The Publishable Final Report of the UVLED Project

Grant Agreement number: 262514

Project acronym: UVLED

Project title: Energy efficient UV LED curing without inerting

Funding Scheme: Research for the benefit of SMEs

Period start: **1st January 2011**

Period end: **31st December 2012**

Project Coordinator: **Dr David Anderson**

Project Coordinator Organisation: **Lambson Ltd, UK**

Project website address: http://www.fp7-uvled.eu/

Contents

Executive Summary

UVLED is a 2 year €1.1 million project supported by the Seventh Framework Programme of the European Commission. The project brings together 4 SMEs from Italy, Finland and the UK, that represent different aspects of the industrial wood coatings supply chain from photoinitiator manufacturer to the wood applicator. Although this project focuses on UV LED industrial wood coatings, the materials developed have extensive application to inks, vinyl flooring and conformal coatings. Our aim is to develop new photoinitiator and anti-oxygen inhibition technology that will enable UV LED coatings to run at the same, or better, line speeds, than conventional UV coatings without needing to create an inert atmosphere on the coating line.

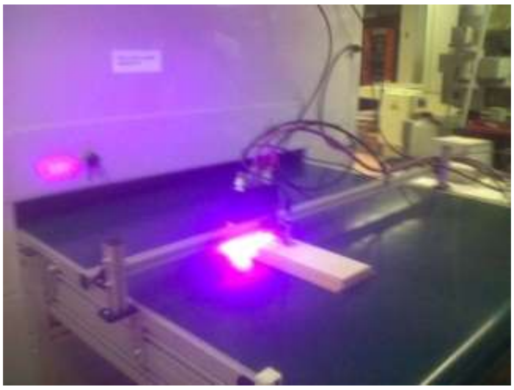
Experiments undertaken by the RTD partners (PRA and TUV) have evaluated various initiator packages with the conclusion that under the right combination of UVLED radiation and with the addition of selected additives in the formulation adequate surface and bulk film cure can be obtained. Specifically, selected combinations of an acylphosphine oxide, thioxanthone and oligomeric amine, as the initiator package, has resulted in the elimination of undesirable surface tack for in-air curing at cure speed of ca 15m/min under a combination of UV-diode arrays. A summary of the project conclusions are provided here:

- On a laboratory scale satisfactory in-air cure of typical clear and pigmented model wood coating formulations were achieved at commercially viable line speeds, using radiation from UVLED arrays.
- Combinations of photoinitiators together with specific formulation additives have been identified and used as necessary to achieve the required level of surface cure.
- The use of combination diode arrays, each array emitting at a distinct UV wavelength, has proved to be beneficial.
- Novel photoinitiators and specific anti-oxygen inhibition strategies have been explored and some of these, if used in conjunction with the identified approaches to formulation and diode arrays may lead to further productivity increases.
- One of the novel photoinitiators has undergone further efficacy examination together with a review of its potential for manufacture and commercialisation.
- A pilot scale coating and curing trial has been carried out to confirm the commercial viability of the UV LED project’s curing approaches. The product test pieces from the trial were subjected to industrial tests to ascertain that no detrimental effects have been introduced to the cured coating’s in service performance.

Images illustrating the industrial validation trial, including application of the coating, curing with a UV LED array and post-cure adhesion testing.

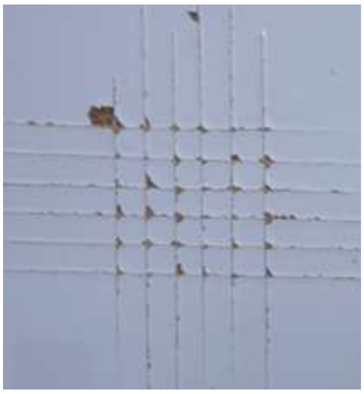
Application of a pigmented UV coating with a Burkle roller

UV coating spray coated with a low pressure high volume gun



UV LED array attached to a conveyer belt activated by a sensor as the sample approaches

Clean sanding disc to demonstrate that the upper surface is fully cured



Adhesion of 100% UV Spray Primer

2 x 80g/m^2

Surface Quality and Hiding Power of Spray Applied System

2 x 80g/m^2 of 100% UV spray primer + 100g/m^2 of WB UV spray topcoat

1. Introduction

1.1 Market needs & current technologies

This project is focussed on supporting more than 60000 SMEs, producing wood products in the EU, by reducing their energy consumption. EU industrial wood product manufacturers are coming under increased competition from imports and are looking to reduce their costs.

About 11% of industrial wood products in the EU are coated with UV curable coatings, which can be VOC free and are fast curing. UV LED lamps, which emit near-UV radiation, are 60-80% more energy efficient than conventional UV lamps and have environmental, health and safety benefits, but UV LED cured coatings tend to cure much slower than coatings cured with traditional UV lamps, even under an inert atmosphere. Although this project focuses on UV LED industrial wood coatings, the materials developed could have extensive applications to inks, vinyl flooring and conformal coatings.

1.2 Novel solutions

The technological objective of the UVLED project is to enable UV coatings to cure using UVLED lamps at the same rate as conventional UV curing but without the need for an inert atmosphere. Our approach was to prepare new, high efficiency near-UV photoinitiator packages, by developing novel photoinitiators and new chemical methods of overcoming oxygen inhibition.

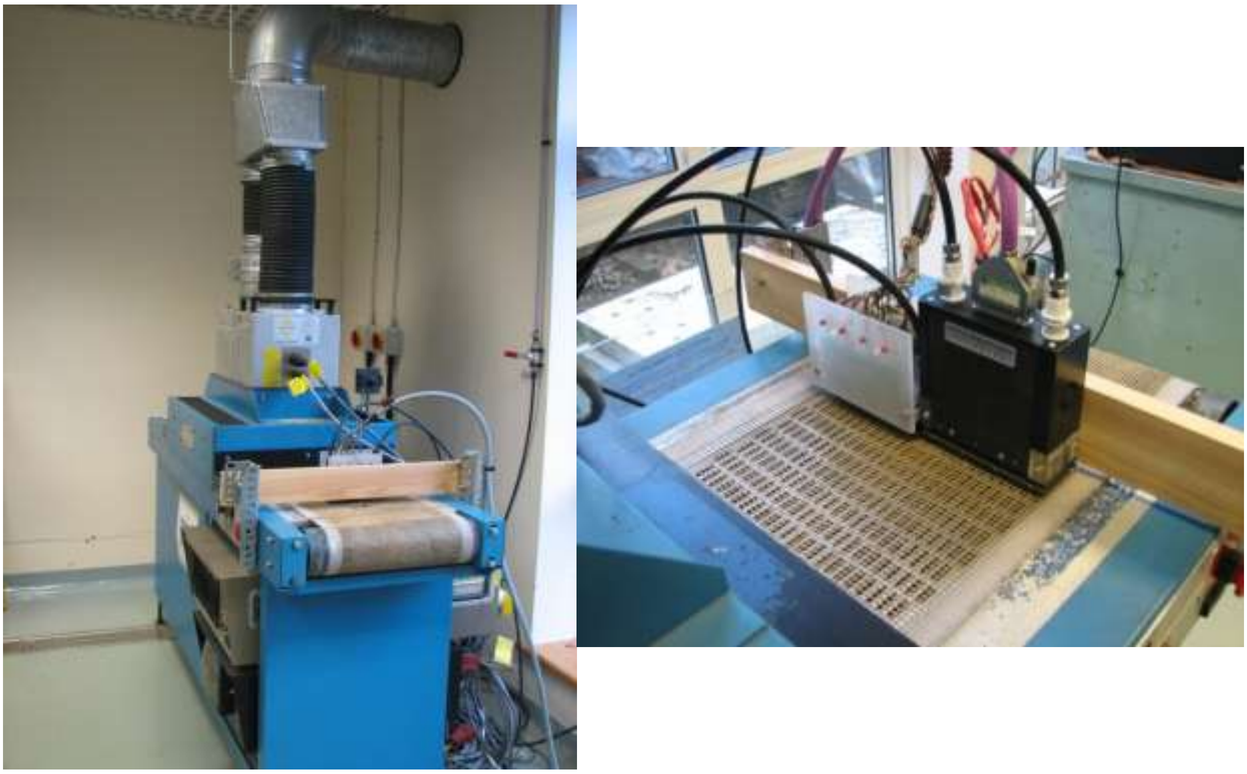


Figure: Conventional UV mercury curing unit (left hand side picture) adapted for a (right hand side picture) single 395nm (left LED box) and dual wavelength 405nm with 365nm (right LED box) arrays.

2. Project Execution

2.1 The UVLED Consortium

The project involved 7 partners from industry, research organisations and universities. This facilitated the integration of various disciplines including organic chemistry, polymer science, coating technology and electrical engineering to cure UV formulations with LED lamps.

No.	Participant name	Short Name	Country
1	Lambson Ltd	LAM	UK
2	Integration Technology Ltd	ITL	UK
3	Microglass Srl	MGLASS	Italy
4	Topi-Kalustaja Oy	TOPI	Finland
5	Tikkurila Oyj	TIK	Finland
6	Vienna University of Technology	VUT	Austria
7	Paint Research Association LBG	PRA	UK

Table 1. List of project participants

2.2 Project Objectives

The technological objective of the UVLED project is to enable UV coatings to cure using UV LED lamps at the same rate as conventional UV curing, without the need for an inert atmosphere. In order to achieve this, a number of technical hurdles were addressed:

Development of a novel photoinitiator (based on silicon and germanium chemistry) that has a significant absorption at 395nm ± 5nm and efficiently produces polymerisation initiating radicals.

The photoinitiator, once put in a formulation, must allow a comparable speed of cure to the same formulation containing the same quantity of acylphosphine oxide photoinitiator cured using a conventional UV lamp system. It should be noted that the quality and quantity of cure will vary with the formulation composition, film thickness, the lamp system and even the substrate.

The requirements for a cured coating are that there is adequate crosslinking to give appropriate performance. The coating is surface cured (i.e. the surface is not tacky) and through cured (i.e. the coating will resist a thumb twist test).

The surface cure quality is therefore defined by the coating resisting 200 methyl ethyl ketone (MEK) double rubs, a pendulum hardness measurement of at least 60 seconds (according to BS EN ISO 1522:2001) and satisfying stain resistance tests (according to BS EN 12720: 1997).

The through-cure quality is therefore defined by the coating resisting a cross-cut adhesion test (rating 5 according to BS 3962: Part 6 or ISO 2409).

To develop a new anti-oxygen inhibition strategy that can improve the speed of cure in air and is more effective than the commercially available amine synergists. The newly developed strategy must not introduce any yellowing, other appearance defects (such as bubbling) or odour.

The photoinitiator package should be commercially viable at <€80/kg.

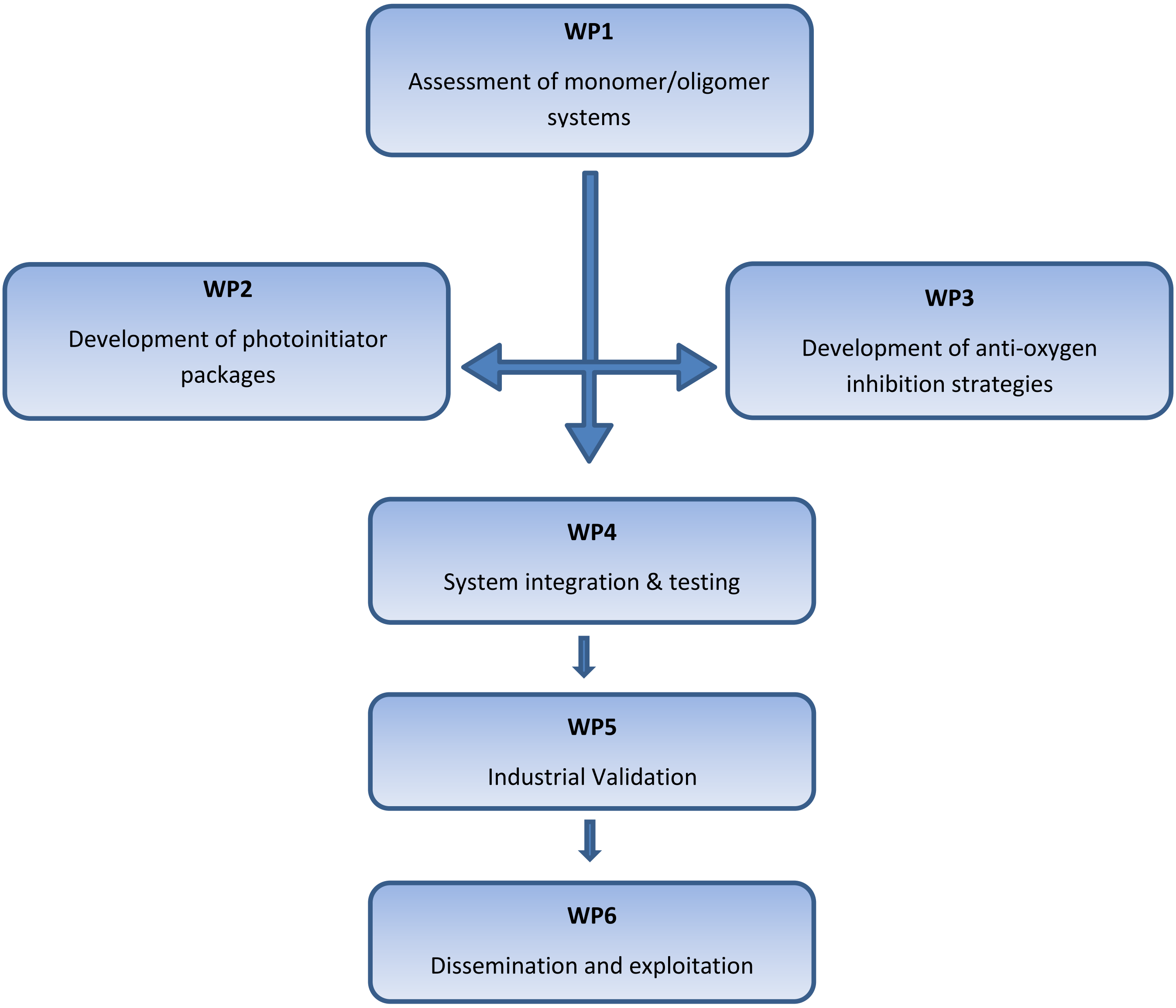
The optimised photoinitiator synthesis must be scalable to produce large quantities of photoinitiator (1-10 tonnes).

2.3 Methodologies and Approaches

The science and technology approach to develop commercially viable coatings has centred on five work packages involving an extensive experimental program:

- Optimisation of existing commercial photoinitiator packages
- Incorporating novel additives into the formulations
- Development and testing novel initiators and initiator packages
- Identifying and testing specific anti-oxygen inhibition strategies
- Evaluating the effects of wavelength, wavelength combinations and dose for commercially available LED sources

The main aspects of these work packages were brought together for system integration. An industrial trial was carried out to validate commercial viability of the UV LED cured coatings.



3. Achievements

3.1 Experimental Work

In the first year of the project, the commercial and academic research and technical delivery teams worked with the photoinitiator manufacturer Lambson Ltd and UV LED array suppliers, Integration Technology, to ensure compatibility of their activities with the goal of producing a UV LED coating without inerting to give properties similar to those cured with conventional mercury lamps. The following work packages contained tasks that would allow the project partners to apply their background knowledge and expertise to cure novel coatings to give a non-tacky upper layer without using an inert gas:

WP1 Assessment of monomer/oligomer systems

Identify at least two model formulations for test purposes in WP2 & 3 by month 3.
Identify the two most promising radiation curing chemistries that will achieve the desired line speeds using UV LED lamps that will compete with acrylate systems and conventional UV lamps.

WP2 Development of photoinitiator packages

Prepare two model photoinitiator samples for use in work packages 1 and 3. Prepare two optimised photoinitiator systems for use in work package 4.

WP3 Development of anti-oxygen inhibition strategies

Identify two leading candidate methods of reducing the effects of oxygen inhibition.

WP4 System integration & testing

Optimise photoinitiator synthesis and scale-up.
Optimise one coating formulation, bringing together the results from work packages 1-3, suitable for use in a validation trial.
Design and build UV LED curing rig.

3.1.1 Milestones

Progress within this experimental stage was monitored and regulated by the following 4 key milestones:

M1 – after 3 months the cure speeds for two model formulations were benchmarked. The formulations were cured using conventional UV lamp(s) and acylphosphine oxide photoinitiator.

M2 – after 9 months the components for two wood coating formulations were modified to incorporate new model photoinitiator packages. A range of coatings were cured with a 395nm UV LED lamp system and suitable formulations were suggested for further development in WP3.

M3 – after 6 months two model photoinitiator samples for work packages 1 and 3 were supplied by VUT. Performance was verified by using a UV LED lamp system and model formulations (from milestone 1).

M4 – after 18 months two optimised photoinitiator packages were used for UV LED curing formulations. The optimized photoinitiator synthesis needed to be scalable to produce quantities of 1-10 tonnes of photoinitiator. The photoinitiator should be commercially viable at <€80/kg. This was verified by using a UV LED lamp system and model formulations (from milestone 1).

M5 – after 21 months the new anti-oxygen inhibition technology should improve speed of cure relative to amine synergists, without introducing yellowing, other appearance defects or odour. This should be verified by using a UV LED lamp system, photoinitiators (from milestone 3) and model formulations (from milestone 1).

3.1.2 Achievements and their impact

WP1 Assessment of monomer/oligomer systems

A clear and a pigmented formulation were identified providing the appropriate physical and mechanical properties required for an industrial wood coating.

Impact: Establishing these model formulations will allow results to be compared and enable the correct assessment of UV LED cured coatings.

The addition of thiols and tertiary amines in combination with the appropriate photoinitiator resulted in tack free upper surfaces. Industrial line speeds were achieved using a 395nm UV LED array.

Impact: The use of UV LED arrays is an environmentally friendly method of curing coatings which does not produce ozone, therefore a large extraction unit is not required. Extensive quantities of heat are not produced and coatings applied to temperature sensitive substrates can be cured if an adequate coating formulation is available.

WP2 Development of photoinitiator packages

A germanium based and a water soluble bisacyl phosphine oxide photoinitiator were synthesised and their efficacy was tested within model formulations. Despite achieving good levels of cure with the latter initiator the estimated production cost would be well in excess of €100/kg. This would not be realistic for wood coatings however it would be viable for high value applications.

Impact: Despite achieving cured coatings, the cost of the germanium photoinitiator does not fall within the stipulated limits. However, this photoinitiator may be beneficial for use in high value (e.g. medical) applications.

The two classes of commercial photoinitiator most suitable for use at the wavelengths emitted by available LEDs are those based on thioxanthones and those based on acyl phosphine oxides. Experimental work was carried out and a number of combinations were identified for use in WP4, clear or pigmented formulations.

Impact: These combinations have been beneficial for reducing the effects of oxygen inhibition and can be used for other formulations to ensure that a tack free upper surface is achieved.

WP3 Development of anti-oxygen inhibition strategies

The photoinitiator package in combination with tertiary amines has been beneficial in reducing the effects of oxygen inhibition. Property and performance relationships using various amounts of photoinitiator were investigated to ensure results were comparable to coatings cured with conventional mercury lamps.

Impact: A chemical additive strategy has been achieved as an alternative to using nitrogen to overcome issues of incomplete curing. An extensive review paper has been written by the project partners at the Vienna University of Technology discussing the chemical and physical methods for reducing oxygen inhibition in photopolymerisation.

WP4 System integration & testing

A novel phosphine oxide with additional photoactive functionality was synthesised. In combination with an amine synergist and a small amount of a sensitiser absorbing at 380 nm, this material gave acceptable levels of through-cure and resulted in a non-tacky upper layer. Initial lab work was carried out at Vienna University of Technology and research laboratories at Lambson Ltd. The scale-up process was undertaken and for similar yields, the selling price is foreseen to be below the limit of €80/kilo.

Impact: Photoinitiators absorbing light at 385-400 nm are limited to the acyl phosphine oxides and thioxanthones. Acyl phosphine oxides give excellent through-cure for highly pigmented systems. Since UV LED arrays emit light within a narrow range, the novel phosphine oxide in combination with a tertiary amine results in coatings that have reduced levels of tack when cured with a UV LED array. A patent has been filed for this material and similar structures.

A sprayable primer containing appropriate amounts of oligoamine, a polymeric thiol and an acylphosphine oxide photoinitiator was formulated using the information obtained in WP1-3. The coating formulation was successfully sprayed onto medium density fibreboard using an air assisted spray gun. Sufficient levels of cure were achieved and it should be noted that the introduction of air did not interfere with the cure. This formulation was proposed for use in the demonstration industrial trial.

Impact: Degassing a formulation was not part of the scope for this project. This work has highlighted that despite using a method of application which may drive more air into the formulation, it was possible to achieve a tack-free upper surface.

A range of UV LED arrays of various power and wavelength were evaluated. The model formulations were cured with combinations of the different arrays to determine their effect upon the degree of cure. Consideration was also given to the intensity profiles and the positioning of the arrays. A framework was designed to allow the diode arrays to be mounted on a production line for the validation and demonstration trials. A switching unit was designed by Microglass Srl and was integrated with the power supply to enable the array to switch on and off as required.

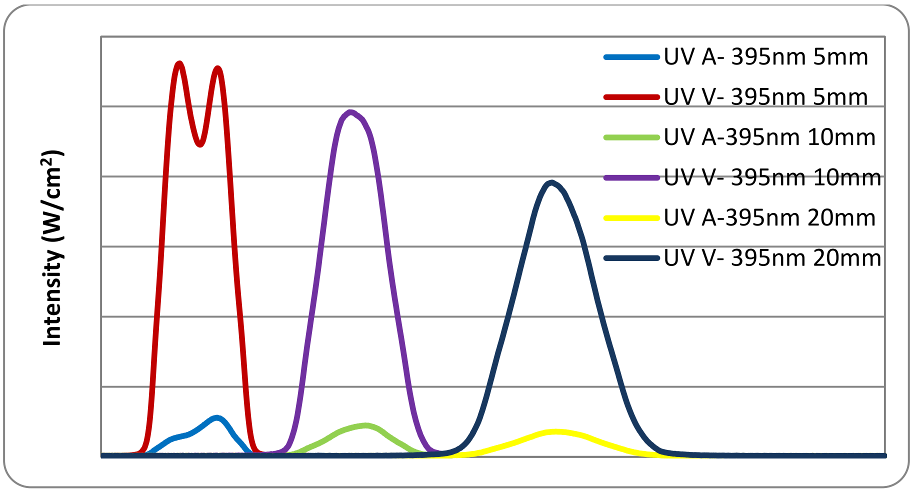


Figure: Intensity measurements using a UV PowerMAP for a 395nm array at 5mm, 10mm and 20mm

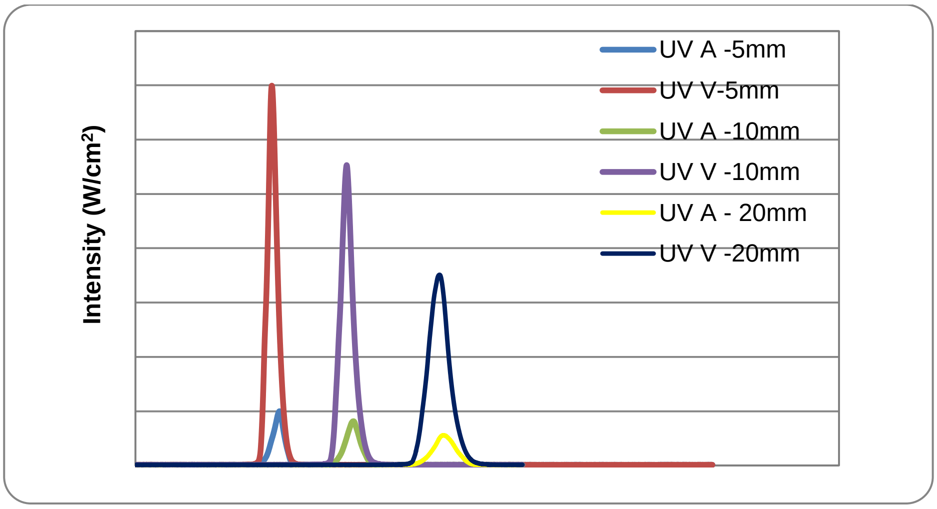


Figure: Intensity measurements using a UV PowerMAP for a 405nm +365nm array at 5mm, 10mm and 20mm

Impact: The use of combination arrays allows numerous formulations to be cured with photoinitiators absorbing the UV light emitted by the selected LEDs. From a commercial perspective the intensity of light emitted is adequate to fully cure these UV formulations.

3.2 Development on an Industrial scale

3.2.1 Technical objectives

The primary goal of WP5 was to apply knowledge gained from WP1-4 to ensure that the model coatings could be reproduced and applied on an industrial scale and also to validate cure speed performance, appearance, coating property performance and cost.

3.2.2 Milestones

Progress within this developmental stage was monitored and regulated by the following key milestone:

M6 – after 24 months an industrial validation trial of a UV LED curing wood coating was carried out. The objectives identified as parts of milestones 3 and 4 are of equal importance in this milestone. The industry experts provided a subjective opinion on the suitability of the new wood coating, which took into account the feel and appearance of the coating (a tactile and visual assessment) which are difficult to put into test measurement terms.

3.2.3 Achievements and their impact

Two novel coatings were formulated from the experimental work carried out in WP1-4. Industrial validation trials were conducted at Tikkurila Oyj. The UVLED array was supplied by Integration Technology Ltd and fitted with a sensor from Microglass Srl. Two trials were conducted, in which drawer front panels were coated, by spray and roller coating processes, with primers made at Tikkurila Oyj. Curing and sanding was carried out between coats, before finishing with a waterborne topcoat. Two primers were formulated: one for spray application and one for roller coating application. Both of these primer formulations utilised oligomers and photoinitiator packages previously determined to be the most satisfactory ones found for overcoming oxygen inhibition. The application, cure, recoatability, final appearance and dry film properties, obtained in both trials, were considered to be satisfactory by Tikkurila Oyj and Topi-Kalustaja Oy. The overall objective of the project has been fulfilled, since coatings have been formulated, which can be cured using a UV LED array set-up on a coating line, running at a realistic commercial line speed, without inerting. After curing the coating could be sanded and over-coated with the same product or with a suitable commercial topcoat. Any oxygen inhibition effects were sufficiently reduced to make them immaterial to the application and curing process.

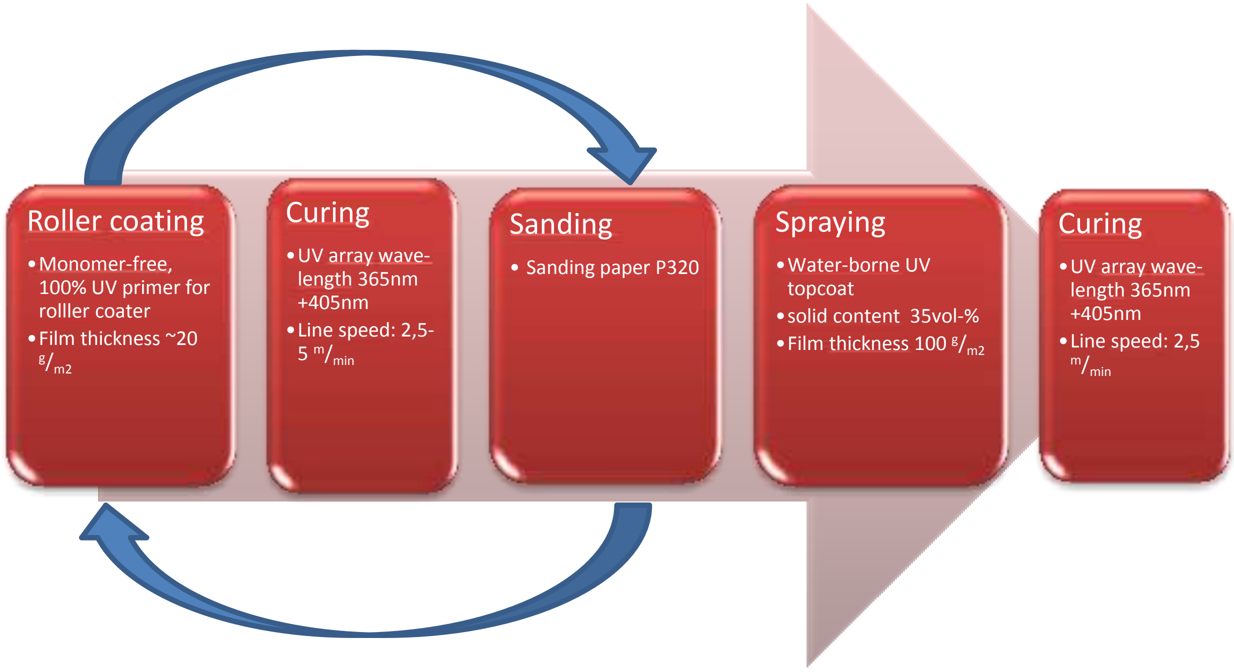


Figure: Schematic of the Roller Coating and Curing Process

Impact: The industrial trial was critical to the transition between a laboratory based Research and Development program to that of a commercial environment. The scale-up process was successful resulting in coatings possessing a non-tacky upper layer with good adhesion to the substrate.

3.3 Dissemination and exploitation

3.3.1 Technical Objectives

Technical project content should be disseminated in an appropriate manner at selected conferences and exhibitions. The industrial trial process needs to be recorded as a five minute movie and made available on the internet to promote the success achieved from the coloration of various partners with the assistance of the 7th Framework program.

3.3.2 Achievements and anticipated impact

WP 1–4 has been disseminated as described below. Dissemination of WP 5 is covered in the five minute film recording the process used during the industrial trial. This has been uploaded on the internet and may be accessed via You Tube. Results covered within WP 2 and WP 3 have been presented both in poster and oral format by project partners from VUT at international chemistry conferences (APME 2011 in Cappadocia, TR and ESPS 2012 in Torino, IT). Results from WP 1–4 were disseminated by partners from PRA, ITL, and VUT at PRA's 8th International Woodcoatings Congress in Amsterdam, NL (October 2012) and at PRA's Radiation Curing Technology training course in Hampton, UK (May 2012). A patent application has been filed by Lambson Ltd on photoinitiators developed partially from the experimental work carried out in WP 2 and WP 4. Also, one academic review paper with authors from VUT and PRA relating chiefly to WP 3 but also to WP 1 and WP 2 has been preapproved and submitted to *Chemical Reviews*, the top cited chemical journal in the world. An additional publication with experimental results from WP 3 has been prepared for submission to Progress in Organic Coatings in March 2013.

Dissemination activity	Number of items
Conference presentations with proceeding	**3**
Conference presentations with abstract	**2**
Workshop presentations	**1**
Patent applications	**1**
Academic papers, unsubmitted	**1**
Academic papers, under preparation	**1**

Conference presentations with proceeding

[1] Lockwood, A.; Smith, J. “UV LED Light Sources for the Curing of Wood Coatings”. In *Proceedings of the PRA’s 8th International Woodcoatings Congress*, Amsterdam, Netherlands, Oct 30–31, 2012; PRA: Hampton, UK, 2012; Paper No. 15.

- *PRA’s Woodcoatings Congress has become the premier event for professionals from the global wood coating industry to meet and network. A. Lockwood here presented the challenges and barriers to the UV LED light sources technology by the economic comparisons between UV LED and UV arc systems. (pertains chiefly to WP4)*

[2] Husár, B.; Hoffmann, H.; Ligon, S. C.; Liska, R.; Wutzel, H. “Assessment of Effectiveness of Various Anti-oxygen Inhibition Strategies in LED Curing”. In *Proceedings of the PRA’s 8th International Woodcoatings Congress*, Amsterdam, Netherlands, Oct 30–31, 2012; PRA: Hampton, UK, 2012; Paper No. 16.

- *This paper gives an overview of known anti-oxygen inhibition strategies and aims to compare their effectiveness in UV LED curing. (pertains chiefly to WP3)*

[3] Bahia, R.; Buxton, A.; Collins, P.; Holman, R. “UV LED Curing Without Inerting for Wood Coatings”. In *Proceedings of the PRA’s 8th International Woodcoatings Congress*, Amsterdam, Netherlands, Oct 30–31, 2012; PRA: Hampton, UK, 2012; Paper No. 17.

- *This paper addresses the challenges that arise from using UV LEDs to cure coatings, whilst attempting to achieve a degree of similar cure to that obtainable with a conventional medium pressure mercury lamp. (pertains to WP 1–3)*

Conference presentations with abstract

[4] Wutzel, H.; Ligon, S.; Husár, B.; Dworak, C.; Hoffmann, H.; Liska, R. “Comparison of different chemical strategies to overcome oxygen-inhibition in LED-curing of thin films assessed by IR-spectroscopy”. *Program & Abstract Book.* IUPAC 9th International Conference on Advanced Polymers via Macromolecular Engineering (APME 2011), Cappadocia, Turkey, Sept 5–8, 2011; P-147, p 257.

- *APME 2011 is a conference packed with innovative and application driven papers detailing in advances in the macromolecular chemistry. H. Wutzel in his poster provided the comparison of methods for overcoming the oxygen inhibition effects. (pertains to WP2 and 3)*

[5] Ligon, S. C.; Husár, B.; Wutzel, H.; Hoffmann, H.; Torgersen, J.; Liska, R. “Assessing anti-oxygen inhibition strategies for LED-based wood coatings by FTIR”. *Book of abstracts.* European Symposium of Photopolymer Science 2012, Torino, Italy, Sept 4–7, 2012.

- *ESPS brings together academic and industrial leaders in the photopolymerization field in order to address critical and fundamental questions related to photopolymerization. S. C.*

Ligon in his oral contribution aimed to identify the leading candidate methods of reducing the effects of oxygen inhibition. (pertains chiefly to WP3)

Workshop presentations

[6] Bahia, R. "A New Slant on Applications". Radiation Curing Technology Training Course, PRA, `Hampton, UK, May 22–24, 2012.

- *This three day intensive workshop provides a firm foundation in the chemistry, principles and applications of ultraviolet and electron beam technologies. R. Bahia discussed the UV LED arrays and the issue of tackiness on the upper surface. (pertains to WP 1–3)*

Patent applications

[7] A patent has been filed for a novel phosphine oxide with additional photoreactive functionality and similar structures.

- *This invention relates to novel phosphine oxide photoinitiators developed by Lambson Ltd. (pertains to WP2 and 4)*

Academic papers

[8] Ligon, S. C., Husár, B., Wutzel, H.; Holman, R.; Liska, R. "Strategies to reduce oxygen inhibition in photoinduced polymerization". *Chem. Rev.*, ID: cr-2012-00311d, submitted December 2012.

- *This extensive review covers all physical and chemical methods for reduction of oxygen inhibition in photopolymerization including the associated problems. The manuscript contains 19,000 words and more than 360 references. After a peer review by two anonymous experts, on October 26, 2012 we received an invitation from the editor of Chemical Reviews for a submission of the manuscript. Chemical Reviews is a journal with the highest impact factor in the field of chemistry. (pertains chiefly to WP3 but also WP1 and 2)*

[9] Husár, B., Ligon, S. C., Wutzel, H.; Liska, R. "Experimental overview of anti-oxygen inhibition strategies in photopolymerization". To be submitted to *Prog. Org. Coat.*by April 2013.

- *This experimental overview compares the effectiveness of known anti-oxygen inhibition strategies under the same conditions. The manuscript is being prepared and should be submitted in January 2013. (pertains chiefly to WP3)*

Anticipated Impact: The transfer of new knowledge to Research and Development Sectors interested in the chemical and engineering aspects of UV LED curing without inerting.

4. Impacts of the Project

4.1 Impact on industry

As a result of the UVLED project, we expect to improve our collective competitiveness and generate increased sales of coating and equipment products into the EU industrial wood products market of at least €106M over a 5 year period. In addition, we estimate that an end-user with just one UV curing unit would save about €13K in energy costs per year, compared to the use of conventional UV curing lamp systems. We therefore expect to improve the competitiveness of the European coated wood products industry.

It is estimated that there are about 1000 wood coating lines in the EU currently using UV curing technology. On an annual basis, it is thought that 10% of these lines are renewed (i.e. the average lifetime of a coating line is about 10 years) and the number of UV coating lines is growing by about 6% per year. We believe that the benefits of UV LED curing will probably be more advantageous to new lines than the renewals (principally because they would gain most from reduced air extraction costs). Therefore we estimate that 20% of renewal lines and 40% of new lines would take up UV LED curing technology. On this basis, there would be 44 lines per year taking up UV LED curing technology for each of the first 5 years and 220 lines over 5 years (but equally the % take up would likely increase each year as the benefits of the technology become more widely recognised).

The average coating line coats 4000 sq m per day. At a coating weight of 60 g/sq m, this equates to 240 kg per day. These lines are run on at least a two shift basis and therefore this equates to a coating weight of 80 tonnes per year per coating line or 54k tonnes over 5 years. For clear coatings, the typical photoinitiator concentration is about 3%, so over 5 years that amounts to about 1600 tonnes (growing from about 100 tonnes in year 1 to over 500 tonnes in year 5). Assuming that the target price for the photoinitiator is €80/kg and that Lambson can capture 50% of the market, then in the first year Lambson should have sales of circa €4.3M.

The price for UV LED arrays (typically 1.2m wide) for wood coating is €33K according to Integration Technology. Assuming there is typically only one UV system per line (but note that parquet flooring lines, for example, typically have 4-5 UV arrays per line), 44 new UV LED lines per year at €33K for each system amounts to a market of more than €1.5M per year, and Integration Technology would look to capture at least 50% of the market with support from Microglass. On the basis of the same market take-up of UV LED curing, Microglass should generate sales of about €1.3M.

4.2 Impact on the Research Sector

Enhanced knowledge regarding the effect of near-UV radiation from UV LED systems (the effect of narrow band width radiation and the absence of any infrared radiation) on the cure behaviour of a range of radiation curing chemistries.

Increased knowledge regarding the behaviour of photoinitiators, including acylphosphine oxides, when exposed to UV LED radiation, particularly the relationship between emitted radiation and the photoinitiator absorption bands.

4.3 Impact on the Environment

Quality of life and health & safety

Many wood products particularly furniture and parquet flooring are used in an indoor environment. In recent years, there have been concerns regarding sick building syndrome and particularly the slow release (‘outgassing’) of formaldehyde from acid-catalysed coatings (a coating commonly used on wood) and particleboard products. Formaldehyde is classified as carcinogenic to humans (Group 1) by IARC: there is sufficient epidemiological evidence that formaldehyde causes nasopharyngeal cancer in humans and causes contact dermatitis. High heat and humidity can increase the rate of outgassing. The European Furniture

Manufacturers Federation (UEA) and the European Building and Wood Workers (EFBWW) have jointly declared their concern about formaldehyde emissions and called for "legislation requiring that all materials used in furniture put on the market in the EU have the lowest possible emission level based on the best available technology". Radiation curable coatings are faster curing than any other class of coating, therefore provide high throughput benefits and they do not contain formaldehyde.

Impact on pollution reduction or prevention

UV LED technology has two environmental benefits. Firstly the energy savings in terms of reducing running costs, replacement lamp costs and air extraction costs can be related to reduced use of fossil fuels and reduced carbon dioxide emissions. According to the Carbon Trust and based on the carbon dioxide emissions from a coal-based power station, one coating line using a UV LED lamp system would reduce CO_2 emissions by 40 tonnes CO_2 per year.

Secondly unlike conventional UV lamps, UV LED systems contain no mercury. Although LED arrays will have to conform to the requirements of the Waste Electrical and Electronic Equipment (WEEE) Regulations, which aim to reduce the amount of this waste going to landfill and improve recovery and recycling, the replacement of conventional UV lamps by UV LEDs would reduce the amount of mercury recycling. UV LEDs use silicon nitride and aluminium nitride-based chips, which have a lifetime of at least 10000 hours and likely much longer, which compares to a typical lifetime of a conventional UV lamp of about 1500 hours.

Impact on health and safety in the workplace

Use of UV LEDs will have two effects on health and safety in the workplace. Firstly, unlike conventional UV lamps, UV LEDs do not contain mercury and therefore the solid state lamps do not represent a health and safety risk in the event of an accident or fire.

Secondly, conventional UV lamps emit low wavelength UV radiation, which in an oxygen atmosphere creates ozone. The ozone is largely extracted from the workplace by using quite powerful air extraction units (which typically act as a means of cooling the lamps as well). UV LEDs emit in the near UV region and do not produce ozone (and indeed there is no need to install air extraction units). Although conventional UV curing units protect the users from exposure to harmful UV radiation, a further consequence of UV LEDs emitting in the near-UV region is a lower risk of accidental exposure to harmful UV radiation, which can cause dermal and retinal damage.

Impact on sustainability of raw materials

The absence of infrared emissions from the UV LEDs allows coatings on heat-sensitive substrates to be cured without having a detrimental effect on the substrate. For example, pine wood has a tendency to bleed rosin when curing coatings under conventional UV lamps. Consequently UV LED curing technology provides additional support to the use of the more sustainable wood resources, especially pine, which is available in Central and Northern Europe.

4.4 Broader Socio-Economic Impacts

The cost of a UV LED lamp system is about €11K higher than the equivalent conventional UV lamp system: a wood coating applicator would therefore expect to pay back the additional equipment costs from their energy savings over a period of about 12 months. Indeed, for a typical wood coating line 1.2m wide, the applicator would expect to pay back the cost of the UV LED lamp system entirely within 3 years (of a typical 10 year lifetime) from energy savings alone.

Employment opportunities

One of the principal benefits for UV LED technology is the energy savings in terms of reducing running costs, replacement lamp costs and air extraction costs, relative to conventional UV curing. These cost savings will help SME wood product manufacturers remain competitive with larger organisations within Europe and with imports from outside the EU. The principal benefit from take up of UV LED technology will be averting manufacturers from moving their manufacturing operations outside the EU and preventing a loss of jobs in the EU.

An increase in use of UV LED curing systems should create long term jobs for Lambson, Integration Technology and Microglass.

5. Dissemination and use

5.1 Dissemination Activities

Each partner was responsible for publications and conferences related to the project. Before any information was submitted into the public domain all members of the consortium were consulted and any appropriate modifications made. Some specific activities contributing to dissemination include:

- Project Website with updated results and current news.
- Production of posters and banners made available for project partners own use, promoting the project at trade shows, conferences, etc.
- Specific dissemination activities organised throughout the project

The following publications are in production as part of the project.

LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES											
No.	DOI	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Permanent identifiers (if applicable)	Is open access provided to this publication?
1		Strategies to reduce oxygen inhibition in photoinduced polymerization	Ligon, S. C	Chemical Reviews	Submitted December 2012, Accepted Awaiting publicatio n	American Chemical Society		10/07/2013	Not yet published	cr-2012-00 311d	No
2		Experimental overview of anti-oxygen inhibition strategies in photopolymeriza tion	Husar, B.	Progress in Organic Coatings	To be submitted by April 2013	Elsevier		30/09/2013	Not yet published		No

The following dissemination activities have been carried out within the project.

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Conference	INTEGRATION TECHNOLOGY LTD	UV LED Light Sources for the Curing of Wood Coatings	31/10/2012	PRA's 8th International Woodcoatings Congress, Amsterdam, Netherlands	Scientific community (higher education, Research) - Industry	100	Europe inc: AT, BE, CZ, DE, DK, ES, FI, FR, HU, IT, NL, NO, PL, SI, SE, SZ, TR, UK ROW inc: AU, US
2	Conference	TECHNISCHE UNIVERSITAET WIEN	Assessment of Effectiveness of Various Anti-oxygen Inhibition Strategies in LED Curing	31/10/2012	PRA's 8th International Woodcoatings Congress, Amsterdam, Netherlands	Scientific community (higher education, Research) - Industry	100	Europe inc: AT, BE, CZ, DE, DK, ES, FI, FR, HU, IT, NL, NO, PL, SI, SE, SZ, TR, UK ROW inc: AU, US
3	Conference	THE PAINT RESEARCH ASSOCIATION LIMITED BY GUARANTEE	UV LED Curing Without Inerting for Wood Coatings	31/10/2012	PRA's 8th International Woodcoatings Congress, Amsterdam, Netherlands	Scientific community (higher education, Research) - Industry	100	Europe inc: AT, BE, CZ, DE, DK, ES, FI, FR, HU, IT, NL, NO, PL, SI, SE, SZ, TR, UK ROW inc: AU, US
4	Conference	TECHNISCHE UNIVERSITAET WIEN	Comparison of different chemical strategies to overcome oxygen-inhibition in LED-curing of thin film	08/09/2011	IUPAC 9th International Conference -APME 2011, Cappadocia, Turkey	Scientific community (higher education, Research) - Industry	220	25 countries inc.Europe and Rest of the World
5	Conference	TECHNISCHE UNIVERSITAET WIEN	Assessing anti-oxygen inhibition strategies for LED-based wood coatings by FTIR	07/09/2012	European Symposium of Photopolymer Science 2012, Torino, Italy	Scientific community (higher education, Research) - Industry	130	80% from various countries in Europe, 20% from China, Japan, Turkey
6	Workshops	THE PAINT RESEARCH ASSOCIATION LIMITED BY GUARANTEE	A New Slant on Applications	24/05/2012	Radiation Curing Technology training course, PRA, Hampton, UK	Scientific community (higher education, Research) - Industry	9	UK, Germany, Switzerland, Spain, Norway
7	Videos	INTEGRATION TECHNOLOGY LTD	The FP7.eu UV LED Woodcoatings Project	17/01/2013	YouTube, GB, UK	Scientific community (higher education, Research) - Industry		Europe and Rest of World

5.2 Exploitation Activities

Project partners collated information about their exploitation results as part of WP6, which were uploaded into the SESAM exploitation database.