Implementing UV LED Curing for Wood Coatings

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Abstract

The paper undertakes a critical evaluation of implementing UV LED technology for curing wood coatings. In particular it will discuss water borne UV applications and assess the benefits of the technology from an environmental and carbon foot print perspective. It will also discuss the performance criteria for a fully UV LED curable wood coating system in terms of its technical performance. And also look at the economic impact of the total solution/system. The aim of the paper is to demonstrate that UV LED technology and compatible coatings can greatly reduce the environmental impact and carbon foot print of wood coating processes without compromising on coating performance.

Introduction

While the current economic downturn has affected all markets, the UV curing market segment continues to be a bright beacon of opportunity. There are many drivers that keep the interest in moving to UV active such as reduced operating costs, higher productivity and a more environmentally friendly solution which more and more end customers are demanding.

As manufactures are developing UV curing systems, knowing how the key sub-components work together will help in creating the optimum system and thereby reducing the overall environmental impact of the process and at the same time maintaining or improving productivity and product performance.

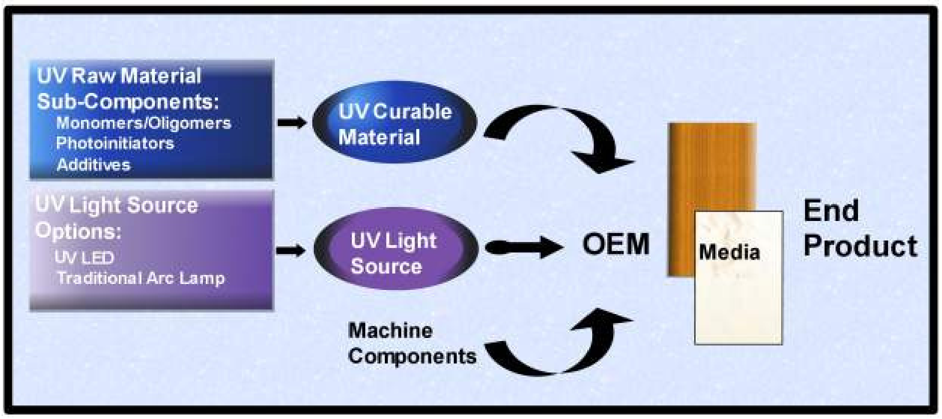


Figure 1: UV System Level Diagram

Energy Savings & Environmental Impact

When comparing UV curing systems the following factors were considered:

- Cost of ownership of system
- Performance of Lamp
- Performance of System

Cost of Ownership of System

A detailed cost of ownership model was developed in cooperation with Tikkurila AB and Robert Bürkle GmbH based on actual industrial coatings applications which will be reviewed in this paper. When comparing costs between an Arc lamp and UV LED system it is important to consider all the relevant factors to assess the total cost of ownership, which include the following:

- Cost of acquisition
- Cost of energy and services
- Cost of installation
- Cost of maintenance and consumables
- Cost of downtime and yield
- Depreciation and replacement costs

Taking these factors into consideration Bürkle was able to demonstrate that for a 1.4M lamp savings of the order of €10,000 per lamp per annum can be achieved. About 60% of this comes directly from energy savings alone and the rest from reductions or elimination of the following:

- Elimination of Ozone extraction requirement
- Reduction in air extraction volumes by ~50% (UV cooling eliminated)
- Reduction in Down time associated with Repair & Maintenance requirements by ~80%
- Improvement in Yield by ~5%

Figure 2: Factory Air Extraction for Mercury Vapour Lamp

From a carbon footprint perspective each UV LED lamp consumes on average 50% less energy than an equivalent Arc lamp as a result of:

- Instant on/off allows the lamp to be switched on/off immediately when required. No standby mode. This duty cycle also considerably extends the useful life of the lamp by up to 6-8 years.
- LED technology is more efficient at converting electrical energy into useful UV light 25-30% compared to <10% for an Arc lamp.

- For a typical coating line energy savings of the order of 30% are achievable for the line in total which more than off-set the increased investment cost of about 6.5% in selecting LED vs. Arc lamps and of course the energy savings are ongoing.
- Each lamp uses about **€6K** electricity less per annum. This equates to about **25 Tons of CO_2** (electricity from a gas fired power station, 2x for Coal). To offset the CO_2 emissions from a single 1.4M arc lamp around **200** trees would need to be planted annually or **10** cars taken off the road per year.

In some applications the energy savings could indeed be much more significant. For example with one Water Borne UV coating from Tikkurila it was possible to replace as many as four conventional lamps (2xHg+2xGa) with one UV LED unit without any loss of performance.

One could argue that much of the heat from the Arc lamps could be recycled for heating but this would be a very inefficient way to provide heating where more efficient alternatives exist. Also from a process and equipment design perspective there are many down sides to the excess heat provided by the Arc lamp systems.

At LIGNA 2009 in Hannover, Germany, 1st place in the Resource Efficiency segment was awarded to Robert Bürkle's KA UV-LED curing technology system with Phoseon's UV LED SLM based light source in recognition of the improvement in environmental impact UV LED technology can provide for wood coating curing.

Performance of Lamp

There are several UV sources available to manufacturers including traditional mercury vapour arc lamps, microwave lamps and solid state LED UV light sources. Understanding their differences and specifications is important in light source selection.

Energy Input and Measured UV Output

When a traditional UV lamp manufacturer specifies power in "watts per inch" (WPI) or "watts per cm", they are specifying the power applied to the bulb, not the power output. A 400 WPI bulb does not produce 400 WPI, it consumes it. For an Arc lamp only a small percentage of the optical output is UV. Most of the energy generated does not contribute to the curing process.

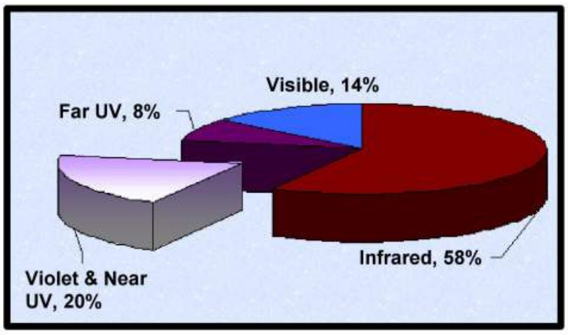


Figure 3: Typical Mercury Vapour Lamp Wavelength Distribution

UV LED sources are typically specified in terms of their output power – either total UV optical output (Watts) or peak intensity/energy density (W/cm2). The most practical way to specify the output is in terms of measured output as the energy exits the system where it can practically be checked and confirmed using a radiometer. In some cases UV LED systems are defined in terms of peak intensity of the individual diodes. While this has some validity it can be misleading as it applies only to the individual LED device and has limited applicability to a practical curing system where the practical output will never be close to the energy density at the surface of the emitting device.

For an LED curable system where the optical output is matched to what the process requires. The optical conversion efficiency when compared to an arc lamp is substantially improved. As a result there is less wasted energy and the curing process is more efficient.

Spectral Distribution – Useful Wavelengths

In addition, most mercury vapour lamps emit a broad spectrum of light (200-800nm – with specific emission patterns dependent on doping) of which only a small % is typically useful for UV Curing.

Within the useful UV region, the emitted energy per wavelength of a mercury vapour lamp when compared to a UV LED source is very different. When the spectral energy per wavelength is evaluated for a mercury vapour lamp with its broad emission spectrum to a LED source with its narrow spectral emission, it is easy to see that an LED source has a higher UV peak intensity. Figure 4 shows a comparison of the spectral intensity of a traditional mercury vapour lamp and an LED source one with a peak intensity centred at 395nm.

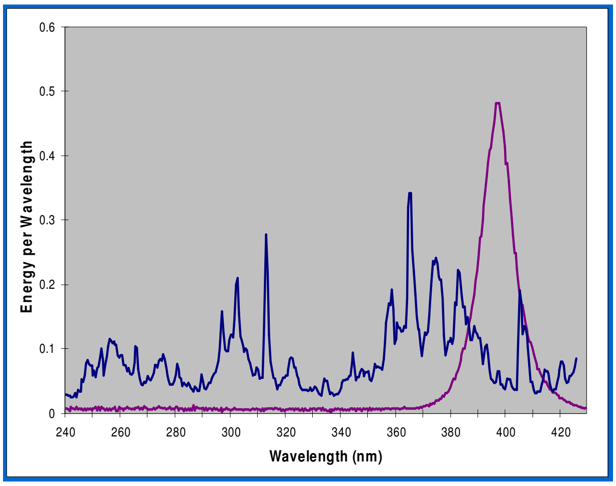


Figure 4: Mercury Vapour Lamp Wavelength Distribution for different dopants

As the figure shows, a LED source has a more concentrated narrow spectral emission. LED sources are typically described by their peak emitting wavelength, but in practice UV LED sources emit in a distribution that is typically +/-20nm from the specified peak. For example a “395nm” LED source typically emits 96% of its energy between 380nm and 420nm with the distribution being essentially Gaussian.

Performance of the System: Material Formulations

When selecting a UV Light source it is not only important to consider the performance of the UV source, but also the formulation of the material which in many respects is even more critical to a successful curing “system”.

Materials suitable for UV LED curing

One of the main issues restricting the widespread adoption of UV LED has been the availability of suitable materials that cure in the UVA range and dealing with curing efficiency and managing “UV-A only” output (Surface Curing more difficult).

Customers have been quick to identify the potential benefits of UV LED curing and already in some industries such as digital printing there has been wide scale adoption of this technology.

Materials suppliers and equipment manufacturers have responded to the challenge. In the wood coatings industry innovative companies such as Robert Bürkle GmbH rise to the challenge and are now offering a commercial solution for UV LED curing. With further developments planned.

Materials suppliers such as Tikkurila AB working closely with Phoseon Technology have been one of the earliest companies to identify the potential that

UV LED could offer the industry. They have made significant progress in the area of UV LED curable coatings in particular with regards to water borne UV coatings and 100% UV.

Whilst currently materials compatibility still remains one of the biggest barriers, ongoing development by many of the world’s leading material suppliers would suggest that it is only a matter of time before we can expect to see UV-LED suitable materials becoming widely available in many applications.

Figure 5: Robert Bürkle KA Line UV LED System

Figure 6: Tikkurila internal UV LED R&D System

Photoinitiators

The photoinitiator or photoinitiator blend plays the pivotal role determining the cure rate but oligimer and monomer selection are also factors. For free radical curing, the reaction begins with the absorption of UV energy by the photoinitiator and then the photoinitiator becomes excited and generates free radicals and polymerization occurs.

The photoinitiator is just one small component of the material which also contains oligomers (pigments) and monomers. In fact the photoinitiator makes up only a small percentage of the UV system typically 0.5-10%.

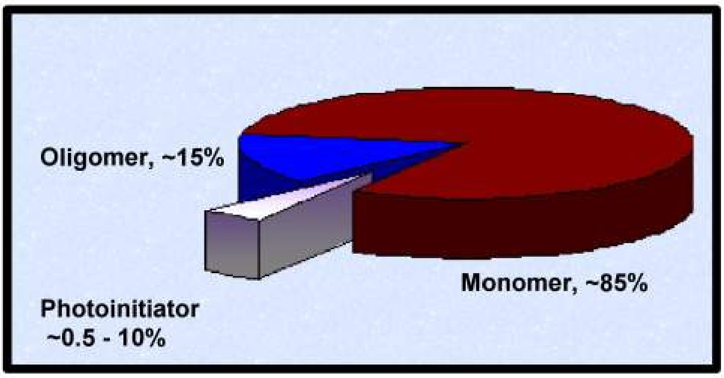


Figure 7: Typical UV Formulation of Materials

Usually reformulation of existing chemistry is required for optimum curing although some existing UV cure systems will work without reformulation.

Tests have been carried out with and without inerting. However work is ongoing on developing formulations for 100% UV coatings that will cure without inerting.

There is no doubt that the availability of UV LED optimized materials makes UV LED sources, with their inherent advantages, a very attractive option for many applications. But UV LED sources do have technical limitations in terms of their application to a wide range of existing UV materials where they are often not suited and where existing Mercury Vapour lamp technology still remains the best option.

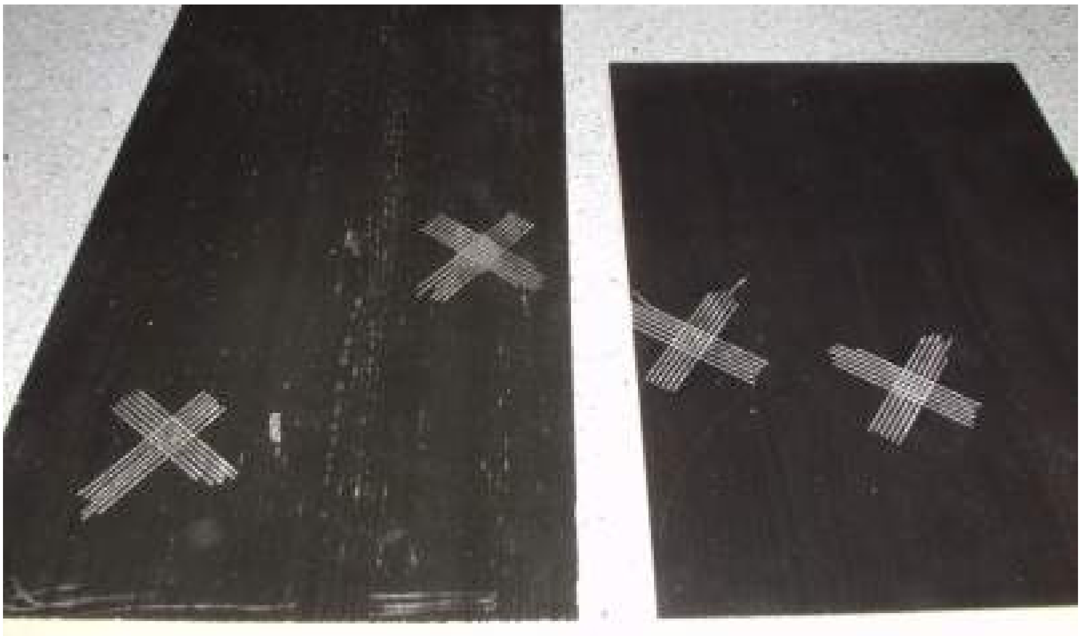
Application Focus: Wood Coatings

Application results from tests carried out by Tikkurila AB include a study of Pine wood using a clear sealer as well as waterborne pigmented system, waterborne clear and pigmented versions for doors and stairs as well as parquet flooring. In addition, the cure rate was analyzed for a top coat using FTIR analysis.

LED Curing of temperature sensitive pine wood

In a recent study carried out by Tikkurila AB the following observations where made with regards to the curing of coatings on temperature sensitive pine wood and with regards to Water Borne UV.

LED curing of temperature sensitive pine wood demonstrated significant improvement in adhesion on the knots. The class of adhesion after LED curing was 0-1 compared to very low adhesion levels equal to 4 after standard UV curing. No resin bleeding was observed (Figure 8b).



a) Cured with conventional

b) Cured with UV LED

Figure 8: Clear 100% UV curable sealer adhesion to temperature sensitive massive pine wood: a) cured with conventional UV, b) cured with UV-LED unit.

Lower heat emissions, lower surface temperature

Due to high operating efficiency and water cooling a UV LED light sources generate very little heat. The surface temperature of a UV LED light source is 40–50 °C, which results in very low product surface temperatures (25-30 °C). This permits UV curing on very heat-sensitive materials. Traditional UV units convert 65–70 % of their input power into heat.

Until now, excessive surface temperatures on coated products have caused problems on application lines. This can cause stains to boil, resins to exude from pine, delamination of glued veneer and UV-cured products to turn yellow.

LED Curing of water borne pigmented system

UV LED curing results for water borne pigmented system in an inert atmosphere are shown in Table 1. Curing was carried out at oxygen concentration levels of 6% with a UV dose of 356mJ/cm2. Commercially available pigment paste concentrations were added, about 10 volume-% of each pigment paste.

The test results show that the pendulum hardness increases significantly with UV LED curing in all shades when compared to conventional curing by Ga and Hg UV Arc lamps. The pigmented systems which are difficult to cure with conventional UV technology even to tack-dry can be fully cured in an UV LED oven.

Table 1. Hardness of a clear waterborne paint cured by standard UV lamps and UV-LED technology

Pigment index	Paste added (w.-%)	Pendulum hardness UV LED curing	Pendulum hardness Ga + Hg curing
P.W.6 (white)	18.2	45	28
P.Y.42 (oxide orange)	16.7	26	11
P.R.122 (pink)	10.0	68	53
P.Bk.7 (black)	11.5	25	16

LED curing in door and stair industry = joinery
In this test water borne clear and pigmented versions were tested at Tikkurila. In this test inerting was not required; this gives possibilities for profiled substrates. Tests at Tikkurila on samples for a stair manufacturer and on door skins are ongoing. The aim is to develop pigmented products for lines currently using two Gallium and two Mercury lamps to be substituted with only one UV LED lamp.

In this case with help of our UV LED solution we were able to demonstrate to the customer that they will have fewer challenges in controlling the heat caused by the existing UV-units.

Some additional benefits identified in this project were

- Improved lacquer properties = improved prices/sales
- Increased line speeds and reduction in double coating requirements
- Less heat (-80%), curing at near room temperature
- Use of bottom wood

The total resulting profit improvement of the proposed solution for them was +98 (1.319) k€ / year (+4 % increase in EBIT).

Tinting systems Tests with Tikkurila's current Symphony tinting colorants have shown that paints tinted with the colorants cure as well and mostly better than curing with Ga + Hg lamps. In future Fonte colorants will be tested.

LED curing in parquet industry
Tikkurila AB has developed top lacquer for use of parquet industry. The following properties were noted.

- Less smell when cured
- Lacquer is yellow as wet but it yellows much less when cured in UV compared to conventional UV curing lacquer (ΔB 0,04/0,94),
- Less difference chemically between surface and rest of lacquer
- Better chemical resistance (ethanol, ammonia)
- Higher friction coefficient (0,41/0,30)
- As good or better in Stuttgart microscratch resistance

Cure Rate Analysis
In terms of UV cure rate the general assumption is that increased peak intensity is the key factor in increasing cure speed/cure rate. If a $2W/cm^2$ UV LED light source is good, then $8W/cm^2$ should be four times better! Of course in practical terms the reality is more complicated, cure rate is a function of not only amount of UV energy, but also how well

matched that UV energy is to the spectral response of the photoinitiator used in the formulation.

The objective of the testing was to gain a better understanding of the effect of delivery of dose (peak intensity) and of wavelength on cure rates especially as these relate to UV LED sources using FTIR.

FTIR – Real Time Fourier Transform IR is based on how infrared radiation is absorbed by chemical bonds. Each bond type has a distinctive response at a given wave number (1/wavelength) where the peak represents the number of bonds. The peak will decrease and finally disappear over time as the polymer chain is formed. This allows the measurement of percent conversion as a function of time by measuring the change in area under the curve at different time intervals.

$$\text{Conversion (\%)} = \frac{[\text{Initial Area}] - [\text{Area at Time t}]}{[\text{Initial Area}]} \times 100\%$$

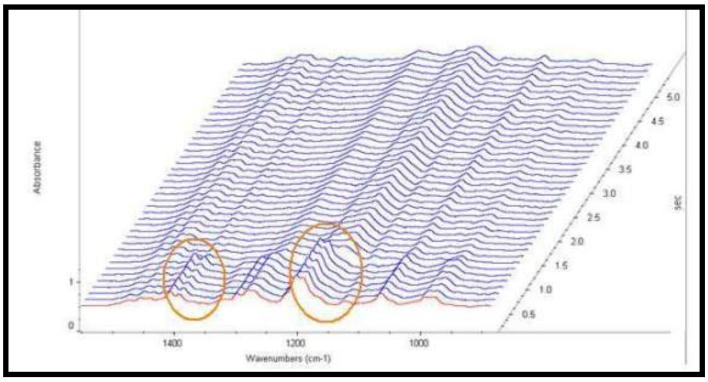
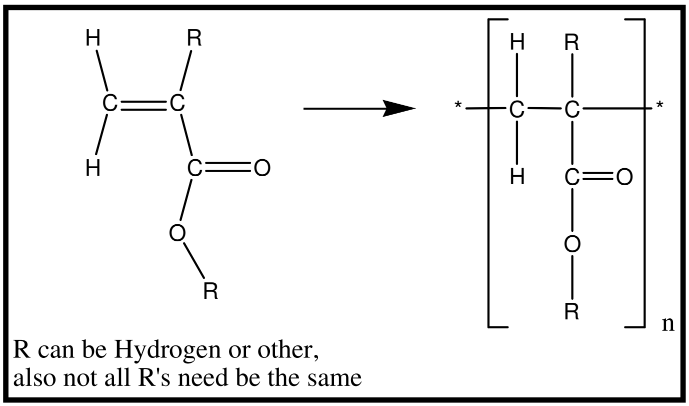


Figure 9: Absorbance versus Wave number FTIR Plot for Ink Sample

The coating tested in this paper show diminishing peaks around ~800-815 cm^{-1} these correspond to the C=C bond in an acrylate group being consumed.



R can be Hydrogen or other,
also not all R's need be the same

Figure 10: Depiction of C=C bond reaction in acrylate group

As the reaction takes place, the double bond is converted into a single bond as the polymer grows, so at 100% conversion no absorption for the double bond will take place.

Tikkurila's UVIPAR TOP 2D single coating top coat that was formulated to cure with a UV LED light sources was tested with 3 different light sources and at different intensities of the UV LED source with an output centred at 395nm. Even though this material was formulated for the UV-A region, it shows that a mercury vapour lamp not only cures the material, but can cure the material at the same rate as the UV LED source with its peak centred at 395nm. The 365nm UV LED light source is not well matched to this material and does not cure as effectively with the light source. As shown in Figure 13, as the peak intensity is increased, the cure rate increases linearly. This underscores the importance of knowing how a given material formulation will interact with a specific wavelength.

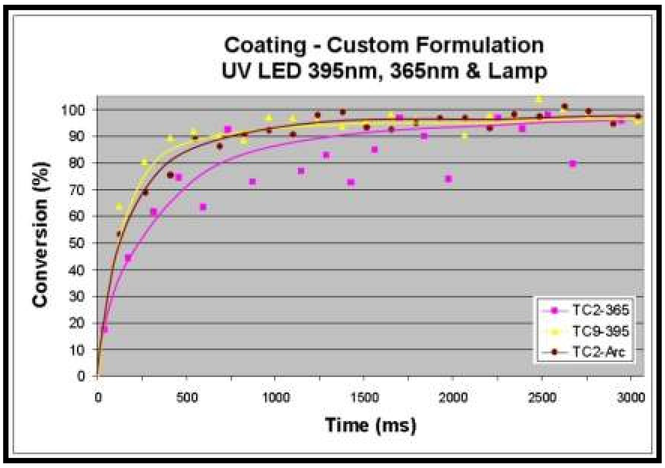
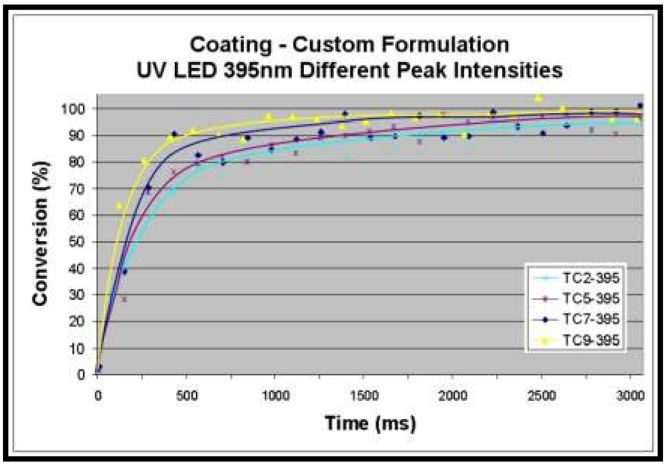


Figure 11: Conversion Rate for UV LED 395nm, 365nm and Mercury vapour Lamp



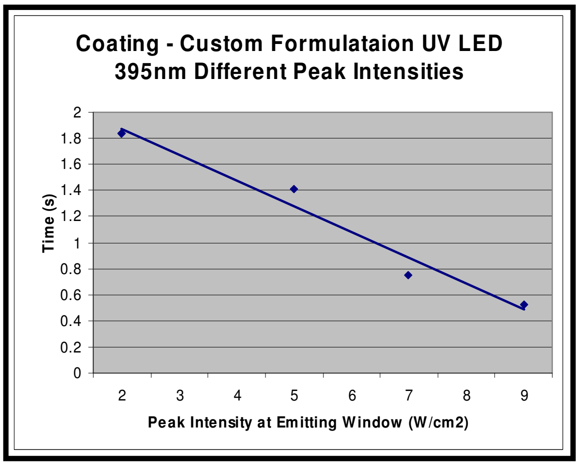


Figure 12: Conversion Rate for UV LED 365nm and Mercury Vapour Lamp

Figure 13: Linear relationship 395nm, Peak Intensity vs. Cure Rate

While not specifically part of the experimental setup and data collected, it should be noted, of course, that UV cure rate as measured using FTIR is only one of several decision factors in determining suitability of UV sources for curing. The physical, mechanical, chemical and process properties of the cured material are in often cases even more critical.

General advantages of UV-LED for Wood coating

- Uniform power of the lamps across the entire working width
- No waste disposal of old lamps containing heavy metals such as gallium and mercury
- Excellent penetration of the UV radiation, also with pigmented lacquers
- Less danger of uncured photo initiators
- Use of lower grade bottom wood

Summary of Benefits of LED Sources

LED technology has several distinct differences when compared to traditional Arc lamp systems. In summary they are:

- Small package size
  - Easier to integrate
  - Less weight
- Low energy consumption
  - No "stand by" required
  - Instant on/off
- No mechanical components
  - Shutters or reflectors
  - Minimal maintenance
- Minimal heat impact
  - On equipment
  - On materials
- Environmental issues
  - No Hg
  - No ozone
  - Low carbon footprint
- Uniformity
  - Over entire length
- Safer working environment
- Lower cost of ownership

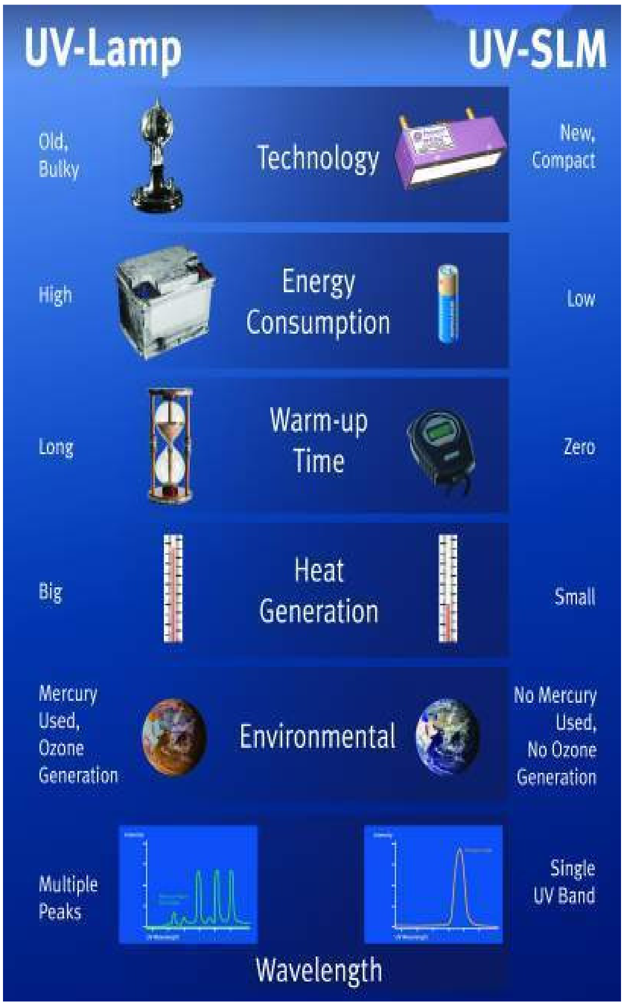


Figure 14: Benefits of LED vs. Mercury Vapour Lamp

Conclusion

The data taken is at least suggestive of some general conclusions - many of which have been validated by the testing and applications reviewed in this paper as well as our own experiences with testing many different UV materials over several years (both UV LED optimized and “non-optimized”).

1. For a typical coating line energy savings on the order of 30% or better are achievable.
2. Improvements in both yield and processing parameters are possible with UV LED technology.
3. UV LED technology and compatible coatings can greatly reduce the environmental impact and carbon foot print of wood coating processes without compromising on coating performance.
4. UV LED Sources are more than capable in most UV curing applications when the material is formulated to accept the energy provided. While there are still limitations in the range of base UV materials available to formulators there is no doubt that practical formulation is possible – for almost any UV application.
5. The peak intensity and total energy of a UV LED source in the UV-A region is relatively more important for cure performance than the specific peak wavelength of the UV LED source in the UV-A region (365nm vs. 395nm). In the end Energy trumps wavelength in terms of the reaction – at least when the wavelength ranges are relatively close together in the spectrum.
6. Increasing the speed of cure is important in many practical UV applications but can be limited by the formulation of the material regardless of any practical increase in peak intensity or energy input. As a practical matter, know that not all UV materials show better material performance with faster cure rates.

The prospect of ever increasing availability of suitable base materials to allow for optimized UV LED formulations - as well as the fast increasing capability and cost effectiveness of commercially available UV LED systems – is likely to accelerate the use of UV-LED systems in many applications.

Acknowledgments

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