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Final Technical Report

High Power UV LED Industrial Curing Systems

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List of Acronyms

AlInGaN	Aluminum Indium Gallium Nitride
DOE	Department of Energy
GaN	Gallium Nitride
GHG	Green House Gases
Hg	Mercury
IP	Intellectual Property
LED	Light Emitting Diode
LLO	Laser Lift Off
SOPO	Statement of Project Objectives
SSL	Solid-State Lighting
TWHr	Terra Watt Hours
UV	Ultraviolet
UVA	Ultraviolet A (315 to 400 nm)
UVB	Ultraviolet B (300 to 315 nm)
UVC	Ultraviolet C (200 to 300 nm)
VOC	Volatile Organic Compounds

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1.0 Executive Summary

The goals of this project were twofold: (1) Demonstrating that Light Emitting Diode (LED) devices emitting ultraviolet (UV) radiation could be used to effectively replace mercury (Hg) lamps that are used today in industrial curing applications, and (2) Evaluate the potential impact on widespread adoption of UV LEDs for industrial printing, coating and painting applications on industrial energy consumption and the reduction of Green House Gas (GHG) emissions typically associated with these industries.

It is widely accepted that UV curing technology is a green technology, reducing energy consumption and reducing GHG emissions if it is used. For almost 100 years, the only UV source available for UV curing was a medium pressure Hg arc lamp, and Hg lamp systems require complex cooling, monitoring and safety equipment. Relative to well-established but highly energy intensive oven based drying technology, these Hg lamp impediments has limited the adoption of UV curing technology, and hence limited the benefits of this green technology.

Recent progress on LED technology for solid state lighting applications has also resulted in new UV LED technology that is now being used for some UV curing applications. However, current UV LED systems are low power and the LED semiconductor chip designs are optimized for lighting and not for industrial UV curing applications. As a result, commercial UV LED curing systems available today are not suitable replacements for current Hg lamp industrial systems.

In this project, a modular, scalable high power UV LED platform was designed, constructed and tested to demonstrate a new approach to UV LED curing suitable for industrial applications. To develop this platform, specialized, large, high power UV LEDs were designed and developed that were suitable for industrial UV curing applications. LED cooling technology needed for efficient, reliable operation was also designed, and a flexible, reflector based optical design was optimized for use in almost any industrial application where Hg lamp based systems are used today. A key design goal achieved in this project was the development of a modular technology platform capable of making UV LED curing systems ranging from several inches to several meters long. This is important since Hg lamp systems today cover a similar range of lengths for various manufacturing applications.

To test this UV LED curing platform, various UV LED modules operating at different UV wavelengths and powers were evaluated in an industrial testbed used to cure coatings for flooring products. The results of this testing were extremely encouraging, demonstrating that these systems can work efficiently in industrial curing equipment, but that more work on optimizing coating chemistry and increasing the UV LED output power was needed. The studies also suggest that the range of UV wavelengths produced by UV LEDs will need to be expanded to more closely mimic the spectral output of Hg lamps used today. Though not part of this study, the LED industry is making good progress on extending high power UV LED performance into the deep UV range (below 300nm) and the UV LED platform developed in this project is fully compatible with using a wide range of UV LED devices to more closely mimic Hg lamp spectral output.

In parallel with the successful development and demonstration of the UV LED equipment platform built in this project, an assessment of the impact on the use of UV LED technology on reducing industrial electrical energy use and GHG emissions was performed. Admittedly, this turned out to be a daunting task, as there is very little information on the actual size of the UV curing market.

Similarly, very limited data are available on the amount of energy used and GHG emitted in printing, painting and coating industries regardless of drying method, as these industries are very highly segmented and current government energy and GHG data collection programs do not include them for that reason.

To circumvent this challenge, a top down estimate approach based on Hg lamp market data and published data on solvent usage in printing, painting and adhesives markets was combined to estimate the impact that efficient UV LED systems would have on industrial energy and GHG emission, and the finding suggest that the impact could be tremendous. At current UV LED operating efficiencies, simply replacing current inefficient Hg lamps would reduce industrial energy consumption by 10 TWhr (34 TBtu). In this scenario, GHG emission reduction would be minimal since UV curing technology is already emission free. The bigger and more impressive impact would result from broader use of UV LED enabled curing technology, replacing conventional drying technologies (e.g. electric and gas fired drying ovens). The model developed in this project suggests that the total potential for CO₂ emissions reduction were all industrial processes to convert from conventional oven drying processes to UV LED curing could be approximately 88 M metric tons annually.

These numbers represent a significant fraction (6.8%) of the total annual industrial CO₂ emissions as reported by the EPA (2009 estimate). This number is consistent with other estimates made by UV industry organizations, but the real question is whether or not UV LEDs can be developed to the point of wavelength range and efficiency to fulfill even part of this potential reduction. If the very rapid progress of LEDs for solid state lighting applications were applied to LEDs operating in the UV region, the environmental impact of LED based industrial curing processes will become quite significant. If one assumes that only 10% of this potential is reached over the next 5 years, it is still a significant contribution. While this project did not specifically address reduction of volatile organic compound (VOC) emission reduction through the use of solvents, additional environmental impact would be derived here, as the printing, coating and sealing industries consume about 4 billion pounds of solvents (2007 data).

Commercialization of the technology developed in this project requires additional private funding. Efforts are underway to secure this funding to convert the pre-production prototypes developed in this project to production ready versions carefully targeted on a suitable growth segment of the UV curing industry (the printing sector). In addition, key commercial relationships developed during this program with high power LED suppliers, including those developing shorter wavelength high power UV LEDs will be expanded to develop mixed wavelength UV LED curing systems designed to work with chemical formulations originally developed for Hg lamps. The UV LED system optimization and target market selection projects are just now underway. Given the modular scalable properties of the UV LED system platform developed in this project, this first production unit will be easily extended into other UV curing applications and markets, delivering significant savings, reduction of electrical energy consumption, and the concomitant reduction in GHG and volatile organic compound (VOC) emissions that are part of solvent based ink and coatings used today for most industrial application.

2.0 Introduction

Whether used for LED lighting or for making UV curing systems, all LEDs being developed for these markets are fabricated from the compound semiconductors gallium nitride (GaN), aluminum nitride (AlN) and indium nitride (InN). By adjusting the composition of the alloys of these materials, the wavelength of light emitted by LEDs made from these materials can be adjusted to cover almost all regions of UV emission between about 250 and 400 nm. While LEDs emitting blue light have been highly optimized for the emerging solid state lighting industry, UV LEDs have not yet been optimized for industrial curing applications. By improving material quality and the electronic and physical design of LEDs made from these materials, one can make devices capable of emitting large amounts of UV optical power. Careful attention to the electronic, thermal and optical design of industrial UV curing systems has led to the design of a novel, large chip linear LED array that can mimic many of the physical and optical features of current Hg lamp system, but with improved reliability, ease of use and cool operation.

Ordinarily, inks, paints and other coatings are applied in liquid form and the solvents they contain are driven off by heating, leaving a dried film. In the process, energy is used to heat the material, and solvents are evaporated. It was recognized more than 30 years ago that a new approach to printing and coating that uses “UV drying” could be used. This alternative approach uses UV light to polymerize specially formulated inks and coatings that contain no solvents. In this approach, no heat is applied, no gaseous process emissions result, and the product is dried instantly. With Hg Lamps, the UV output spectrum produces UV power at specific wavelengths characteristic of mercury atomic emission, with the highest Hg lamp UV power available at 254 nm and 365 nm. Most UV inks and coatings in use today have been optimized to use both wavelengths. While UV LEDs can cover a similar range of wavelengths, the highest power UV LED devices today operate between 385 nm and 400 nm, so new coating formulations that cure at these UV wavelengths are needed. Optimization of new coating formulations requires understanding how UV power and UV wavelength(s) impact curing and coating performance.

In this project, a key goal was to create a UV LED system platform suitable for industrial UV curing applications. Current UV LED curing systems utilizing small LED chips are not modular, scalable or useful for industrial applications because of the very close working distances (3 to 5 mm) these systems require to cure effectively. To overcome this challenge, a novel, high power UV LED system needed to be developed that could simulate the basic optical properties of Hg lamp operation (high irradiance at working distances of up to 150 mm). This development required efficient, large UV LEDs packaged in a manner that could allow a string of LEDs, packed closely together, to imitate the performance of the electrical discharge in an Hg arc lamp. This was necessary to create a compact, linear, high intensity irradiance source that could be imaged using carefully optimized reflective optics on to a product surface for UV curing. To achieve high irradiance, good uniformity and reliability, thermal management systems also needed to be designed that were both modular and provided good thermal uniformity.

As part of this project, new UV LED curable chemical formulations for flooring material coating applications were developed. This was needed to assess the performance of the UV LED prototype systems created in this project, as both wavelength and UV power can have a large impact on coating performance (hardness, adhesion, stain resistance, etc.). This was a complex development project, as coating formulations are highly customized chemical systems, and tradeoffs in chemical

formulation, performance UV wavelength and UV irradiance will all play a role in the performance of the final UV cured product. The area will continue to evolve, as new high power UV LEDs become available over a wider range of wavelengths and as new chemistries are developed that are optimized for the new mix of UV wavelengths and power levels that can be produced by LEDs.

3.0 Background

State of the art LEDs are beginning to significantly impact the lighting field. As mentioned in Section 2.0, the semiconductor materials system used for visible light LEDs can be used for UV LED manufacturing. The wall plug efficiencies of LEDs versus wavelength are shown in Fig. 3.1.

Figure 3.1: Wall plug efficiency versus wavelength in 2009 and 2012 based on industry discussion and published data. Blue LEDs are approaching very high levels of efficiency, and progress is also being reported for UV LEDs. In principle, UV LEDs can be as efficient as blue LEDs if the material quality and device structures can be improved.

[3.1] As can be seen, the performance of UV LEDs is improving rapidly, and even more rapid improvement can be expected as UV LEDs enter UV curing and germicidal purification markets. UV germicidal markets require wavelengths in the UVC spectral region (200 nm to 300 nm), and wavelengths in this range are also important for UV curing applications. The other UV spectral regions of interest are UVB (300 nm to 315 nm) and UVA (315 nm to 400 nm). The LEDs typically used for UV curing today are UVA LEDs operating between 365 nm and 400 nm.

UV LED curing technology is still an emerging field. Commercially available units are typically capable of curing narrow widths (0.25 m), whereas Hg lamps over 3 m wide are commercially available.[3.2] Perhaps more importantly, commercially available units typically require a short distance (a few mm) between the LED array and the substrate, making them impractical for many industrial applications to ensure adequate curing energy into the coating.

Because UV LEDs have so much in common with LED designs used for solid state lighting, they are most commonly available in a small (1.5 mm or smaller) chip format. This poses problems for the design and fabrication of high power UV LED systems, since adequate UV power requires arrays of many LED chips [3.3]. This is important since a key performance requirement of any UV curing system is high irradiance (W/cm^2) at the cure surface. Rules of optical design (Conservation of

Etendue [3.4]) dictate that delivered irradiance depends on source irradiance, and arrays have lower source irradiance because the packing density cannot be as high as that in a single large LED die. This is the basis of a patent application (from before the start of this project) [3.5] covering the design of the high power UV LED array system utilized in this project.

It is widely agreed that UV curing is a green technology and that it is typically regarded as a zero emissions technology [3.6]. There are no industry wide assessments of the energy savings potential of UV curing relative to conventional drying technologies, but case studies of specific applications of UV curing installations suggest significant (50 to 70%) reductions in energy consumption when production lines are converted from oven to UV drying technologies. [3.7, 8] A review of the literature suggests that non-UV methods are still widely used, as solvent sales to markets that UV curing addresses are still significant and growing [2.2] – 2007 data are shown in Fig. 3.2.

Figure 3.2: Estimated solvent consumption by market sector showing that approximately 54% of solvent usage is in markets (printing, painting and adhesives) addressable by UV curing technology.

Recent accurate data for the relative amounts of UV curable versus solvent bearing inks, coatings are not available, but 2005 data from Radtech (as reported in [2.1]) estimate an annual consumption rate of 9.5 million kg of radiation curable solvents, and the data in Fig. 3.2 would suggest the weight of solvent based inks, coatings and adhesives is about 400X greater, so the estimate that the market share of UV coatings is just a few % of the total available market is consistent with this estimate.

Finally, to benchmark the potential electrical energy savings possible with widespread conversion to LED based UV curing technology, the data for the total electrical and GHG emission data for the US industrial sector was obtained. [3.9] Upon examining this data, one finds that industrial energy consumption by coating, printing and other industries using either UV or non-UV dried materials is not reported. This is because it is too low a value to report, or it is already incorporated in other large industry sectors in the study. In discussions with EPA officials [3.10], it was learned that it is almost impossible to collect data from the many users of inks, coatings and adhesives, and that it is quite possible that electrical energy consumption and GHG emissions in the inventory report are not included.

The project goals and objectives include estimating the environmental impact of UV LED curing, the design and fabrication of high power large LED UV curing prototype systems, and the field testing of these prototype systems in an actual manufacturing testbed. The approach to the environmental impact assessment is discussed in Section 4.1. Prototype UV LED curing system development required the new design, fabrication and efficiency improvement of UV LED chips, and this work was performed by SemiLEDs Corporation, one of the few manufacturers of high performance vertical LED chips suitable for this application. During the program, SemiLEDs

conducted an IPO and is now currently traded on the NASDAQ (LEDS) and they continue to manufacture and sell very high power UV and visible LEDs.

The development and testing of UV curable formulations was performed by Armstrong Global Industries. Armstrong is well known as a leading manufacturing of many types of building materials, and this project engaged their research team leading the development of coatings used for flooring products, where their work on developing UV solutions for green manufacturing initiatives is well known. [3.8] A simple graphic showing the difference between UV curing and thermal drying is shown in Fig. 3.3.

Figure 3.3: Simple graphic showing the difference between UV curing and thermal drying. With UV processes, no solvent vapors are emitted and films “dry” instantaneously. In conventional thermal drying, solvents are either vented or scrubbed.

The project was led by SolidUV, Inc., a startup pursuing the development of very high power UV LED industrial curing solutions. The principals of the company have over 50 person years in the development, packaging and systems development of optoelectronic semiconductor components and equipment, including laser diode systems, communications systems, and high power LED systems.

4.0 Results and Discussion

This section follows the Statement of Project Objectives (SOPO) outlined in the project award. The first objective of this project was to assess potential energy and GHG reductions that could result from a widespread adoption of UV LED based curing systems. In this section, the method used to estimate the benefits is addressed and the benefits are described in Section 5.0. The rest of this section describes the approach and technical accomplishments related to the development of industrial high power UV LED curing systems.

4.1 Potential Benefits Assessment

A key deliverable of this project was the assessment of the potential environmental impact of UV curing. This assessment was comprised of two separate parts:

1. Impact on electrical energy consumption if UV LED systems could replace existing Hg lamp systems for processes where UV curing is already employed and,
2. Potential impact on industry in general if the advantages of UV LED based curing could drive a much wider adoption across industries still using solvent based systems.

The practice of coating, painting, printing and sealing (or using adhesives) is spread across a very wide range of industries, no one single source of energy consumption or GHG emission for these

Coors Brewing Company			
Total Energy Usage			
	W/B Thermal Uncontrolled	W/B Thermal +Incineration	UV Curing
Electrical	16,300	19,500	15,900
Natural Gas	23,900	60,100	0
Total	40,200	79,600	15,900
Total Air Emissions (Metric Tons/Billion Cans)			
	W/B Thermal Uncontrolled	W/B Thermal +Incineration	UV Curing
CO₂	2,909	5,182	1,727
Nitrogen Oxides	8.1	11.6	6.5
VOC	28	0.56	0.52
HAP	11.5	0.23	0.12
Non-Methane HC	0.05	0.10	0.02
CO	0.52	1.11	0.15

Figure 4.1: Summary results of energy saved and emissions avoided by converting to UV curing processes (Hg lamp based). (data supplied by Coors to Radtech [4.2].

particular industrial processes could be found. One of the leading sources of data for radiation curing technologies, Radtech (www.radtech.org) agrees that these data are not available and is currently in the process of trying to generate the type of assessment required for this project. [4.1], and similar statements were made by various UV curing experts, including the subcontractor participating in this study. As a result, getting baseline data from which to make a quantitative assessment was not possible, so several different approaches (beyond literature searches) were tried.

First, there are a few case studies of energy savings associated with the conversion from oven to UV drying methods. One such study is summarized in Figs. 4.1 [4.2]

for the conversion to UV curing of Al beer cans at the Coors Brewing Company. It is clear from this example that significant reductions of energy consumption and GHG and VOC emissions are avoided by switching to UV curing for this particular industrial application. Efforts were made to calculate, from thermodynamic principles, the energy related components of these reported results so that a process could be applied to high level market data on the volumes of inks, coatings and adhesives sold annually, but it became clear from these calculations that a significant amount of the energy saved did not involve heating the product or evaporating the solvents, but rather the energy needed to heat large pieces of equipment and the air flowing through it. The calculations and issues with this approach are discussed in the Appendix. Discussions of modeling the empirical Coors data are still in progress, with discussions now focusing less on the thermodynamics of curing as on the amount of energy needed to heat the manufacturing equipment needed for conventional oven based drying.

Note that in the Coors example, reference is made to the drying of the coating with incineration – as in some conventional processes, gas fired ovens are used, and double as incinerators for VOCs released during the drying process. UV curing is essentially emissions free as shown in Fig. 4.1.

In order to estimate the potential benefits relative to both Hg lamp based UV curing as well as the potential impact for replacing all non-UV curing processes, a different, somewhat unorthodox approach was selected, and then tested for reasonability using a variety of comparison data. This process is outlined in Fig. 4.2.

Figure 4.2: Simplified process for making high level estimates of UV LED environmental impact for two scenarios: (1) where UV LEDs just replace Hg lamps, and (2) where 100% market adoption of UV curing completely displaces oven based industrial drying systems.

Specifics of the calculations of energy savings and GHG emission reductions for both cases using this form of analysis are shown in Section 5.0. Since energy consumed in industrial applications is a combination of both primary (fossil fuel, hydro, nuclear) energy sources and secondary (electric) energy, comparisons between technologies will be made in metric tons of CO₂ where a conversion factor of 6.8956 x 10⁻⁴ metric tons CO₂ / kWh [4.3] is used.

4.2 Large UV LED Chip Development

The development of large, high power UV LED chips involved the design and fabrication of a special, high power 3mm square LED semiconductor die, and the optimization of both the epitaxial growth conditions (needed to make the high quality AlInGaN alloys as described in Section 2.0) and is comprised of four subtasks that are described below.

Figure 4.3: Vertical LED chip design selected for this project is comprised of a thin light emitting layer bonded to a high thermal conductivity substrate. made with little or no penalty in efficiency. (Fig. 4.4)

The basic LED chip design selected for this effort is known as a vertical LED as shown in Fig. 4.3. This design was selected because the thermally conductive submount (Cu in this case) enables higher efficiency operation. Another advantage of the vertical design is the improved optical design, with efficient extraction of the UV light produced inside the LED chip through a thin, optimally structured surface. Since very little light is trapped inside the LED with this design, large LED chips can be

4.2.1 Mask Design and Fabrication

A key feature of the vertical LED chip is light extraction through the top surface as shown in Fig. 4.3. An electrical contact must be made to this surface, and the optimization of this electrical contact is required to insure uniform electrical current injection and minimal blocking of the light coming through the surface of the LED chip. Several designs were evaluated (Fig 4.5) and the optimal design, based on chip emission uniformity (a measure of current injection uniformity) and brightness data.

The fabrication process used for the manufacturing of vertical LED chips involves a process known as laser lift off (LLO). Since the LED epitaxial structures are initially grown on sapphire substrates, this substrate needs to be removed during the fabrication process. In order to fabricate the large 3mm square LEDs chips to be evaluated in this project, new laser optics needed to be developed and used so that the very large chips could be produced in high yield.

Figure 4.4: A feature of the vertical chip design that efficiency is independent of chip size. Large LEDs are advantageous for UV power applications because of optical considerations in the system design

4.2.2 Test and Iterate Design

After several iterations of mask design and LLO process development, a final design for the production of 3 mm chips was selected and used in the subsequent packaging and UV system design.

Figure 4.5: The mask designs above were initially evaluated and following testing, a hybrid design (not shown) was selected. Since these LEDs operate at high drive current, factors including contact resistance, light blocking and uniform current injection needed to be considered in the optimization process.

Design iteration included the fabrication of wafers including fabrication of special test structures where all of the individual mask designs were combined on the same wafer. This enabled the optimization of the mask design without interference from wafer-to-wafer performance variation typically observed in the course of normal LED manufacturing.

4.2.3 Demonstrate Improved Efficiency

To improve the UV intensity of the 3mm square LED chips developed, a complex series of epitaxial growth optimization steps was completed to improve the operating efficiency of the LED chips. The results of this process are shown in Figure 4.6, showing the optical output performance improvement of the LED material obtained during this project.

Figure 4.6: Significant improvement in the UV efficiency at both 365 nm and 395 nm wavelengths was demonstrated over the course of this project. It is expected that significant continued improvement will continue as epitaxial growth process development continues. These data are shown for small (~1mm) LED die since that is the size of die run at the largest volume in manufacturing. Since the same material is used for the 3mm die in this project, performance improvement is the same for large die, but too few wafers were fabricated for statistically significant results as large size die are not yet in production.

4.2.3 Evaluate the growth of UV LEDs on Large Diameter

Wafers

During the course of this project, the wafer size used for manufacturing was moved to a 100 mm (4") diameter platform, except for product at 365 nm, where a different crystal growth reactor was used that could not accept large diameter wafers. For longer wavelength UV LEDs (> 375 nm), 150 mm (6") wafers can be used and they have already been used on similar crystal growth reactors used for blue LED devices used for solid state lighting. The technical issues involved with migrating to larger wafers for more economical LED manufacturing have now largely been addressed, and the current barriers are crystal growth reactor design (for 365 nm devices) and the cost of 150 mm sapphire substrates. As more LED manufacturers involved in solid state lighting move to larger 150 mm wafers, it is expected that the price of large sapphire substrates will drop dramatically.

Finally, it is important to note that UV LEDs are riding the coattails of the visible LED market that is growing rapidly for solid state lighting. Continued development of visible LEDs will drive continued performance improvement and cost reductions in UV LEDs, making UV LED curing systems more powerful and affordable. These continued developments include:

- Gradual migration to 150 mm sapphire wafers is currently underway, and LED growth on 200 mm wafers has been demonstrated
- Low cost manufacturing of large diameter substrates using new sapphire boule fabrication methods is underway. Price reductions of 4X to 5X for 150 mm wafers should be possible in the next 12 to 24 months
- Significant progress on shorter wavelength UV LEDs needed for improved curing with formulations now used with Hg lamps is being made by several companies. During this project (and in part because of it) samples of high power short wavelength UV LEDs have been obtained for evaluation
- Continued progress on the design and performance of visible LEDs will be extended to attain continued improvement in UV LEDs, since the materials and fabrication processes are similar.

4.3 High Power System Design

This project required the design and building of high powered UV LED Curing Systems. Originally the task called for building a single 40" long curing module. However, in discussions with the evaluating sub-contractor it was agreed that a shorter 16" long module would be best for initial testing as the evaluation line they were using was 12" wide. This initial prototype was built and shipped to insure the mechanical form, fit and function of subsequent units shipped for the formal coating cure testing. The working distance or focal distance of 5" was deemed to be very important and was a hard design goal given the other physical constraints of the curing evaluation test bed.

After the initial 16" 385 nm module was evaluated, it was determined that testing other wavelength UV LED systems was more important than constructing a full 40" unit. An additional 3 units were constructed with different wavelengths: 365 nm, 385 nm (improved chips) and 405 nm. In total, four 16" modules were fabricated and evaluated for curing performance; two at 385nm, one at 365nm and one at 405nm. A total of 64" linear inches of LEDs were constructed and due to the modular nature of the internal "light engines" they could be arranged to provide 64" of integrated linear curing if desired.

4.3.1 LED Power Package Design

The design, sourcing and assembly of the LED packaging method, especially regarding the heat transfer from the LED to the heat sink, was a critical part of this task. The design goal was to achieve at least 40 watts of electrical power to each 3 x 3 mm LED and have the LED generating maximum light output or capable of generating even more light with additional current, but not enter the "thermal droop" region of performance, where optical output power drops due to heating. A design goal of 1 C/W (change in temperature for a 1 watt increase in input electrical power) was set as reasonable for this iteration.

As shown in the Fig. 4.7, thermally induced droop (sometimes called thermal rollover) occurs when the LED output decreases with increasing input current. By effecting better cooling, lower LED junction operating temperatures can be achieved, moving the maximum optical output power to higher drive currents. Therefore maximizing heat transfer out of the LED junction region is the major design goal in high power LED applications, and will be an area for continued improvement and innovation beyond this project.

In the course of this project, the LED package thermal impedance was reduced from 1.6 C/W to an estimated 0.78 C/W. This was accomplished by completely revising the existing thermal packaging methods. In the system design, there are several interfaces and thermal interface media that make up the thermal impedance path and during this project, LED die attach material and methods, bulk packaging materials, electrical isolation materials, and package-to-heatsink materials and methods were significantly improved. These improvements are proprietary, and will be improved upon in subsequent designs.

Figure 4.7: The dependence of the LED optical output power on input current showing roll over due to heating. By significantly improving the thermal performance of the LED package design in this project, thermal roll over was significantly reduced.

4.3.2 Module Design and Test

The design of the four 16" modules was quite similar with improvements based on the first prototype unit incorporated into the final three units operating at different wavelengths. All design work was done in SolidWorks including Thermal Finite Element Analysis performed with the SolidWorks Simulation package. The complete redesign of the packaging platform detailed in Section 3.1 required a complete redesign of the previous water cooled heat sink design. The new design is a very thermally effective heat sink and is an elegantly simple, low cost design with superb thermal uniformity along the LED array axis. Thermal uniformity is essential for uniform irradiance and more importantly, is modular: built in 4" sections and designed to provide a constant LED pitch within the 4" segment and at the joint between segments.

The module shell, optical subassembly and electrical and cooling water interconnects were designed for ease of manufacturing and for durability as required by industrial manufacturing conditions in the flooring coating industry. (The curing modules may occasionally be impacted by large pieces of wood moving at high speed.) The internal optical subsystem is a machined rib design similar to an aircraft wing's internal structure, and forms the profile of the reflective elliptical optic. The mechanical accuracy provided by the ribs is a very important design feature as the shape of the elliptical reflector is critical to obtaining high irradiance reproducibly from module to module. For this project, the optical system was designed to provide a 5" working length with minimal impact on irradiance at the cure surface. The design has an extremely high strength / rigid/ light weight "space frame" structure to reduce weight without sacrificing rigidity or optical precision. The elliptical optic is designed to retain its shape over a wide range of operating temperatures for good irradiance stability. The UV LEDs and internal reflective optics are protected by a bottom cover glass, which,

in this project did not have an anti-reflection coating (which would have increased irradiance by approximately 6 to 8%). The first 16" prototype assembly is shown in Fig. 4.8 and is shown under operating conditions in Fig. 4.13 at the end of this section.

Figure 4.8: The first 16" prototype assembled on a simple frame for testing at the curing development subcontractor. The modular assembly could be connected to additional units to increase the working length by removing the end cap and coupling two (or more) units together.

4.3.3 Optical Design

By using a linear array of large, closely packed LEDs, it is possible to synthesize an “arc” that can be re-imaged with a simple elliptical reflector. The LED array is set within the module very accurately to ensure the emitting surface of the LED array is a focal line of the elliptical reflector, and the other conjugate focal line is at the cure surface (as shown in Fig. 4.9 in a concept sketch for an earlier system design). The light emission pattern from the LED surface is Lambertian. The elliptical reflector collects light emitted from the LED array and reimages it at the conjugate focal line at the cure surface. Perpendicular to the cross-section in Figure 4.9, the emitted radiation continues to spread. For the 5" working distance optical design used in this project, irradiance along the conjugate focal line drops near the ends of the 16" module, as shown in the optical simulation (Fig. 4.10) and the measured optical uniformity (Fig. 4.11). This effect is well known in Hg lamp curing systems as the “short lamp” effect, and can be reduced at shorter working distances

Figure 4.9: A sketch showing how the emission from an LED block is refocused onto a cure surface

Figure 4.10: The optical system was modeled using TracePro™. Results agree well with the measured uniformity data in Fig. 4.11

Figure 4.11: Measured irradiance uniformity (385 nm) at the cure plane measured at an operating current of 10 A. Note that the measured length is 11 inches longer than the module, showing considerable irradiance outside the module length. Subsequent designs will employ new optics to improve the irradiance uniformity.

4.3.4 Power Supply Design

Each 16" module was comprised of 4 water cooled subunits containing 18 LEDs each. These LEDs were operated in series and the design was selected for reasons of optimizing the current-voltage characteristic of the power supplies. Constant current power supplies with a peak current capability of 14.5A and a compliance voltage limit of 100V. Series operation of the LEDs is preferred to obtain uniform current through each LED. In this project, commercial power supplies were used and to ensure safe (to the LEDs) operation, a soft start feature was used to prevent an initial current surge at turn on.

4.3.5 Assembly and Test and Installation at Curing Test site

Each module was supplied with an adjustable height support stand. Before shipment, each module was tested for power output and uniformity. These data were provided for the cure testing of the modules. Due to the simplicity of the design and instructions provided with the units, no on-site installation support was required. Support documents included assembly instructions with photos and advice regarding electrical shock hazards and blue/UV light optical hazards. No setup or operating issues were reported.

4.3.6 Design and Construction of Two Optical Test Sets

In order to test and assemble the UV LED systems described above, part of the project involved the design and testing of a high power packaged UV LED test stand and a programmable 3D irradiance uniformity mapping system. The completed units are shown in Figs. 4.12. Additional details are provided in Appendix B.

Figure 4.12: The X-Y-Z mapper system in the foreground and the integrating sphere (red) LED test system (background) are shown. Both systems operate under computer control and were used to optimize LED package design and UV LED module irradiance optical uniformity.

Figure 4.13: The first prototype undergoing evaluation before shipping for curing tests.

4.4 Formulation Development and UV LED Prototype Evaluation

4.4.1 Module Installation and Field Testing

During this project, it was decided to build an early 16” prototype for preliminary evaluation and testing on some simple UV curable coatings, mostly to determine whether or not the external form of the prototype module could be adequately installed and tested at the subcontractor. As a result of this initial installation, a total of 4 – 16” modules were tested, each operating at a different wavelength. This was required to optimize the tradeoff between UV LED power and wavelength versus coating composition. The design of these units were such that they could have been connected end-to-end to create a 64” cure unit, thus meeting the length design goal of this project, but in this field testing, they were operated individually to assess wavelength and power effects on cure performance.

In conventional UV curing using Hg lamps, coated product to be cured is usually passed under several, separate banks of lamps to get the desired UV dose and cured film properties. In these studies, multiple passes combining UV LED units and an Hg lamp unit were combined and film properties were assessed. Following curing, various coating formulations were assessed using proprietary testing procedures used to assess gloss, discoloration due to cure, and stain resistance.

4.4.2 Coating Cure, Test and Report

After extensive preliminary testing, a standard (proprietary) floor coating formulation was selected for baseline testing (coating 0). A set of five coatings were tested as shown in Table 4.1. Coatings (1) through (4) were modified with a commercially available photoinitiator (Irgacure 819) specifically designed for longer wavelength UV curing.

Table 4.1: Differences in coatings used to test the UV LED curing units.

Coating	% Irgacure 819
#0	0.0
#1	1.2
#2	0.6
#3	2.4
#4	1.2*

*The total photoinitiator amount in #4 was half that of the other coatings.

Each coating was cured using a mixture of LED and traditional arc lamps. The LED unit was used as either the pre-cure or the final cure.

Initially, coating #0 was cured using the 385 nm UV LED unit, either as a pre-cure or as a final cure, in conjunction with traditional Hg lamps (Table 4.2). All samples achieved acceptable gloss. Sample 3 had the lowest gloss. This is likely due to the UV LED unit being used for final cure, since for this sample the Hg lamp was used to initially set the gloss. Ordinarily, a delay time after the pre-cure allows flattening agent in the formulation to rise to the surface, decreasing the gloss. Since the final cure with the UV LED unit required several passes, the delay time was increased, possibly

impacting the final gloss of the coating. The Delta E, or discoloration of the flooring before and after coating, was low for all samples. Sample 2 showed more discoloration than the others and Sample 3 exhibited unacceptable stain test results. This may be due to the lack of short wavelength UV (UVC) in the UV LED unit. UVC irradiation provides enhanced surface cure in a coating, and that was not provided in Sample 3, leading to poor stain performance.

Table 4.2: Performance results of #0, cured using 385 LED.

Sample	LED Cure type	Gloss (60 deg)	Delta E	Stain Resistance
1	Pre-cure, 1 pass	good	Very good	Good
2	Pre-cure, 2 passes	good	fair	Good
3	Final	low	Very good	Poor

Based on these initial results, further studies were done on UV LED curing units, using the modified coatings, as described in Table 4.1. Additional UV LED units (365 nm and 405 nm) were also tested in these next experiments. The additional coatings were variations of baseline #0 formulation that included an additional photoinitiator, Irgacure 819. The 365 nm LED unit was of interest, as mercury arc lamps have a strong emission at 365 nm, and therefore would be expected to provide the higher energy/photon needed to activate a traditional photoinitiator. The 405 nm LED unit was of interest as it had a starting irradiance approximately 3X greater than the 365 nm unit, but lower energy/photon due to the longer wavelength. The results of the curing tests for these formulations with the different wavelength UV LED curing units are shown in Tables 4.3 and 4.4.

All samples shown in 365 nm Table 4.3 test results showed low gloss if the UV LED unit was used for the final cure. This is shown in Fig. 4.14 and the effect is independent of the coating formulation. The discoloration of the flooring after coating was largely influenced by the quantity of Irgacure 819 present in the coating. A coating blended with Irgacure 819 is brightly colored yellow prior to UV cure, so it is no surprise that the final coating is influenced by this factor (Fig. 4.15). Finally, most samples performed satisfactorily for stain resistance.

Table 4.3: Performance results of several coatings cured using 365 nm LED

Sample	Coating	LED Cure type	Gloss (60 deg)	Delta E	Stain Resistance
3	#0	Pre-cure, 1 pass	good	good	fair
4	#0	Pre-cure, 5 passes	good	good	good
5	#0	Final cure	low	good	good
6	#1	Pre-cure, 1 pass	good	Fair	good
7	#1	Pre-cure, 5 passes	good	poor	fair
8	#1	Final cure	good	good	good
9	#2	Pre-cure, 1 pass	good	good	good
10	#2	Pre-cure, 5 passes	Low	good	good
11	#2	Final cure	low	good	good
12	#3	Pre-cure, 1 pass	good	Fair	Very good
13	#3	Pre-cure, 5 passes	good	fair	good
14	#3	Final cure	good	poor	good
15	#4	Pre-cure, 1 pass	good	good	poor
16	#4	Pre-cure, 5 passes	low	good	good
17	#4	Final cure	low	good	good

Figure 4.14: Gloss results are best when the delay between pre-cure and final cure is minimized.

Figure 4.15: Yellowing increases as the concentration of Irgacure 819 added to the formulation increases

Table 4.4: Performance results of several coatings cured using 405 nm LED

sample	Coating	LED Cure type	Gloss (60 deg)	Delta E	Stain Resistance
18	#0	Pre-cure, 1 pass	good	good	good
19	#0	Pre-cure, 10 passes	good	good	good
20	#0	Final cure	good	fair	Very good
21	#1	Pre-cure, 1 pass	good	poor	good
22	#1	Pre-cure, 10 passes	good	fair	fair
23	#1	Final cure	good	poor	fair
24	#2	Pre-cure, 1 pass	good	fair	good
25	#2	Pre-cure, 10 passes	good	good	Very good
26	#2	Final cure	good	fair	good
27	#3	Pre-cure, 1 pass	good	good	good
28	#3	Pre-cure, 10 passes	good	fair	good
29	#3	Final cure	good	good	good
30	#4	Pre-cure, 1 pass	good	good	good
31	#4	Pre-cure, 10 passes	good	fair	good
32	#4	Final cure	good	good	fair

In Table 4.4, the results are shown for the 405 nm UV LED curing unit. All samples in this data set also achieved adequate (good) gloss. Similar to the results for the 365 nm UV LED unit (Table 4.3), there is an effect of the delay time on the gloss level. However, with the 405 nm LED curing, this effect does not appear to be statistically significant. As with the 385 nm LED data, the samples cured at 405 nm generally performed satisfactorily for stain resistance, with no clear trends emerging

for coating identity or LED cure type.

In summary, extensive formulation and cure testing of several different wavelength UV LED cure systems was performed. Overall, encouraging results were obtained and the best performance was obtained with the baseline formulation, but more work would be needed to improve overall performance, especially where gloss requirements are high. This could possibly be done by changing the formulation to match the wavelength and power levels of the UV LED units tested in this project. Alternatively, higher power units, and in particular, future UV LED curing units containing both short (UVC) and longer wavelength (UVA) LED sources may perform better.

5.0 Benefits Assessment

Following the method described in Section 4.1, the following estimates were made for the environmental impact of UV LED based curing. The assumptions are shown in Table. 5.1.

Table 5.1: Assumptions used for Calculating Hg Lamp Power Consumption

Item	Quantity	Unit	Reference
UV Equipment Market Size	1.70E+09	\$/yr	Estimated size of Hg Curing Equipment Sales (normal year)
Hg Replacement Lamp	2.00E+08	\$/yr	Estimated \$ Value of Hg Lamp Sales (Jole Market Survey)
Ratio	0.117647059	lamps to systems	Ratio of UV lamp to UV equipment sales
Average lamp life	2000	hours	Assumption
Average lamp power	400	W/inch	Assumption
Most popular Lamp length	20	inches	Assumption
Price of 20" lamp	200	\$	Assumption
Operational Assumptions			
operation	3200	Hr/yr	2 shifts/day, 5 days/week, 50 weeks/year, 80% on time
Bulb changes/system	1.6	changes/year/system	Based on total use hours and estimated lifetime
lamps sold/year	1.00E+06	lamps/year	Hg market size/average price of average lamp
lamps in operation	1.60E+06	running lamps	1.6X more lamps in operation than sold per year
power of lamps running	1.28E+10	W dissipated	assumes 300 W/in is average power for all bulbs
Energy used	4.10E+10	KWH	Energy Used just to power Hg lamps
% Lamps in US	25%		Assumes half of UV curing is in US
Energy used in US only	1.02E+10	KWH	Energy use in US only

In Table 5.1, assumptions regarding the size of the Hg bulb market, the average size (inches) and power (W/inch), and nominal manufacturing operation characteristics are used to estimate the amount of electrical energy consumed by Hg lamps used in UV curing applications. Assuming that 25% the Hg lamps used in the world today are in the US, Hg lamps consume approximately 1.0×10^{10} KWH of energy (10 TWHr). This estimate can be compared to the amount of energy used for powering a particular kind of light bulb (PAR 38 – typically used for flood lighting). The DOE estimates that approximately 90M PAR 38 bulbs installed in the US today consume approximately 11 TWHr/year of energy. [5.1]

In terms of GHG emissions, the electrical energy used by Hg lamps for industrial curing applications corresponds to approximately 7 M metric tons of CO₂, or approximately 0.5% of all industrial GHG emissions in 2009. [3.9] If one assumes that UV LED systems can produce UV radiation 25% more efficiently than Hg lamps, then the energy saved by replacing all Hg lamps used for UV curing would amount to electrical energy savings of 2 TWHr (7 TBtu) or about 1.4 M metric tons of CO₂. This is shown in Table 5.2.

Table 5.2: Potential Impact of Replacing All Hg Lamps with LEDs

Environmental Upside with LEDs (assuming 25% more efficient at producing UV Radiation)			
Metric Tons CO2	2.82E+07	Metric Tons CO2	From electrical energy used to run Hg bulbs
Metric Tons CO2 US	7.06E+06	Metric Tons CO2	US only
Upside for UV LED	25%	percent	UV LED 25% more efficient than Hg bulbs
Electrical reduction	2.05E+09	KWH	Improvement in just converting current Hg Lamps to LED
CO2 reduction with LED	1.41E+06	metric tons	Improvement in just converting current Hg Lamps to LED

Of course, significant improvements still need to be made in UV curing systems, as the absence of adequate UV power, especially in the short wavelength UVC region, limits the performance of high

power UV LED systems. With the rapid progress on the efficiency of UV LEDs in both the UVC and UVA regions, the ability to replace Hg lamps complete may be possible in the next 5 to 10 years, if the lessons learned from the rapid efficiency increases in blue LEDs for solid state lighting can serve as an example.

Using the market assumptions shown in Table 5.1, one can make a very rough estimate of the total GHG emissions reductions possible if it were possible to achieve 100% market adoption of UV LEDs for all industrial drying applications. Under these market assumptions and 100% penetration of UV LEDs into the current printing and coatings industries, a reduction of 88 M metric tons of CO₂ (or about 6.8% of the total CO₂ industrial emissions currently listed in the EPA's GHG inventory) could be eliminated as shown in Table 5.3. Energy savings in this 100% penetration scenario would be over 120 TWhr (over 400 MBtu) per year.

Table 5.3: Potential Impact with 100% UV LED Market Penetration

Potential Upside if All Applications were UV LED Cured			
Reduction in CO ₂ with UV	50%	percent	based on various case studies (limited)
Penetrated market for UV	10%	percent	90% of market is still heat dried (conservative assumption)
CO ₂ emitted by non-UV cured apps	1.41E+08	metric tons	based on UV market penetration
	7.06E+07	metric tons	US CO ₂ Reduction if Hg lamps had 100% of curing market
CO ₂ reduction if fully LED	8.83E+07	metric tons	US CO ₂ Reduction if LED lamps had 100% of curing market
Total Industrial CO ₂	1.30E+09	Metric Tons	2011 EPA GHG inventory for industrial sector
CO ₂ reduction with 100% UV LED	6.79	percent	possibly missed in GHG inventory?

This estimate of the maximum potential upside for UV LED curing are consistent with estimates made by others assessing the environmental impact of UV curing. There are three key factors that need to be considered when considering a realistic environmental impact of UV LED based curing:

1. Not all industrial coating, painting, printing and fabrication (adhesive) processes are amenable to UV curing.
2. Considerable improvement in the performance of UV LEDs will be required to access a large share of the UV curing market.
3. The return on investment for converting to UV LED curing needs to be attractive before industry will convert to UV LED systems.

While it is difficult to assign a UV addressable market size (1), it is clear from the rapid performance improvement, price reduction and reliability of visible LEDs for solid state lighting that, were similar progress be achieved for UV LEDs, UV LED based curing systems will become more attractive for industry over the next several years. It is possible that with rapid improvements in UV LED technologies and UV curable formulations, 10% market penetration over the next 5 years should be possible, so the energy savings are still significant.

6.0 Commercialization

Significant progress was made during this project in developing pre-production prototype UV LED curing systems. Based on a careful analysis of the bill of materials (BOM) of the prototypes developed in this study, this approach is certainly commercially viable, and will become even more so with economies of scale possible with increased commercial sales. The breakdown by category for the key components of the system design is shown in Fig. 6.1.

Figure 6.1: The cost breakdown for the systems by subassembly using both off-the-shelf power supply systems and estimated costs of for a custom supply based on fair market estimates based on typical \$/watt values from other industries.

The costs of current Hg Lamp UV curing systems vary widely depending on the application. Expressed in terms of \$/inch (typically the UV lamp length), prices vary from \$300/inch for low power basic systems (low end screen printing and mobile curing systems) to \$1500/inch for more sophisticated high power systems (high speed printing applications). Few UV LED based curing systems are on the market, but data so far indicates that UV LED based curing systems range in price from \$1200/inch to \$3000/inch – and this is for very short units (< 8” linear length).

Figure 6.2: Price range and average price estimates for Hg Lamp and small LED chip UV curing systems. The pricing for the high power UV LED system developed in this project will depend on features and irradiance levels.

The systems developed in this project, with a generous gross margin, would initially be priced in the high Hg lamp system price range even for relatively low sales volume (~1000 inches of UV curing system per year). Since there are no scalable linear UV LED based curing systems on the market, and none capable of high UV irradiance at conventional industrial UV curing working lengths, fully productized version of the

prototypes developed in this project should sell well.

The designs implemented require some further refinement, primarily for the design of a customized electrical power system and computerized graphical user interface for operation similar to those used for Hg lamps today. Key next steps include:

1. Selection of one to two stock module lengths which, when connected, can cover the most popular length ranges of Hg lamps in use today
2. Work with OEM power supply vendors to design a suitable set of power supplies designed specifically for operation with production versions of the systems developed in this project.
3. Work with additional vendors of LED chips to insure adequate supply and secondary sources of high power UV LED chips over a wide range of wavelengths.
4. Establish contract manufacturing relationships with LED package assembly houses capable of fabricating the current (or enhanced) UV package designs developed in this project.
5. Hire additional assembly and test personnel for a first phase launch of a product version of the prototypes developed in this project.

These steps will require additional investment, and that work is in progress. Additionally, strategic relationships with key LED chip manufactures will be sought, including models in which these suppliers invest in the growth of this UV LED systems business. Discussions regarding such funding models are already underway. Additionally, UVC samples are already under evaluation for inclusion in the system platforms designed in this project. The addition of UVC to UVA would, for

the first time, give full wavelength capability to UV LED curing systems and make them very attractive relative to UV Hg lamp based systems.

As is clear from the work in this project, the design of the UV LED curing system and the chemical formulation of the material to be cured are very closely related. One of the early objectives of commercialization would be to supply, at or slightly above cost, high power UV LED curing systems to some of the larger coatings and inks formulators so that the entire UV-chemistry package can be developed. This will be critical to establishing the complete “package” needed to drive revenue, and start securing the environmental benefits of a broader adoption of UV LED curing technology.

Finally, the systems designed in this project could have application in the visible, particularly for horticultural applications (combination of UVA, blue and red LEDs). LED illumination for plant growth is getting increasing attention for local agriculture in order to extend the growth day during winter months. The basics of the design developed in this project would be applicable in these applications.

7.0 Accomplishments

During the course of this project, the company was operated in stealth mode – so little effort was made to advertise accomplishments in publications – either in technical literature, trade journals or in web-based publications. The results of this project have played a strong role in activities aimed at securing additional private investment to accelerate business growth.

The accomplishments of this project are as follows:

1. A high level assessment of the potential environmental impact of using UV LEDs for industrial curing applications was completed.
2. High power vertical design UV LEDs measuring 3 mm square were developed for UV curing applications.
3. The output power of these LEDs was improved by over 30%. At 400 nm, wall plug efficiency in excess of 40% was reported.
4. A modular high power UV LED design capable of long linear designs was designed and tested. Currently, this technology enables long linear UV LED curing systems much longer than UV LED curing systems currently on the market.
5. A new thermal design for the high power LEDs was developed and testing, eliminating problems with thermal roll over at high input current
6. A customized high power UV LED test system and XYZ mapper system were designed, constructed and tested for use in measuring the characteristics of LEDs and assembled UV LED curing systems developed in this project.
7. 16” long UV curing modules at three different wavelengths (365nm, 385nm, 405nm) were tested with various coating formulations used for flooring manufacturing. Good curing was obtained with optimized formulations.

8.0 Conclusions

The potential energy savings and GHG emission reduction possible with LED based UV curing is significant, as printing, coating and painting technology is broadly deployed throughout industry. In 2000, the North American market for UV curable coatings was approximately \$1B, and this represented about 4% of the total coatings, curing and adhesives market at that time [2.1]. While this data is old, it is still representative of the small UV addressable fraction of the total printing, painting, coating and adhesives market, estimated to consume up to 4.3 billion pounds of non-aqueous solvents based on more recent survey of the solvent industry [2.2]. In industrial processes, these solvents need to be evaporated thermally, generating emissions and consuming large amounts of energy needed for electric or gas fired ovens. Collective data for the entire industry are not available, but individual case studies indicate that converting from solvent based to UV cured coating technologies can reduce energy consumption by between 50 and 70%. (See Section 3.0)

As part of this project, a preliminary analysis of the potential impact of UV LEDs on industrial energy use and GHG emissions was performed, suggesting that not only could UV LEDs improve energy efficiency in UV applications where Hg lamps are already used, but have a bigger impact if it could convert the non-UV printing, coating and painting markets still using solvent based systems.

Current target industries include printing, including labeling and packaging, painting/coating (automotive, construction, almost all durable goods manufacturing) and assembly industries where adhesives and glues are used (primarily consumer and medical electronics assembly). In addition, new potential markets are evolving in solar energy, flexible electronics, and various roll-to-roll high speed assembly processes. These processes tend to be heat sensitive and will require UV LED curing technology since Hg lamps emit approximately 65% of their input electrical power as heat, so UV curing systems can be viewed as an enabling technology for these emerging high tech markets.

Prototypes developed in this project demonstrated that modular, scalable UV LED systems can be constructed and used in industrial curing environments. The next steps to commercialize this new UV curing platform involve securing funding to develop robust, manufacturable UV curing hardware with customized power supplies and an expanded range of UV wavelength options, including multi-wavelength units which are supported by this new hardware design platform. Since the UV LED units need to be paired with suitable UV curable inks and coatings, a well-defined market target and set of product formulators will be targeted for the first commercial launch of this new and exciting UV LED curing system design. In addition, a low cost version will be developed specifically for lab use by ink and coating formulators to advance the development of chemical formulations specifically optimized for high power UV curing in a wide variety of industrial applications.

9.0 Recommendations

Given the significant potential for UV LED based curing systems for conserving energy and reducing CO₂ and VOC emissions in industrial printing, painting, coating and fabrication processes, it is appropriate to seek ways to accelerate the adoption of UV LED based curing system development and process implementation in industry. In order to accelerate the adoption of UV LED curing technology, the following actions are recommended:

1. Seek to fund the domestic development of advanced UV LED technology. Currently there are several small US companies working to develop UV LEDs, primarily for germicidal applications, but with improvement in these core LED device technologies, particularly for UVC LEDs, the adoption of UV LED curing will be accelerated.
2. Encourage the conversion of industries using conventional drying technologies to use UV LED based curing systems through economic incentives and/or enforcement of environmental regulations governing the emission of VOC typically associated thermal drying processes.
3. Target and fund development programs for large industries manufacturing coatings to develop new formulations specifically for UV LED curing processes.

Finally, the original proposal for this project included a draft for Stage 3 funding to take the prototype systems developed to a manufacturing readiness stage. SolidUV, Inc. would welcome the opportunity to apply for Stage 3 Manufacturing Readiness funding were such an opportunity to become available.

10.0 References

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11.0 Appendices

Appendix A – Coors UV Conversion Data

The Coors UV curing data (Fig. 4.1) shows that considerable energy savings and emissions reductions are possible. The data reported for 10^9 cans per year represent actual factory measurements for three different can manufacturing processes using a water-based can coating. While the numbers are impressive, an effort to calculate these numbers from first principles proved difficult. From an estimate of the volume of coating required to manufacture one billion cans and a thermodynamic analysis of evaporating the water in the coating and heating the aluminum to an estimated 220 C, one calculates an energy cost much lower than that reported in the data. The assumptions are shown below:

Table A.1: Volume of coatings needed for one billion cans

Parameter	Value	Units	Comment
can diameter	6.5	cm	std 12 oz
can height	11	cm	std 12 oz
can surface area	257.68	cm ²	
wet volume of coating	0.198	ml	Assumes 45% solids
wet volume of coating	5.23E-05	gallons	per can
total volume for 10^9 cans	52306	gallons	per year
total volume of H ₂ O	29291	gallons	per year

The energy needed to evaporate this amount of water at 220 C (and heat the Al cans) is only about 3000 MBtu, far less than the 40,000 MBtu measured reported by Coors (without incineration). It appears that the majority of the energy is used to heat the air and the process equipment, reasonable in that the energy needed to heat 15000 CFM to 220 C for a year at a 70% uptime (about 38,000 MBtu) would make up the difference. Without detailed information of the process equipment, airflow, and other processing details, calculating energy costs of simply curing solvent containing films is difficult. This is, in part, why the alternative energy evaluation method described in Section 4.1 was used to calculate the environmental impact information in this project.

Appendix B – Design and Construction of Two Optical Test Sets

Two LED test systems were designed in this project: A single LED integrating sphere characterization test set, and a large area XYZ irradiance mapping system. These systems were assembled from commercially available components as commercially available systems were either too expensive or simply not available for the requirements of this project. These systems are briefly described below and were shown in Fig. 4.12.

The Single LED Integrating Sphere System:

The single led system was designed and built to characterize the performance of a single packaged LED or a small module consisting of several LEDs packaged onto a heat-sink. The test system is computer controlled and records and stores all test data and parameters in a database.

The system records input power and output optical power and wavelength and can be used to measure LED performance under a variety of operating conditions. Test temperature is also recorded. These data can be used for device binning and reliability testing. The hardware is comprised of the following components:

- Dell Optiplex 980 running Windows 7 operating system – Serves as the system controller and data storage device.
- Custom LabView software system
- Lambda Zup 36-24 computer controlled power supply
- Gigahertz Optics 20 inch diameter Integrating Sphere
- Gigahertz Optics X11 Optometer Power Meter and Sensor
- Gigahertz Optics Calibration Lamp
- Stellarnet C-50 Spectrometer (interfaced to the integrating sphere)
- Custom water cooled heat sink test fixture- Flexible system for any LED package style with rapid load and un-load of LEDs
- Water Cooler

The Large XYZ Scanner System:

The XYZ scanner system was developed to optically and spatially map the output of a complete UV LED curing system to determine the power and wavelength of the light energy in the XYZ space beneath the output window of the LED System. This capability is important to characterize and validate the optical design of the system and the performance of individual units functionally prior to shipment and to enable long term reliability studies of a completed system. The system is comprised of the following units:

- XYZ Motion Control System- A motion control system comprised of stepper motor driven belt drive linear axis, separate X , Y and Z axis and a computer controlled stepper motor driver system
- Support Frame fabricated from 80/20 TM aluminum extrusions to form a strong stable base for the XYZ Motion control and flexible mounting for UV curing systems up to 60 inches in length.
- Gigahertz Optics X11 Optometer Power Meter and Sensor (from the LED test system above – moved to the mapper as needed)
- Stellarnet C-50 Spectrometer (from the LED test system above – moved to the mapper as needed)