Final Scientific/Technical Report

U. S. Department of Energy

Office of Energy Efficiency and Renewable Energy

Funding Opportunity Announcement DE-FOA-0000973

Solid-State Lighting Advanced Technology R&D - 2014

Award Number DE-EE0006701

High-Performance OLED Panel and Luminaire

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February 20, 2017

Reporting Period:
October 1, 2014 – December 31, 2016

Executive Summary

In this project, OLEDWorks developed and demonstrated the technology required to produce OLED lighting panels with high energy efficiency and excellent light quality. OLED panels developed in this program produce high quality warm white light with CRI greater than 85 and efficacy up to 80 lumens per watt (LPW). An OLED luminaire employing 24 of the high performance panels produces practical levels of illumination for general lighting, with a flux of over 2200 lumens at 60 LPW. This is a significant advance in the state of the art for OLED solid-state lighting (SSL), which is expected to be a complementary light source to the more advanced LED SSL technology that is rapidly replacing all other traditional forms of lighting. Due to the efficient conversion of electricity into photons, solid-state lighting has the potential to reduce national lighting electricity usage by 75% over the next 20 years. This reduction is equivalent to a cumulative savings of over 60 quadrillion BTUs - equivalent to nearly $630 billion dollars in avoided energy costs.[1]

Summary of Accomplishments

The project goals and objectives are compared to the actual accomplishments in this section.

The objectives of this project were to:

1) Develop, evaluate, and down-select a set of component technologies that will enable highly efficient and uniform large area white organic light emitting diode (OLED) lighting panels at low cost. The main component technologies are:
    a. White OLED formulation
    b. Light extraction enhancement
    c. Uniform low-resistivity electrode
2) Integrate the selected subset of technology elements to demonstrate the required panel level performance targets of 80 lm/W with 85% brightness uniformity at 2000-3000 cd/m^2 for a large area OLED panel at least 100 cm^2 in size
3) Demonstrate scalability of the low-cost technologies
4) Demonstrate an OLED luminaire using the high-performance OLED panels delivering more than 2000 lumens at >65 lm/W

The first objective was successfully accomplished in that all of the component technologies developed were able to meet the desired criteria:

a) A stacked white OLED architecture was developed that achieved all performance targets for color quality (>85 CRI) and efficacy (70 LPW with external extraction only).
b) Integrated light extraction substrates from four suppliers were initially evaluated before down-selecting 2 of the most promising options in terms of performance and cost. The efficacy target of 80 LPW was achieved at the R&D level.
c) Several options to achieve good brightness uniformity were evaluated. In the end, we achieved the target 85% uniformity using the lowest cost approach which avoided the use of metal grids.

The second objective was to integrate the component technologies in order to achieve the desired performance on a large area OLED panel. The final panel design was slightly larger than originally proposed with dimensions of 120.5x120.5mm and an emitting area of 105cm^2. On these large area

[1] energy.gov/eere/ssl/ssl-forecast-report

panels, we were able to successfully demonstrate 75-80 LPW efficacy and 85% uniformity at the target brightness (2000-3000 cd/m^2).

The third objective was to demonstrate scalability. This turned out to be one of the most challenging tasks in that it relied largely on the capability of the integrated substrate supplier. At this point only one supplier was carried forward due to their ability to scale the integrated substrates during the course of this project. Working with the substrate supplier and patterning vendors, we were able to successfully build a supply chain for high quality patterned Gen2 size integrated substrates. OLEDWorks was able to produce over 500 OLED panels using these substrates on our production OLED coater. We were able to achieve the desired performance characteristics over several production runs with adequate yield.

The fourth and final objective was to demonstrate an OLED luminaire using the high performance OLED panels that could produce practical levels of illumination. Together with our partner Acuity Brands Lighting, a 24-panel Trilia OLED luminaire was demonstrated and measured according to LM-79-08 standard photometric testing. The luminaire produced over 2200 lumens at an efficacy of nearly 60 LPW, while exceeding color quality targets (CCT=3200K, Duv=0.001, CRI=88 and R9=76).

Additional details are provided in the following project activity summary.

Project Activity Summary

In this section we describe the project activities for each task as defined in the SOPO.

Task 1 – Project Management

This was an ongoing task throughout the duration of the project. All project reporting requirements have been fulfilled thus far. During the course of the project, a 6-month no-cost extension was granted to allow more time for successful completion of the project.

Task 2 – OLED Panel and Luminaire Specifications

In this task we defined the performance requirements for both the OLED panels and luminaire. The first milestone (M2.1 – Initial specifications) was completed on time by end of Q4 2014.

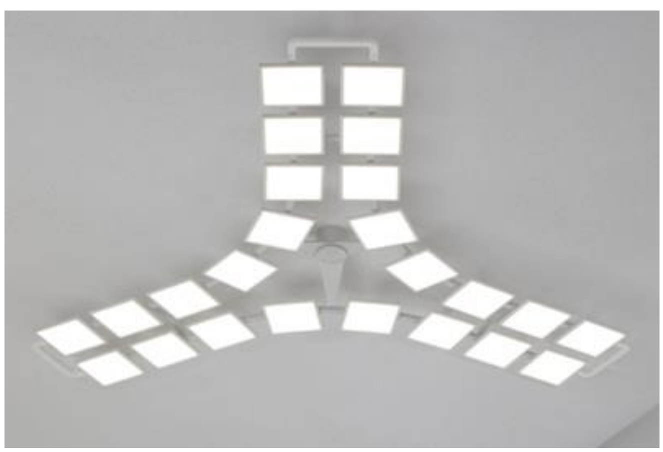
Panel Specifications

The original plan called for two options for the OLED panel form factor: A square panel approximately 100mm x 100mm in size, and a rectangular format (63.5mm x 175mm) which was already available at OLEDWorks served as the back-up option. During the course of the project, it was decided that a larger square panel would be the desired form factor for the luminaire demonstration for this project. A commercially relevant panel size of 120.5mm x 120.5mm was chosen since it matched the product size for the Philips Brite OLED product line, which was acquired by OLEDWorks in 2015. This same panel format was redesigned for manufacture in Rochester to serve as the panel demonstration vehicle for this project. The specifications for the new panel are shown below. The panel was designed to produce 100 lumens at a typical brightness of 3000 cd/m^2. Because of the higher light output from the panel, the luminaire will be able to use fewer panels to produce the desired light output of over 2000 lumens.

Parameter	Large Square	
Panel Dimensions (mm)	120.5 x 120.5	
Panel Emitting Area (cm^2)	104	
Brightness (cd/m^2)	2000	3000
Drive Voltage	8.0	8.2
Efficacy (lm/W)	79	77
Flux (lumens)	65	100
CCT	3000K	
CRI Ra	>85	
CRI R9	>20	
Color consistency panel-to-panel	+/- 2 steps	
Color consistency 0-60 degrees	<0.004 deltau'v'	

Luminaire Design Selection

Acuity Brands Lighting (ABL) planned to use OLEDWorks panels in an existing luminaire design, making modifications based on new panel dimensions and electrical characteristics as necessary. It was decided to use a different luminaire option as the vehicle for demonstrating the panel and luminaire developments in this program, due to the possibility of lower costs, easier integration of different panel sizes, and potential for fewer panels to achieve the target lumen output. The Trilia luminaire is a commercially available OLED luminaire and is pictured below.



Trilia Tri luminaire using 24 square OLED panels

The design is a modular, allowing for lighting designers to use single luminaires or expansive networks consisting of Tri and Straight sections. Assuming at least 100 lumens per panel, a 24-panel Tri section can produce more than the required 2000 lumens for this demonstration. The luminaire performance projections are shown below.

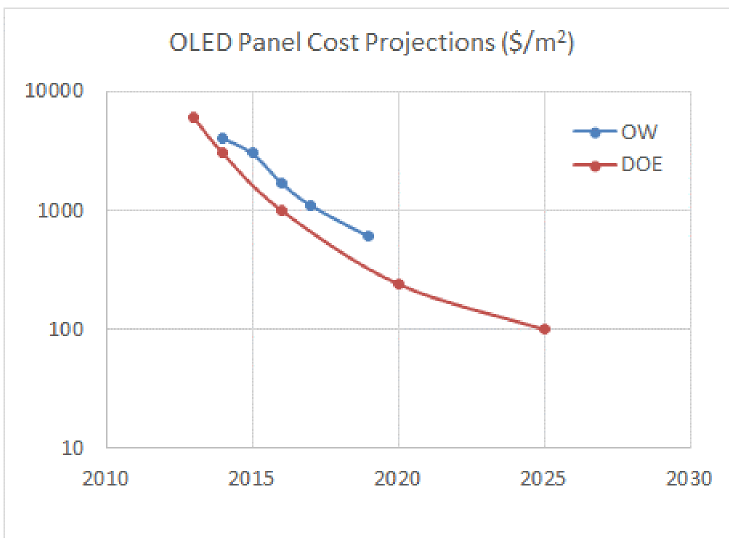
Luminaire Performance Projections

Number of panels	24
Total lumen output	2400 lm
Number of drivers	1
Panel efficacy	77 lm/W
Optical efficiency	98%
Driver efficiency	84%
Luminaire efficacy	63 lm/W

Cost and reliability roadmap

The final item for task 2 was to develop reliability and cost targets for the OLED panels.

The chart below shows the cost translated to area cost ($/m²) and shows a comparison to the most recent DOE roadmap for OLED lighting panel manufacturing costs. Panel reliability is expected to achieve a failure level of 1:1000 by 2020, and 1 PPM by 2025.



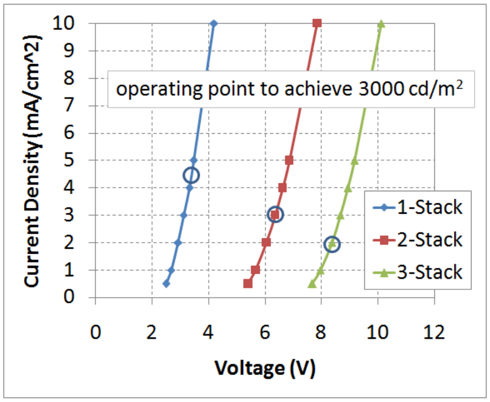
Task 3 – White OLED Formulation Development

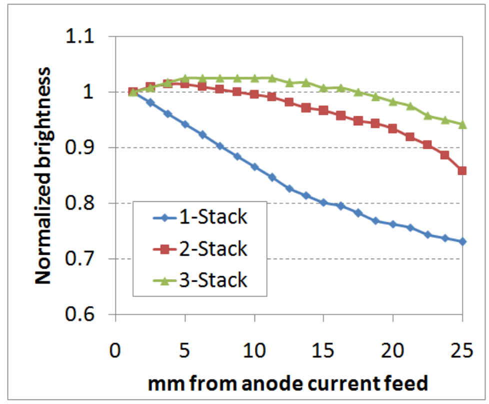
This task consisted of development and optimization of the white OLED formulation to achieve high efficacy by improving the internal quantum efficiency (IQE) and device outcoupling, and reducing drive voltage. The milestone associated with this task (M3.1 - 70 lm/W OLED pixel) was successfully completed on time by the end of Q1 2015.

It was decided to use a 3-stack white OLED architecture to achieve the desired performance. The benefits to the stacking approach are:

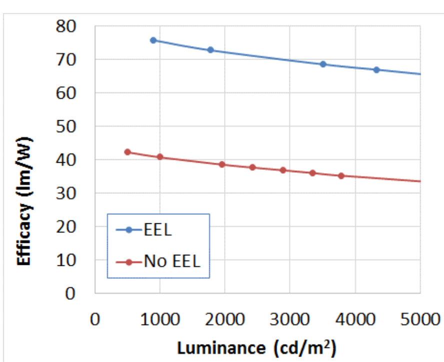
- Longer lifetime – the target brightness can be achieved at lower current density, which greatly extends device lifetime (3-stack achieves ~2X improvement over 2-stack). This is illustrated in the left figure below, showing J-V curves of real OLED devices.
- Higher efficacy, since average voltage per stack decreases with each extra stack

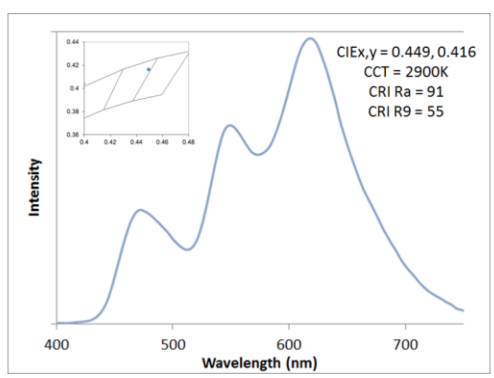
- Improved brightness uniformity – less resistive loss across anode due to lower current density as well as increased OLED stack resistance. Brightness uniformity measurements of real devices are shown in the figure to the right.





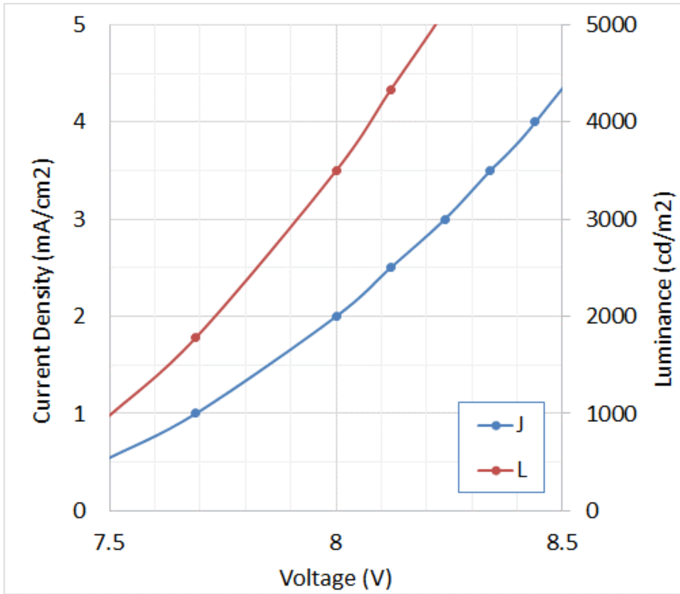
The main drawback is the increased complexity and higher organic materials cost due to the extra layers, however the benefits far outweigh the negatives. Other OLED lighting panel manufacturers have also adopted the stacked OLED approach, including LG Chem (3-stack) and Philips – now OLEDWorks GmbH (6-stack). The 6-stack approach allows for much higher brightness of over 8000 cd/m^2. Since the requirement for this project is standard brightness of 3000 cd/m^2, we focused on the 3-stack approach. The performance achieved with a 3-stack white OLED structure having an external extraction film only (no internal extraction) was 70 lm/W at 3000 cd/m^2. The same 3.0 cm^2 device has excellent CRI (Ra > 90, R9 > 50) with accurate white color at 2900K CCT. The efficacy as a function of luminance is shown below (left) for the device with and without the external extraction layer (EEL). The spectral power distribution curve is shown to the right, and the inset shows the placement of the white color point within the 3000K Energy Star quadrangle. We achieved the milestone 3.1 performance target of 70 lm/W with only external extraction, through further improvements to the materials and device architecture, while maintaining very high quality white light characteristics.





The triple-stack white architecture is a hybrid structure using a fluorescent blue emitter combined with phosphorescent red and yellow-green emitters. Conductive injection and transport layers are used to maintain low voltage, resulting in a low voltage per stack of 2.65 volts. The device achieves

3000 cd/m^2 brightness at a current density of 1.7mA/cm^2 and has a luminance efficiency of 177 cd/A at approximately 7.9 volts. The J-V-L curves are seen in the figure below. The projected lifetime to T70 at 3000 cd/m^2 is in the range of 30,000 to 40,000 hours.

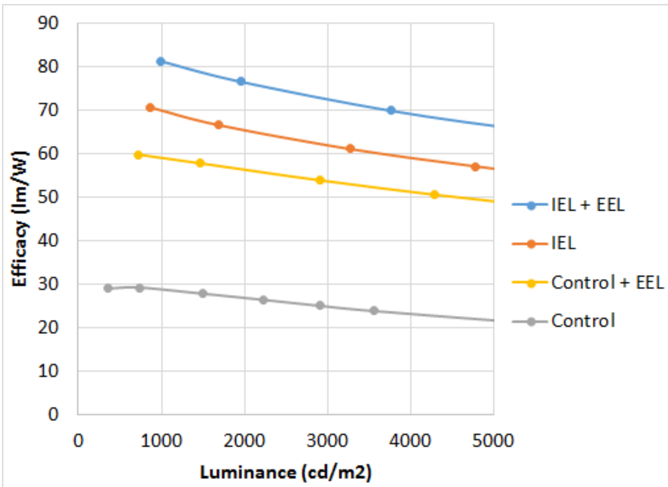


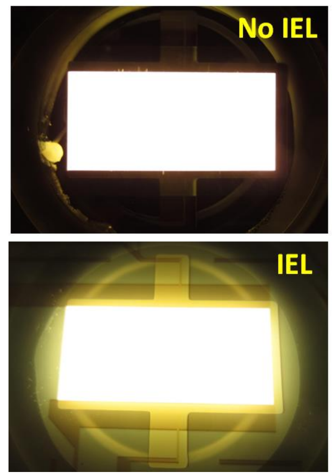
Task 4 – Light Extraction Enhancement Development
This task consisted of procurement and evaluation of integrated substrates that are being developed by several glass manufacturers. The milestone associated with this task (M4.1 - 80 lm/W OLED pixel with IEL) was successfully completed on time by the end of Q1 2015.

Substrates having internal extraction layers (IEL) were received from four different suppliers. In most cases, ITO and busmetal layers were then deposited at OLEDWorks and insitu patterned through a shadowmask before fabricating white OLED structures. Initial tests revealed a number of issues with shorting and leakage current that might be expected from manual processing and rough surfaces. Still, good initial results were obtained on some samples, with an increase in efficacy from 20 lm/W to 39 lm/W, an enhancement of ~1.9X. These initial devices were coated with tandem white structures with an area of 3.0 cm^2. Later samples were coated with 3-stack white OLEDs to improve performance and reliability.

One supplier provided integrated IEL substrates with already patterned ITO. The performance and reliability of these IEL samples was quite good, consistently demonstrating an efficiency enhancement of 1.8X over a control device, and an enhancement of 1.9X with IEL + EEL (external extraction layer). The EEL was a microlens type film applied to the emitting surface of the glass. An attempt was made by this supplier to pattern the IEL. Most OLEDs with the patterned IEL shorted or showed high leakage along the step of the patterned IEL. In most cases, unpatterned versions of this IEL have shown good performance and reliability, with accelerated lifetime test results similar to that of control devices without IEL.

Another supplier provided IEL substrates coated with blanket ITO. OLEDWorks sent these substrates to a laser patterning vendor, where the ITO was ablated in a specified pattern. Reliability and performance was very good on these substrates as well. The figure below shows the efficacy as a function of luminance for one set of these devices, as measured normal to the device surface. More than a 2X improvement is obtained with the IEL over the control devices. A further improvement of 10-15% can be achieved on the IEL devices with the addition of an external extraction film. Also shown are photos of a control (no IEL) device and an IEL device, both $3 cm^2$ in size.





The same devices were measured at various angles from 0-15-30-45-60-70 degrees in order to calculate the integrated light output, as we do not currently have an integrating sphere. The table below shows the integrated EQE for the samples, as well as the efficiency enhancement (gain).

Device	EQE (%p/e)	Gain
Control	38.4%	
Control + EEL	56.3%	1.46
IEL	69.3%	1.80
IEL + EEL	73.6%	1.91

The milestone target (M4.1) for this task was to achieve 80 lm/W on an OLED pixel with IEL. The above results show an achievement of over 80 lm/W at 1000 cd/m^2, and 73 lm/W at 3000 cd/m^2. This was accomplished by combining the high efficiency 3-stack white OLED with the most promising integrated IEL substrates.

Each supplier provided at least 2 different rounds of integrated IEL substrates. Samples were typically spread over multiple OLED fabrication runs to minimize risk of losing valuable samples and data, and to give each supplier a fair chance. For all later testing rounds, IEL samples from different suppliers were processed together in the same OLED production batch to ensure that the OLED device structure was nearly identical on all samples. After all evaluations were completed, a decision matrix was used to select the best performing options based on various criteria. The table below shows the decision matrix including the criteria and rankings for each supplier. Suppliers A and D were initially selected to carry forward into the next integration phase of the project. In the later scale-up phase, only supplier D was carried forward due to their ability to produce scaled-up integrated substrates in the timeframe required for this project. This option did not require patterning of the IEL, therefore we did not need to evaluate patterning options as originally noted in the SOPO.

	Rank 1-5 (1 is poor, 5 is best)			
Criteria	**Supplier A**	**Supplier B**	**Supplier C**	**Supplier D**
Performance	4	1	2	4
Potential to meet DOE MYPP 2020 cost targets (<$10/m2)	4	5	5	4
Glass substrate thickness < 1mm	5	2	1	5
Potential compatibility for flexible	5	1	1	3
Scalability to gen2 +	4	5	5	4
Uniformity of IEL	3	2	3	5
IEL Patterning Required / Demonstrated *	3	5	5	5
Compatibility with subsequent layer patterning (ITO, Metal, Bank)	5	3	5	5
Ability to supply patterned ITO over IEL	5	1	1	3
Yield (OLEDs demonstrate low leakage currrent)	5	1	1	5
Potential for commercial availability by 2016	4	2	2	5
Supplier Responsiveness	5	4	4	4
Other	5	3	2	4
* Not required = 5; Required = 1-4 depending on level of demonstration	57	35	37	56

Task 5 – Uniform Electrode Technology Development

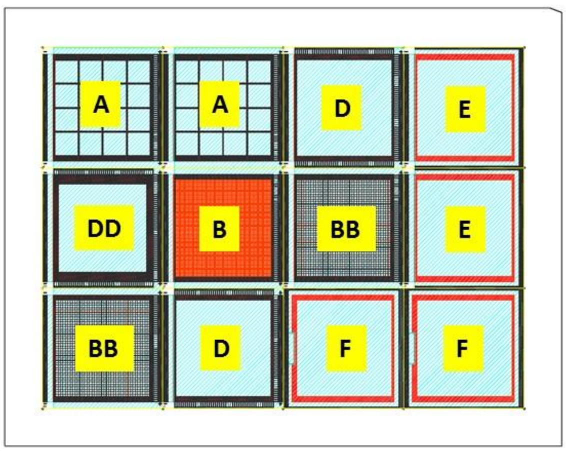
This task consisted of development of low-cost methods to achieve good brightness uniformity across a large area OLED panel through:

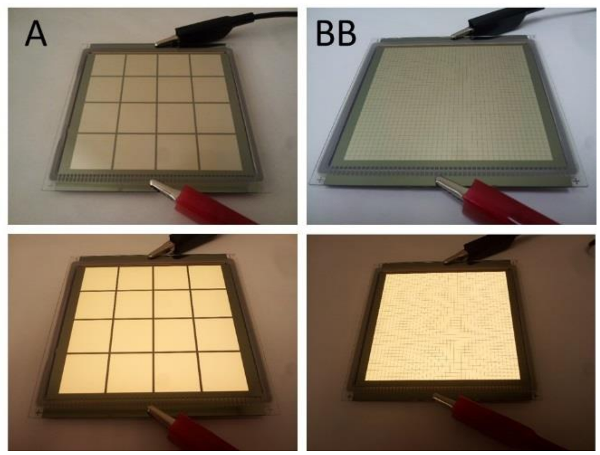
- Implementing stacked OLED architectures to increase vertical OLED stack resistance and reduce the lateral resistance effect through the anode electrode
- Reducing the effective sheet resistance of the anode electrode by introducing metal grids or by using more conductive anode materials
- Improving the heat spreading and removal from the OLED device through solid-state encapsulation technology

Milestone 5.1 (M5.1 – Large area OLED panel with >85% uniformity) was completed on time by the end of Q1 2015. Originally, two different panel designs were being considered for the luminaire demonstration: (1) a 111 cm^2 rectangular panel (63.5x175mm) that produces over 75 lumens and demonstrates brightness uniformity of 80-85% without metal grids, using the 3-stack white OLED architecture; and (2) a square panel having an emitting area of 100cm^2 that can produce more than 100 lumens. In order to understand the design requirements for the larger square panel, several variations of a smaller square panel (4"x4") were designed to fit the existing infrastructure already established at OLEDWorks. A Spice electrical model was used to simulate the resistance and current variations across the panel. The L-I-V characteristics of the 3-stack white OLED were incorporated into the model in order to estimate the brightness uniformity gradients across the panel. The panel design variations consisted of:

- Panel A – wide 1mm metal grids
- Panel B – fine 50um metal grids at 1mm pitch
- Panel BB – fine 50 um metal grids at 2mm pitch
- Panel D – no grids, wide bus bar, 1-side or 3-side connection
- Panel DD – no grids, widest bus bar, 1-side or 3-side connection
- Panel E – no grids, no busbar, 3-side connection
- Panel F – no grids, no busbar, 4-side connection

A Gen2 (370x470mm) substrate was designed with an array of the seven different 4”x4” panel designs as pictured below (left). The right images show actual fabricated OLED panels for designs A and BB, both unlit and lit.



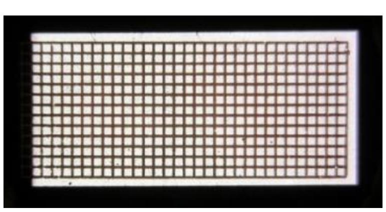
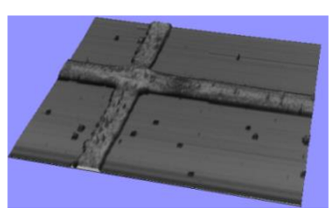
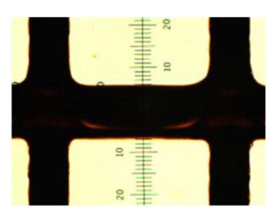


The substrates were used during the integration phase to evaluate uniformity when combined with the latest high efficacy white structures. The substrates were separated into individual 4”x4” pieces for OLED processing and used existing hardware, mask fixtures, and encapsulation cans to fabricate the OLED panels using a 3-stack white formulation. This activity was slightly delayed due to other higher priorities, but evaluations were completed in Q3 2015.

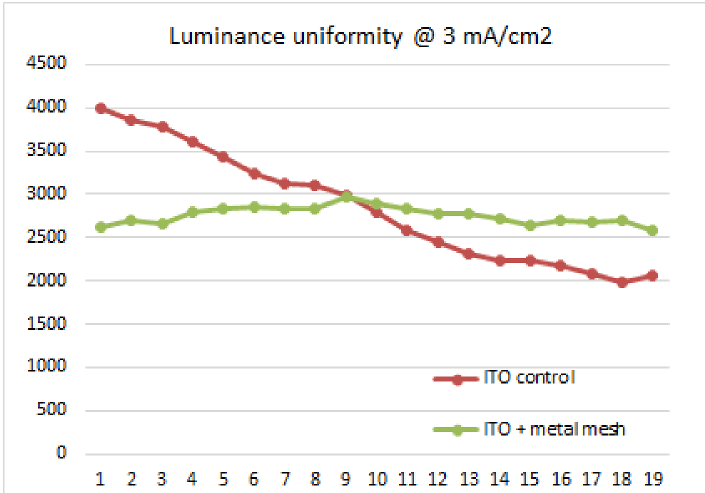
The table below shows a compilation of the uniformity results as measured on multiple panels of each type. A 16-point array of measurements were taken across each panel, then the brightness uniformity was calculated and reported at a current density of 2 mA/cm^2 (approximately 3000 cd/m^2). The metal grid designs (A, B, BB) in general are capable of achieving the best uniformity as expected. Designs E and F, which are desirable from a cost perspective since they do not include busmetal or metal grids, can achieve acceptable uniformity when feeding the current from multiple sides, as will be done in a real product situation. A variation of the ITO-only panel design E and F was carried forward using a 4-sided anode and cathode connection, and will use an insulator layer to provide short protection at ITO edges and mask edges. Having current distributed equilaterally around 4 sides of the panel would allow for > 85% uniformity on the final panel design.

Data summary at 2mA/cm2 (~3000 nits)				Brightness uniformity		
Design	Description	Area (cm^2)	Panel ID	min/max	1-(max-min)/(max+min)*100	predicted
A	Wide (1mm) grid lines	56.5	A2	85.9%	92.4%	88.0%
			A3	81.5%	89.8%	
			2	79.1%	88.3%	
			3	78.3%	87.8%	
B	Fine grids (1mm pitch)	56.4	1	58.9%	74.2%	88.0%
BB	Fine grids (2mm pitch)	60.0	BB1	80.7%	89.3%	83.0%
			BB4	69.7%	82.1%	
			5	76.0%	86.3%	
			7	77.5%	87.3%	
D	No grids, busbar	65.2	D1	69.5%	82.0%	83.0%
			D2	69.2%	81.8%	
			11	69.6%	82.1%	
DD	No grids, Wide busbar	55.0	4	84.9%	91.9%	88.0%
			DD2	71.2%	83.2%	
E	No grids, no busbar 3-side anode contact	65.2	12	52.1%	68.5%	70.0%
			E1	57.1%	72.7%	
			E3	51.4%	67.9%	
			E3*	70.9%	83.0%	
			E4	51.6%	68.1%	
			E4*	72.3%	83.9%	
F	No grids, no busbar 4-side anode contact	65.2	F1	65.3%	79.0%	82.0%
			F2	63.9%	78.0%	
			6	57.9%	73.4%	
			6*	62.8%	77.1%	
			8	60.4%	75.3%	
			8*	63.3%	77.5%	
Philips FL300	No grids, no busbar 4-side perimeter PCB	105.0	6-stack	94.4%	97.1%	
			3-stack	68.7%	81.5%	
*re-measured with anode clips connected on 3 sides						

It is understood that substrates patterned by photolithography are too expensive. To evaluate low-cost printed metal grids, initial tests were done with an ink supplier. Metal grids were inkjet-printed over ITO and over glass. OLED devices were fabricated without additional planarization over the metal. Good uniformity was demonstrated as seen in the left image below of a lit 3cm^2 OLED pixel having a length of 1 inch. Current is fed from the left side only. The center image shows a profilometry image of the metal mesh traces having a height of 200-300nm, and the right image shows an optical microscopy image of the printed metal grids.

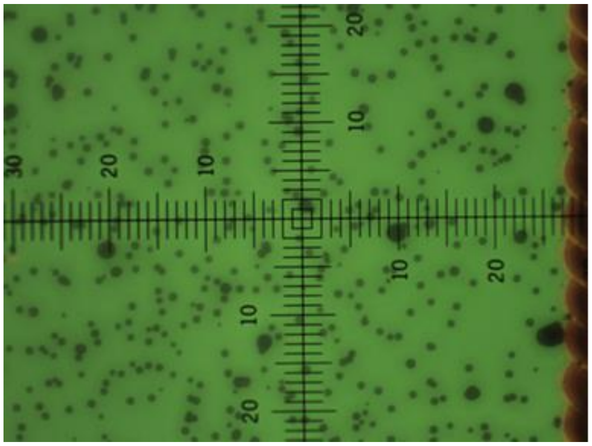




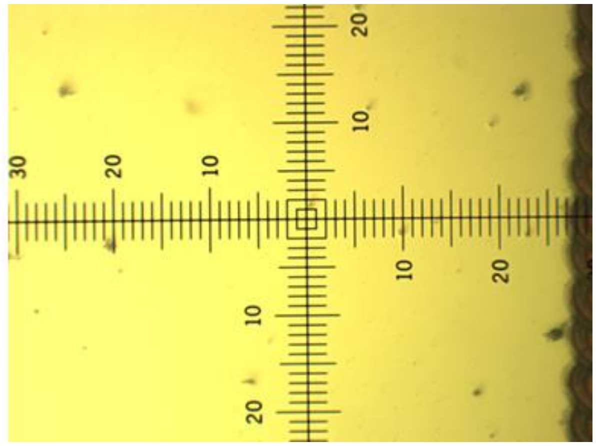
The uniformity was measured for an ITO control device and a device with printed metal grids in a mesh pattern. The graph below show the brightness measured across the 1-inch length. The uniformity was improved from 65% on the ITO-only control to 93% with the addition of the metal grids. Note that this was in-house sputtered ITO with sheet resistance of 30 ohms/square.



Initial samples showed a tendency to form shorts over time along the metal traces. Further work was done to evaluate planarizing methods such as printed insulators. Since initial tests were promising, OLEDWorks purchased a Fujifilm Dimatix DMP-2831 benchtop inkjet printer to continue this work in house. During the integration phase, the printer was used to print metal grids and/or insulators over IEL/ITO substrates to demonstrate the combination of integrated IEL substrates with uniform electrodes. Since it was determined that good uniformity could be achieved without the use of metal grids, printing of metal grids became a lower priority and work focused more on printing of the insulator layer as a lower cost alternative to photolithography-patterned insulators. Initial work showed promising results and a printing process was developed using several commercially available insulator inks. Devices were fabricated with the printed insulator and showed good device yield. Further studies were done to understand if there is any impact from outgassing of the material, and to investigate alternate materials. Based on this work the large area OLED panels were designed to use an insulator layer to provide short protection along the ITO edges. The integrated substrate vendor also demonstrated the capability to pattern both ITO and insulator layers using printing methods, leading to lower cost substrates.

In this task we also evaluated two different options for a highly conductive TCO material with a multilayer Ag stack having a sheet resistance around 5 ohms/square. Glass substrates with several variations of this TCO were provided by two different glass suppliers. The TCO layer(s) were patterned by laser ablation before OLED devices were fabricated. Initial tests with these substrates were not successful, as most devices either shorted or showed high leakage current. A few devices that lit showed many defects in the TCO film. The images below show the same area of the OLED lit (left) and unlit (right). Many of the darkspots that show up in lit mode correspond with particles or defects seen in the unlit mode. Neither of these tests were considered to be successful.



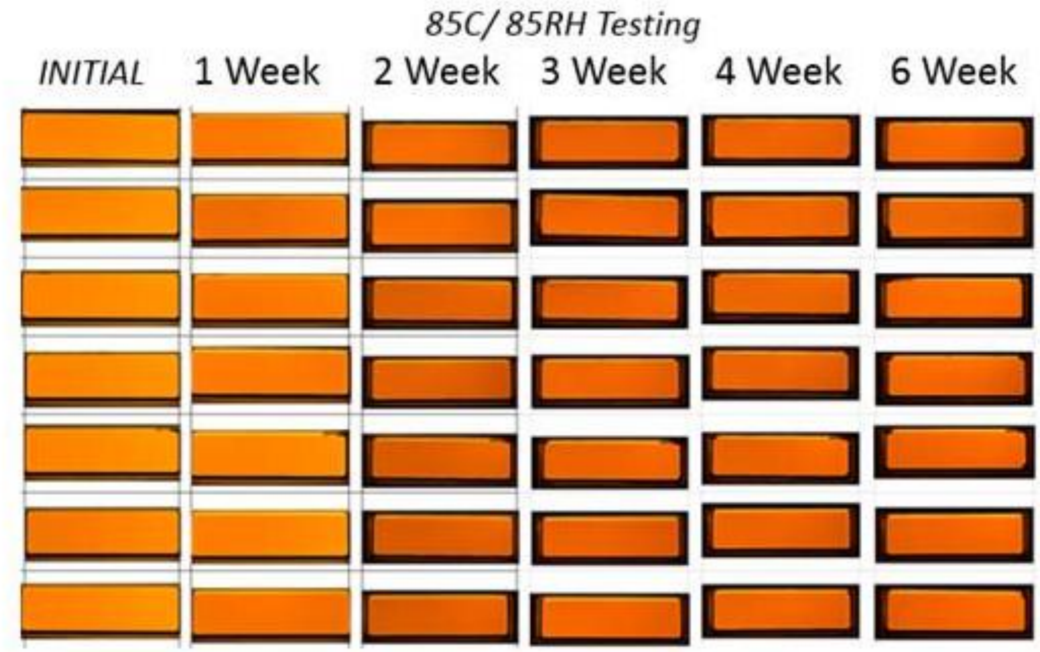


Several commercially available OLED panels were characterized in order to understand what uniformity is possible using different approaches. OLED lighting panels from leading manufacturers LG Chem and Philips were obtained and measured for brightness uniformity. Five square 100x100 mm LG panels from a Home Depot fixture were measured across the panel in a 9-point array, with the edge points approximately 1 cm in from the edge of the emitting area. The uniformity is shown in the table below, using the formula 1-[(max-min)/(max+min)]. These panels produce 75 lumens at a brightness of 3000 cd/m^2, and have an average uniformity of 94%. The LG panels use a metal grid and planarization layer patterned by photolithography, combined with a 3-stack white architecture. Also shown below is the uniformity data for a Philips Brite FL300 panel, which produces 115 lumens at 3000 cd/m^2 or 300 lumens at 8000 cd/m^2. The Philips panels do not use a metal grid; uniformity is achieved by using a 6-stack white architecture and 4-sided electrical connection. The uniformity was measured in a 16-point array starting 1cm from the edge of the emitting area, with and without the heat sink, using the same formula. Uniformity ranges from 93% at high brightness to 97% at low brightness with the heat sink.

LG Chem N6SA30 100x100 mm	Uniformity @ 3000 cd/m2
Panel1	94.0%
Panel2	89.8%
Panel3	95.4%
Panel4	94.2%
Panel5	94.5%
AVG	93.6%

Philips Brite FL300 120x120 mm	Uniformity	
	3000 cd/m2	8000 cd/m2
No heat sink	93.8%	93.6%
Heat sink	97.1%	92.9%

As a method to improve heat removal and therefore uniformity, solid-state encapsulation technology was investigated. Several adhesive and fill materials from different suppliers were evaluated using one of our standard panel designs, a 1”x4” marker light. Completed OLED panels were encapsulated then subjected to accelerated environmental testing in 85C/85%RH environment. Initial testing allowed us to narrow down the many options to a few promising material sets. This work enabled us to select the materials and process as well as specify equipment for a dam/fill encapsulation approach. However, development of the dam/fill encapsulation approach was discontinued in order to focus on a thin film encapsulation approach which is more attractive from a cost perspective. Work proceeded on development of a laminated encapsulation process consisting of a laminated foil with and without getter layers over the OLED device. Initial results were promising and it was decided that the high performance panels made in this project would use the newly developed encapsulation process. Accelerated environmental aging tests at 85C/85%RH were done and showed promising results in terms of darkspot growth. The images below show a series of 22cm^2 OLED panels progressing through 6 weeks of environmental testing, with only some moisture incursion from the edges (1-2mm) as would be expected.



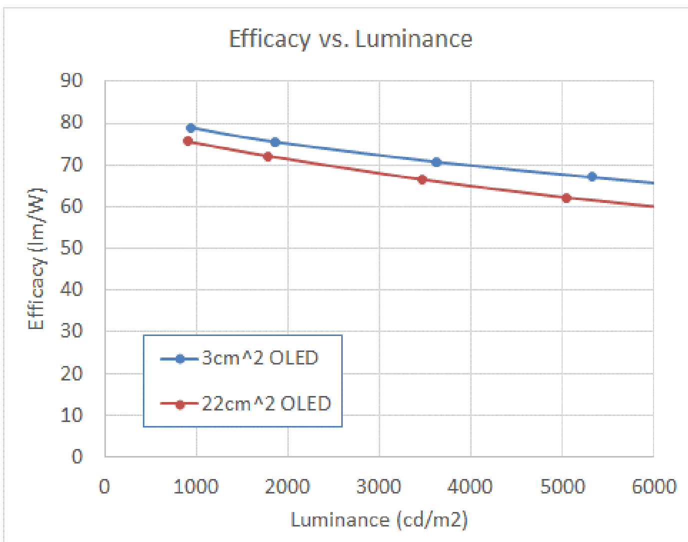
Consideration of all elements investigated in task 5 resulted in the decision to continue with several approaches to achieve high uniformity. The most cost effective approach is to avoid metal grids altogether, as demonstrated by the OW rectangular panel and the Brite FL300 square panel. Standard ITO films with a sheet resistance of 10-15 ohms/square, combined with a stacked white OLED, are capable of achieving > 85% brightness uniformity. The new large square panel was designed with electrical connections on all 4 sides for best uniformity, along with a solid-state encapsulation technology for more effective heat removal. Electrical connection was made with a flexible printed circuit that is attached directly to the ITO around the perimeter of the panel.

Tasks 2-5 comprised the first development phase of the project. At the end of Phase I, OLEDWorks held an internal review to evaluate the status of these tasks and determine if there was sufficient progress to proceed into the next phase of the project. This served as the first decision point as indicated in the project schedule, and having demonstrated success or at least sufficient progress in all technology elements, it was decided to proceed to the next integration phase of the project, comprising tasks 6 and 7.

Task 6 – Integration of IEL and Uniform Electrode

This task consisted of process integration of internal light extraction substrates with stacked white OLED architectures. Milestone 6.1 (M6.1 – Demonstrate compatibility of IEL with uniform electrode) was completed on time by the end of Q2 2015. Given the fact that an ITO-only (no metal grid) approach was selected as the uniform electrode technology, we essentially already demonstrated compatibility of the IEL and ITO through the work in task 5.

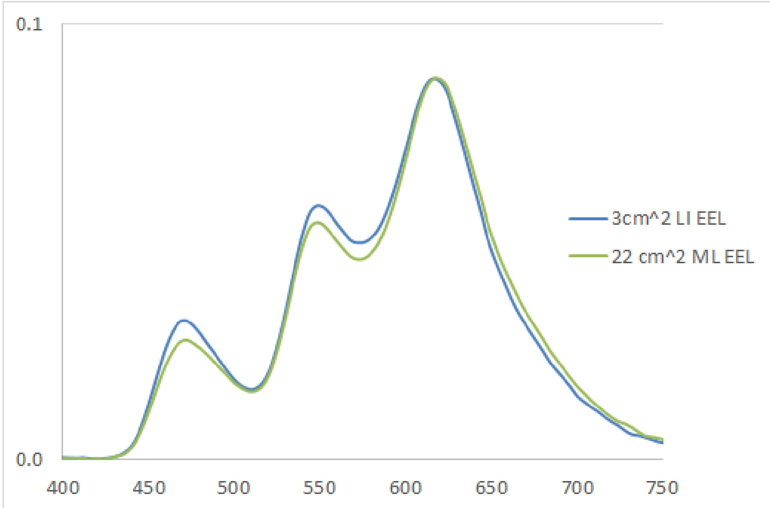
The high-efficiency 3-stack white OLED structure developed in task 3 was successfully transferred from R&D to the production coater (PC). At 3000 cd/m^2 (with EEL only), small area (3.0 cm^2) devices demonstrated 72 lm/W, while larger area (22 cm^2) devices demonstrated 67 lm/W. Devices were fabricated in the same production batch, but the larger area devices were produced on a gen2 sheet. The difference of 5-10% for larger area OLED devices is attributed to resistive losses through the conductive anode and minor process differences between the smaller substrates and gen2 substrates. The efficacy as a function of luminance is plotted for both size devices in the graph below.



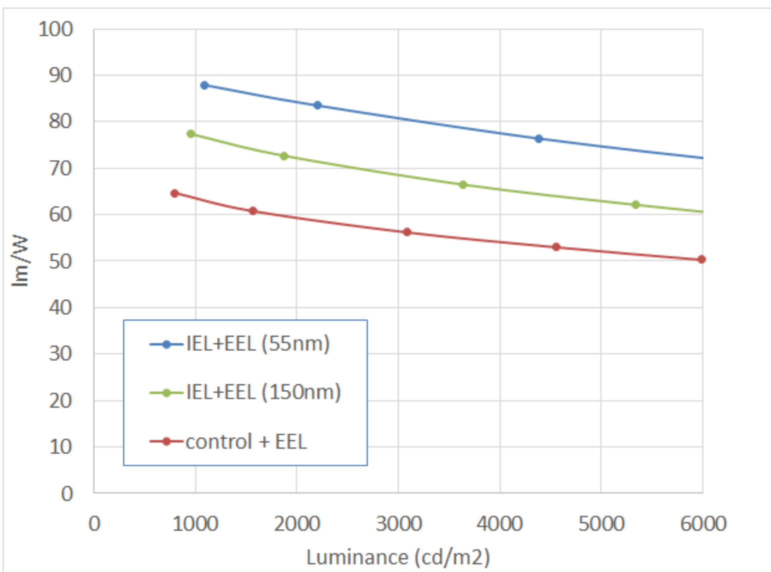
A comparison of the data, including color quality, is given in the table below (data at 2 mA/cm^2).

Device	V	cd/m2	cd/A	CIEx	CIEy	lm/W	EQE	CCT	DUV	CRI Ra	R9	LER
LI (3.0cm2)	8.1	3630	181.0	0.458	0.416	70.7	85.6	2881	0.0024	87	27	327
ML (22cm2)	8.2	3470	173.0	0.467	0.417	66.5	85.1	2742	0.0019	89	36	317

The EL spectra for both devices is seen in the chart below, and shows that similar spectra are obtained with only minor differences in the blue and yellow peaks. The white color quality is very good in both cases, with CCT ~ 2800K, Duv ~ 0.002, CRI > 87, and R9 > 27. Note that this was an earlier version of the white structure. During later tasks we adjusted both the blue and red emission materials to achieve a more desirable CCT along with a high CRI and R9.



Further studies were done to evaluate the impact of ITO thickness on light extraction efficiency. IEL substrates with the standard 150nm ITO (~10-12 ohm/sq) were compared to IEL substrates with thinner 55nm ITO (~30 ohm/sq). An older version of the triple-stack white was used in this evaluation, which gave close to 60 lm/W efficacy with just EEL. The IEL devices were compared to the control device, all with EEL. The graph below shows the efficacy as a function of luminance.



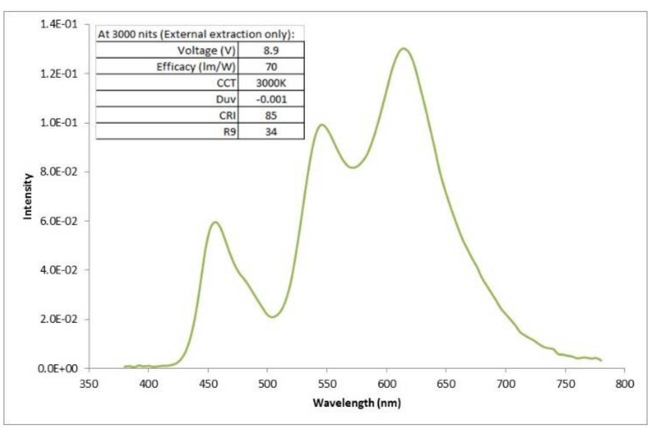
At 3000 cd/m^2, the control achieves 57 lm/W, and IEL with thicker ITO achieves 69 lm/W, which is a 20% improvement. IEL with thinner ITO achieves 80 lm/W, which is another 16% improvement over thicker ITO and 40% improvement over the control. This demonstrates that the ITO absorption plays a strong role in the extraction efficiency. However, this trade-off cannot be made when selecting an ITO-only approach, since the trade-off in anode sheet resistance is too great and will result in unacceptable uniformity. This also demonstrates the need for improved transparent conductors with sheet resistance < 10 ohms/square and transparency > 90%.

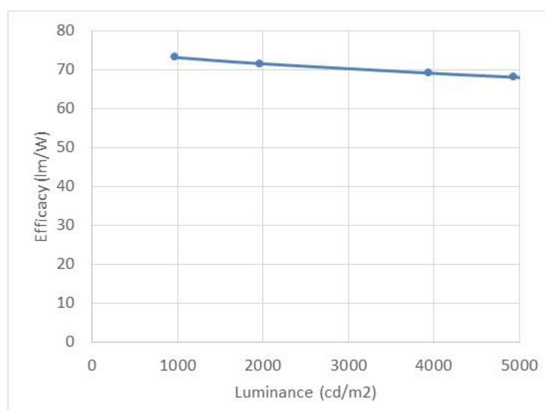
During this task, we experienced some delay as we worked through the process flow issues and supply chain issues between the selected integrated substrate suppliers and ITO patterning vendors. Appropriate pathways for delivery of fully integrated substrates to OLEDWorks were developed, both for initial lower volume supply as well as for high volume supply. Eventually we were able to work through these bottleneck issues, which can be challenging at times due to the low volume requests in the still small but growing OLED lighting market. Due to the confidential nature of these interactions, the details are not disclosed in this report. Due to these delays, we requested and received a 6-month no-cost extension to keep the project on track.

Task 7 – Optimization of Component Technologies

This task entailed optimization of all component technologies, including IEL, uniform electrode, and stacked white OLED with thin film encapsulation, as well as initial work to scale the integrated substrate. Milestone 7.1 (White panel with 80 lm/W and 85% uniformity) was successfully completed during Q2 2016.

The first experiments designed to optimize the color and performance of the efficient white OLED on IEL substrates were carried out in this task. It was observed that the IEL substrates tended to outcouple more light in the green to red wavelengths as compared to blue wavelengths, and this caused a shift in the white color, generally pushing toward lower CCT and higher Duv. This optimization work focused on obtaining a more accurate white color with acceptable Duv while maintaining high efficiency. Work continued on improving the efficiency of the blue emitting stack, which is required to offset the improved outcoupling of the green to red wavelengths in order to maintain the desired CCT of 3000K. The results of this work are summarized below at 3000 nits, showing an efficacy of 70 lm/W with just a microlens EEL and a CCT of 3000K just below the blackbody curve. CRI above 85 and R9 above 20 were maintained.

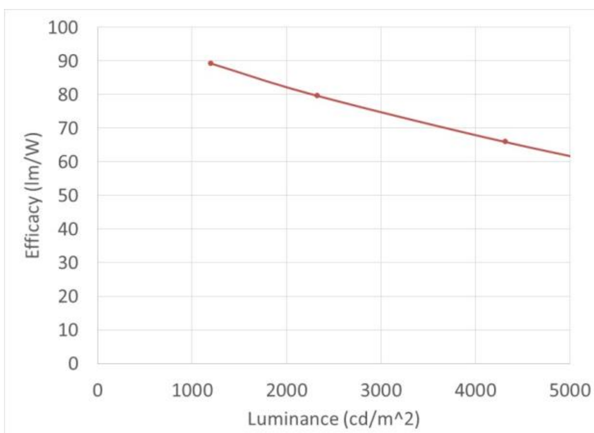




An example of a large area OLED panel fabricated from the Gen2 integrated substrates is shown below in the ON state (left), OFF state (center), and from the backside (right).

The back view shows the laminated film encapsulation and a perimeter flex PCB that is attached to the exposed ITO around the perimeter of the panel using a conductive adhesive. This allows for current to be driven equilaterally around the perimeter of the panel and leads to good uniformity without the use of busmetal. Although there is a small trade-off in electrical contact resistance to ITO as compared to busmetal, the reduced cost of this approach is significant and an acceptable trade-off. The higher resistance to ITO leads to slightly higher drive voltage and reduced efficacy. Even still, we were able to demonstrate up to 80 lm/W and good uniformity at 2000 nits.

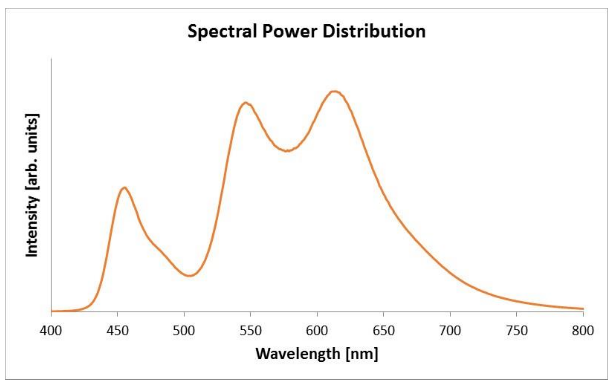
A plot of efficacy versus luminance obtained on a large area 120.5x120.5 mm panel is shown below. The efficacy reaches 75 lm/W at 3000 nits and 82 lm/W at 2000 nits. At a lower brightness of 1000 nits, the efficacy exceeds 90 lm/W.



This same panel has a brightness uniformity of 84% as measured in a 9-point array shown below, using the formula 1-(max-min/max+min). As expected, the center area of the panel is less bright than the edges due to the lateral resistance of the ITO. These measurements were taken at 3000 nits. The uniformity was slightly better at lower brightness such as 2000 nits since the required current is lower, leading to a decrease in the ITO lateral resistance.

3739	3375	3950
2914	2858	3170
3654	3272	3804

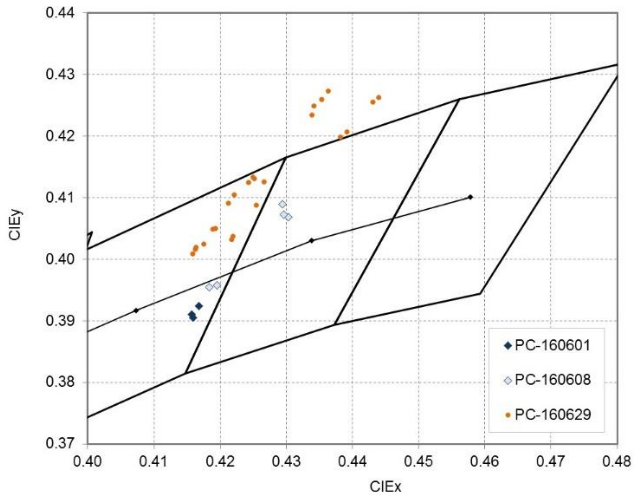
The CCT for this panel is 3300K with a CRI of 80, R9 of 21, and a duV of +0.004. Reducing the Duv to <0.002 and increasing the CRI was expected to reduce the efficacy by 3-5 lm/W. The spectral power distribution is shown below. To reduce the Duv, the yellow peak intensity will be reduced while increasing the red peak intensity. The IEL substrate tends to outcouple more green-yellow photons than blue or red, therefore the white OLED formulation was later adjusted to obtain the proper CCT and Duv. The blue peak is already at maximum efficiency.



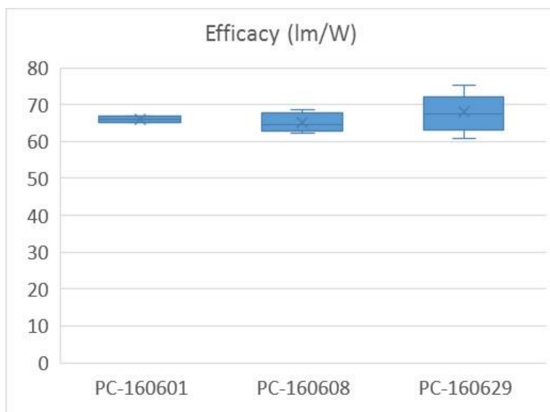
Task 8 – Gen2 Scale Capability

This task involved procuring Gen2 scaled integrated substrates and demonstrating high performance OLED lighting panels fabricated on the substrates. This task began in Q1 2016. Milestone 8.1 (High performance white OLEDs made on Gen2 scale) was successfully completed during Q2 2016.

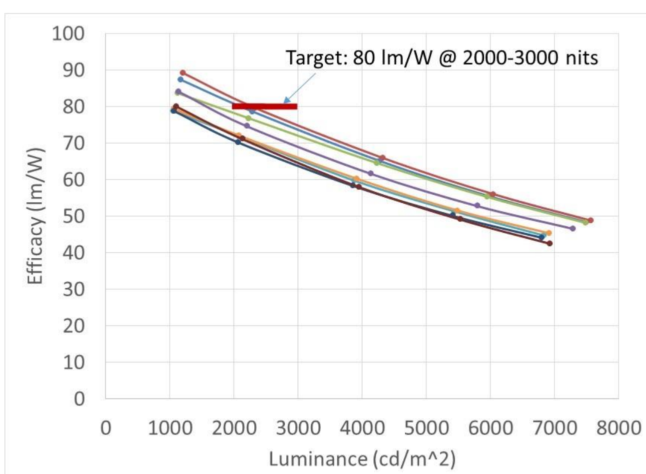
After receiving the first Gen2 integrated substrates in late May 2016, we promptly made 3 batches of white OLED panels in the production coater during June. As mentioned before, there were a few planned OLED stack variations attempting to tune the white color. The 1931 CIE x,y chromaticity plot below shows the white color variations between batches and within a batch. Even within a batch there were planned color adjustments. The white color temperature is mostly within the 3500K or 3000K quadrants. In future runs we attempted to reduce the variability and bring the mean color point closer to the blackbody to achieve Duv < 0.002.



The efficacy at 3000 nits ranged from low 60s to mid 70s as seen in the variability chart below. These data were taken from the average of 9 luminance points measured across each panel (not in an integrating sphere).



A sampling of 8 panels from the last run in June (PC-160629) are shown in the efficacy versus luminance plot below. Some of the panels reach the target level of 80 lm/W in the range of 2000-3000 nits.

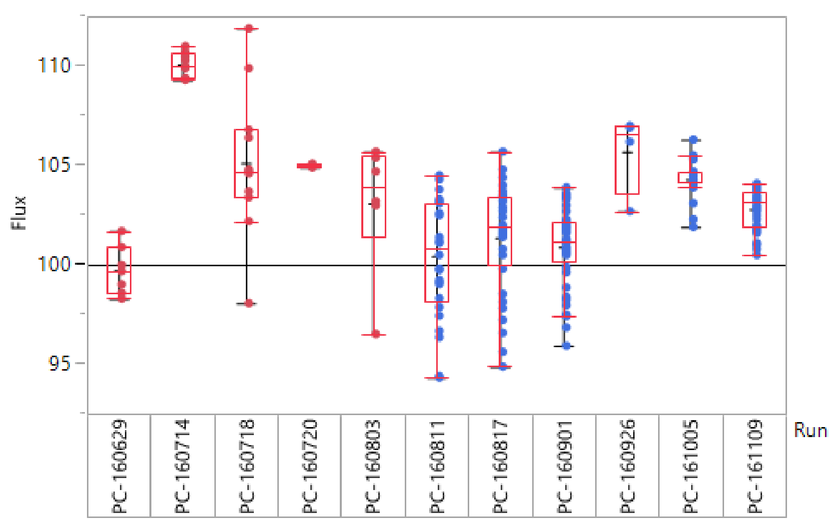


During the scale-up phase we encountered several issues that slowed progress. Visual non-uniformity defects such as those pictured below were found to be related to an interaction between the integrated substrates and a high temperature process used at OLEDWorks. Improved substrate pre-treatment processes resolved these visual artifacts.

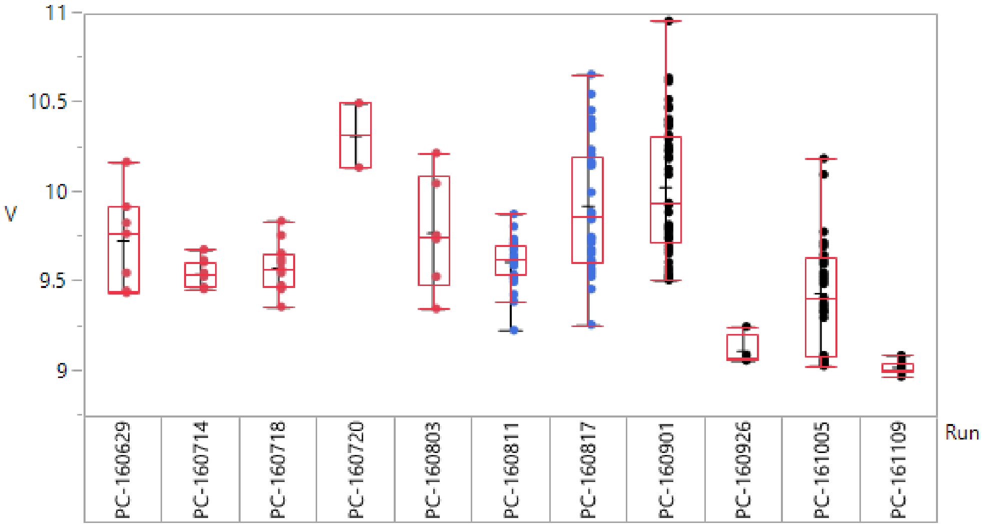
Overall, we successfully demonstrated the capability to produce high performance white OLED lighting panels on our production line, based on a scaled internal light extraction substrate. Many of these technological developments will be utilized in our next generation of high performance OLED lighting products.

Task 9 – Final Panel Evaluation

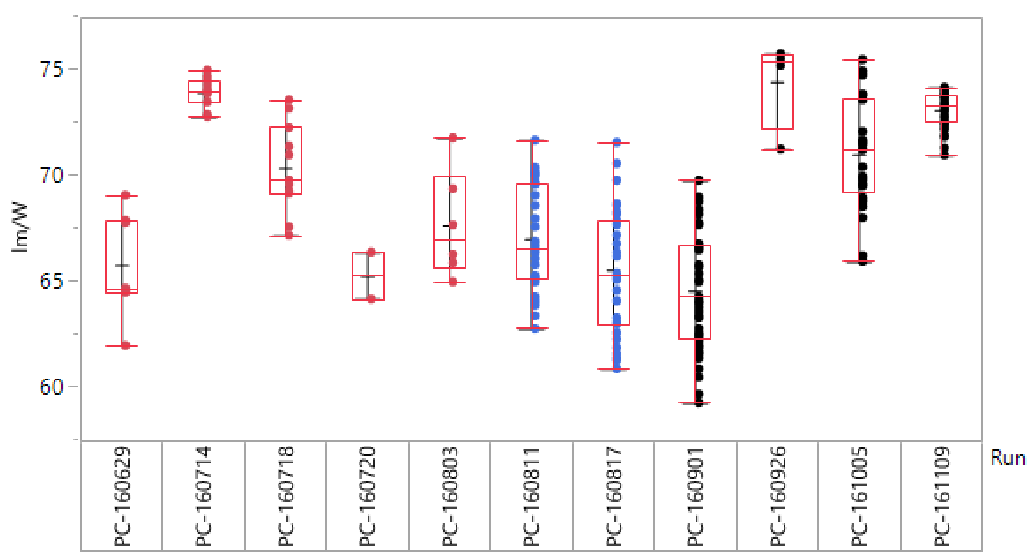
This task involved production of large quantities of OLED panels on the manufacturing line and evaluation of a large sample size of the panels. In the second half of 2016, we produced 12 batches of panels. The run-to-run performance for 11 different batches of panels is shown below. All panels were fully characterized in an integrating sphere at an operating current of 156 mA, which is the current level required to achieve 3000 nits. This translates to a current density of 1.5 mA/cm^2 for the panel having an emitting area of 104 cm^2. Assuming lambertian distribution, it was estimated that each panel would produce 100 lumens, which was verified by the integrating sphere measurements. The average flux was measured to be over 100 lumens per panel as shown in the chart below. For the last 3 runs, the entire distribution was over 100 lumens per panel.



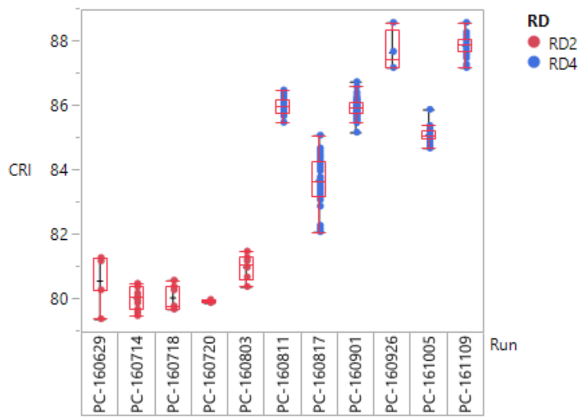
Based on early test device data, it was anticipated that drive voltage would be 8.5V or less for a 3-stack white OLED. During the course of the project we switched to a more stable electron transport material that resulted in higher voltage by ~ 1V. It was also determined later that other substrate preparation processes result in up to 0.5V higher voltage on these large area panels. Overall, voltage averaged between 9.5-10V across several batches of panels as shown below. Process improvements were implemented prior to the last run (PC-161109), and this resulted in a lower voltage of just over 9V with a much tighter distribution.

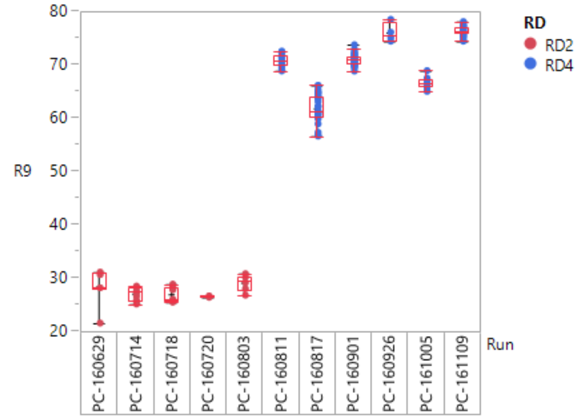


Prior to September, efficacy averaged ~ 67 lm/W as shown in the chart below. With the most recent improvements, the last 3 runs averaged ~ 73 lm/W. Overall, higher voltage was one of the main reasons that efficacy fell short of the 80 lm/W target on average.

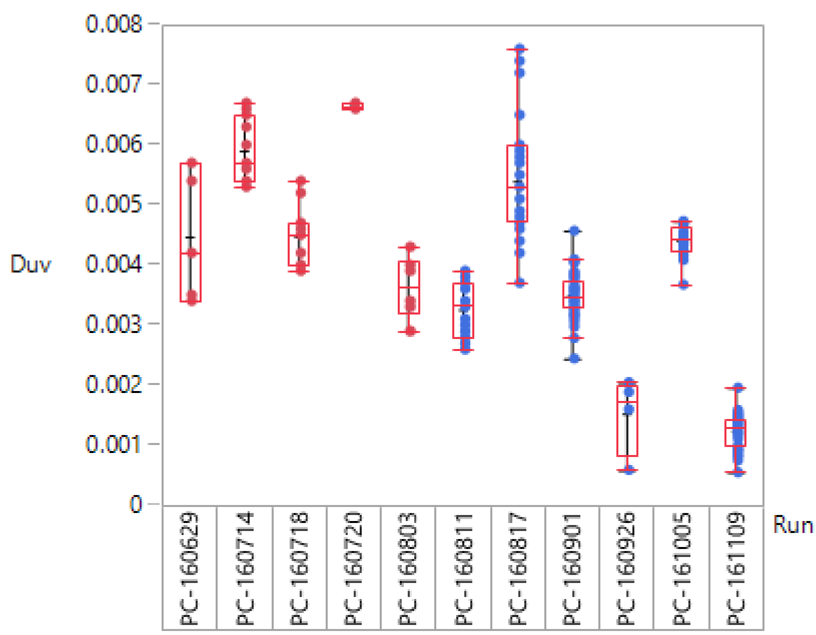


A trade-off to achieve higher color quality was responsible for a loss in efficacy of 4-5 lm/W. Since early panel data showed that we were only achieving a CRI of 80 with the original red dopant (RD2), a deeper red dopant was implemented in order to achieve the target 85 CRI. As seen in the charts below, a step change improvement in both CRI and R9 followed the change to a deeper red emitter (RD4). As mentioned, this change to a deeper red emitter also resulted in lower efficacy. The lower efficacy is attributed to a shift in the peak wavelength of the red emitter to longer wavelengths and forcing more energy outside the visible spectrum into the IR region.

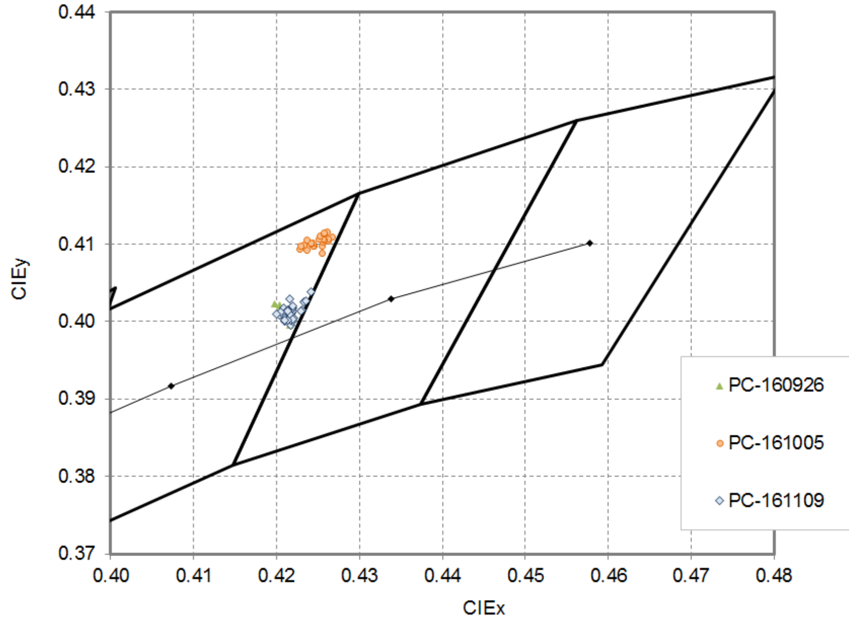




CCT averaged around 3300K and Duv was typically above 0.003 as shown below. After making a minor OLED formulation adjustment, the last production batch produced a Duv of less than 0.002.



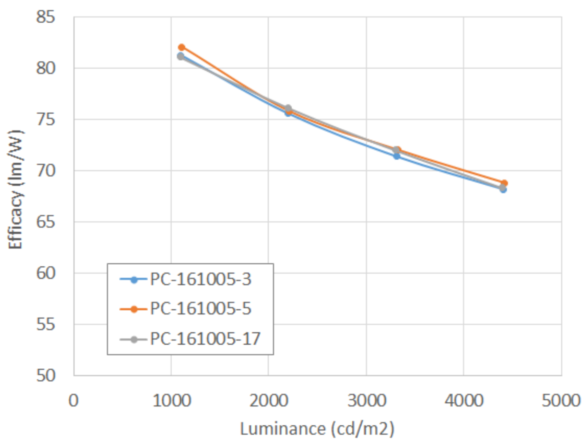
The last 3 runs are plotted on a 1931 CIEx,y chromaticity chart with the Energy Star 7-step color tolerance quadrangles as shown below. Within a run, the color consistency was very good. There was an assignable process issue that caused a slightly elevated Duv on the PC-161005 run.

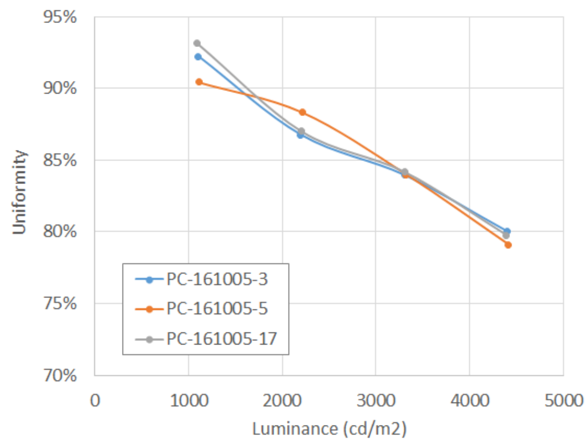


Panels that passed visual inspections and initial testing were placed onto operational burn-in towers in order to assess the reliability and weed out early failures, as pictured below. Panels were operated at accelerated current levels approximately 2-3 times the nominal current.

Prior to September, it was found that over 50% of panels were shorting during the 2 week burn-in process. Higher occurrence of shorting was observed when using the new solid-state lamination encapsulation process, as compared to traditional encapsulation. Several potential yield improvements were implemented in September, resulting in less than 10% shorting loss during burn-in. As a result, we were able to produce enough good yielding panels in the final runs in order to complete the luminaire demonstration.

The typical efficacy and uniformity as a function of brightness are plotted below for the most recent OLED panels. The efficacy exceeds 75 lm/W at 2000 nits and 80 lm/W at 1000 nits, and the uniformity is above the target level of 85% even at 3000 nits.





Task 10 – Luminaire Integration

This final task involved integration of OLEDWorks' panels into a luminaire that has the desired total lumen output and efficacy. The commercially relevant Trilia platform from Acuity Brands Lighting was used for the luminaire demonstration. A Trilia Tri OLED luminaire is shown in the figure below, using high performance panels from OLEDWorks.

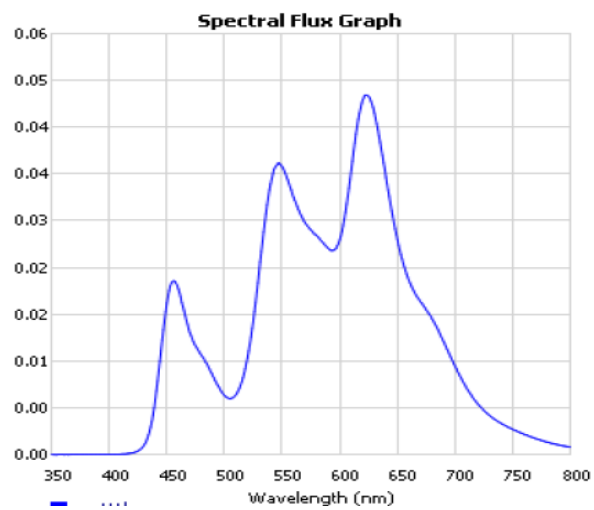
A 50W eldoLED single channel driver with programmable current levels was used for the modified Trilia luminaire with larger OLEDWorks panels. The expected driver efficiency was 85%. The projected luminaire performance was 64 lm/W based on a panel efficacy of 77 lm/W. Since actual panel efficacy averaged around 71 lm/W, the luminaire efficacy was slightly below 60 lm/W as shown in the table below. With each panel producing around 100 lumens, the total luminous flux for the luminaire was over 2200 lm, which is within the specified range of 2000-3000 lumens.

Trilia OLED Luminaire Performance

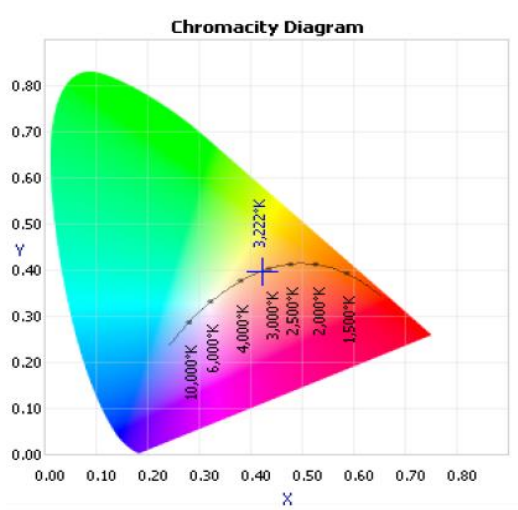
	Initial projection	Actual performance
Number of panels	24	24
Panel output	100 lm	100 lm
Total lumen output	2400 lm	2200 lm
Number of drivers	1	1
Panel efficacy	77 lm/W	71 lm/W
Optical efficiency	98%	98%
Driver efficiency	85%	85%
Luminaire efficacy	64 lm/W	59 lm/W

The Trilia OLED luminaire was tested according to LM-79-08 standards for electrical and photometric measurements of solid-state lighting products. Excerpts from the report are highlighted below. The luminaire produced 2237 lumens with an efficacy of 58.8 lm/W.

PHOTOMETRIC DATA	
LUMINOUS FLUX(LU):	2237
SP RATIO:	1.38
CCT:	3222
CRI:	87.68
CHROMA X:	0.4241
CHROMA Y:	0.4035
CHROMA U:	0
CHROMA V:	0
CHROMA U':	0.2425
CHROMA V':	0.5193
DUV VALUE:	0.0018
ELECTRICAL	
INPUT POWER(WATTS):	38.05
INPUT VOLTS(VOLTS AC):	120
INPUT CURRENT(AMPS):	0.43
FREQUENCY(HERTZ):	60
POWER FACTOR:	0.74
CALCULATED	
EFFICACY(LU/WATTS):	58.79



The white color quality was excellent, with CCT=3222K, Duv=0.0018, CRI Ra=88 and R9=76.



R VALUES	
RA:	87.68
R1:	91.05
R2:	90.75
R3:	78.83
R4:	86.12
R5:	84.31
R6:	80.06
R7:	97.28
R8:	93.06
R9:	75.95
R10:	66.12
R11:	74.03
R12:	49.97
R13:	90.22
R14:	85.61

Project Output

The following products and technology transfer activities were developed under this award.

OLEDWorks signed a license agreement with Universal Display Corporation. The agreement provides access to UDC's high efficiency phosphorescent OLED materials, which enabled the high efficiency white OLEDs achieved in this program. Link to press release from 2/19/2015: http://ir.oled.com/newsroom/press-releases/press-release-details/2015/OLEDWorks-LLC-and-Universal-Display-Corporation-Announce-OLED-Technology-License-Agreement-for-Lighting-Applications/default.aspx

OLEDWorks was invited to publish a paper and present the results at the 2016 Display Week conference sponsored by the Society for Information Display (SID). The paper, entitled "High Brightness OLED Lighting", highlighted some of the results obtained in this program under the section describing future products with higher efficacy. A copy of this paper was submitted to the program manager as well as submitted on the DOE E-link System. The paper is also highlighted on OLEDWorks' website: https://www.oledworks.com/resource/technology/

This project allowed OLEDWorks to develop numerous collaborations with nearly all companies in the OLED supply chain, from substrate manufacturers to suppliers of organic materials and encapsulation materials. We also formed a closer alliance with our luminaire partner in this program, Acuity Brands Lighting. They are now developing and offering several OLED luminaire products based on OLED panels from OLEDWorks.

OLEDWorks leveraged this DOE-funded project to secure matching funding from New York State. We submitted a funding proposal on Dec. 2, 2014 under New York State Energy Research and Development Authority (NYSERDA) Program Opportunity Notice (PON) 2606 Round 5 as follow-on funding to this project, also entitled "High-Performance OLED Panel and Luminaire". At the end of March 2015, OLEDWorks was selected for award by NYSERDA for work related to this DOE project starting in April 2015. NYSERDA covers all of OLEDWorks cost share for this DOE project, plus additional funding for work expanded beyond the scope of the DOE project, for a total of $499,263. Dr. Michael Boroson, the PI on this DOE project, is also the point of contact for the NYSERDA award. The contract with NYSERDA was completed in September 2015.