U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

GATEWAY
Demonstrations

OLED Lighting in the Offices of Aurora Lighting Design, Inc.

March 2016

Prepared for:

Solid-State Lighting Program
Building Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by:

Pacific Northwest National Laboratory

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <http://www.ntis.gov/about/form.aspx>
Online ordering: http://www.ntis.gov

This document was printed on recycled paper.

(8/2010)

PNNL-SA-25337

OLED Lighting in the Offices of Aurora Lighting Design, Inc.

Final report prepared in support of the U.S. DOE Solid-State Lighting Technology Demonstration GATEWAY Program

Study Participants:
Pacific Northwest National Laboratory
Aurora Lighting Design, Inc., Grayslake IL

NJ Miller

March 2016

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory

Preface

This document is a report of observations and results obtained from a lighting demonstration project conducted under the U.S. Department of Energy (DOE) GATEWAY Demonstration Program. The program supports demonstrations of high-performance solid-state lighting (SSL) products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Demonstration Program focuses on providing a source of independent, third-party data for use in decision-making by lighting users and professionals; this data should be considered in combination with other information relevant to the particular site and application under examination. Each GATEWAY Demonstration compares SSL products against the incumbent technologies used in that location. Depending on available information and circumstances, the SSL product may also be compared to alternate lighting technologies. Though products demonstrated in the GATEWAY program have been prescreened for performance, DOE does not endorse any commercial product or in any way guarantee that users will achieve the same results through use of these products.

Acknowledgements

This GATEWAY report is the result of the collaboration of Aurora Lighting Design, Inc., especially its principal Leslie North, who designed and specified the OLED configuration and shared the experience with GATEWAY, along with documentation of the process. Acuity Brands' Winona® Lighting built the modular OLED lighting system, monitored its installation, and generously provided photos, drawings, and technical information for the report.

Executive Summary

Aurora Lighting Design, Inc. made the bold step of installing an organic light-emitting diode (OLED) lighting system during office renovations in 2014. Located in the lower level of a residence on a lake in Illinois, the office has low gypsum wallboard ceilings (7 ft 5 in. with a 7-in. recess depth) with difficult access to the joist space above. The shallow profile and playful pattern options of the Acuity Brands "Trilia™" system offered Aurora Lighting Design, Inc. comfortable ambient light, warm 3000 K color with very good color rendering, dimmability with a standard 0-10 V wallbox dimmer, and a distinctive appearance (Figure ES 1). Compared to the previous installation of recessed medium-base downlights with nominal 20 W PAR38/830 LED lamps, the OLED system delivered much higher quality lighting, according to the responses of Leslie North, Principal, and her staff of three designers. See Table ES 1.

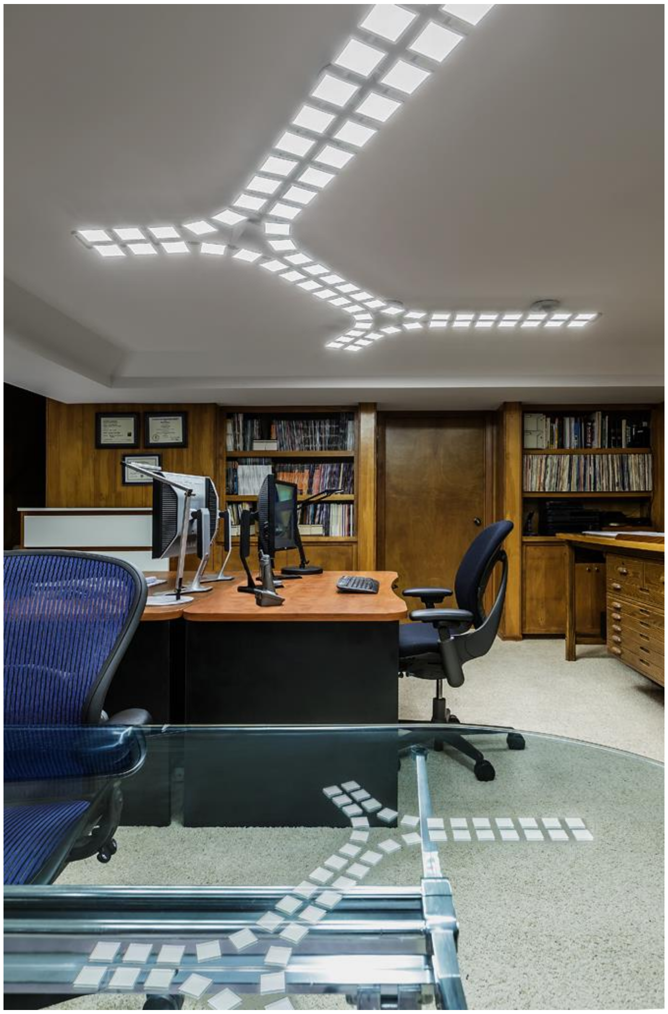


Figure ES 1. Offices of Aurora Lighting Design, Inc., showing the Trilia™ lighting system. (Photo courtesy of Acuity Brands.)

The installation was challenging because it was hard to access the ceiling and because 41 wires had to be run from the drivers, remote-mounted in an adjacent room, to the feed points of the OLED panel assemblies. Because there is no dedicated OLED driver on the market at this time, Acuity Brands equipped the OLED lighting system with LED drivers, which lowered system efficacy because they cannot be precisely tuned to the specific electrical needs of the OLEDs.

The office staff is proud of the unique installation, in spite of a few field issues. Approximately 2 months after installation was complete, a driver failed and was replaced; 2 months later, an OLED panel failed and was replaced. The only unresolvable issue is photometric flicker of approximately 77% to 100% at 261 Hz, when the system is dimmed to between 50% and 80% light output. [1] Although the staff noticed this flicker, it has been tolerated, since none is aware of personal negative health consequences resulting from it.

The staff uses the OLED system to supplement daylight, and almost always uses it dimmed, even in the evening. In fact, some observed that the panels felt somewhat too bright when raised to full output.

Pacific Northwest National Laboratory took a series of measurements in December 2015, including a power measurement that suggested higher power use than anticipated, higher luminances of some OLED panels than expected, and higher workplane illuminances than predicted by Aurora Lighting Design's photometric calculations. These results pointed to one or more incorrect drivers, and indeed, a check of the drivers showed that a mis-sized model of driver had been inadvertently installed in two places. Acuity Brands has since shipped replacement drivers. These were installed in February 2016, and subsequent measurements by PNNL indicate the power and illuminance performance is now within the expected range.

OLED products have several advantages: comfortable direct view because of low surface luminance (<3000 cd/m^2); a light distribution that produces high vertical illuminances on surfaces (such as walls) and excellent facial modeling; a soft light distribution that reduces harsh shadows from objects; and energy efficiency that is lower than the more mature LED technology, but promises to improve. Disadvantages include a soft, cosine light distribution that can be less than exciting if not combined with accent lights and task lights to provide visual focus and scintillating highlights, and high panel cost that limits widespread application.

For full viability of OLED architectural lighting, the systems will need to deliver higher efficacy, better system components, and lower costs. However, the architectural lighting market is taking notice of a product with an entirely different look and function. OLEDs are widely expected to increase in efficacy, longevity, size, and flexibility, giving designers and engineers a new tool for creative and effective lighting.

[1] JD Bullough et al., Detection and acceptability of stroboscopic effect from flicker, *Lighting Research and Technology*, October 2011.

Table ES 1. Details of OLED lighting system installed at Aurora Lighting Design, Inc. Room size is 14 ft 9 in. x 20 ft 6 in. x 7 ft 5 in. Illuminances in lux (lx) were measured. For comparison, the table includes calculated data on the previous PAR38 LED downlight layout, as well as for the same downlight equipped with compact fluorescent lamps (CFL). Details of the final installation, based on spot measurements taken after the incorrect drivers were replaced in February 2016, are noted in the last row.

Lighting description	Total estimated lumens	Power	Ltg. Power Density (LPD)	Illum. Horiz.	Illum. Vert.	Color Metrics
120 OLED panels in configuration, 11 drivers, including two incorrect drivers as originally installed	8518 at full output, based on Acuity photo reports. (Likely higher with incorrect drivers installed.)	240 W	0.79 W/ft^2	269 lx (avg. of points measured at 30” ht. 80 lx min to 576 lx max)	223 lx avg. on faces; 54 to 286 lx on bookcase wall	2974 K CCT D_{uv} 0.0019 CRI (R_a) 89 R_9 29 R_f 86 R_g 98
8 downlights with PAR38 LED 25º at 19.5 W, 1050 lumens each, based on GE Lighting lamp listing	8400 initial lamp lumens at full output, based on mfr. listing	156 W	0.52 W/ft^2	291 lx avg. (26 lx min to 2087 lx max; calc’d at 30” ht.)	78 lx avg. on faces; 17 to 37 lx on bookcase wall	3000 K CCT D_{uv} 0.0019 CRI (R_a) 80+, based on mfr. listing
8 downlights with 26W CFL PAR38 screwbase lamp	10,400 initial lamp lumens (approx.)	208 W	0.69 W/ft^2	N/A	N/A	2700 K CCT 82 CRI (approx.)
120 OLED panels in configuration, 11 drivers, including corrected drivers as installed in February 2016	8518 at full output, based on Acuity photo reports	189 W	0.62 W/ft^2	115 lx min to 506 lx max, measured at a limited number of points; see Section 4.5	169 lx avg. on faces	2974 K CCT D_{uv} 0.0019 CRI (R_a) 89 R_9 29 R_f 86 R_g 98
CCT is correlated color temperature; CFL is compact fluorescent lamp; CRI is color rendering index; R_9 is specific color rendering index of red color sample; R_f and R_g are IES TM-30-2015 fidelity index and gamut index, respectively.						

Contents

1.0 Introduction

Aurora Lighting Design, Inc. is a small architectural lighting design office located in the lower level of a residence 50 miles from downtown Chicago. With large windows overlooking a lake, the office uses daylight as its principal light source, supplementing with electric lighting for general and task lighting on heavily overcast days and outside of daylight hours. Leslie North, principal, decided to remodel the office lighting in March 2014, changing out the existing recessed downlights. She was intrigued with organic light-emitting diode (OLED) panels because of their soft appearance, their shallow profile, and the playful pattern options of the Acuity Brands Trilia™ system. She designed the configuration as an OLED demonstration, specified the products, and agreed to share the cost with Acuity Brands, with Acuity Brands supplying the OLED system and Aurora Lighting Design, Inc. paying for installation.

Figure 1. The Aurora Lighting Design, Inc. office with a lighting system using OLED panels. (Photo courtesy of Acuity Brands.)

At the time, choosing OLED technology for this installation was bold because OLED panels and drivers had a short track record. The technology was still very new and there was little solid information about panel and driver life, lumen maintenance, and dimming compatibility. With the September 2014 installation, Aurora Lighting Design, Inc. became the first office test site for the use of OLEDs in general lighting (Figure 1).

2.0 Project Description

Aurora Lighting Design, Inc. was founded in 2005 and is widely known for their attention to both sophisticated design and engineering details. Founder Leslie North has made a reputation in lighting healthcare facilities and large commercial spaces. She has two full-time staff specializing in design and production, and a part-time intern. The office is located in the lower level of her home in Grayslake, IL. The office space was originally equipped with shallow R-30 incandescent recessed downlights, since the tray ceiling height is only 7 ft 5 in. with 7 in. of recess depth. To reduce energy use, the designers first relamped these with 26 W PAR38 CFLs, and then with 20 W PAR38/830/25º narrow flood LED lamps as LEDs became a viable technology. With this lamping, the downlights produced non-uniform puddles of light on the workplane, with maximum-to-minimum illuminance ratios as high as 20:1 between downlights (Figure 2). In the absence of daylight, they also produced a dark ceiling, which the staff found gloomy.

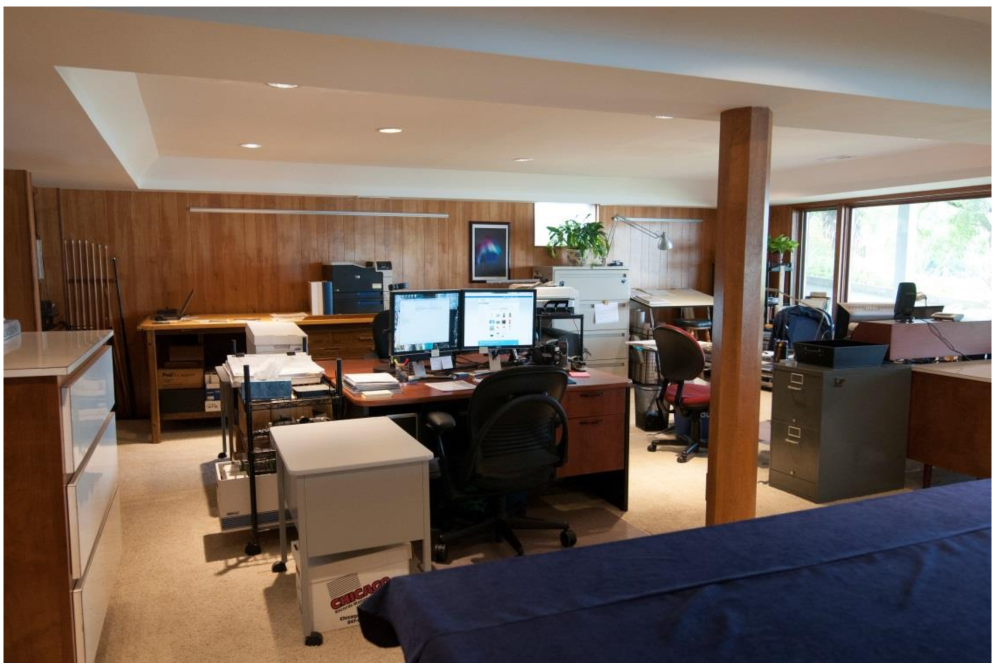


Figure 2. The Aurora Lighting Design, Inc. office before the lighting renovation, showing the recessed downlighting system. (Photo: Leslie North.)

The principal office work area is 14 ft 9 in. by 20 ft 6 in., with ceiling heights typical of lower floors in residential construction, reaching a maximum height of 7 ft 5 inches in the center of the tray ceiling, with a 6 ft 7 in. height soffit around the edge of the room. The upper ceiling is gypsum wallboard mounted to the bottom of wood joists. Ceiling finishes are white; wall finishes are medium-tone wood paneling. The carpet is a light cream color, which helps to reflect light back onto the ceiling.

Goals for the OLED installation included the following:

- 3000 K correlated color temperature (CCT), at the low end of normal office lighting, but warm enough to suggest the ambience of a home
- 80+ color rendering index (CRI), with an R9 > 20

- 320+ average lux (30+ footcandles (fc)) on the 2.5-ft-high workplane of ambient lighting, with a "soft" light distribution that produced minimal shadows from objects
- Dimmability
- A visually comfortable lighting system that did not interfere with the visibility of computer screens used for computer aided design (CAD) work
- A decorative appearance that was stylistically acceptable in a home, in the event of selling the house
- A playful luminaire aesthetic that would stimulate creative thought and announce to visitors that this is a lighting design office, inviting attention and comment

Leslie North and her colleague, Ashley Mikels, selected the Trilia™ system because of its design flexibility. Trilia™ assemblies are available in linear sections of eight 100 mm by 100 mm (4 in. by 4 in.) OLED panels each (one driver per assembly drawing an estimated 13.13 W), and triangular assemblies that use 24 panels each (two drivers per assembly, drawing an estimated 38.09 W). The panels can be assembled in multiple ways to produce unique patterns. The individual OLED panels are designed to deliver about 70 lumens, with a diffuse light distribution and a luminance of 3000 candelas per square meter (cd/m^2). The system uses four triangular sections and three straight sections for a total of 120 OLED panels. The designers ran workplane lighting calculations using the manufacturer's photometric files, using a light loss factor of 0.85. See Figure 3.

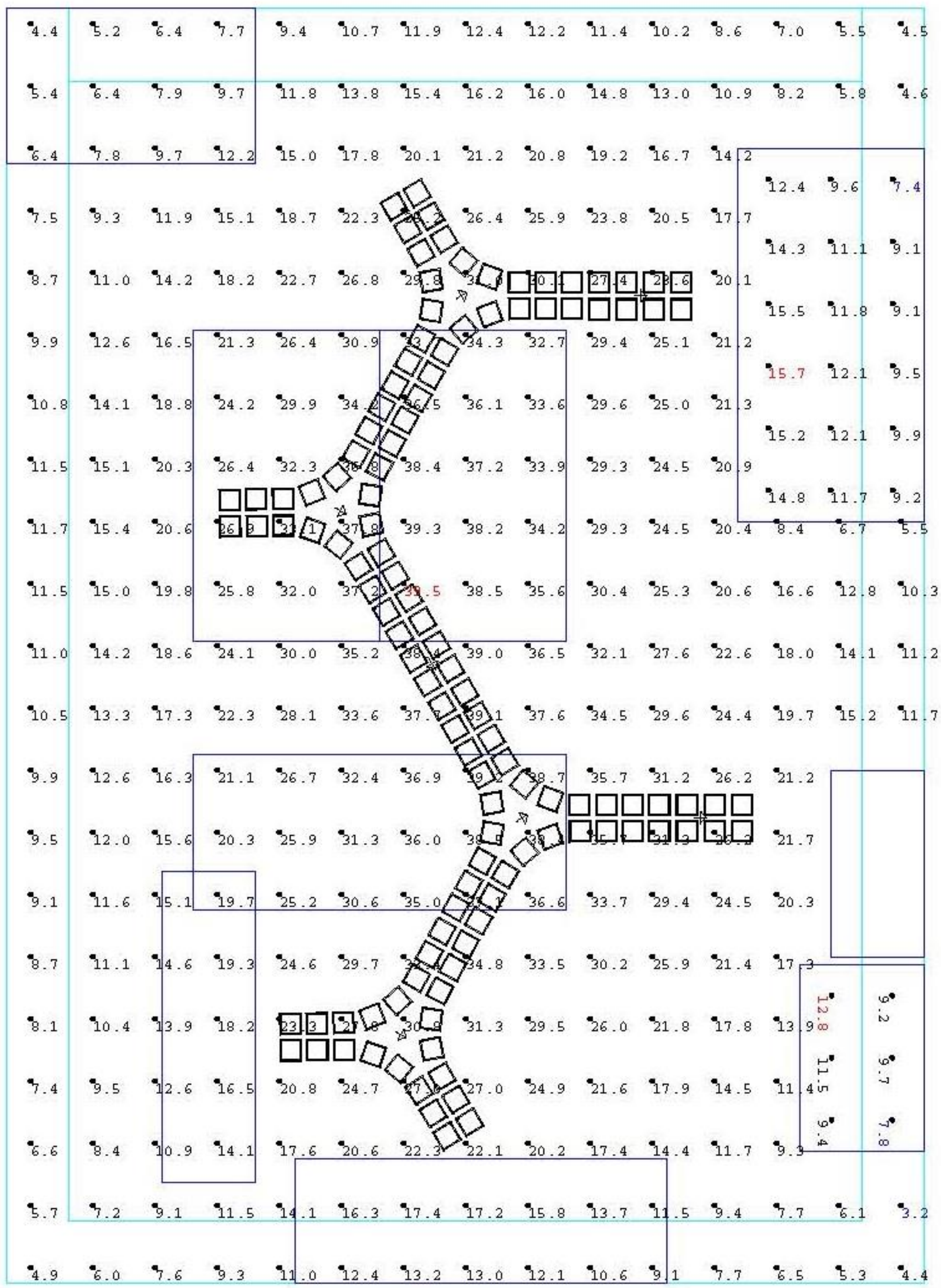


Figure 3. OLED system layout showing the calculated 30-in. workplane illuminances, using AGI32 software. Furniture locations are shown as rectangles and are approximate. Values are in footcandles. (Multiply by 10.76 for lux.) Calculation points are 1 ft on center. The light loss factor applied in the calculation was 0.85. The two areas with offset grids are calculated at a 3 ft 0 in. drafting table height. (Calculation: Aurora Lighting Design, Inc.)

The drivers supplied were intended to be identical, the Optotronic OT25W/4x150C/UNV/DIM from Osram. At 120 VAC input, this driver is listed with power factor > 0.9, total harmonic distortion < 20%, and is capable of delivering a constant 150 mA current output on four independent channels with a voltage range capability of 10 to 40 volts. In total, the driver is able to deliver 25 W of power and dim to a 10% minimum light output with a 0-10 V dimmer. Designed as an LED driver, it was adopted for use with OLED panels.

A Lutron "Diva" DVTV preset 0-10 V dimmer with remote power pack was specified to control all panels in the configuration, together (Figure 4).

Figure 4. A 0-10 V dimmer installed to control output of the Trilia OLED system. (Photo: Leslie North.)

2.1 The Installation

The Trilia™ equipment was ordered in July 2014 and delivered to the job site at the end of August 2014. The contractor started the installation soon thereafter. The Trilia™ OLED configuration used three straight assemblies and four triangular assemblies, with each assembly requiring a precise mounting location for feeding the power and control wires, and anchoring the panel support structure to the ceiling. When the electrical contractor arrived, it was clear that the hard ceiling would make it challenging to locate these points. Access holes for feeding wires were cut into the gypsum wallboard between joists, and the mounting points carefully calculated and marked on a CAD drawing, then transferred to the ceiling. Once the feed wires were pulled through the ceiling at the mounting locations, another layer of gypsum wallboard was applied to the ceiling for a smooth, clean appearance (Figure 5).

The system was designed to use 11 drivers, which were mounted remotely in an adjacent storage space because they were too large to be integral to the luminaire, and the inaccessible ceiling made it difficult to mount them above the ceiling. The drivers were mounted in individual boxes on the wall dividing the office from the storage space, and the wires, three per straight assembly and 8 per triangular assembly (41 wires in all), were fished through, above the ceiling, to the feed points for the drivers (Figure 6).

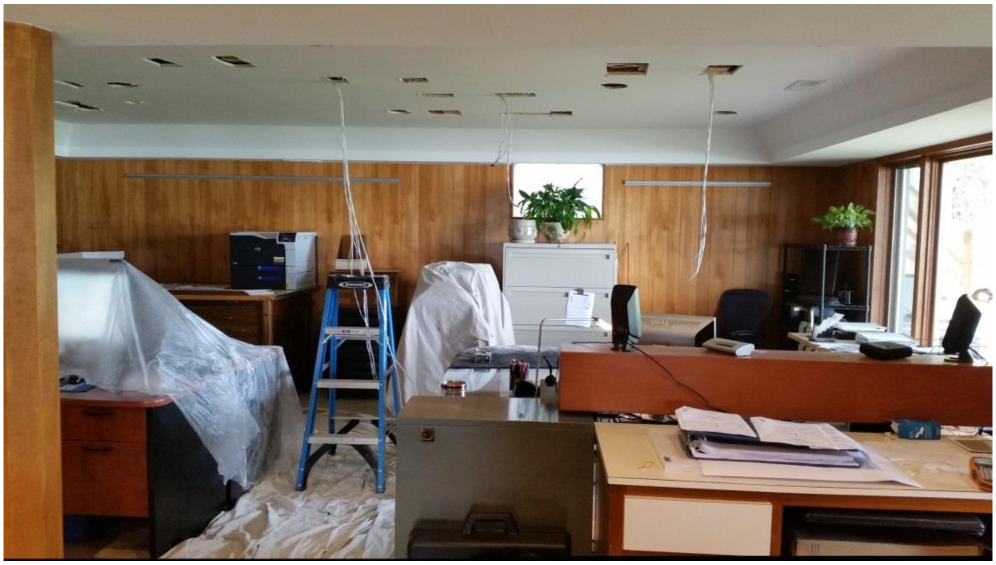


Figure 5. Office ceiling during construction, showing holes for fishing wires as well as precise mounting locations for the Trilia™ sections. (Photo: Leslie North.)

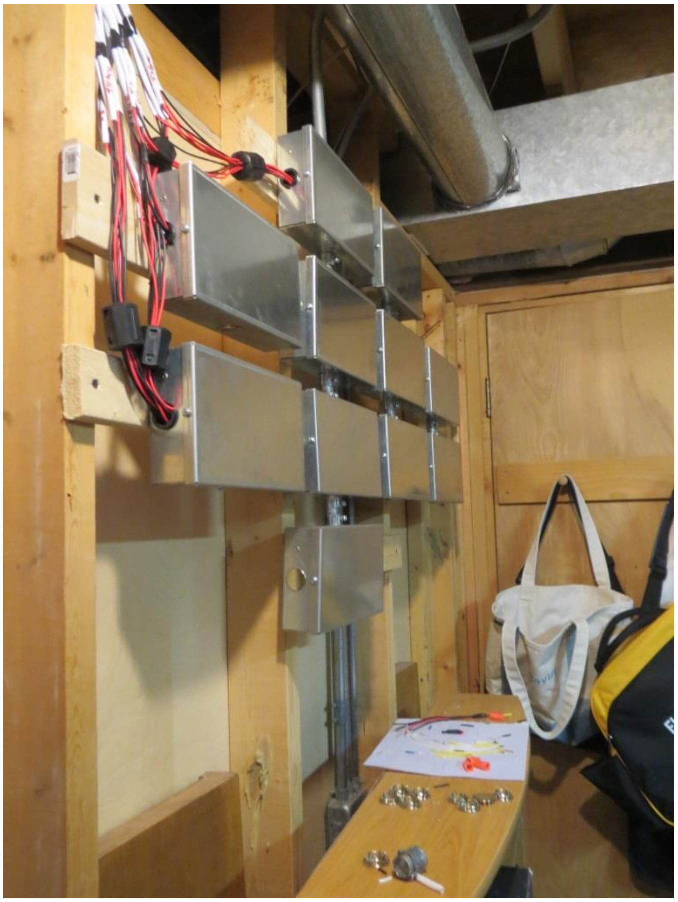


Figure 6. Eleven driver boxes, installed on wall separating the office from the storage room. (Photo: Leslie North.)

The installation was time-consuming because the contractor had not installed such a system before, and because of the high level of precision required to locate mounting points in a limited-access ceiling, and the complexity of the wiring between the panel sections and the many drivers. A lot of extra work went into patching holes and pulling wire, an issue that needs to be resolved whenever a luminaire has a remote power supply, whether the light source is fluorescent, LED, or OLED.

Installation was complete and the system was operational on September 21, 2014. Within the first four months of operation, three field issues developed:

1. On November 17, 2014, half the panels in a triangular section (12 panels out of 24) failed to light, indicating a probable driver failure. A replacement driver was shipped from the factory, and because the driver boxes were clearly labeled, an electrician was able to make the change three days later, resolving the problem (Figure 7).

2. On January 19, 2015, one OLED panel failed to light (Figure 8). It also exhibited a dark spot, indicating a shorting defect in the panel, believed to be related to the introduction of unwanted particles during panel manufacturing. Acuity Brands quickly shipped a replacement panel along with video instructions for Aurora Lighting Design, Inc. to make the replacement themselves. The OLED panel is sensitive to static electricity and to treatment that could compromise the panel's sealed edge, so it required special gloved handling.

3. The staff noticed a photometric flicker from the OLED system when operated at less than full output. Using a simple flicker detection method (a spinning flicker top), they determined that some flicker was present, possibly because the driver was using pulse width modulation to reduce the light output from the OLED panels (Figure 9). This problem could not be easily fixed, and the staff decided they could tolerate this shortcoming since none of them had noticed any personal adverse health effects (headaches, visual fatigue, etc.). When asked about this issue, Acuity Brands said that they had measured flicker for this product using a VISO Systems Flicker Checker Phone App, showing 3% flicker at 47 Hz at full output, 77% flicker at 261 Hz at 80% output, and 100% flicker at 261 Hz at 50% output. Although these values should be considered provisional because the instrument used was not calibrated, they suggest that the flicker could be noticeable to some observers at 80% and 50% light output.[1]

[1] JD Bullough et al., Detection and acceptability of stroboscopic effect from flicker, *Lighting Research and Technology*, October 2011.

Figure 7. Failure of half the panels in the 24-panel triangular assembly, indicating one of the two drivers for this assembly had failed. (Photo: Leslie North.)

Figure 8. Failed OLED panel, showing dark spot in upper right corner that indicates a shorting defect in the OLED material. (Photo: Leslie North.)

Figure 9. Flicker top showing “spokes” that indicate some level of flicker (stroboscopic effect) from the OLED and driver system dimmed with the 0-10 V dimmer. (Photo: Leslie North.)

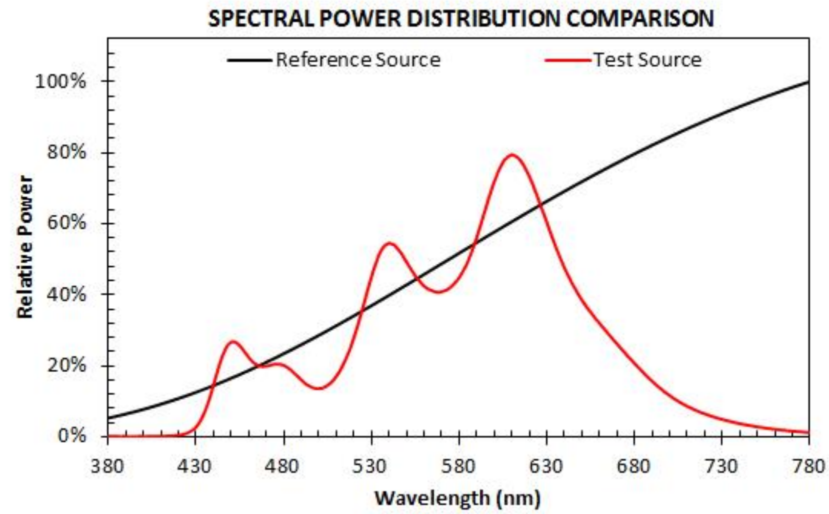
2.2 Reaction from Office Occupants

The staff of Aurora Lighting Design, Inc. was very pleased with the finished appearance and function of the OLED system. They made positive descriptive comments about the lighting, such as “soft,” “inspiring,” “desirable uniformity of light for the office, especially when compared to the recessed downlights,” and “visitors are intrigued by the Trilia™ appearance and ask to touch the panels.” They also noted that using 100% OLED lighting would not produce an “exciting” space, probably because of the diffuse nature of the lighting, which produces little shadowing or highlights. It provides a comfortable ambient layer of light, but needs to be supplemented with task and accent lighting for some lively visual highlights.

When working at night, they routinely used the system dimmed down to 50-60% of full output and raise it to 80% of full output at dusk hours and heavily overcast days. In fact, they reported that at full output, the exposed OLED panels were somewhat uncomfortably bright.

Staff greatly appreciated the color quality of the OLED system. Based on the spectral power distribution (SPD) file provided for the LG OLED panels used in the Trilia™ system, the color metrics are 2974 K CCT with a D_{uv} of 0.0019; and CRI (R_a) of 89 with an R_9 of 29. Referencing the new IES TM-30-2015 color metrics, the panels have an R_f (fidelity) index of 86 and R_g (gamut) index of 98. (The gamut value of 98 indicates a slight reduction in average color saturation compared to the reference source, with 100 indicating the test and reference source are identical in gamut.) See Figure 10 for color metrics and TM-30 graphics.

R_f	**86**
R_g	**98**
CCT (K)	2974
D_{uv}	0.0019
x	0.4417
y	0.4105
CIE R_a	89



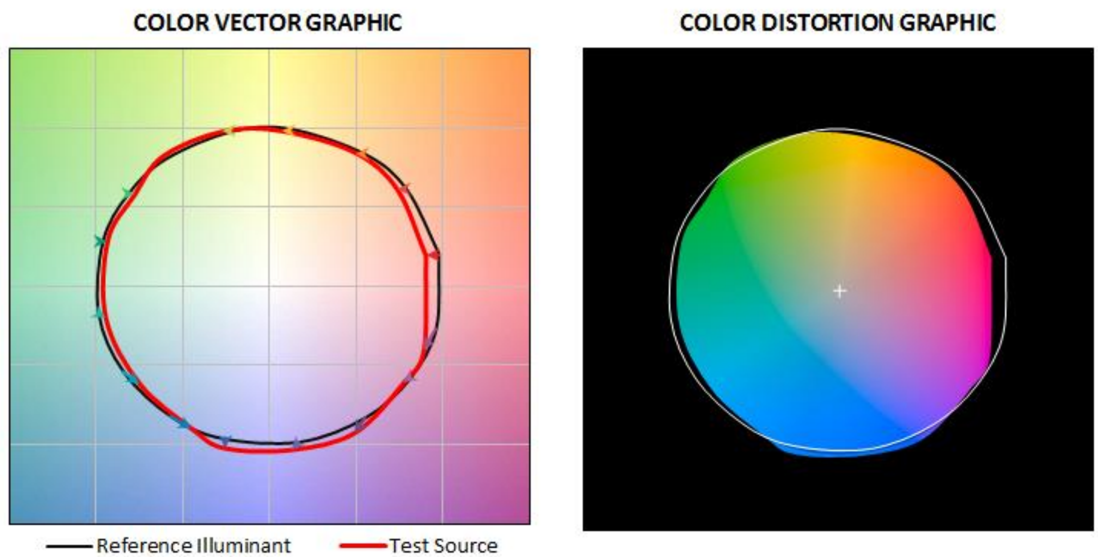


Figure 10. SPD, color metrics, and color rendering graphics for the 3000 K OLED panels.

OLED panels produce a soft, almost spherical, light pattern, technically called a cosine distribution because the candela values, outlined by the circle of light emitted from the origin of the polar plot, can be described as the nadir intensity multiplied by the cosine of the angle from nadir.[1] The cosine distribution (Figure 11) gives the panel the same luminance from all viewing angles up to 90º. That luminance could result in the perception of glare, especially when viewed from angles of 60º to 90º from the luminaire's nadir. During an interview, the designers of the Trilia™ product commented that they specifically kept the panel luminances below 3000 cd/m^2 to avoid that issue.

[1] A cosine distribution is one where the intensity at 5° from nadir is the nadir intensity multiplied by the cosine of 5°, the intensity at 10° from nadir is the nadir intensity multiplied by the cosine of 10°, etc. This appears as a circle on a polar plot, drawn from the origin. By definition, the luminance of the evenly lit surface at any viewing angle below 90° is identical, and only small variations from this value are expected from field measurements.

The cosine distribution of light also produces relatively high vertical illuminances on walls and faces in a space, and reduces the sharpness of projected shadows from objects, much like the effect from indirect lighting.

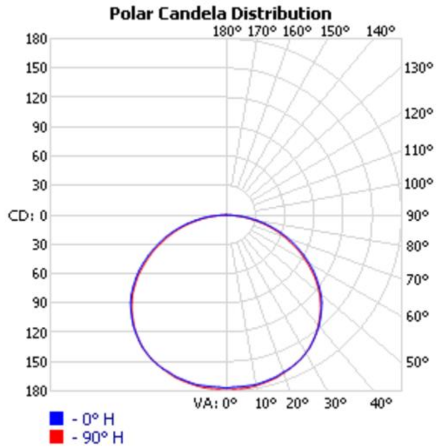


Figure 11. Polar plot of the photometric distribution from an eight-panel straight assembly of the Acuity Trilia™ OLED lighting system. The blue and red lines represent the 0° and 90° measurement planes, and are nearly identical. (Source: Acuity Brands' Winona® Lighting, Test Report LTL25137.)

When asked about reflections on computer screens from the OLED system, none of the staff had noticed any problems. This is likely in part because the vertical computer screens face away from the OLED panels, and in the few places where the panels are visible in the screen, the low panel luminance renders the reflected panel image indistinctly low in contrast.

3.0 Field Measurements

On December 7, 2015, Pacific Northwest National Laboratory supervised the use of a simple power measurement device (newly purchased Klein Tools 400A AC/DC TRMS Clamp Meter, CL-2000) to determine the OLED configuration power draw. In addition, spot horizontal illuminance values were measured as close to the 30-in. workplane height as possible without disturbing the working office. A few vertical illuminances were also collected to assess how the OLED Trilia™ system delivers light to walls, bookshelves, and faces, also using a Konica-Minolta T-10A illuminance meter (calibration date 5/4/2015). In addition, individual OLED panel luminances were measured using a Minolta LS-110 1/3° luminance meter (calibration date 10/6/2014). Measurements were completed after 4:45 p.m. to minimize any contribution of daylight.

4.0 Results

The measurements pointed to some differences between the actual values and the expected performance values in horizontal illuminance, panel luminance, and power measurements.

4.1 Illuminance

Illuminances were measured with the OLED configuration at full output, with no contribution from daylight, task lighting, or lighting contribution from adjacent spaces, at a 30-in. workplane height where possible, and at a 3- or 4-ft height where necessary to accommodate furniture in place. Field measurements were not taken on a strict grid because of furniture, computer screens, resource materials, and other impediments that are common in working offices, so these measurements should be considered less rigorous than those from more highly controlled field studies. However, when the illuminances (in lux, shown in blue in Figure 12) were compared with AGI32 calculations performed during the design stages (shown in Figure 3, in footcandles, multiply by 10.76 to convert to lux), it was clear that measured light levels near the center of the room were 20% to 65% higher than calculated. This difference is greater than the 18% over-lighting that the 0.85 light loss factor would have predicted, had there been no decline in light output in the 15 months since the system's installation.

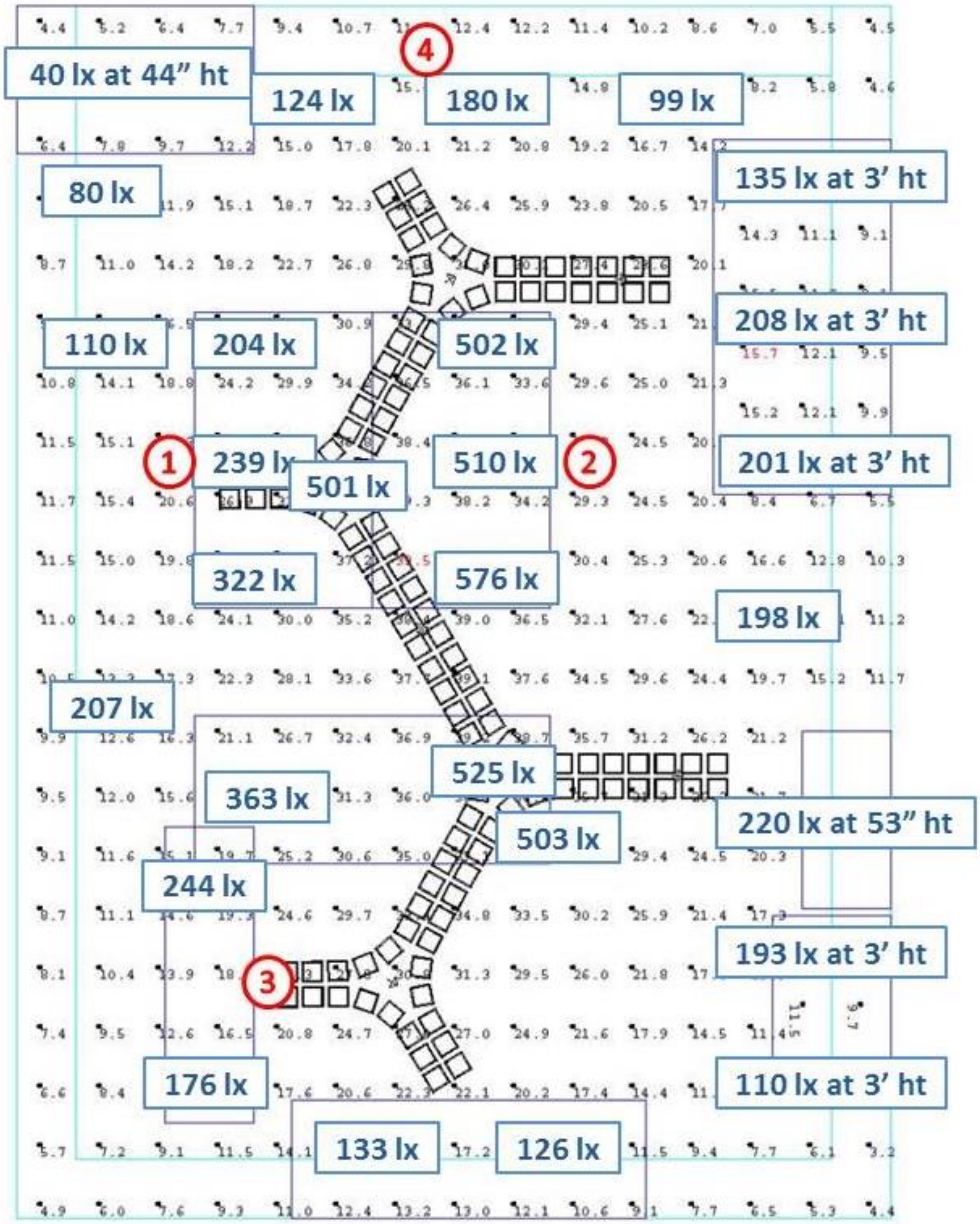


Figure 12. Illuminances in lux, shown in blue, measured in the Aurora Lighting Design offices. These are superimposed on Figure 3's original calculated illuminances in footcandles (multiply by 10.76 to convert to lux). All are measured on a 30-in. workplane height unless otherwise noted. Measurement points are immediately beneath each illuminance value. Red circled numerals indicate vertical illuminance measurement points; see accompanying text.

One advantage of OLED panels' relatively low-luminance, soft, cosine distribution of light (see photometric distribution polar plot, Figure 11) is a very softly lit environment, with gradual transitions between horizontal and vertical surface lighting and no sharp shadows. Another is relatively high vertical illuminances that can contribute to visibility of faces, walls, and bookcases. Vertical illuminances were measured at 4 ft above the floor at the desk locations, in the direction an occupant would be facing, and ranged from 251 lx at the desk chair at location 1 (noted in the red circle in Figure 12) to 354 lx at location 2, the second desk chair in the center of the space. These values are at least 65% of the horizontal illuminance value at the desk at the same location, much higher than typically found with a more directional lighting system such as downlights, suggesting that faces would be easy to see. This may contribute to comfortable communication in the office. The vertical illuminance was 65 lx at the third chair location, where the desk occupant faced away from the lighting system and there was no nearby wall to reflect light toward the face. This lower value is approximately 30% of the horizontal illuminance at that desk location. Location 4 is where vertical readings were taken at a set of recessed bookshelves, 112 lx at a 3-ft height, 286 lx at 4 ft 6 in., and 54 lx at 6 ft.

For comparison, calculations of the previous downlight installation using 20 W PAR38 LED lamps, show corresponding light levels that range from 26 lx to 2087 lx on the workplane (2.4 fc to 194 fc) with a more than 20 to 1 maximum to minimum ratio between illuminance measured directly beneath come downlights and the point between downlights; with facial vertical illuminances of 57, 143, and 37 lux, respectively, at the three desk locations; and very low bookcase wall illuminances ranging from 17 to 37 lx. The calculations are shown in Appendix A and summarized in Table 1.

4.2 Luminance of OLED Panels

Six panels were randomly selected for luminance measurements. First, measurements were taken on site to determine how sensitive these measurements would be to measurement angle. No tested panel exhibited more than a 50 cd/m^2 (2%) difference between a luminance measurement from nadir up to 45° from nadir, as would be expected from a light source delivering a cosine distribution. Luminance measurements were first taken of the ceiling (20 cd/m^2), and then of six panels, with luminances of 2625, 2716, 2760, 3735, 3881, and 3908 cd/m^2. The three lower measurements were as expected, but the three higher measurements were a surprise, given that one goal of the Acuity Brands OLED product line was to keep panel luminances at or below 3000 cd/m^2. In spite of a 49% increase between the lowest luminance reading and the highest, Aurora Lighting Design staff did not perceive a dramatic difference in brightness among the panels, probably because at no point could they compare the different panels side by side.

4.3 Power and Lighting Power Density

The circuit feeding the Trilia™ system was measured for current (2.05 A) and voltage (120.8 V) for a total of 247.6 volt-amps. The datasheet for the Osram Optotronic OT25W/4x150C/UNV/DIM driver shows a power factor no lower than 0.968 when operated between 4 and 25 W. Assuming the panels are operated within this range, the power draw at full output is no lower than 240 W. This value seemed 25% too high given that the system was expected to draw about 192 W, per the manufacturer's literature and calculations.

The lighting power density (LPD) for the office area from the connected load of the OLED system is 0.79 W/ft^2. For energy code compliance, Aurora Lighting Design's task lighting (six luminaires at 9 W each) would add 0.18 W to the total, for a combined LPD of 0.97 W/ft^2. For reference, ASHRAE/IES Standard 90.1-2013 lists the maximum LPD for open offices, using the space-by-space method, as 0.98 W/ft^2.

For comparison, the previous lighting system of eight recessed medium-base downlights with nominal 20 W PAR38 LED 25º lamps (19.5 W actual), drew slightly less power at 156W at full output. However, it proved to be unsatisfactory because it produced high-contrast puddles of light and harsh highlight-and-shadow patterns on faces. Similarly, the downlights had been lamped with 26 W CFL PAR38 screwbase lamps when the office first occupied the space, drawing 208 W total. That solution was disliked because of long warm-up time, low illuminance levels, and poor color. See Table 1.

Table 1. Details of OLED lighting system installed at Aurora Lighting Design, Inc. Room size is 14 ft 9 in. x 20 ft 6 in. x 7 ft 5 in. Illuminances in lux (lx) were measured. For comparison, the table includes calculated data on the previous PAR38 LED downlight layout, as well as for the same downlight equipped with compact fluorescent lamps (CFL). Details of the final installation, based on spot measurements taken after the incorrect drivers were replaced in February 2016, are noted in the last row.

Lighting description	Total estimated lumens	Power	Ltg. Power Density (LPD)	Illum. Horiz.	Illum. Vert.	Color Metrics
120 OLED panels in configuration, 11 drivers, including two incorrect drivers as originally installed	8518 at full output, based on Acuity photo reports. (Likely higher with incorrect drivers installed.)	240 W	0.79 W/ft^2	269 lx (avg. of points measured at 30” ht. 80 lx min to 576 lx max)	223 lx avg. on faces; 54 to 286 lx on bookcase wall	2974 K CCT D_{uv} 0.0019 CRI (R_a) 89 R_9 29 R_f 86 R_g 98
8 downlights with PAR38 LED 25º at 19.5 W, 1050 lumens each, based on GE Lighting lamp listing	8400 initial lamp lumens at full output, based on mfr. listing	156 W	0.52 W/ft^2	291 lx avg. (26 lx min to 2087 lx max; calc’d at 30” ht.)	78 lx avg. on faces; 17 to 37 lx on bookcase wall	3000 K CCT D_{uv} 0.0019 CRI (R_a) 80+, based on mfr. listing
8 downlights with 26W CFL PAR38 screwbase lamp	10,400 initial lamp lumens (approx.)	208 W	0.69 W/ft^2	N/A	N/A	2700 K CCT 82 CRI (approx.)
120 OLED panels in configuration, 11 drivers, including corrected drivers as installed in February 2016	8518 at full output, based on Acuity photo reports	189 W	0.62 W/ft^2	115 lx min to 506 lx max, measured at a limited number of points; see Section 4.5	169 lx avg. on faces	2974 K CCT D_{uv} 0.0019 CRI (R_a) 89 R_9 29 R_f 86 R_g 98

CCT is correlated color temperature; CFL is compact fluorescent lamp; CRI is color rendering index; R_9 is specific color rendering index of red color sample; R_f and R_g are IES TM-30-2015 fidelity index and gamut index, respectively.

4.4 Resolving the Discrepancies

The illuminance, luminance, and power measurements all produced higher values than expected in some locations, so members of the Acuity Brands Horizon Group who were responsible for the design of this OLED system were contacted to find out why. The best explanation was a mismatch between the specified drivers and the installed drivers, and Aurora Lighting Design agreed to open the driver boxes to check the drivers. Of 11 drivers, nine were the specified Osram Optotronic OT25W series drivers, but two were an OT35W series driver, which is designed to provide 220 mA of current and 35 W of power rather than 150 mA of current and 25 W of power. While the higher-current drivers probably explain the elevated illuminance, some higher panel luminances, and power readings noted, it is not known whether the higher wattage operation of some OLED panels in the configuration would ultimately lead to faster lumen depreciation or to shorter panel life.

This unexpected higher OLED panel luminance may explain why the Aurora Lighting Design staff prefers the system dimmed, even when daylight is not available. Panels at the higher light output level may have exceeded the threshold of visual comfort for exposed luminous surfaces.

4.5 The Final OLED Installation with Corrected Drivers

Acuity Brands immediately shipped out proper replacement drivers once the issue was identified, and these were installed in February 2016. Aurora Lighting Design performed spot illuminance measurements at night on March 25, 2016 using their Konica Minolta T-10 meter (S/N 39521062, calibrated October 2015) in slow setting mode, with the Trilia system at full output. At the subset of points measured, horizontal illuminances showed an average reduction of approximately 10%, and vertical illuminances showed a 24% reduction (248 lx, 203 lx, and 57 lx at locations 1, 2, and 3, respectively). See Figure 13. Furthermore, power measurements using the same meter used by PNNL in December 2015 showed 122.9 V and 1.59 A, yielding a power draw of 189 W with an assumed power factor of 0.968. All of these are much closer to the expected values.

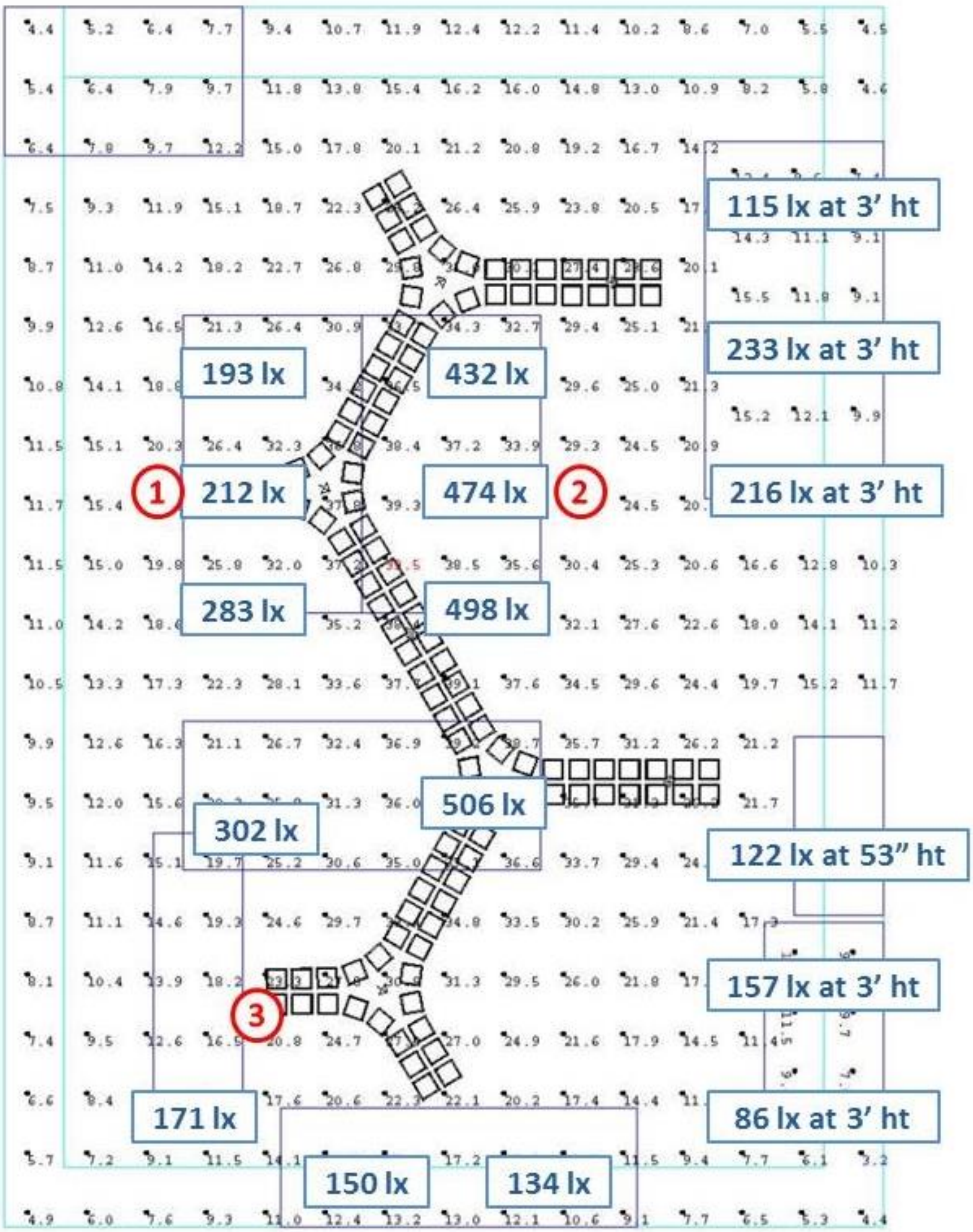


Figure 13. Spot check of illuminances in lux, shown in blue, measured in the Aurora Lighting Design, Inc. offices after the driver correction. These are superimposed on Figure 3's original calculated illuminances in footcandles (multiply by 10.76 to convert to lux). All are measured on a 30-in. workplane height unless otherwise noted. Measurement points are immediately beneath each illuminance value. Red circled numerals indicate vertical illuminance measurement points; see accompanying text.

5.0 Costs

The economics of the OLED installation at Aurora Lighting Design, Inc. are challenging. At full retail cost, the OLED Trilia™ system would have been prohibitively expensive. The cost details are confidential, but the donation of the OLED lighting system made this installation viable, since the lighting design firm only needed to pay for installation, which cost more than it would in typical commercial construction because the ceiling was inaccessible.

6.0 Conclusions

6.1 Summary

Aurora Lighting Design, Inc. boldly specified OLED lighting for their office ambient lighting system, knowing that a new lighting technology always comes with some bumpy experiences for the companies that develop the technology, the manufacturers that integrate the technology into working luminaires, the contractors who deal with unfamiliar wiring and mounting methods, and the end-users who live and work under the system for 8+ hours per day, and deal with maintaining the system over time. This installation was successful in the following respects:

- The appearance of the lighting system expresses creativity and innovation, making a statement to Aurora Lighting Design clients who visit the offices.
- The system's shallow profile works well with the low-ceiling residential space, and the warm 3000 K color temperature is appropriate for this residential office. The color quality is very high, with a CRI of 89, R_9 of 29; R_f of 86, R_g of 98.
- The system is dimmable, enabling Aurora Lighting Design to save energy, reduce output and potential visual discomfort when lower illuminances are preferred, and use daylight as the prominent light source.
- The exposed OLED panels deliver a soft, minimal-shadow lighting that makes faces and expressions visible, and increases room brightness by delivering light to vertical surfaces. When the surface luminance is controlled, this is achieved with no increase in glare.
- Lighting energy use for the ambient OLED system is moderate, at 0.62 W/ft^2 when operated at full output with the corrected drivers.
- The staff of Aurora Lighting Design enjoys working under the system, and uses it in a dimmed state most of the time.

The installation was complicated in the following respects:

- The mounting and wiring details were unfamiliar to the electrical contractor, and required pulling large numbers of driver wires through a hard (gypsum wallboard) ceiling, to multiple mounting points. The access holes couldn't be easily patched, necessitating a new layer of wallboard on the ceiling.
- Eleven separate remote drivers were needed to power this relatively small system. Their size necessitated mounting the drivers in the next room.

- The system dims smoothly with a 0-10 V dimmer, but dimming introduces flicker. This may only be an issue for very sensitive occupants and visitors, since the flicker frequency appears to be well above 120 Hz.
- Within four months of operation, one OLED panel and one driver had failed. Replacement parts were promptly shipped by the luminaire manufacturer and changed out with little frustration. An electrician replaced the driver, and Aurora Lighting Design replaced the panel themselves.
- Two incorrect drivers were shipped from the factory, which was the cause of higher-than-expected power draw, higher luminances in some OLED panels, and workplane illuminances that were 20% to 65% higher than originally calculated. Replacing these drivers brought the performance into the expected range.

6.2 The Future of OLEDs

The OLED installation at Aurora Lighting Design, Inc. is an important demonstration of the potential performance of OLED panels. The panel technology itself is maturing, and problems such as shorting defects are already being solved with new panel architectures. The system that was installed in September 2014 represents the state-of-the-art of the technology at that time, with a system efficacy around 46 lumens per watt (LPW). Two manufacturers have promised 80-LPW OLED panels for delivery in 2016, and higher efficacies soon afterward.

However, panel efficacy is only part of the story of OLED systems. One frustration of luminaire manufacturers is that there are no dedicated OLED drivers on the market as of this writing because the total demand in the architectural market is low. Instead, manufacturers have to work with LED drivers, customizing them as best they can to deliver the current and voltages needed, which are often outside the optimized efficiency range of the driver. This makes the driver a weak point in the system efficacy.

The OLED panels are thin and light, and deliver a unique quality of light. However, the drivers are still relatively large and brick-like. They do not fit gracefully into the OLED luminaires or mounting canopies, so they must be mounted remotely. That creates extra work for the designer and contractor to find an accessible location hidden from normal view where drivers can be located in compliance with the electrical code. If OLEDs are to fulfill their promise, driver elements will need to be integrated sleekly and discreetly into the luminaire or mounting elements.

The flicker from OLEDs is a function of the driver, just as it is for LEDs. Like many performance aspects, e.g. dimming, it may be compounded by the fact that the driver, designed for LEDs, may be operating outside of its optimal operating area. This can be corrected by driver manufacturers with an improved electronic circuit design. Acuity Brands has already been converting its OLED product line to a different brand of programmable driver that will have current ranges appropriate for the OLEDs, with improved dimming performance and dramatically higher light modulation frequency to eliminate flicker complaints.

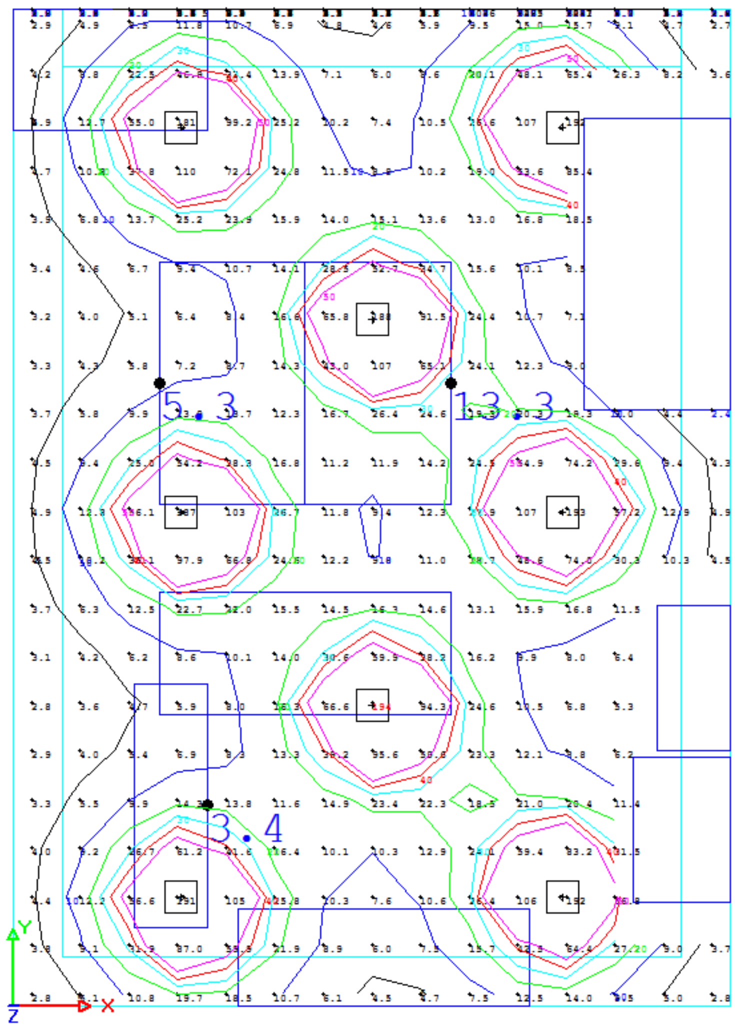
For full viability of OLED architectural lighting, the systems will need to deliver higher efficacy, better system components, and lower costs. OLEDs are in their infancy compared to LEDs, but the architectural market is taking notice of a lighting product with an entirely different look and function. If

OLEDs continue to increase in efficacy, longevity, size, and flexibility, designers and engineers will have a new tool for creative and effective lighting.

Appendix A

Calculations of the Previous Downlight Installation

The following shows the lighting calculation of the Aurora Lighting Design, Inc. office with the previous installation of recessed medium-based downlights, equipped with 20 W PAR38 LED 25º narrow flood lamps. Values are in footcandles (multiply by 10.76 for lux), calculated with a light loss factor of 0.85. Black dots with blue text indicate locations where vertical illuminances on faces were calculated.



Luminaire Schedule						
Symbol	Qty	Label	Total Lamp Lumens	LLF	Description	Lum. Watts
	8	GE_LED20P38S83025_fixed	1109.8	0.850	LED Downlights	19.5

Calculation Summary									
Label	CalcType	Units	Avg	Max	Min	Avg/Min	Max/Min	Grid Z
Room_Wall_3	Illuminance	Fc	3.55	14.7	0.0	N.A.	N.A.	0.71
Room_Workplane_1	Illuminance	Fc	27.04	194	2.4	11.27	80.71	2.5
Vertical 1	Illuminance	Fc	5.30	5.3	5.3	1.00	1.00	N.A
Vertical 2	Illuminance	Fc	13.30	13.3	13.3	N.A.	N.A.	N.A
Vertical 3	Illuminance	Fc	3.40	3.4	3.4	N.A.	N.A.	N.A