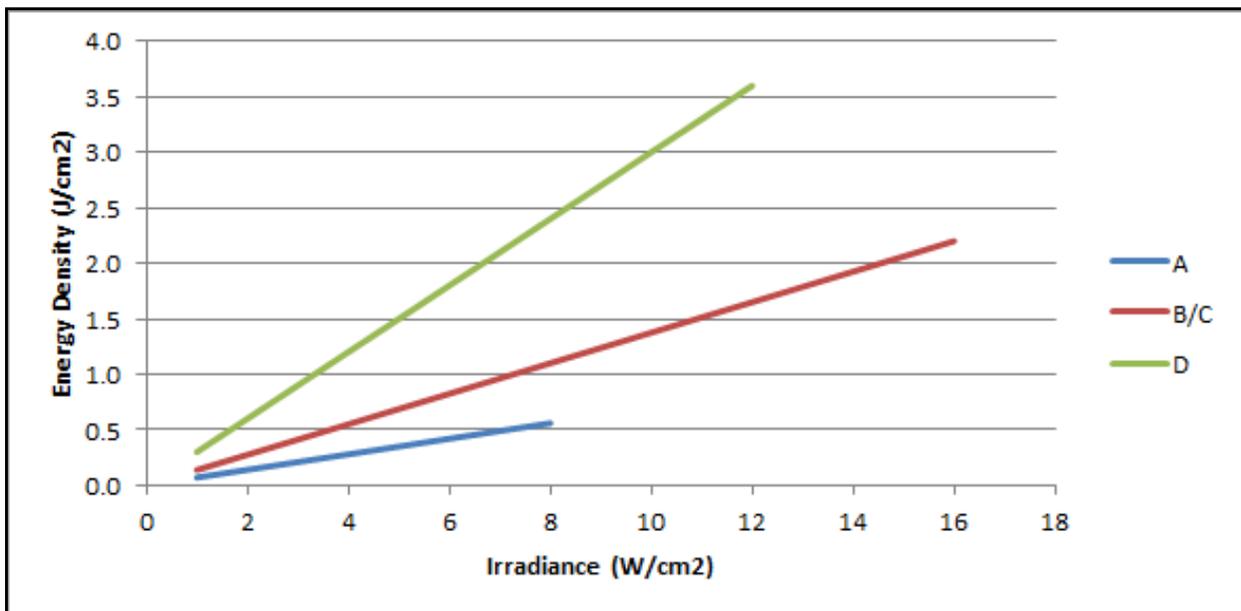


Figure 2: Irradiance vs Energy Density for Four Different UV LED Models.

Actual values for irradiance and energy density directly depend on the construction and configuration of the UV LED curing system. This includes the design and specifications of the raw diodes, the way the LEDs are arranged, packaged, powered, and cooled, the width of the emitting window, and whether optics or reflectors are incorporated into the design. One of the great technological benefits of UV LEDs is that they have a much greater ability than conventional UV systems to be properly matched to the needs of the chemistry and application since irradiance and energy density can be decoupled in source design. This is illustrated in Figure 3.

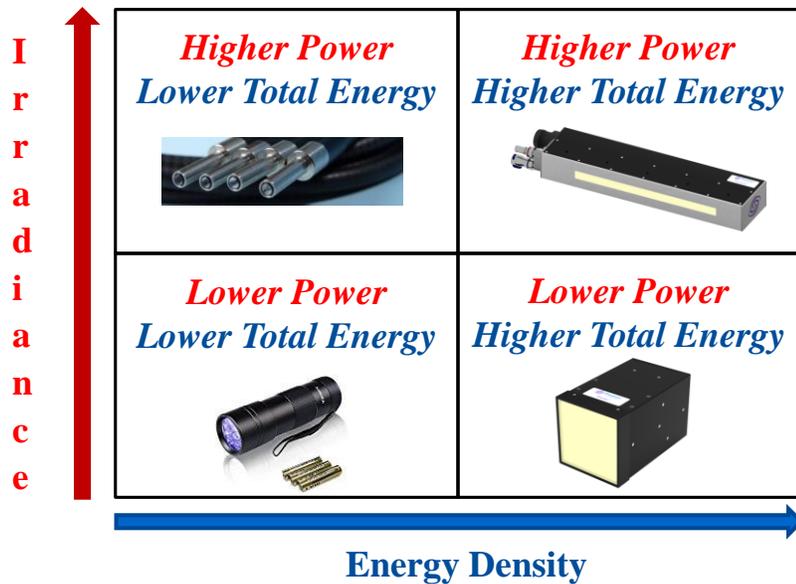


Figure 3: Irradiance vs Energy Density can be De-coupled in UV LED Source Design.

The fiber optic light guides shown in the upper left produce a high irradiance over a small area, but they also deliver very low energy density. When they are used to bond adhesives on a work bench, the required dose is provided through a longer exposure time. The product in the upper right has both high irradiance and high energy density. It is most suitable to high speed as well as specialty web applications. The product in the lower right quadrant is most commonly used in sealing and bonding general assembly or electrical products such as mobile phones, tablets, and flat screen televisions. In these applications, the lower irradiance level is more suitable to heat sensitive components, the wider area enables the LED to cover the entire part evenly, and the greater energy density is more suited to the formulations used. The remaining product in the lower left is a typical handheld UV LED curing device that can be purchased online for minimal cost. Unfortunately, it's not powerful enough in either irradiance or energy density for the vast majority of industrial processing applications this paper is targeting. With a bit of analysis and measurement, all the UV LED curing systems on the market today could be positioned somewhere on this grid; however, very few would occupy the exact same location.

When evaluating different UV LED product models from the same supplier or systems from different suppliers, understanding spectral output, irradiance, and energy density is essential for formulating UV curable materials, selecting the correct UV sources for a production line, and ensuring the desired production speeds and cure results are achieved. You can either work with your UV LED equipment supplier to gather this information or you can collect it yourself with a radiometer. The EIT L395 meter is commonly used in conjunction with a flatbed conveyor and UV LED system to collect both irradiance and energy density data.

Ultimately, determining the correct UV LED system for a given application should also be done in collaboration with your UV equipment and formulation suppliers as well as your machine builder. In many cases, the OEM machine builders should be doing this work for you, but it's up to the buyer to confirm. The great benefit of UV LED curing is that unlike conventional UV curing, once the process window is defined, the process is incredibly repeatable and controllable over time.

Electrical Input

If the energy density values for the UV LED systems being considered are not available and you aren't in a position to measure them, you can evaluate and compare the system power requirements. Doing so assumes that the efficiencies of all the heads being evaluated are similar. While this is not technically the case, the efficiencies are still relatively close which lends merit to the exercise. The head power requirements should be available in most product data sheets or on the system rating plates. Please note that rating plates for the selected DC PSU(s) will specify a bit more power than the actual heads draw.

Table I provides nominal power data for three UV LED systems and four conventional mercury systems, all 18" in length, at various irradiance and nominal power levels. Column four in the chart shows that the wattage requirements for even the highest powered UV LED systems are significantly less than those required to power conventional lamps. This is why UV LED curing systems are promoted as more efficient. It should be noted that this is just the wattage to power the heads and does not include the wattage of the chiller for the LED systems or the exhaust blower and make-up air for the conventional systems. A fully comprehensive energy analysis, which this is not, will look at all sources of power consumption. In either case, the total UV LED system will still consume less energy than the conventional lamp, but it won't be as drastic of a difference as when only the heads are compared.

One other aspect worth mentioning is that the nominal power in column five can sometimes be used to compare UV LED curing systems to other UV LED curing systems and conventional mercury systems to other conventional mercury systems, but it should not be used to compare UV LED curing lamps to conventional curing lamps as nothing can be drawn from such a comparison. Nominal power is simply the wattage of the power supply divided by the length of the lamp. It is how conventional mercury lamps have always been specified for purchase and use, but it isn't the most relevant spec for comparing conventional lamps to LED sources since the efficiencies of the lamp technologies are so drastically different. Please note that this table is just a representation of typical lamps, and the values will vary for the actual products being compared.

Table 1: Electrical Input Power vs Output Irradiance for Typical Mercury and LED Systems

Product	Wavelength (nm)	Length (mm/in)	Supply Power (Watts)	Nominal Power (Watts/in)	Irradiance (Watts/cm ²)
LED	395	450/18	4,361 DC	240	16
LED	395	450/18	5,451 DC	300	20
LED	395	450/18	5,775 DC	320	24
Mercury	Broad Band	450/18	5,400 AC	300	1 – 2
Mercury	Broad Band	450/18	7,200 AC	400	2 – 3
Mercury	Broad Band	450/18	9,000 AC	500	3 - 4
Mercury	Broad Band	450/18	10,800 AC	600	4 - 5

A similar comparison shown in Table II can be used for UV LED curing systems with the added data point of energy density. This table compares four different models of UV LED curing systems all with a similar head length and dialed to the exact same peak irradiance. The power into the head is directed into a combination of irradiance and energy density. For an identical peak irradiance of 8 Watts/cm², if a UV LED system (refer to product A) has a lower DC power wattage (145 Watts), then it likely provides minimal energy density. By comparison, if a UV LED system (refer to product D) has a high DC power wattage (1,400 Watts), then product D most likely provides considerably more energy density than product A. This is an evaluation by relative comparison. It doesn't confirm what is needed for the application, but it provides considerable more insight than just comparing peak irradiance values on a spec sheet. In general, a greater energy density emitted at an irradiance level above the minimum threshold provides better cure and allows for faster line speeds.

For similar peak irradiance values, the correlation of DC power and energy density can be confirmed through actual measurement. The last column in the table provides energy density values which were measured at 20 fpm using an EIT L395 radiometer. The top of the radiometer was 5 mm from the emitting window of the LED sources. Since both line speed and irradiance affect energy density, when performing this type of a comparison, it's important to use the same irradiance across products and a line speed selected for the sampling rate of the radiometer. A slower belt speed is always better for measurement purposes.

Table 2: Similar UV LED Irradiance Does Not Mean Similar Input Power and Similar Energy Density

Product	Emitting Window L x W (mm)	Irradiance (Watts/cm ²)	DC Supply (Watts)	Nominal Power (Watts/in)	Energy Density (Joules/cm ²)
A	80 x 10	8	145	45	0.56
B	75 x 20	8	670	225	1.10
C	75 x 20	8	960	325	1.10
D	75 x 40	8	1400	475	2.40



Uniformity of Output

When building a UV LED curing system, numerous raw or native LEDs are typically arranged in a single line or in a matrix configuration. The UV output from each discrete LED follows lambertian characteristics in that there is no glare, no reflection, and no shift in brightness as the viewing angle changes. Without the use of reflectors or optics, the diodes emit from a planar source a full 180° degrees. The output from each LED is divergent and blends uniformly with the output of neighboring

LEDs. The uniformity at the cure surface improves as the distance from the line or matrix of LEDs increases. The peak irradiance of the output is generally contained in an emission cone that is less than 180°.

For most applications, it is critical to have uniformity of output along the length of the LED curing source as well as between mating sources. When individual UV LED sources are mated end-to-end, this is referred to as scaling the heads. It should be noted that not all commercially available systems offer the same uniformity characteristics, and it is recommended that uniformity be discussed with the UV LED supplier. Sources that exhibit better uniformity along the length of the head as well as between scaled heads deliver better quality and consistency of cure across the width of the web or part. In all cases, uniformity improves as the distance between the matrix and the substrate increases. See images in Figures 4 and 5.

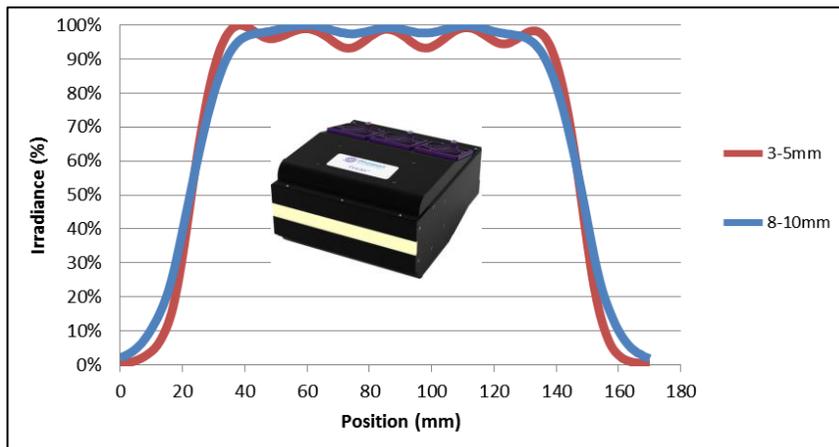


Figure 4: Uniformity of Irradiance along a UV LED Source vs Distance from Source

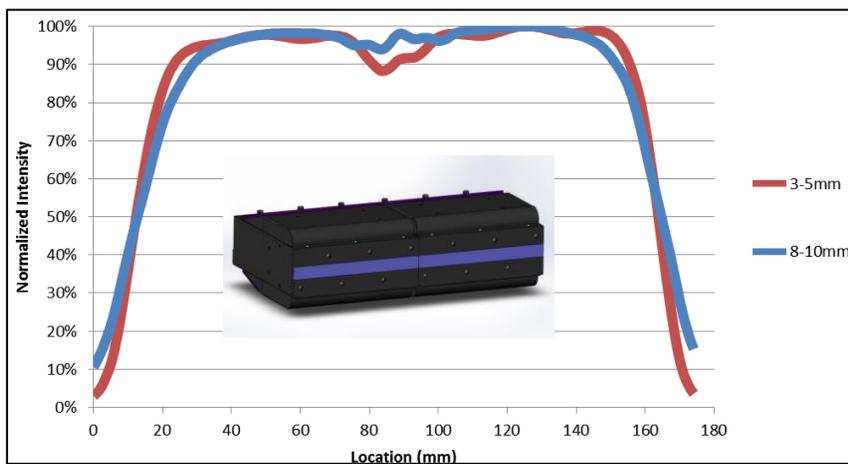


Figure 5: Uniformity of Irradiance along Scaled UV LED Sources vs Distance from Sources

UV LED curing systems that locate the drivers in the UV LED head and allow for internal tuning at the time of manufacturing will also produce more uniform devices. When these drive components are located remotely in a common control system, there is no way to adjust for differences in output from the raw diodes, and uniformity is compromised. This is the case within a single head and when heads

are swapped between stations on a press. This tuning or balancing process is not something that all suppliers currently incorporated into their designs or manufacturing processes but is necessary for superior uniformity. The uniformity of unbalanced heads rapidly becomes worse with use.

Optics

There are four main categories of UV LED optics including flat glass, rod lens, external reflectors, and internal reflectors. These categories address the larger mechanical optics and do not address micro-optics at the diode level.

Most UV LED sources are equipped with a protective flat glass emitting window or rod lens that is placed in front of the LEDs and is generally fabricated from quartz. The emitting window or rod lens is meant to serve as both a physical impact barrier as well as a means of keeping ink, coatings, adhesives, dust, solvent, and other foreign matter from depositing on the LEDs and creating localized hot spots. Hot spots negatively impact the device's efficiency and useful life. Raw diodes and their corresponding solder joints are brittle and should not be directly handled without proper training or outside of a clean room.

Properly designed UV LED assemblies are engineered to protect the diodes. As a result, the lamp assemblies can be easily handled but should not be taken apart. Doing so generally voids all warranties. A visual inspection of the UV LED head will confirm whether an emitting window or rod lens is present, the thickness of the quartz, whether it is a single piece of glass or multiple pieces, and whether the assembly is sealed. Unsealed emitting windows or assemblies that can be taken apart by end users are susceptible to foreign material ingress resulting in a shortened lifespan.

Other UV LED source designs incorporate external or internal reflectors to produce narrow, columnated, or directional output that keeps the UV rays from spreading out. Directional optics better maintain peak irradiance over distance; however, this distance is not without limit. Eventually the rays start to diverge again. The goal of optics is often to reduce stray UV reflection onto other machine components and/or cure at a greater distance from the emitting source. It should be noted that the use of internal reflectors or rod lens optics produce systems that often deliver less energy density when compared to flat glass sources. This is due to the physical limitations in the width of the matrix when incorporating the use of optics and internal reflectors. The result is almost always a narrower matrix with fewer diodes and less total energy density. These features should be understood and matched to the needs of the application. In some cases, optics benefit the application. In other cases, they compromise performance. See Figure 6.

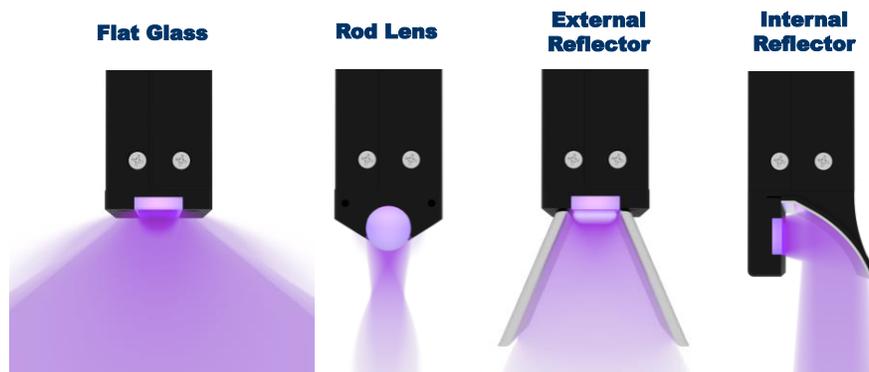


Figure 6: Illustration of How Optics Impact Concentration or Spread of UV LED Light

It is generally recommended that a flat glass UV LED source be mounted such that the emitting window is between 3 and 15 mm from the substrate. For applications that do not require high irradiance or for systems with optics, sources are sometimes mounted as much as 75 to 100 mm from the substrate. An increased distance improves uniformity, decreases irradiance at the cure surface, and spreads the rays over a greater surface area. The optimal distance for a given application is formulation and process specific. It should be noted that while irradiance decreases significantly as the distance between the UV LED source and the substrate increases, the corresponding energy density is constant.

Life

A UV LED is a solid state device with no moving parts. When current flows through the LED, light is emitted. The degradation of the device, under ideal conditions, is negligible. It will last indefinitely. When LEDs are packaged into subassemblies, bonded to heat sinks, powered, and cooled, inefficiencies are introduced. The life of the LED is most affected by how well the diodes are cooled and protected from foreign matter. UV LED systems with poor packaging, sealing, and thermal management will not last very long, despite product claims. Proper designs today that are maintained and not abused will last between 20K and 50K hours. Products that aren't often fail within a few thousand hours.

The most extensive life testing has exceeded 70K hours with less than 15% degradation in output. Downgrading for manufacturing environments is typically 50% from life test. As a result, properly engineered, manufactured and maintained UV LED heads should nominally operate 35K hours with less than 15% degradation in output. In practice, this is a bell curve centered at 35K, which is why a reasonable expectation of life is between 20K and 50K hours. Many companies often rate their products at 20K plus hours without the engineering studies or life test data to back up the claim. Buyers and engineers should perform due diligence and not assume that all products on the market will experience the same life. A product expected to last 20K hours but only lasts 2K hours compromises any ROI calculation based on an expectation of longer life.

A key design feature ensuring long life is a sealed UV LED head. Think of a UV LED curing head as you would a smart phone or a tablet. All three devices should be manufactured in a clean room and properly sealed to keep out inks, coatings, adhesives, moisture, dirt, dust, and foreign matter. Anything that penetrates inside to the diodes will create localized hot spots which elevate the LED junction and solder joint temperatures leading to premature life and catastrophic failure. A sealed head is simply a better head. Period!

A final note on life involves maintenance. While UV LED curing systems are definitely low maintenance, they are not NO maintenance. If your manufacturing process results in lamps that are constantly being covered in inks, coatings, and adhesives and never cleaned, they will not last. Lamp bodies and emitting windows must be regularly inspected and wiped clean. Head brackets should be designed so that the heads can be quickly accessed for cleaning. Sealed heads operating in these dirtier environments will last longer than unsealed heads but could still experience shortened life. The same applies to air cooled lamps operating in environments with high concentrations of air particles. This includes wood, paper, or ink dust; PVC powder; or other air-borne contaminants in high concentration which gum up cooling fans and coat the fins of the internal heat sinks. Preventative maintenance schedules should always be implemented based on local operating conditions.

Thermal Management and Cooling

Thermal management of UV LED curing sources is critical in maintaining proper irradiance and uniformity as well ensuring a long lifetime. The thermal component in UV LED systems is not the

radiated infrared energy typical with conventional curing sources. Instead it is energy created by the electrical inefficiencies that are present in any solid state device. While significantly greater in magnitude, the nature of this thermal heat is similar to that produced in cell phones, lap tops, and chargers as well as other high tech electronic devices.

In general, a UV LED curing system is an electrical device with strict requirements on maximum LED junction temperatures. This temperature limit is typically less than 110°C. By comparison, conventional quartz bulbs operate with surface temperatures between 900 and 1200°C. With UV LED curing, approximately 30 to 40% of the input power is converted to useable UV output while 60 to 70% is converted to unwanted heat. If this unwanted energy is not removed, the LEDs will overheat and fail catastrophically. As a result, it is necessary for UV LED source suppliers to engineer an optimal cooling system that is balanced against the power of the device. The ability to deliver on this capability is what differentiates most UV LED products on the market as some suppliers do this well and others have not yet fully developed the necessary engineering. See Figure 7.

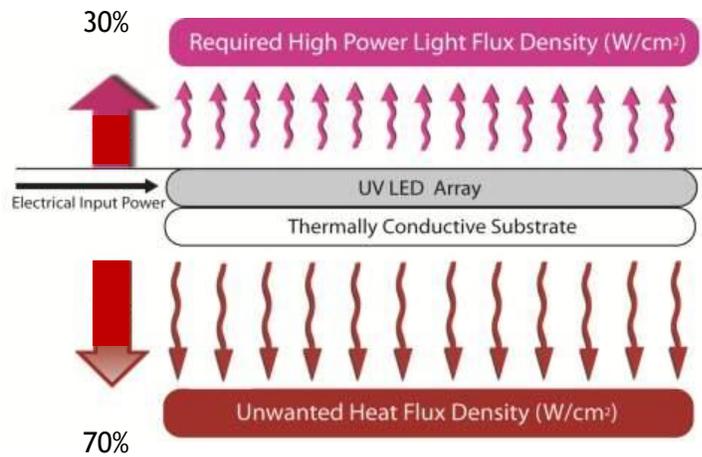


Figure 7: Typical Efficiency in the Conversion of Electrical Input Power into UV LED Output and Dissipated Heat

Either forced air or circulated liquid coolant can be used to remove the unwanted electrical heat and maintain the desired operating temperature, thereby, optimizing the performance of the LEDs and prolonging their useful life. Higher powered systems are generally cooled with liquid circulation as liquid is more efficient at removing the heat load. The peak irradiance and energy density of air-cooled systems, however, has increased in recent years and currently lags only slightly behind that of liquid-cooled systems. Regardless of the cooling method, if the engineering is done properly, the UV output is the same for similar source constructions. As a result, the choice of liquid or air-cooling has more to do with the environmental conditions of the operating location or the subjective preference of the person making the UV LED selection.

Ruggedness and Reliability

UV LED curing systems continue to be engineered for greater ruggedness and reliability. This is an iterative process and not something that is accomplished easily right out of the gate. UV LED curing systems are quite often used in harsh manufacturing environments. They are exposed to elevated temperatures both internal to the device and in the ambient air, machine and material handling vibrations, accidental impact, environments with high air particle concentrations, humidity, UV

chemistry, improper coolant solutions, and manufacturing solvents and cleaners among others. Highly Accelerated Life Test (HALT) chambers are used to simulated extreme physical operating conditions in order to force premature failure, understand the root cause, and then engineer away those failures.

The better performing and longer lasting UV LED curing systems have likely gone through various HALT studies giving more credibility to companies that use them and companies that have been developing systems for longer. It isn't too difficult to assemble a UV LED curing system. It is, however, challenging to make ones that operate reliably over time in real world production environments and across high production volumes of tens of thousands annually.

Manufacturing processes and quality inspections as well as clean room assembly are also instrumental in driving ruggedness and reliability. It is highly encouraged that companies perform vendor audits on the conditions of UV LED manufacturing. Not all systems are subjected to the same rigorous standards of production which means not all companies are delivering the same reliability in their UV LED products. This makes due diligence in vendor selection incredibly important in the decision making process.

Intended Use

It is critical that a discussion of the application, material handling, and environment be part of the evaluation analysis. As a result, all of the previously described UV LED system characteristics should be evaluated against the intended use including:

- Profile of part to be cured (shape, size, construction)
- Substrate or Construction (web or sheet, width, material)
- Speed under UV LED (linear speed, part rate, or sheet rate)
- Material handling and UV exposure (inline, scanning, indexed)
- Physical or optical restrictions in distance of UV LED to cure surface
- All UV and non-UV formulations used in the process (ink, coating, adhesive)
- Application method of formulation (inkjet, screen, flexo, gravure, offset, letterpress, coater, spray, etc.)
- Confirmation on whether formulator has UV LED offerings
- Food or non-food packaging requirements
- Stipulated cure inspection methods
- Post cure processing steps
- Air quality and ambient conditions
- Available floor space or limitations
- Frequency of use
- Current process bottlenecks and issues

An experienced UV LED supplier and OEM machine builder should be able to have a conversation on these items and direct you to the proper product particularly for proven applications such as digital inkjet, screen, offset, fiber coatings, and flexo. For each of these, there is a target process window for wavelength, irradiance, and energy density. Not all applications require the same process window, and not all UV LED products on the market will provide what is needed. A broad portfolio of UV LED systems is required to meet the needs of all the different commercial UV LED applications. Companies with broader portfolios have tailored the designs to meet the needs of these applications as previously illustrated in Figure 3. If you are having issues in your application, the UV LED equipment supplier

should be able to provide guidance as to how to adjust irradiance and energy density or suggest a different product in order to improve the cure for the given process conditions.

Just like the hardware example for home lighting, if the UV LED system is not matched correctly, you will no doubt be disappointed in the cure performance. UV LED technology is proven technology and should be something that you are using today, but if your decision making process is simply meant to make you feel good about the process of making a decision, it will likely leave you disappointed on the shop floor.

It is so incredibly important to work with all the parties in the supply chain at this stage of UV LED technology implementation including formulators, suppliers of the material dispensing or transfer equipment, UV LED equipment manufacturers, and machine builders. It is recommended to schedule testing in the lab or on the actual line for first timers or new formulations. Leverage experience from those in the industry who have previously figured out the applications and can guide you through the process. In the end, it is up to you to understand what is needed. Otherwise, you aren't doing anything more than blindly throwing darts.