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CALiPER

Report 24:

Photometric Testing, Laboratory Teardowns, and Accelerated Lifetime Testing of OLED Luminaires

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Prepared by:

Pacific Northwest National
Laboratory

CALiPER

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Photometric Testing, Laboratory Teardowns, and Accelerated Lifetime Testing of OLED Luminaires

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1 Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER typically relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[4]) conducted by accredited, independent laboratories.[5] However, in the case of Organic Light-Emitting Diode (OLED) lighting, there are no industry consensus standards. As a starting point, CALiPER pursued photometric testing following the conventions established by IES LM-79-08. Results from this CALiPER testing are available to the public through summary reports, which assemble data from several product tests and provide comparative analyses.[6] Any insight gained from CALiPER investigations are contributed to new test procedures that are not industry standards; investigations using these procedures provide data that is essential for understanding the most current issues facing the SSL industry.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's website at the time of purchase.

CALiPER normally purchases products through standard distribution channels, acting in a manner similar to that of a typical specifier. CALiPER cannot control for the age of products in the distribution system, nor account for any differences in products that carry the same model number.

Selecting, purchasing, documenting, and testing products can take considerable time. Some products described in CALiPER reports may no longer be sold or may have been updated since the time of purchase. However, each CALiPER dataset represents a snapshot of product performance at a given time, with comparisons only between products that were available at the same time. Further, CALiPER reports seek to investigate market trends and performance relative to benchmarks, rather than to serve as a measure of the suitability of any specific lamp model. Thus, the results should not be taken as a verdict on any product line or manufacturer. Especially given the rapid development cycle for OLED products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products.

CALiPER tries to purchase conventional (i.e., non-SSL) products for comparison, but the unique form factor of OLED panels is such that there are no directly comparable benchmarks.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, photometric testing alone is not enough to fully characterize a product—quality, reliability, controllability,

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[4] IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.ies.org/.

[5] CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, which is available through the National Voluntary Laboratory Accreditation Program (NVLAP).

[6] CALiPER summary reports are available at http://energy.gov/eere/ssl/caliper-application-reports. Detailed test reports for individual products can be obtained from http://www1.eere.energy.gov/buildings/ssl/caliper/default.aspx.

physical attributes, warranty, compatibility, and many other facets should also be considered carefully. In the end, the best product is the one that best meets the needs of the specific application.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

2 Report Summary, with Supplement August 2017

This report documents an initial investigation of OLED luminaires and summarizes the key features of those products. In addition to photometric testing of four commercial products in independent laboratories, PNNL examined many of the products through teardown testing (disassemblies to identify parts and functionality) in PNNL laboratories. Results of these tests as well as results of stress testing of several OLED luminaires at RTI International have been included.

OLEDs are a solid-state lighting product new to the architectural lighting marketplace. Although IES LM-79-08 protocols were followed in the CALiPER goniophotometer and integrating sphere testing, LM-79-08 was developed for LEDs, and may need to be modified for accurate and consistent testing of OLEDs. There are also no established testing protocols equivalent to IES LM-80-15 and IES TM-21-11 for estimating panel lumen maintenance and life, so it is difficult to compare published life estimates from manufacturers.

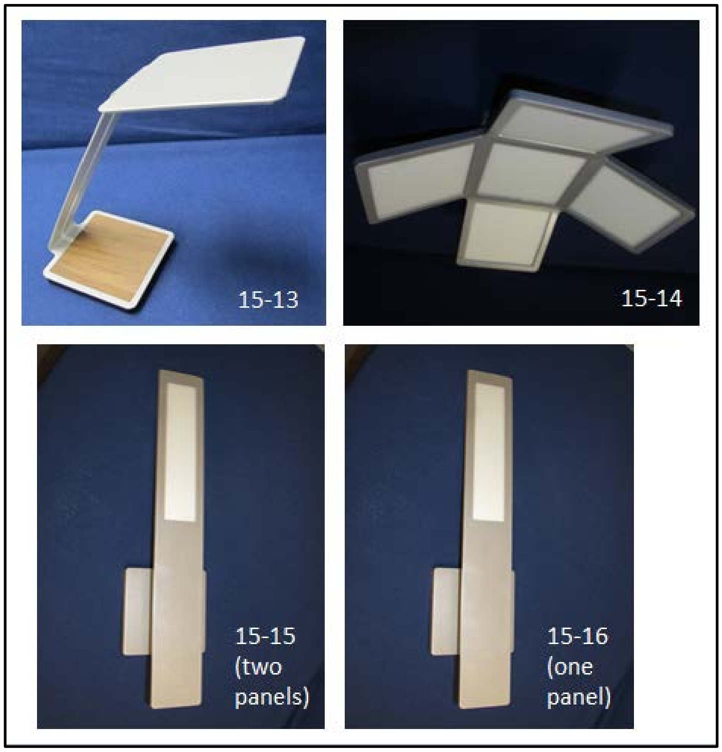

Figure 1. OLED luminaires tested for this CALiPER report.

Overall, efficacy of the tested OLED luminaires was low compared to contemporary LED luminaires, ranging from 23 lm/W up to 45 lm/W. OLED panels themselves range between 42 and 55 lm/W according to panel manufacturer data, and much of the efficacy reduction in the luminaire performance is due to very inefficient transformer and driver selections and combinations. The wider availability of dedicated OLED drivers should improve efficacies in the near future.

Color quality of the OLED luminaires depends on the panels used. One of the CALiPER products used OLEDWorks panels, with color quality metrics that are somewhat lower than those of the LG Display panels used in the other procured OLED products. The CCT of both sets of panels was about 2900 K, although the nominal CCT for the LG panels was 3000 K, according to manufacturer data.

Light distribution was consistent among the tested products. The OLED panels produced a soft diffuse roughly Lambertian distribution of light, moderated only by the physical configuration of the luminaire hardware. This is expected to produce very soft shadows from objects in the path of the light, and patterns of light on surfaces with very soft gradients.

A spectrophotometer gonio test of one pair of CALiPER 15-16 luminaires showed only minor color differences over a full range of viewing angles, likely due to the factory application of the external light extraction (ELE) layer, which unifies the color and luminance appearance of the panel, and raises efficacy by increasing the amount of light exiting the panel.

CALiPER tested one multi-panel product in two orientations and found that whether it was wall-mounted or ceiling-mounted, the lumen output, input power, efficacy, power factor, color characteristics, and THD were within 1% variation. This simplifies photometry and luminaire design considerations for manufacturers.

The CALiPER OLED luminaires performed very closely to the available manufacturers' published technical data.

Teardown testing was done in the PNNL Lighting Metrology Laboratory, in order to examine a failed OLED panel in one of the CALiPER samples, and to examine driver efficiency. In the damaged panel, a compromise in the OLED seal along one edge of the glass was the likely cause of the discoloration. Such a compromise can allow air and moisture to penetrate the panel and interact with the organic layers.

The drivers for all four CALiPER luminaire types were different, with one luminaire type using a single driver, and others using a combination of electronic components for voltage transformation, conversion from AC to DC, and panel voltage/current control. One OLED task luminaire's power electronics were estimated at 80% efficiency, with additional losses likely due to the addition of a cell phone charging circuit. The power control electronics efficiency of a larger 5-panel luminaire was estimated at a respectable 85%. Two wall sconces using one or two OLED panels used tandem drivers, operating at a combined low estimated efficiency of 47% to 58%. The low driver efficiencies are a concern because they directly affect system efficacy.

Accelerated lifetime testing of OLED luminaires performed by RTI International yielded the following results: some failures occurred from degradation due to operations under continuous elevated ambient temperature conditions, at either 45°C and 150 mA, 75°C at 150 mA, 75°C with 75% relative humidity (RH) at 150 mA, or high current operation (200 mA) at 45°C. Several failure modes were observed during this testing including shorting within the panel which significantly decreased panel impedance. Another failure mode was breakage of the small gauge wires between the driver and panel, suggesting that the wiring and connectors may need closer attention.

It became clear over the testing that panels tested under elevated ambient temperature conditions can fail as electrical shorts, allowing multi-panel luminaires to continue operating even when one or two panels have failed. Impedance of failed panels was found to be much lower than that of operational panels, and a close visual inspection revealed that failed panels all had a dark spot indicating a short.

Decay in light output under elevated ambient temperature conditions was steeper than expected at room temperature, with a steady decline over operation. After 4250 hours of continuous operation at 45°C, lumen maintenance averaged 87%. Chromaticity shifted toward blue at a nearly linear rate, possibly explained by a reduction in output from phosphorescent red and green organic layers while the fluorescent blue layer was steady.

High heat at 75° C and high RH (75%) tolled the death knell for OLEDs. However, there is not enough long-term data to know whether this accelerated testing is predictive of OLED long-term performance and failure modes.

OLED panels, drivers and transformers are still in a steep curve of development. Goals are higher efficacy; longer life before panel replacement on the jobsite is needed; better lumen maintenance over time; even better color quality and wider CCT options; higher efficiency drivers; and robustness under high temperature, high humidity, and rough handling from shipping and installation. Improvements in these areas will make OLED luminaires more accepted in the architectural marketplace, and adopted as a trusted lighting solution.

Report Supplement, August 2017

In the fall of 2016, CALiPER tested two samples of two additional OLED luminaires, the Designplan “Blade” luminaire and Visa Lighting Limit™ luminaire (Table 1, Figure 2). Whereas the earlier luminaires tested by CALiPER were acquired through on-line purchases, these supplemental luminaires were acquired as part of a planned GATEWAY evaluation at the DKB Offices in Rochester NY. Like the products covered in the original 2016 CALiPER report, these were tested by an independent testing laboratory, and the results follow.

Table 1. List of OLED luminaires tested by CALiPER in 2015, and in the fall of 2016 (in blue).

DOE CALiPER Test ID	Brand	Model	Test Date
15-13	Aerelight	DS-TL-AAL-72562-81-001857	12/3/2015
15-14 Ceiling	Acuity Brands Lighting	CHALINA-HCWM-OLEDA1-5P-345LM-30K-120-DIM	12/2/2015
15-14 Wall	Acuity Brands Lighting	CHALINA-HCWM-OLEDA1-5P-345LM-30K-120-DIM	12/3/2015
15-15	Acuity Brands Lighting	AEDAN-WM-OLEDR1-2P-140LM-30K-120-DIM-BNP	12/9/2015
15-16	Acuity Brands Lighting	AEDAN-WM-OLEDR1-1P-70LM-30K-120-BNP	12/9/2015
16-17	Visa Lighting	LIMIT-CP5734PSX-L30-24VDC-GSIL-GSIL-DIM10	9/21/2016
16-18	Designplan	BLADE-BL4O430-02B00	10/21/2016

Figure 2. Photos of the two supplementary OLED luminaire types tested. Photos courtesy OLEDWorks Inc. and DeJoy, Knauf, & Blood, LLP.

Table 2. Tested performance characteristics of all report luminaires, with the supplemental OLED luminaires highlighted in blue.

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CRI (R_a)	R_9	R_f	R_g	R_f -- Hue bin 1	$R_{cs,h1}$ Chroma shift, hue bin 1	CCT (K)	D_{uv}	THD (%)
15-13	270	9.6	28	0.45	78	-6	78	95	74	-13%	2952	0.0010	188.1
15-14 Ceiling	332	7.4	45	0.99	88	21	86	97	83	-8%	2946	0.0030	8.6
15-14 Wall	329	7.4	45	0.99	88	20	86	97	83	-9%	2940	0.0030	7.8
15-15	130	4.3	30	0.42	88	21	87	97	83	-8%	2912	0.0020	189.1
15-16	65	2.8	23	0.40	88	21	87	97	83	-8%	2855	0.0030	192.2
16-17	806	27.5	29	1.00	79	1	79	95	75	-12%	2907	-0.0015	n/a
16-18	1,246	54.0	23	0.98	79	-3	78	95	74	-12%	2963	0.0000	8.6

Both of these supplemental luminaire types use OLEDWorks LLC “Brite 1” panels, nominally rated at 300 lumens per 100 mm x 100 mm panel, a luminance of 8300 cd/m^2, efficacy of 41 lm/W, and drawing 7.4 W of power when new. Each panel is paired with a single Philips OLED driver, each having an input requirement of 24VDC. Product 16-18 was similar to the OLED products tested in 2015, in that the manufacturer included a power supply that converts from 120VAC to 24VDC, so the test accounted for power supply losses. The 16-17 products were tested in the laboratory using a regulated power supply to deliver 24VDC to the drivers, so losses from the power supplies normally installed between the normal mains power (120VAC or 277VAC, for example) and the OLED panel drivers are not factored into the 16-17 power and efficacy values listed in Table 2. (Efficiency of the transformer/power supply is expected to be about 85%, resulting in a power and efficacy increase of 17.6% for the complete system compared to what is listed in Table 2 for 16-17.)

Photometrically, the supplementary OLED luminaires produce a similar cosine distribution to the earlier luminaires tested, based on the orientation of the OLED panels in the luminaire. Luminaires 16-17 exhibits an asymmetrical pattern due to the panel orientation, modified slightly by blockage from the undulating housing (Figure 3).

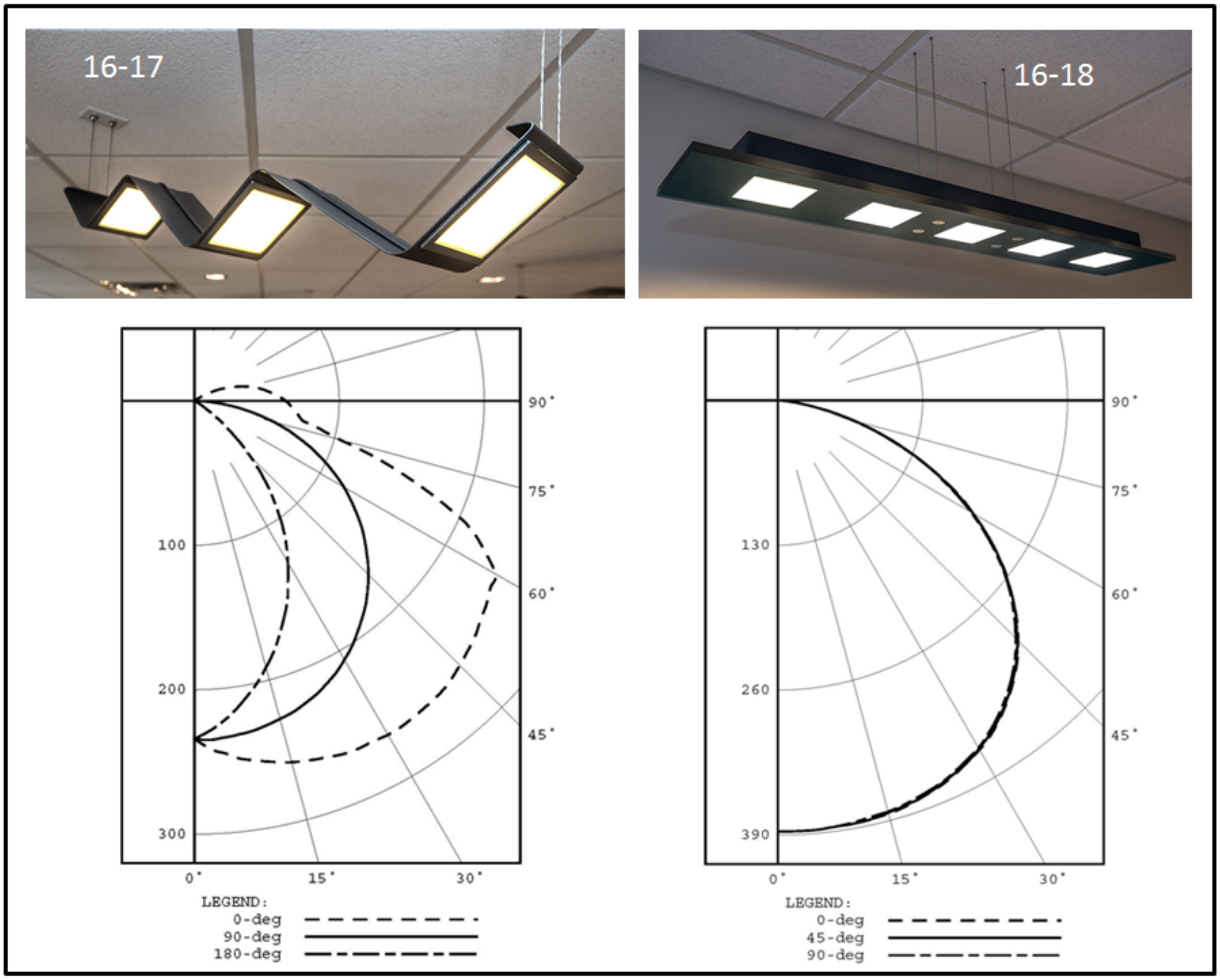

Figure 3. OLED luminaires tested for CALiPER, shown with polar plots showing their photometric distributions. Photos courtesy OLEDWorks Inc. and DeJoy, Knauf, & Blood, LLP.

Unlike the earlier luminaires tested, the performance of these supplemental luminaires as measured through independent laboratory testing varies somewhat from the claims of the manufacturers. (Table 3**.**) The manufacturer's reported input power for CALiPER 16-17 was 27% lower than the tested values (not including losses from the transformer/power supply) and the reported lumen output exceeded the tested values by 5%. In the manufacturer's favor is that the product specification sheet makes it clear to the specifier to anticipate a 25% increase in panel power draw over life.

For CALiPER 16-18, the manufacturer did not specifically list the input power on the specification sheet, but listed (5) 10W OLEDs, which suggests usage power of approximately 50 W. Actual power draw (at 120VAC input power) was 8% higher, at 54.1 W. Manufacturer-reported lumen output was 20% higher than tested values. CCT and CRI (R_a) values reported by the manufacturers were within 4% of tested values except the manufacturer of CALiPER 16-18 claimed 90 CRI (R_a) while the test data show 79 CRI (R_a).

Table 3. Luminaire test data and comparable data from the luminaire manufacturer's literature, with supplementary products highlighted in blue.

	Test Data					**Manufacturer Data**				
DOE CALiPER Test ID	**CCT** (K)	**CRI (R_a)**	**Efficacy** (lm/W)	**Input Power** (W)	**Initial Output** (lm)	**CCT** (K)	**CRI (R_a)**	**Efficacy** (lm/W)	**Input Power** (W)	**Initial Output** (lm)
15-13	2952	78	28	9.6	270	2900	>80	n/a	n/a	n/a
15-14 Ceiling	2946	88	45	7.4	332	3000	88	46	7.4	342
15-14 Wall	2940	88	45	7.4	329	3000	88	46	7.4	342
15-15	2912	88	30	4.3	130	3000	88	31	4.3	135
15-16	2855	88	23	2.8	65	3000	88	24	2.9	69
16-17	2907	79	29	27.5	806	3000	80	n/a	20.0	850
16-18	2963	79	23	54.0	1246	3000	90	n/a	50.0	1500

Independent test results of these two additional commercially-available OLED luminaires show performance has not improved since the testing done on OLED luminaires purchased in 2015. However, a new generation of OLED panels has appeared on the market in mid-2017, with panel efficacies of 60 lm/W, improved color qualities, and increased panel life. It is likely some of the products tested by CALiPER for this report will be available with the higher-performance panels in the near future.

END OF AUGUST 2017 REPORT SUPPLEMENT

3 Background

Organic light-emitting diodes (OLEDs) are solid-state devices that are dramatically different in appearance and lighting performance from light-emitting diodes (LEDs). They are large in surface area, low in luminance, thinner than LEDs, and usually diffuse in appearance. OLED panels are already showing great aesthetic potential, as tiles, as soft panels for lighting faces without glare, and as task lights. The luminaires that incorporate them often take surprising shapes that celebrate the luminous panel rather than concealing it as a mere light source. The United States Department of Energy (DOE) Solid-State Lighting Program sponsors the CALiPER program. This CALiPER report is the first to examine commercially-available OLED luminaires, and will address the issues of testing standards in addition to documenting an initial set of OLED testing results.

There are still few OLED architectural luminaires, but there has been a modest expansion of products in 2015 and 2016, with more luminaire manufacturers designing and marketing dedicated OLED luminaires to both the commercial and residential markets. OLED panels and their drivers are rapidly evolving, and improvement in panel efficiency and life, ease of connection and dimming, and stability in light output and color are expected. Although OLEDs represent a niche market segment today, they may expand into general lighting applications as the issues of cost and durability are overcome. At this point, it is important to understand the tradeoffs, limitations, and issues, so that the industry can work together to maximize the rate of product improvement.

The number of luminaires discussed in the report (four) is limited but is sufficient to cover important variations in product performance, such as two different panel types and three different driver configurations. Laboratory tear-downs (disassemblies to identify parts and functionality) were performed on some of the luminaire components to explore driver efficiencies, electrical characteristics, and one OLED panel failure.

OLED panels

An overview of current and in-development OLED technology is available on the DOE website. Figure 1 illustrates a typical structure of an OLED lighting panel, which includes a substrate on which all layers are coated, a cover glass or metal that protects the multiple organic layers from the environment, and an external light extraction film, intended to improve the panel's efficacy and create a more uniform visual appearance. The organic layers are sandwiched between a transparent anode, which is typically indium tin oxide (ITO), and a metal cathode, which is typically aluminum or silver. The cathode material may be either highly reflective or transparent, depending whether the panel is intended to emit light through the substrate only or through both the substrate and a transparent cover. While transparent OLEDs are not yet commercially available, they represent a unique opportunity in applications where a combination window and light source is desired.

Exposure to moisture and oxygen are known to degrade OLEDs and may create artifacts, such as dark spots, that can grow over time and dramatically shorten panel lifetime.[7] The most common approach to protecting OLEDs from the environment is to use glass as both the substrate and the cover, and to seal these around the edges with an epoxy adhesive to prevent moisture and oxygen permeation. A metal cover can also protect against the elements. Another common practice is to use a desiccant, sometimes referred to as "getter" material, to capture any moisture and oxygen trapped inside the panel during manufacturing or that may leak into the panel through the edge seal over time.

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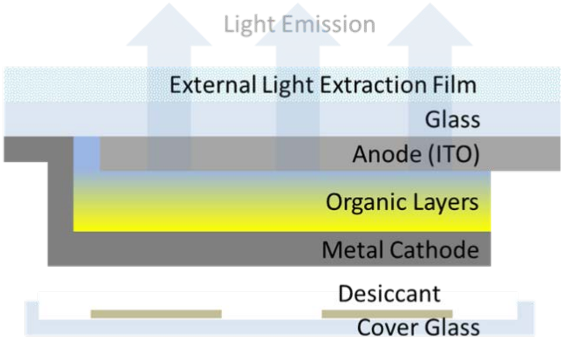
[7] McElvain J, H Antoniadis, MR Hueschen, JN Miller, DM Roitman, JR Sheats, and RL Moon. 1996. "Formation and growth of black spots in organic light-emitting diodes." *Journal of Applied Physics* 80, 6002. Available at http://scitation.aip.org/content/aip/journal/jap/80/10/10.1063/1.363598. doi:10.1063/1.363598



* Layers are not drawn to scale

Figure 4. **Illustration of OLED layers. (Illustration: PNNL)**

An exciting opportunity for OLED lighting panels, and OLED displays, is the potential to use flexible substrates to provide products that can be curved, rolled, or even folded. The most commonly selected substrate material for non-rigid OLED applications is some form of plastic, such as polyethylene terephthalate. However, the rate at which oxygen and moisture permeates plastics can challenge OLEDs, given their sensitivity noted above. Various thin film encapsulation techniques have been developed and implemented, both as methods to eliminate the need and cost of a cover glass and as a way to enable flexible devices on plastic substrates.[8] Thin, flexible glass substrates are another material that may open opportunities for OLEDs[9]. As these technologies improve, and the price to implement them drops, non-rigid OLED lighting products may offer differentiation and a competitive advantage over LED and other lighting technologies.

OLED panels are operated inside, or attached to, luminaires, and it is important to distinguish the efficacy of the panel itself operated in a laboratory, the efficacy of the panel combined with a driver and other components, and the OLED and driving components integrated into a luminaire as a complete system. This CALiPER evaluation focuses on the performance of the complete luminaire system.

OLED drivers and systems

Transformers and OLED Drivers

Like light-emitting diodes, many OLED panels available to luminaire manufacturers are designed to operate with a DC low-voltage constant current driver, rather than the mains voltage of 120 VAC or 277 VAC typical in homes and businesses. While some OLED products are shipped with all the power electronics necessary to provide constant current from the mains voltage, others are shipped with the expectation that the power supplied to the product will be 24 VDC. Thus, to compare OLED products on an even footing with other lighting technologies, it is necessary to include the losses incurred in generating a regulated constant current supply from the mains voltage. This approach extends to external power supplies that may be utilized (i.e., plugged in) to power a luminaire, such as a desk lamp, since it plays a part in the conversion from AC to DC power, as well as to electronics needed to reduce, for example, mains voltage to 12 VAC or 24 VAC.

To simplify, some OLED luminaires have a single power supply built in that takes the mains voltage input of 120 VAC and through an integrated single driver, produces 24 VDC for the panel. Others perform this same function

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[8] OLED-Info (n.d.). *OLED Encapsulation: technological introduction and market status*. Available at http://www.oled-info.com/oled-encapsulation.

[9] http://energy.gov/eere/ssl/articles/doe-publishes-2016-ssl-rd-plan , Section 6.1.4.

in two steps, usually with a transformer/power supply in the first stage, and a power supply/driver in the second. While a few dedicated OLED drivers exist, their operation is similar to that of their LED counterparts. Power factor requirements are met in the first stage; the second stage regulates the output current used to drive the OLEDs. Single stage designs can provide an improvement in efficiency, cost, and size. However, those improvements must be balanced with some tradeoffs including higher output ripple and total harmonic distortion. The range of efficiencies for OLED drivers or LED drivers, can vary based on choices made in the driver design (such as input voltage range (e.g., 90-277 VAC), power factor correction, selectable current output, dimmability, and output voltage range), as well as actual operating conditions.

Remote drivers

For large OLED luminaires, drivers may be located and operate separate from the panel itself, generally remoted from the luminaire in a mounting canopy or an electrical box located out of sight. The specifier must be aware of the need to locate a driver in an accessible, enclosed, dry place. Because the drivers are typically operating at a low voltage (below 30 V), the wiring between the driver and the panel is Class I and is safer and easier to run. It can be installed using a knowledgeable installer, as opposed to Class II wiring (above 30 V), which may require higher installer qualifications. However, the wire run length needs to be carefully considered, as running wires over long distances may reduce overall system efficacy and cause a drop in voltage that could cause the OLED luminaire to receive a reduced driving current.

Integral drivers – commercial off-the-shelf (COTS)

OLED luminaire designers have multiple options in selecting constant current drivers, as LED drivers may also be able to provide the required driving current and voltage ranges needed to drive the OLEDs. However, many LED designs are optimized for typical LED current levels (e.g., 350 mA, 700 mA, etc.), and, even if adjusted to provide an alternate current level, may not provide optimal efficiency. Unlike LEDs, OLED panels may encounter a significant amount of voltage rise due to increase in panel impedance as a result of aging, and this needs to be accounted for in selecting a driver with enough “headroom,” so that the panel can be driven at a voltage that is necessary to produce a constant current.

A luminaire designer may need to equip the OLED luminaire to dim using 0-10 V, DALI, or some other dimming protocol. In some cases, a luminaire may use one power supply or driver to convert the AC voltage to a DC voltage (e.g., 24 V) that can serve as an input to a DC-to-DC driver that fits the product requirements in terms of drive current, voltage range, dimming, etc. One of the CALiPER products evaluated exhibited this power supply/driver design.

Integral drivers – dedicated

Another approach that may be taken by a luminaire designer is to build a driving circuit from scratch, specific to the product design and the OLED panel(s) used. The benefit of such an approach is that all factors can be considered (i.e., voltage of OLED panel throughout its life, driving current range, number of panels, dimming/stepping of light output, etc.), and a circuit designed to maximize the efficiency of the driver, and thus the efficacy of the product. The input to such products may be mains voltage or a common DC voltage (e.g. 12 V or 24 V) that may require the use of a low-cost, readily-available power supply. The drawbacks of such an approach include the time and cost required to design, prototype, test, and manufacture the circuit, and also the need to have a level of sales to ensure a return on investment over simply having used COTS solutions. While this approach is most common in high volume production, in this CALiPER study one such product was encountered. In addition to the driving circuit for the OLEDs, the luminaire designer also incorporated a wireless charging circuit for electronic devices and touch-sensitive step dimming. The ability to incorporate smart logic into a design, as well as other functionality as noted here, can serve as distinguishing features of a premium product using OLEDs and help justify the added cost.

OLED luminaires and systems

As with any light source, luminaire designers must consider the entire system as part of the product development effort. However, some characteristics particular to OLEDs should be kept in mind to ensure a product meets the required specifications and performs as expected throughout its rated lifetime.

Voltage rise over the life of the panel(s)

OLED panels will experience some amount of voltage rise for a given drive current as the panel is operated over time. The amount depends on the materials used in the manufacture of the OLED, as well as driving conditions in the luminaire. This is a key consideration in optimization and selection of a driver to ensure that the product will be able to provide the required driving current to all the panels at the start of life, as well as at the end of its rated life, generally considered to be L_{70}, the point at which its light output has dropped to 70% of its initial output. (This L_{70} target is likely a default standard adopted from the LED industry.) The voltage rise is outside the control of the luminaire designer, so they must work closely with the OLED manufacturer to understand the magnitude of change expected over the life of the OLED panel. Testing of some laboratory-sized test cells have demonstrated that voltage rise is closely correlated with the normalized light output of the OLED.[10] In other words, regardless of the current level to the panel, the voltage rise can be expected to be the same when the panel's light output reaches, for example, L70. (So, the expected voltage rise at L70 may be 1 V, for example, whether the panel is driven at 150 mA or 300 mA.) In a controlled environment, this characteristic may serve the function of a built-in feedback loop to inform a driving circuit and logic as to the age, or level of fade, of the panel.

Panel life vs. current density

As is the case with LEDs, the harder an OLED panel is driven, the lower its lifetime will be. OLED manufacturers typically provide some guidance regarding lifetime to customers, linked to the luminance of the panel as tested (e.g., 15,000 hours at 3000 cd/m^2). See Figure 2. Some may perform limited testing under different operating conditions, but may not provide the results from a wide range of testing conditions in their general literature. However, as was discussed in the DOE report, "OLED Lighting Products: Capabilities, Challenges, Potential,"[11] a rule of thumb is "doubling luminance cuts lifetime by a factor of three,"[12] expressed by the following equation[13].

$$\frac{t_2}{t_1} = \left(\frac{L_1}{L_2}\right)^m$$

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[10] Cok, R. S. and Leon, F. (2006), P-180: Active Compensation for OLED Aging. SID Symposium Digest of Technical Papers, 37: 905–908. doi:10.1889/1.2433667

[11] http://energy.gov/eere/ssl/downloads/oled-lighting-products-capabilities-challenges-potential

[12] Lisa Pattison, SSL Consultants, Inc., correspondence with Naomi Miller, PNNL, May 27, 2016.

[13] Pang, H; Michalski, L; Weaver, MS; Ma, R; and Brown, JJ, 2014. Thermal behavior and indirect life test of large-area OLED lighting panels, Journal of Solid State Lighting. **DOI:** 10.1186/2196-1107-1-7 Equation (1).

Where L_1 and t_1 are the baseline luminance and lifetime to L_{70}, respectively; L_2 is the increased luminance, t_2 is the lifetime associated with that increased luminance, and m is an acceleration factor ranging between 1.5 and 1.7. The relationship between luminance and current (i.e., mA), or current density (i.e., mA/cm^2), is a fairly linear one, so the same rule of thumb may be applied in cases where lifetime is noted in terms of either current or current density.

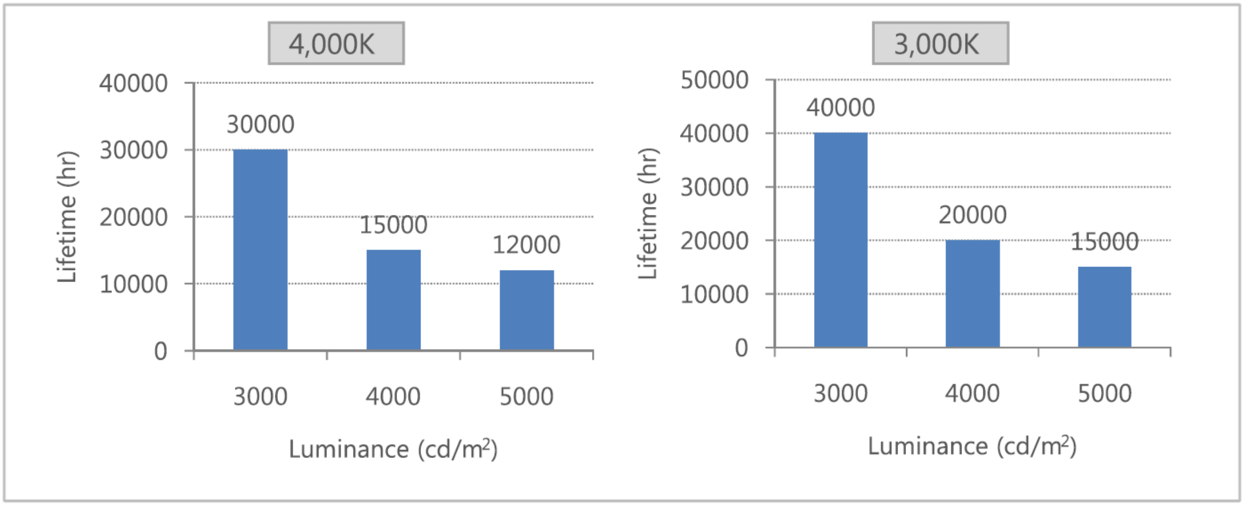

Figure 5. **Plots of expected OLED panel life by panel luminance, for LG Chem (now LG Display) 4000 K and 3000 K panels. Source: LG Chem OLED Light Division, User Guide V1.0.**

Wiring, interchangeability, and end-of-life considerations

In the recent past, luminaires have typically been designed to use replaceable lamps, because the lifetime of the luminaire far exceeded the lifetime of the lamps it used. With the increase in the expected life of many LED packages, it’s almost possible to eliminate replaceable light boards and modules and just assume that the luminaire will be replaced before the LED light source fails. However, if an LED shifts significantly in color, decays unacceptably in light output, or if a driver fails, it is still necessary to have replaceable components, unless the manufacturer offers a full luminaire replacement option. Similarly, OLED panels and drivers have not yet reached a reliable point of longevity, lumen maintenance, or color stability, so the luminaire manufacturer must assume that end-users and facility managers will expect to change out components at some point in the future. At this point in time, panels from different OLED manufacturers are not interchangeable, so one panel must be replaced with another of the same make and model, same pin and wiring connection, and driver with the same mounting and electrical characteristics. Some of the CALiPER products for this round of testing did not exhibit easy panel replaceability.

Products Tested

Table 1 lists each OLED product tested, followed by the product photos in Figure 4. CALiPER product 15-13 is a desk-top task light using an OLEDWorks panel; 15-14 is a wall or ceiling-mounted decorative luminaire using an LG Display OLED panel; and 15-15 is a wall sconce using one outward-facing OLED panel and one facing the wall side, while 15-16 is a one-panel version of the same sconce style.

Table 4. List of OLED products tested for CALiPER report.

Brand	Model	DOE CALiPER Test ID
Aerelight	DS-TL-AAL-72562-81-001857	15-13
Acuity Brands Lighting	CHALINA-HCWM-OLEDA1-5P-345LM-30K-120-DIM	15-14
Acuity Brands Lighting	AEDAN-WM-OLEDR1-2P-140LM-30K-120-DIM-BNP	15-15
Acuity Brands Lighting	AEDAN-WM-OLEDR1-1P-70LM-30K-120-BNP	15-16

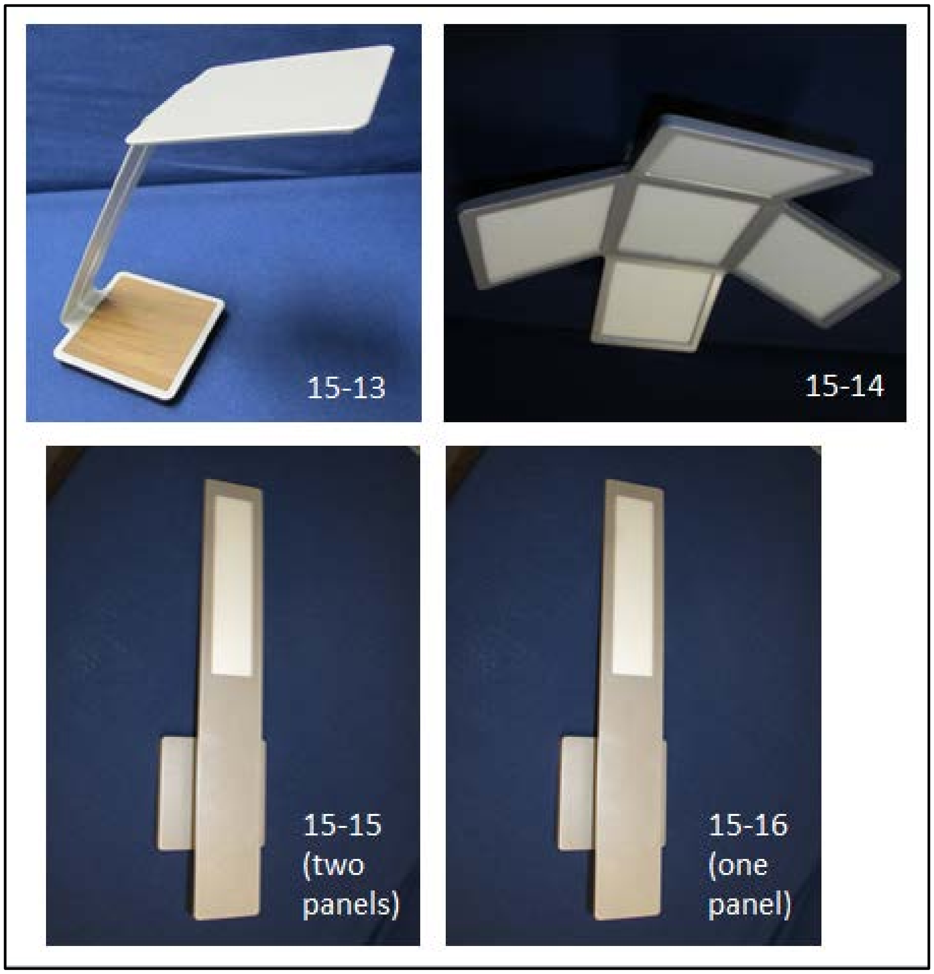

Figure 6. Photos of the four tested OLED products.

4 Test Methods

Testing standards for OLED products

No testing standards are available to date for OLEDs. IES LM-79-08 was developed for LEDs, and includes instructions for powering, pre-warming, and monitoring the LED output for thermal and light stability. LM-79-08 specifies tests for absolute, not relative performance, both in goniophotometry and sphere photometry. OLEDs are similar to LEDs in that they are also solid-state devices, tested with a specific driver; however, there have been no published studies of procedures for testing OLED products so that they are reliable and repeatable among different laboratories.

IES LM-80-15, a standard method for testing LEDs for light output and color change over time, and TM-21-11, a technical memorandum for projecting LED lumen maintenance (one aspect of product life) from those data, are unlikely to apply to OLEDs since the technology for producing light and its expected performance over time are expected to be significantly different from those of LEDs. If OLEDs grow in architectural lighting use, these standards and procedures will need to be developed through an industry consensus process, so that photometric performance data are consistent and reliable.

Laboratory testing

For this CALiPER study, two samples of each product were sent to an independent laboratory for both goniophotometric testing (for spatial intensity values commonly reported in a standard-format ".ies" file), and integrating sphere photometric testing (for spectral power data and electrical characteristics). These tests were conducted following procedures established in IES LM-79-08.

In the case of luminaire 15-16, spectroradiometer testing was also ordered, where a detector capable of collecting full spectral data was used with the mirror goniophotometer to explore whether color of the panel varied by viewing angle. In this case, the average color temperature was averaged from intensities 50% of the maximum or greater on two planes of data collected. The laboratory followed the ENERGY STAR Program Requirements, Product Specification for Luminaires (Light Fixtures), Version 2.0.

For each pair of luminaire samples, the test data were averaged for analysis. The exception was sample 15-15, where one OLED panel failed between being successfully powered up at the receiving location and arrival at the testing laboratory. In that case, the data are from one luminaire only.

Laboratory product exploration (teardown)

After independent laboratory testing, the luminaires were shipped to the PNNL photoelectric laboratory for exploratory testing, or "teardown" (disassemblies to identify parts and functionality). Among the items of interest in this exploratory testing were:

- Understanding the cause of dark spot failure on damaged panel from CALiPER 15-15A
- Evaluate driver selection, configuration, and efficiency
- Assess uniformity of an OLED panel
- Understand impact of light extraction layer on panel performance
- Observe luminaire design practices using OLED panels

Heat and stress testing

A separate testing effort was conducted at the laboratories of RTI International in Research Triangle Park, NC on the same make and model of luminaires as CALiPER 15-14. These luminaires were purchased separately from the CALiPER program. The testing and results are described in Section 6 of this report.

5 Product Performance

This report analyzes the independently tested performance of four OLED products which were anonymously purchased in November 2015. Products were selected based on OLED products available for sale in the US market at that time, either through on-line sales or through an electrical distributor. In all cases, the OLED products were ordered through on-line websites. Because of a limited availability of products, only two manufacturers are represented in the selection. Three product types of one manufacturer were ordered, in an effort to get a variety of products in terms of mounting, orientation, and panel size.

Independent photometric testing laboratory performance

All of the units were tested according to IES LM-79-08, using both an integrating sphere and a goniophotometer; for all but one of the products, the difference in measured lumen output between the two methods was less than 1%, which is lower than is typical for LEDs. Except for luminous intensity distribution characteristics, all values included in this report were measured using the integrating sphere method. All reported values are the mean of the two samples that were tested; the exception is D_{uv}, which is reported as the value furthest from zero. Table 2 summarizes key results from CALiPER testing, with product identification provided in Table 1. All results presented in this report are for a single luminaire operating on a 120 VAC laboratory power supply, with manufacturer-supplied transformers and/or drivers. Field performance may vary.

OLEDs are unique in form factor and are not manufactured as a replacement for any other light source. Thus, no benchmark luminaires have been tested as a baseline.

Table 2 provides colorimetric, photometric, and electrical measurements for the four products discussed in this report, including one product photometered in both a ceiling-mount orientation and a wall-mount orientation (15-14). The values listed all correspond to full output of the product.

Table 5. Summary of colorimetric, photometric and electrical data for OLED products.

DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CRI (R_a)	R_9	R_f	R_g	R_f -- Hue bin 1	CCT (K)	D_{uv}	THD-I (%)
15-13	270	9.6	28	0.45	78	-6	78	95	74	2952	0.0010	188.1
15-14 Ceiling	332	7.4	45	0.99	88	21	86	97	83	2946	0.0030	8.6
15-14 Wall	329	7.4	45	0.99	88	20	86	97	83	2940	0.0030	8.6
15-15	130	4.3	30	0.42	88	21	87	97	83	2912	0.0020	189.1
15-16	65	2.8	23	0.40	88	21	87	97	83	2855	0.0030	192.2

Efficacy, Lumen Output, and Power Draw

The OLED luminaires range in initial output between 65 and 270 lumens with input power between 2.8 and 9.6 W for single-panel luminaires (15-13 and 15-16). The two-panel wall sconce (15-15) produces 130 lumens at a power draw of 4.3 W; and the five-panel luminaire (15-14) produces 329 to 332 lumens with an input power of 7.4 W. Efficacies for all of the luminaires range from 23 to 45 lumens/watt (lm/W). Compared to LED performance, OLEDs are at one-third to one-half of interior LED luminaires in the LED Lighting Facts database, where the mean efficacy was 86 lm/W in 2014 for combined LED downlights, industrial luminaires, track heads, troffers, and linear fixtures[14]. (The 2014 value is more comparable to the luminaires purchased in 2015 for this CALiPER study than today's average of 98 lm/W).) Their performance is also below the ENERGY STAR minimum threshold of 65 lm/W for solid-state surface-mounted retrofit for diffused wall sconces or ceiling lights, or 50 lm/W for solid-state portable desk task lights[15].

The panel-level efficacies for these four luminaires are estimated by the panel manufacturer as exhibiting 42 lm/W (OLEDWorks) for 15-13; and 55 lm/W (LG Display) for 15-14, 15-15, and 15-16. This means that the OLED systems undergo an 18 to 59% loss compared to the original panel's efficacy potential, due partly to optical and thermal losses from the luminaire, but largely from the additional electrical power losses from transformers and drivers.

As expected, the effect of orientation, ceiling-mounting versus wall-mounted, produced a difference of less than 1% on the efficacy, lumen output, and power values of product 15-14.

Color Quality

All color metrics are calculated from the luminaire's SPD. Appendix B provides SPDs and both numerical and IES TM-30-15 graphical color performance illustrations for all five product tests at full output, with one chart for each product. (The data are from one of two samples.) Product 15-13 uses a different manufacturer's panel than do 15-14, 15-15, and 15-16, and its color quality values are slightly lower. Its CRI (R_a) is 78, ten points below the others; the R_9 value is below zero; and the color gamut illustration suggests that it would desaturate reds. In the correspondingTM-30 metrics, its R_f is 78, eight to nine points below the panel used in 15-14, 15-15, and 15-16; with an R_f in hue bin 1 (i.e., red) nine points below the R_{fhb1} of the other tested OLED luminaires.

All of the tested luminaires had a Correlated Color Temperature (CCT) of 2855 K to 2952 K, with D_{uv} values of less than 0.003, meaning that all produced color coordinates close to that of the black body radiator. The u'v' chromaticity coordinates of product pairs were very similar, with a maximum Δu'v' difference of 0.0016, a barely distinguishable visual difference.

Power Quality

Except for luminaire 15-14, the power quality was poor for the tested products. Power factor was high for 15-14 (0.99), but below 0.50 for all others. Total harmonic distortion (THD) was also high for all but 15-14. While 15-14 produced less than 10% THD, the others exceeded 100%. Whether a "low" to "normal" power factor or "high" THD value is an issue in buildings with contemporary electronic devices is debatable, because switching power supplies have a very different impact on building electrical loads and building power factor than electromagnetic loads that were more common decades ago. It is also worth noting that power factor and THD are seldom considered a problem when they comprise a low percentage of the building's power circuits.

Color variation with viewing angle

The testing laboratory photometered luminaires 15-16A and 15-16B (wall sconces with single OLED panels) in two orthogonal planes using a spectrophotometer in order to explore spatial non-uniformity of chromaticity. The spectral data was resolved into CCT and u'-v' coordinates. In analyzing the data, the measurement point with the highest CCT value was compared with the lowest in terms of CCT difference and Delta (Δ)u'-v'. For the first sample, the maximum CCT difference was 96 K, and the maximum spatial color difference was Δu'-v' of

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[14] DOE CALiPER Snapshot Indoor LED Luminaires, 2014. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/snapshot2014_indoor-luminaires.pdf

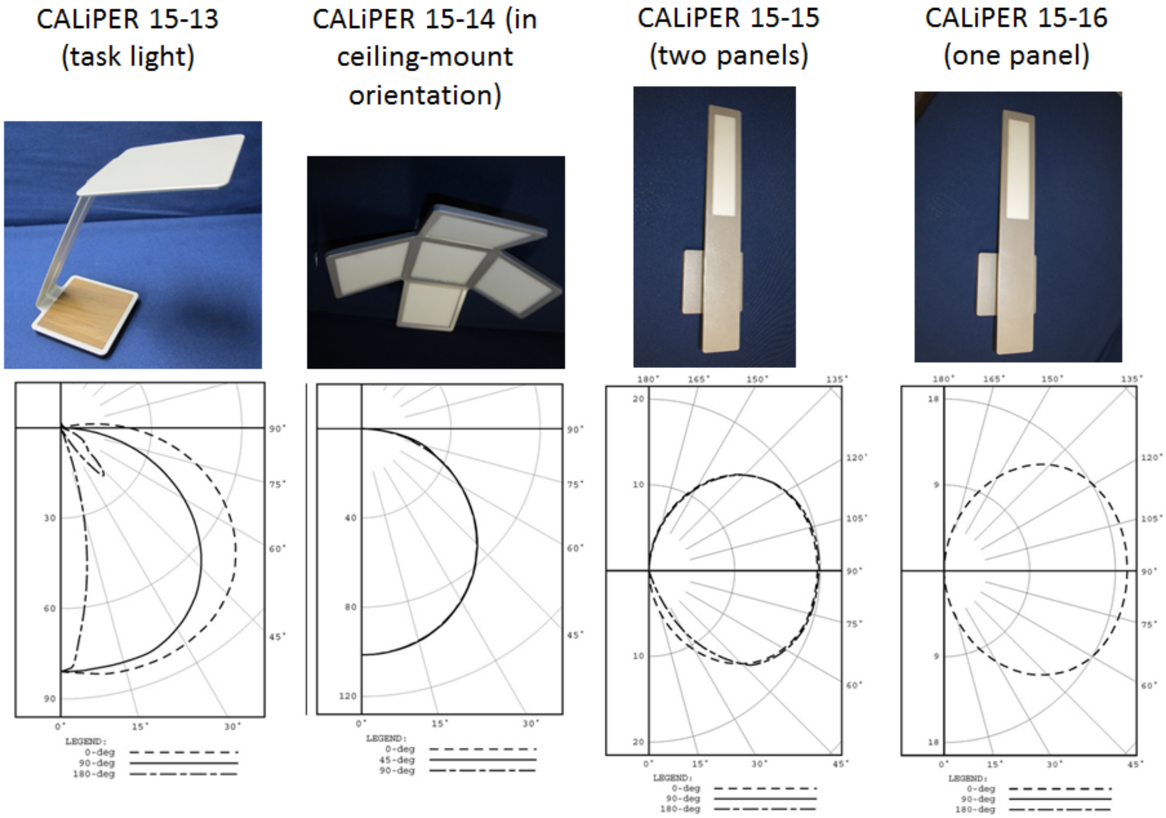
[15] ENERGY STAR® Program Requirements Product Specification for Luminaires, Version 2.0. https://www.energystar.gov/sites/default/files/asset/document/Luminaires%20V2%200%20Final.pdf

0.0042. The second sample, the maximum CCT difference was 81 K, and the maximum spatial color difference was Δu’-v’ of 0.0044. Both of these values are small, well within ENERGY STAR tolerances of 0.007 for Δu’-v’, and suggest that for this luminaire incorporating OLED panels with extraction film, there was little apparent color difference looking at the OLED panel from different viewing angles.

Light distribution

OLEDs produce a light distribution pattern that is diffuse, often called a “cosine distribution.” All of the tested products produced this soft pattern. (Figure 5) Products with this kind of pattern produce very soft shadows from objects, similar to the light quality produced by indirect lighting. The two wall sconces are similar in appearance, but in addition to the outward-facing OLED panel, product 15-15 has one panel facing toward the wall, to deliver a soft halo of light on that surface.

The only unusual pattern of light generated by these products is from CALiPER 15-13, where the angled head of the luminaire create an asymmetrical pattern, with a backward spike created by the blocking of the arm.



CALiPER 15-13 (task light)

CALiPER 15-14 (in ceiling-mount orientation)

CALiPER 15-15 (two panels)

CALiPER 15-16 (one panel)

Figure 7. Four OLED luminaires tested for CALiPER, shown with their photometric distributions.

Performance compared to manufacturers' published data

The CALiPER tests showed that the luminaire performance was very similar to the manufacturers' published performance, where available. In efficacy, there was less than a 5% difference; in input power, less than a 4% difference; in lumen output, less than a 6% difference. The CCT varied from the nominal CCT by 52 K in the case of 15-13, and as much as 145 K from the nominal CCT in the case of 15-16, both within the ANSI C78.377-2011 chromaticity tolerances. The larger difference in CCT could make product 15-16 appear noticeably warmer than other 3000 K products located nearby, although it depends on the exact chromaticity coordinates of the two sources.

Table 6. **Luminaire test data and comparable data from the luminaire manufacturer's literature.**

	Test Data				Manufacturer Data			
DOE CALiPER Test ID	**CCT** (K)	**Efficacy** (lm/W)	**Input Power** (W)	**Initial Output** (lm)	**CCT** (K)	**Efficacy** (lm/W)	**Input Power** (W)	**Initial Output** (lm)
15-13	2952	28	9.6	270	2900	n/a	n/a	n/a
15-14 Ceiling	2946	45	7.4	332	3000	46	7.4	342
15-14 Wall	2940	45	7.4	329	3000	46	7.4	342
15-15 (2 panel)	2912	30	4.3	130	3000	31	4.3	135
15-16 (1 panel)	2855	23	2.8	65	3000	24	2.9	69

Laboratory Teardown Testing

The OLED products ordered for the CALiPER tests were shipped to PNNL's Lighting Laboratory for further examination and analysis in order to learn more about the failure on one panel, and also about the electronics used in the products.

When the OLED products were ordered for CALiPER testing, three of the products were shipped directly from a big-box retail chain. Two of each product were ordered for delivery in Portland OR, and all six unpacked, wired using compatible 0-10V dimmers, and tested to ensure expected operation. They were then carefully repacked in their original packaging and shipping boxes, shipped to PNNL in Richland WA for photography, labeling and documentation, then again repacked in their original boxes and shipped to a testing laboratory in Boulder CO. All but one luminaire were received in operating condition. Test sample 15-15A is a wall sconce with two OLED panels, and one of the two panels exhibited dark spots when the system was energized. (Note that the spots are not visible on an unenergized panel.)

Evaluation of damaged OLED panel in CALiPER test sample 15-15A

This compromised wall sconce product was not photometrically tested, as one of the two panels exhibited dark spots when received at the independent laboratory. The luminaire was returned to PNNL as faulty, and the sconce panel with its dark spots was observed first in December 2015 (Figure 6) and then in the PNNL laboratory in March 2016 (Figure 7). The dark spots had grown worse over that 3 month period, even though the luminaire had not been operated except briefly to examine its condition. In order to assess the potential cause of failure, teardown of this luminaire was performed.

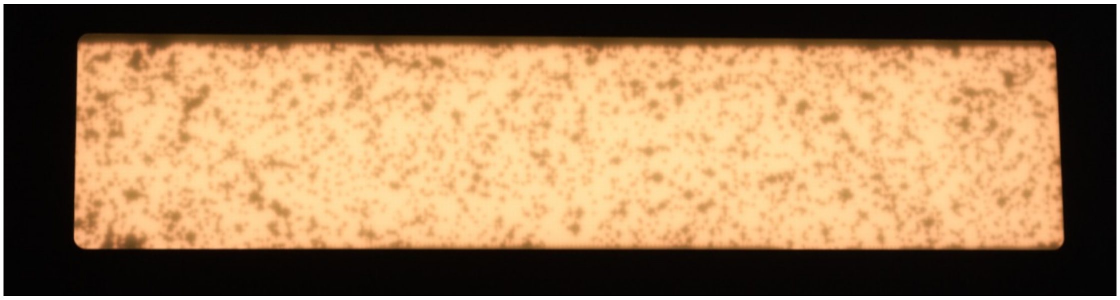


Figure 8. Photo of damaged panel from CALiPER 15-15A, December 2015.

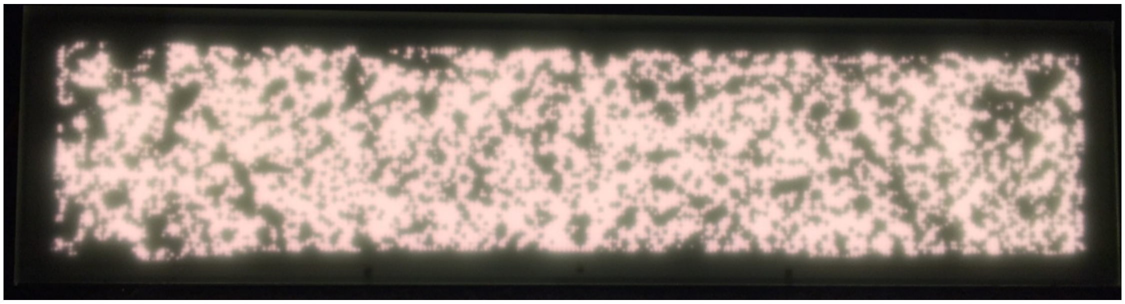


Figure 9. Photo of same damaged panel from CALiPER 15-15A, March 2016.

External inspection of the luminaire showed a slight bulge on the metal plate that is used to secure the wall-facing OLED panel to the body of the luminaire. Upon removal of the plate holding one OLED panel in place with the use of Kapton® tape, a banding rainbow-like effect was noticed on the edge of the room-side panel. The typical approach used for protecting OLEDs from moisture ingress is attaching a cover glass to the substrate glass via an edge seal using an epoxy adhesive, typically cured using ultraviolet light. The presence of the banding observed near the corner of the panel and again near the center edge, may be indicative of a broken seal that would allow moisture ingress. Figure 8 shows the observed plate bulge, the removable cover plate and luminaire, and the banding effect on the corner of the panel.

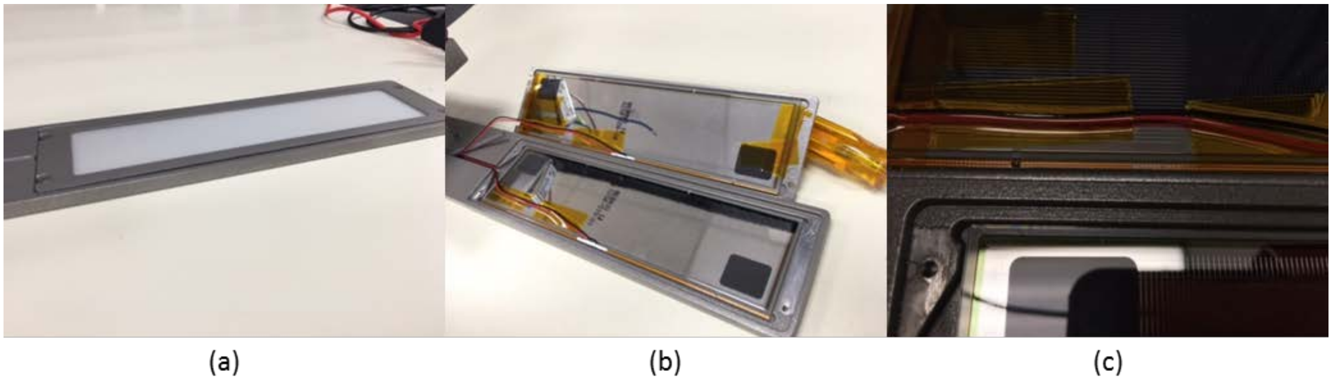

(a) (b) (c)

Figure 10. CALiPER 15-15A sconce is shown (a) with wall-facing OLED and removable plate, (b) with plate and OLED removed, and (c) with noticeable banding effect on upper-left corner of room-facing OLED on bottom of picture.

Careful inspection of the back-side of the room-facing OLED panel (i.e., the lower panel in Figure 6-b) showed that near the observed mid-panel banding there was a smudge of what appeared to be silicone glue that is used to secure the anode (red) and cathode (black) wires in place on the panels. While it is not definitive that pressure applied on the glass near the edge seal was the cause of failure, it is suspect and coincidental that the damage appears to originate in this location. Figure 8 shows the observed banding near the mid-section of the luminaire-side panel and the silicone "smudge".

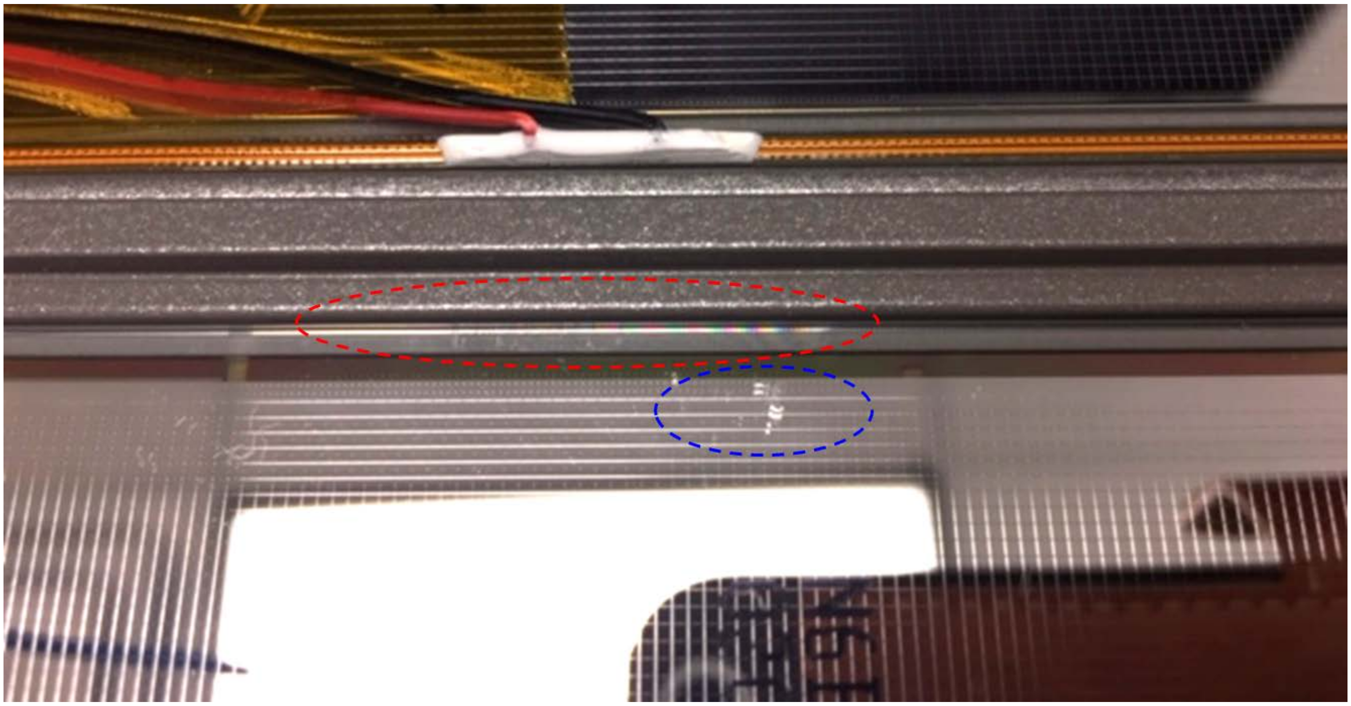


Figure 11. Banding observed on the luminaire side panel (red ellipse) with small smudge of silicone glue just below it (blue ellipse).

A damaged panel, in this case, will not only produce a distracting appearance, but will reduce light output over time as the dark spots grow.

CALiPER 15-16A

This sconce product is identical to CALiPER 15-15A, with the exception that it equipped with only one OLED panel (room-facing), and uses an OLED that is dimensionally the same, but has interconnects on the short edge of the panel. No bulge was observed on the back plate of this product (Figure 9), and no banding on the panel (Figure 10).

Figure 12. Back side of CALiPER 15-16A showing a metal plate used to secure the OLED panel to the luminaire.

Figure 13. CALiPER 15-16A with back plate removed, showing interconnects on short side of panel and no visible damage (i.e., banding) of the edge seal.

CALiPER 15-14

This is a five OLED panel product that can be mounted either as a wall sconce or a ceiling luminaire. Its OLED panels are connected in series, with each noted as 8-9 V and 1.6 W. The voltage range of the five panels would then be expected to be in the range of 40-45 V and the power requirement around 8.1 W, if driven at the rated 180 mA current level. However, this product uses a 150 mA constant current driver, and thus the voltage would be expected to be slightly lower. Figure 11 shows the back side of the luminaire, with one of four rear metal plates removed to expose the wiring and the OLED panel.

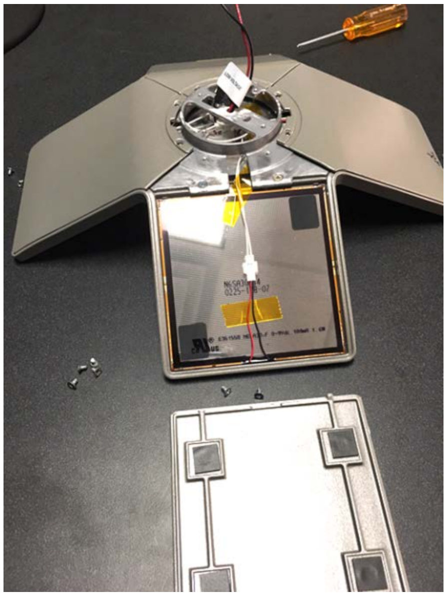


Figure 14. CALiPER 15-14A with one backplate removed to expose the square OLED panel, the wiring to the OLED panel, and the interconnect used to facilitate assembly.

CALiPER 15-13

This task light product used an OLEDWorks panel (120 mm X 120 mm), and is powered by a corded external power supply. As an additional feature, the task light has a cell phone charging circuit built into the base and allows for multi-level touch dimming of the OLED panel. A noticeable difference in this product is the method used for interconnects: a visible 5-wire flat flexible cable is permanently attached to the OLED, with the other end capable of being easily plugged into a printed circuit board connector, similar to approaches used for LCD displays. This approach gives the product a sleek appearance, and makes it easy to integrate the OLED into a luminaire, as no spot soldering or thick layer of silicone adhesive is utilized. Figure 13 shows the flex cable running from the OLED panel to the printed circuit board that contains the constant current driver.

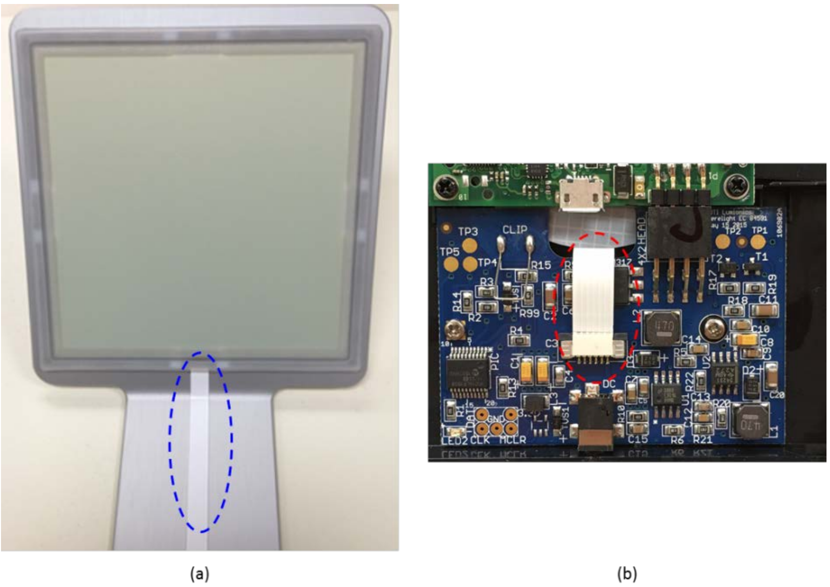


Figure 15. CALiPER 15-13 desk lamp showing (a) the OLED and flex cable (blue ellipse) running along the panel exterior and (b) the flex cable connected to the driving printed circuit board (red ellipse).

Performance of the external light extraction (ELE) layer

OLED panels most often have a light extraction film applied by the panel manufacturer, which increases the luminous output by a factor of 1.5 or more. This film converts the panel from a mirror-like finish to a matte finish, increases the color temperature, and obscures both fingerprint smudges and the gridded appearance of the panel. Figure 14 shows the damaged panel from CALiPER 15-15A with its light extraction film removed on the right half of the panel. In this CALiPER study the performance of the ELE on a single panel was evaluated by performing measurements in an integrating sphere, both before and after removal of the ELE film. Results showed the extraction layer increased the total luminous flux of the panel by a factor of 1.55X, and also increased the luminance of the panel (measured orthogonal to the panel) by a factor of 2.3X.

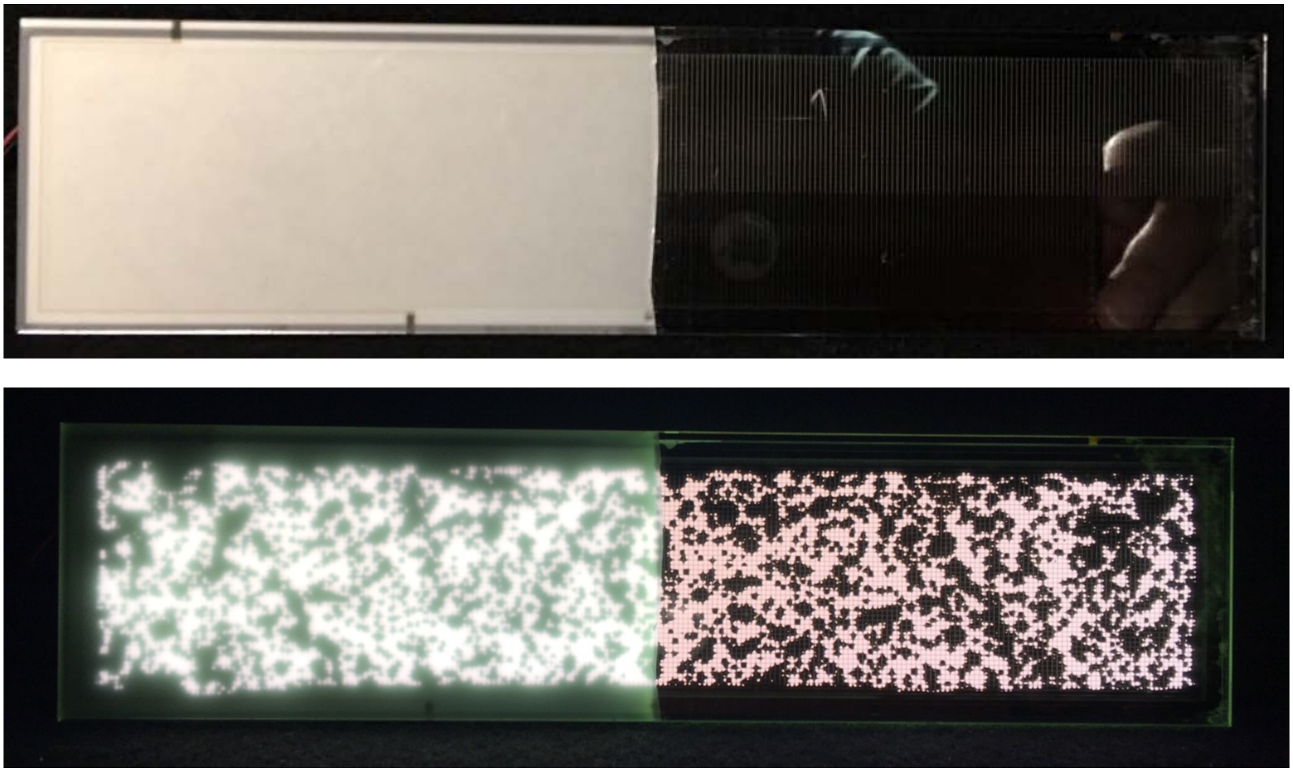
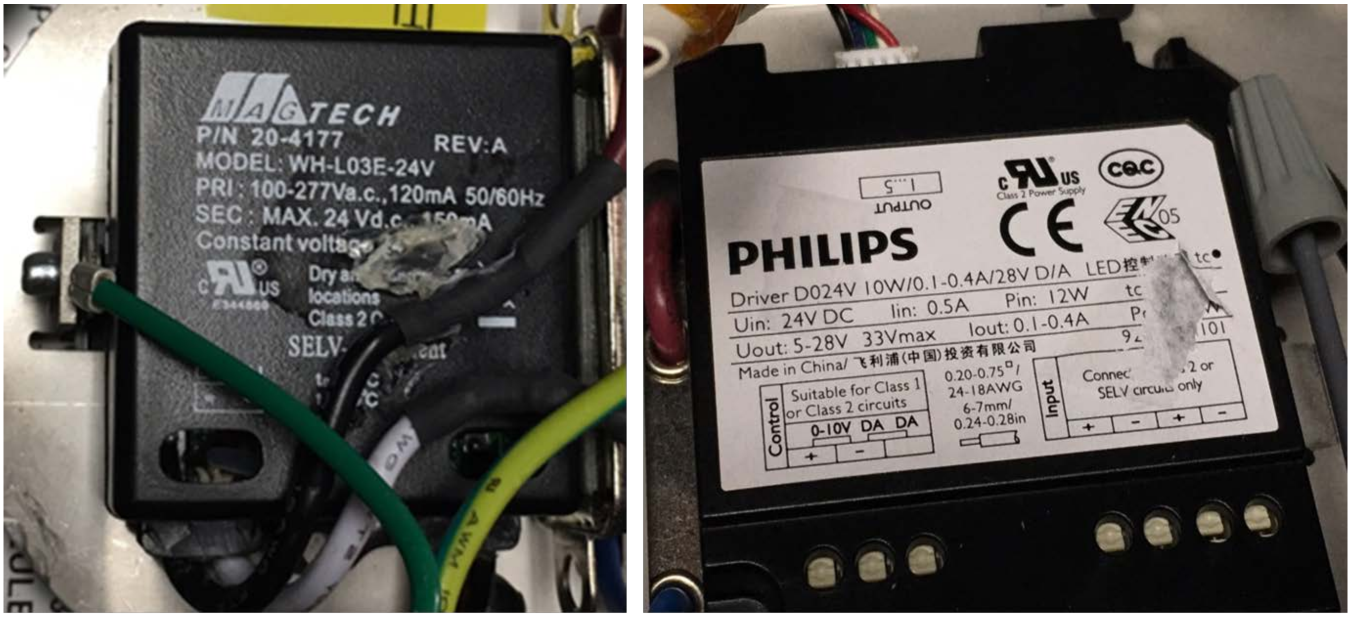


Figure 16. Damaged OLED panel with half of light extraction film removed from the right side. The top photo illustrates the shiny finish of the OLED when that film is removed. Note a change in color appearance visible in the lower photo.

Evaluation of drivers and electronics used in OLED products purchased for CALiPER testing

Only three basic types of luminaires were obtained for this CALiPER study, but the variety of driving approaches represented illustrates different driving techniques for OLED panels. The wall sconces (CALIPER 15-15 and 15-16) used two discrete COTS drivers, the decorative luminaire (CALiPER 15-14) used one single COTS dimmable driver, and the desk lamp (CALiPER 15-13) used a driving circuit developed specifically by the luminaire designer for that application. All three approaches can result in dramatically different efficiencies and may perform differently at end-of-life. This analysis used the driver specification sheets rather than measured driver performance to study the design approach of the luminaire, as it relates to driver selection.

The wall sconce was available in two varieties: a single OLED panel version (CALiPER 15-16) and a two-panel version (one panel facing the wall, CALiPER 15-15). 15-15 uses two drivers, with the first driver[16] converting the mains AC voltage into a DC voltage that then provides power to the second (OLED) driver[17]. That second driver provides a constant current to the series-wired OLED panels, and adjusts this current based on a dimming signal it receives via a 0-10 V control line. The same two drivers were used in the single-OLED sconce design, with only a minor addition of an external resistor. Another resistor is used in both designs, to set the design OLED current of 146 mA. Figure 15 shows the two drivers used in the both sconce designs, while Figure 16 illustrates the driving circuit for both the 1-panel and 2-panel versions of the wall sconce.



(a)

(b)

Figure 17. The drivers used by CALiPER 15-15 and 15-16 to convert (a) mains AC voltage to 24 VDC, which is used to provide power to the driver (b) which provides a driving current to the OLED panel(s) depending on the 0-10V dimming control signal.

Figure 18. Driver configuration for CALiPER 15-15 2-panel wall sconce or 15-16 1-panel wall sconce.

The combination of these two drivers can result in overall efficiencies of between 47% and 58%, for the one-panel and two-panel sconce designs, respectively. The reason for the difference in efficiency can be observed in the output power vs. efficiency performance curve of the second driver. Figure 17 shows that as the output power decreases, the efficiency of the driver is also expected to decrease. The power of the single panel design is one-half the power of the two panel design.

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[16] MAGTECH P/N: 20-4177, Model WH-L03E-24V, constant voltage, 24 VDC, 150 mA (max)

[17] Philips Lumiblade OLED driver, low voltage, D024V 10W/0.1-0.4A/28V D/A

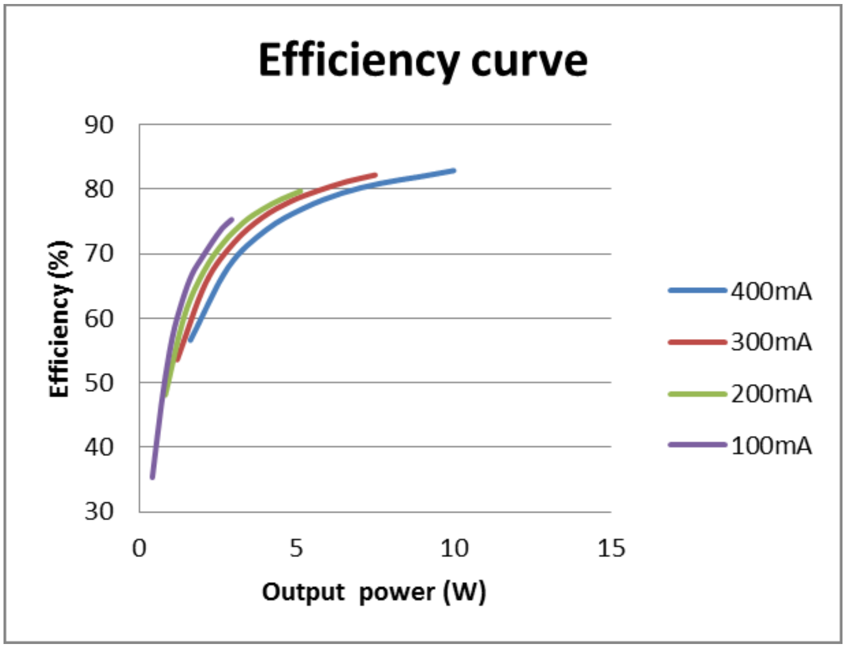

Figure 19. The output power vs. efficiency curve for the second OLED driver used in the wall sconce luminaires. Source: Philips Lighting.

In the sconce design, the two panel version presents a particular challenge to the driving circuit. The OLED panel specifications indicate they are designed for 8-9 V at their 150 mA design current, resulting in 18 V for two panels in series. (For the purpose of this discussion, it will be assumed that the difference between 146 mA and 150 mA is insignificant.) The power required to drive two panels at 150 mA is 2.7 W (2 * 9 V * 0.15 A). For 2.7 W output power, the second driver efficiency is approximately 75%, and the driver would thus require an input power of 3.6 W. The first driver, which was specified as capable of providing 24 V at 150 mA max is just capable of providing the second driver with the power it needs to adequately drive the OLEDs when new. As these OLED panels age and increase in panel impedance over their operating life, the drivers would be expected to provide sufficient power to maintain a constant current. If, however, the first driver was already at its maximum output when new, and the OLEDs experienced a 1 V rise over their L_{70} life, then they would demand 3 W (2 * 10 V * 0.15 A) at L_{70}. The first driver, however, would not be capable of providing the required power, causing the luminaire to experience a decay in light output due to OLED efficiency loss and the inability of the driver to compensate by keeping the panels operating at the design current. The one panel sconce design, while operating at lower efficiencies, is not expected to encounter a similar issue at end of life. (It should be noted that the panels evaluated in this CALiPER report were lower in voltage, at about 8.5 V each, than the maximum voltage in the specified range.)

Luminaire CALiPER 15-14 was designed with a different driver system: one single 0-10 V dimmable driver[18] with a maximum output power of 7.2 W, and design current of 150 mA at a voltage range between 35 V and 48 V. Figure 18 shows the label on the driver used with this luminaire. A specification sheet of this particular driver was not available, but a review of a similar driver from Energy Recovery Products, with a similar appearance and model number, suggest an efficiency of 87% and higher. In CALiPER teardown testing, the efficiency was estimated as 86.8% (7.35 W input during photometric testing, 6.38 W output to OLED panels at the rated 150 mA design driving current during teardown).

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[18] AcuityBrands Lighting, ESS010W-0150-48-ABL, 150 mA, 35 – 48 VDC, 7.2 W maximum power.

(a) (b)

Figure 20. Driver used in the 5-panel decorative luminaire (CALiPER 15-14), showing (a) input ratings and (b) output ratings.

The five OLED panels used in this design were observed to be connected in series, so with each panel at 8-9 V, the five panels can range between 40 V and 45 V at start of life. (CALiPER measured 42.5 V for the five OLED panels in CALiPER 15-14.) The maximum power of this driver is achieved at 150 mA and 48 V, which means that only 3 V are allotted as headroom for the five panels, or 0.6 V per panel. The LG OLED panel specification sheets do not state the panel impedance increase that can be expected at end of life, but the same concern noted in the sconce driver design applies to this luminaire.

The OLED desk lamp evaluated in this report (CALiPER 15-13) used a driver designed by the luminaire manufacturer based around the National Semiconductor (now Texas Instruments) LM3414 constant current buck LED driver. The driver built into the luminaire uses an external power supply to convert mains AC voltage from a plug outlet into a 24 VDC signal with a maximum of 1 A and 24W. See Figure 19 for an illustration of the driving circuit. This product was drawing under 10 W at full brightness in photometric testing, suggesting the capacity of the external power supply is sufficient to meet the luminaire's lifetime driving requirements, neglecting any power requirements of the cell phone charging circuit. This Efficiency Level V power supply is expected to have a minimum efficiency of 82%; the efficiency of the LM3414 driving circuit is expected to be approximately 94%, based on the OLEDWorks specification sheet (i.e., 7.4 W at rated conditions and 9.59 W measured power in photometric testing). 77.2% is then the overall driver efficiency. Since the input voltage to the driving circuit is 24 V (from the external power supply), and the rated voltage for the OLED panel is calculated to be approximately 24 V at end of life (OLEDWorks panel specification sheet lists the OLED voltage at end of life as 25.5 V, but at 390 mA rather than the 368 mA design current), it is unclear if this driving circuit could encounter similar issues as those described for CALiPER 15-14 and 15-15 at end of life.

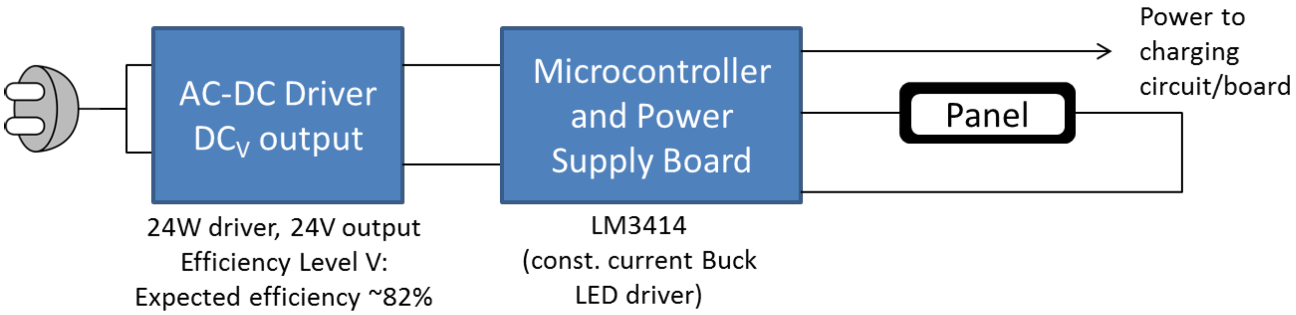

Figure 21. Illustration of driver circuit for CALiPER 15-13.

Uniformity of OLED panels

One of the unique characteristics of OLEDs is the ability to directly view and interact with the panels due to their relatively glare-free appearance. For some applications, one of their important attributes is the appearance of luminance uniformity across the entire panel. Visual appearance metrics can be challenging to quantify and currently do not exist for OLED lighting panels, though some manufacturers or luminaire designers may use terms such as “smudge-free” or “no dead pixels/areas” to define an acceptable appearance of the panel. Manufacturers of OLED panels for display applications, more likely to encounter such defects, have taken steps to characterize and quantify what is referred to as “mura”, a Japanese word meaning non-uniformity or unevenness, and these methods may be leveraged by the lighting panel manufacturers.[19] Uniformity, on the other hand, can be measured and quantified. In the CALiPER teardown study, the good panel from the compromised 15-15A sconce luminaire was removed and luminance measured orthogonal to the panel at various current densities, using a Photo Research luminance meter, first with its external light extraction (ELE) layer in place, then with the ELE removed. The uniformity variation is defined by the following equation:

$$Variation\ in\ Luminance\ Uniformity(\%) = \frac{L_{max} - L_{min}}{L_{max}} \times 100$$

In performing this characterization of a rectangular panel, a mask was developed to enable consistent measurements at the corners and center and some locations corresponding to a 3 x 2 matrix near the panel center. See Figure 20.

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[19] http://sensing.konicaminolta.asia/2015/11/quantitative-evaluation-of-mura-in-display/

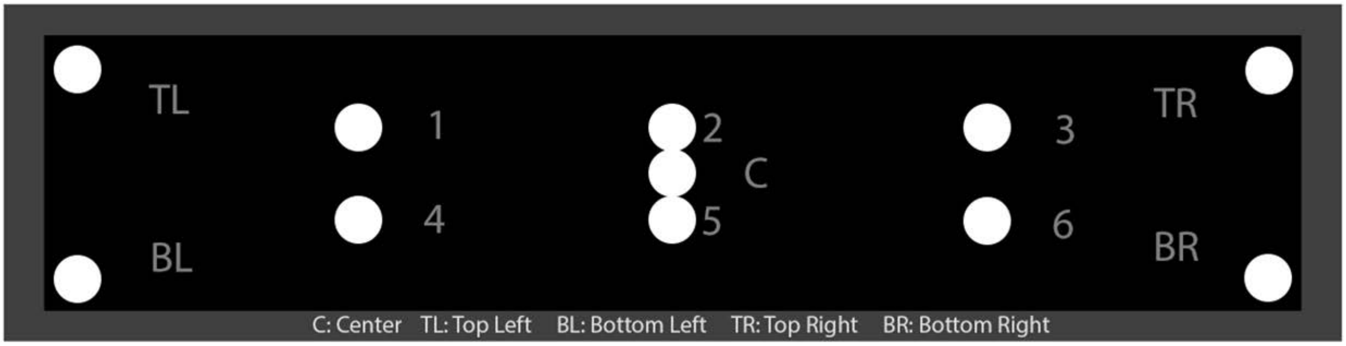

Figure 22. Mask used to measure OLED uniformity, including corners, center, and a central 3 x 2 matrix described by numbers 1 through 6. Only a subset of spots were measured for this CALiPER test.

The results in Table 4 show that the panels with the ELE layer exhibit minor variations in luminance uniformity, only a 3.3% variation among center measurement points and a maximum of only 17.2% across the full panel at the highest current loading. As expected, the test also shows that the ELE layer helps improve the uniformity across the panel, especially at edges. (Compare to the same uniformity values of the panel without the ELE layer, where at the higher current loading the panel exhibits a 34.2% variation in luminance uniformity.)

Stripping the ELE also demonstrates the effectiveness of current spreading across the panel. Current loading of 2 mA/cm^2 represents the set of measurements closest to the actual in-use performance, as this luminaire's panel current density is approximately 1.9 mA/cm^2 at full brightness. (It is important to note that the measured locations in this study include extreme edges of the panel and may not be representative of how OLED manufacturers characterize OLED panel uniformity, since there is no standard.)

Table 7. Luminance uniformity results for CALiPER 15-15A panel with and without extraction layer, and at four levels of current loading.

Panel Uniformity Variation	0.5 mA/cm^2	1 mA/cm^2	2 mA/cm^2	4 mA/cm^2
With ELE (central)	2.9%	2.5%	2.3%	3.3%
With ELE (full panel)	8.1%	10.9%	11.2%	17.2%
W/O ELE (central)	1.0%	1.8%	4.6%	15.0%
W/O ELE (full panel)	2.9%	6.9%	18.6%	34.2%

6 Accelerated Lifetime Tests of OLED Luminaires and Panels (Testing by RTI International)

Method

In 2015, RTI International began performing accelerated stress testing (AST) and failure analysis of the Acuity Brands Lighting, Inc. CHALINA™ OLED luminaires (same make and model as CALiPER product 15-14.). Testing is on-going, performed on both entire luminaires and individual panels (dimensions of 100 mm by 100 mm) operated by an external power supply. Four AST protocols have been used to date.

1. 45°C bake of luminaires operated at 150 mA
2. 75°C bake of individual panels operated at 150 mA
3. Exposure of luminaires to 75°C and 75% RH (75/75) while operating at 150 mA
4. High current (200 mA) operation of an OLED panel in 45°C bake

The 45°C elevated ambient was chosen as an AST protocol because of its use in previous CALiPER testing of LED products.[20,21] Thus, performance in this test environment can provide some comparison to the performance of conventional LED products from the 2012 to 2013 timeframe. Additional AST protocols were chosen to examine the behavior of the devices under higher stress levels.

All devices under test (DUTs) were operated continuously during the AST protocol. The OLED panels within whole luminaires were exposed to elevated ambient conditions of either 45°C or 75/75, but the power supplies operating the OLEDs were placed outside the AST chambers. The luminaires were mounted on riser brackets to allow air contact on the majority of the luminaire surfaces while baking and the drivers were placed outside the test chamber. Only individual panels were exposed to elevated ambient temperatures of 75°C or operated at 200 mA while in an ambient temperature of 45°C. Whenever individual panels were put into the AST environments, they were placed on open racks that allowed access to ambient conditions on both sides.

After completion of each AST cycle, photometric measurements were performed at 25°C on each DUT in a calibrated 1.625 m (65") integrating sphere, and photometric properties such as luminous flux, SPD, and chromaticity were recorded at regular intervals. In addition, electrical properties of the individual panels were checked with an Agilent handheld LCR meter (Model U1733).

Results

As described below, during AST exposure, some degradation and damage occurred to various samples in the form of pixel failure, abrupt failure (i.e., complete loss of luminous intensity), and glass breakage. The particular failures observed for each test protocol are noted below within each AST section. Extreme care had to be taken in handling individual panels since the connecting wires can be easily broken away from the panel. When this happened, wire failure seemed to occur within the wire itself rather than at the solder-pad interface. This suggests that better connector methods or thicker gauge wires may eliminate this type of failure.

45°C Bake AST Results

Four OLED luminaires (DUTs 224 – 227) were tested in the 45°C bake for more than 4,000 hours. One luminaire (DUT 224) exhibited the complete failure of one panel between 125 and 250 hours of testing, as shown in Figure 21. The loss of this panel resulted in a reduction of power consumption as shown in Figure 22. However, the

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[20] CALiPER Report 3.2. "Lumen and chromaticity maintenance of LED A-lamps operated in steady-state conditions," December 2014.

[21] CALiPER Report 20.4. "Lumen and chromaticity maintenance of LED PAR38 lamps," December 2014.

device continued to produce illumination, albeit at a reduced level, suggesting that the non-operable panel failed as an electrical short circuit. This was confirmed in subsequent testing.

Figure 23. Picture of two OLED DUTs during testing in elevated ambient of 45°C. The device drivers were placed outside of the chamber. One OLED panel on the bottom luminaire DUT is not functioning.

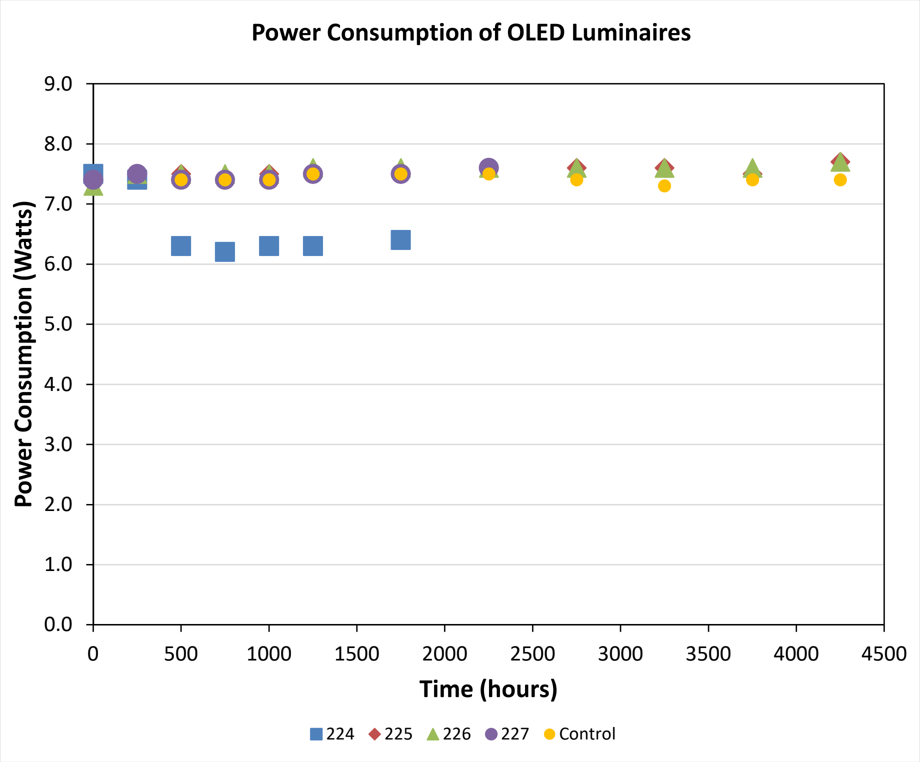


Figure 24. **Power consumption of the control luminaire and four DUTs (#224, #225, #226, and #227) subjected to elevated ambient conditions of 45°C for extended periods of time.**

DUT #224 remained in testing until it exhibited abrupt failure sometime between 1,750 hours and 2,250 hours. The abrupt failure of the driver was traced to the metal-oxide field effect transistor (MOSFET) that serves as the power switch in the switch-mode power supply (SMPS) driver. Upon further examination of DUT #224, it was also discovered that a second OLED panel had stopped working. Since the driver for this luminaire was outside the chamber, it was subject to milder conditions than the luminaires. Thus it is unknown whether the driver failure was due to the loss of two OLED panels and the change in the electrical load experienced by the driver, or a latent defect in the MOSFET or other circuit components.

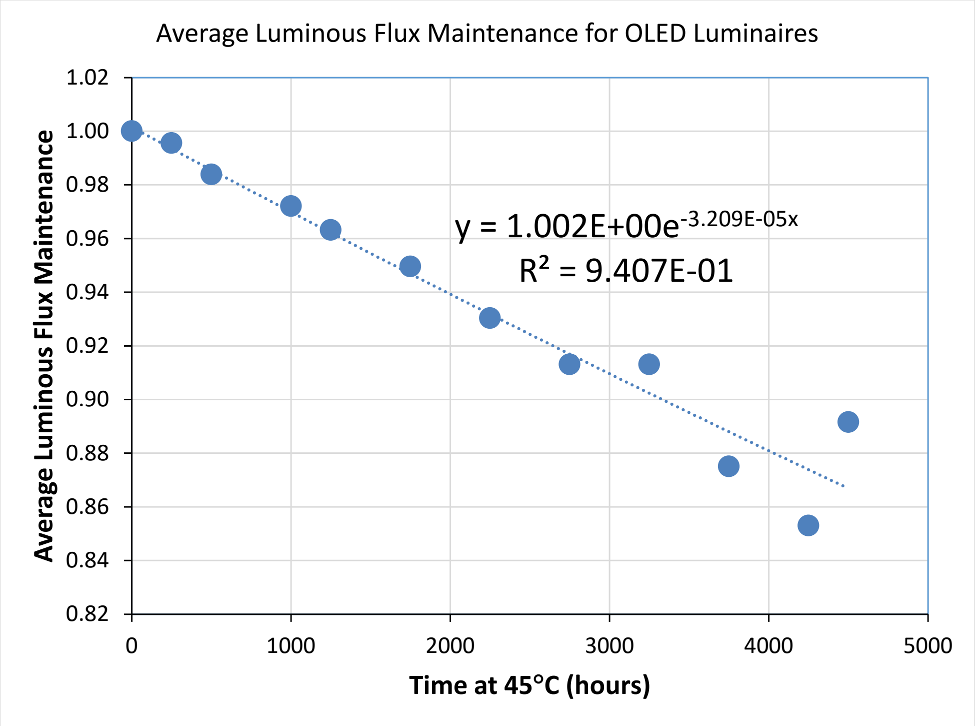
As part of the characterization of the OLED luminaires, the impedance of the five panels in the control luminaire were compared with that of the 18 operating panels and 2 failed panels from DUTs 224-227. The impedance of each panel was measured at three frequencies, 100 Hz, 1,000 Hz, and 10,000 Hz as shown in Table 5. A close inspection of the data reveals several main trends. First, the impedance of the failed panels is much lower than that of the operational panels, indicating the presence of an electrical short in the panel. This was confirmed by a visual inspection of the panels where a dark spot on the OLED can be observed. The finding that these panels fail as electrical shorts explains why the device still operated with only two panels functioning. Second, the mean impedance of the panels from luminaires subjected to the 45°C elevated ambient is higher than that of the control sample at all measured frequencies, and this difference was found to be statistically significant using the t-test. This finding helps to explain the observed increase in panel voltage during use with a constant current driver. Third, the measured standard deviations of the DUTs subjected to the 45°C elevated ambient is larger than the control. This last observation indicates an increase in variation in panel impedance for the DUTs subjected to the elevated ambient, which is consistent with aging of the DUTs.

Table 8. Average impedance of individual OLED panels from the control luminaires, fully operational panels from 45°C tests, and failed panels from 45°C tests.*

Frequency	**100 Hertz**	**1000 Hertz**	**10,000 Hertz**
Panels from Control	2,375 ± 10 ohms	248 ± 1 ohms	25.9 ± 0.1 ohms
Operational Panels from 45°C Bake	2,579 ± 48 ohms	272 ± 6 ohms	28.1 ± 0.6 ohms
Failed Panel #1 from 45°C Bake	7.1 ohms	7.1 ohms	6.8 ohms
Failed Panel #2 from 45°C Bake	3.3 ohms	3.3 ohms	3.3 ohms

[*] The reported uncertainties represent one standard deviation.

Through 4,500 hours of exposure to 45°C, the average luminous flux maintenance of three luminaires (DUTs 225 – 227) decreased to below 87%. Figure 23 shows that this decrease occurred steadily over time, and can be plotted in two ways. The top plot shows an exponential equation for the decay rate, with a calculated constant of 3.55×10^{-5}; the bottom plot shows a linear equation for the decay rate. The exponential decay rate corresponds to the industry accepted behavior; the linear decay rate is a simpler representation. More data is needed to determine the best fit.



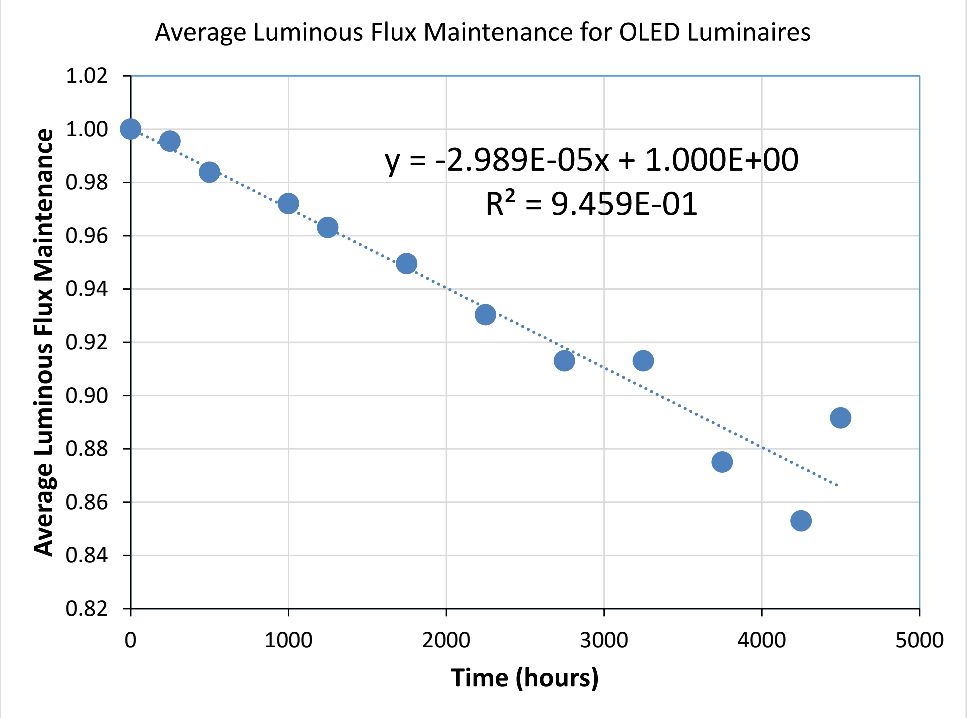


Figure 25. Luminous flux maintenance of tested commercial OLED products in an elevated ambient environment of 45°C. The top plot shows an exponential decay equation, the lower plot shows a linear equation for the same data.

Chromaticity shift in the OLED luminaires during the 45°C AST is proceeding in the blue direction with both u′ and v′ decreasing at a nearly linear rate as shown in Figure 24. This behavior is analogous to chromaticity shift mode 1 (CSM-1) behavior that was observed for PAR38 lamps containing inorganic LEDs.[22] A representative SPD from DUT #226 is given in Figure 25, and similar measurements were made for the other DUTs. One explanation

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[22] J.L. Davis, J. Young, and M Royer, "CALiPER 20.5: Chromaticity shift modes of LED PAR38 lamps operated in steady-state conditions."

for the observed chromaticity shift is a reduction in emission from red and green sources while the blue emitter decreases much less. The lower stability of the red and green emitters is characteristic of phosphorescent sources which have higher initial efficiencies but lower stability than fluorescent emitters.[23] In contrast, the higher stability of the blue source suggests that it is a fluorescent emitter.

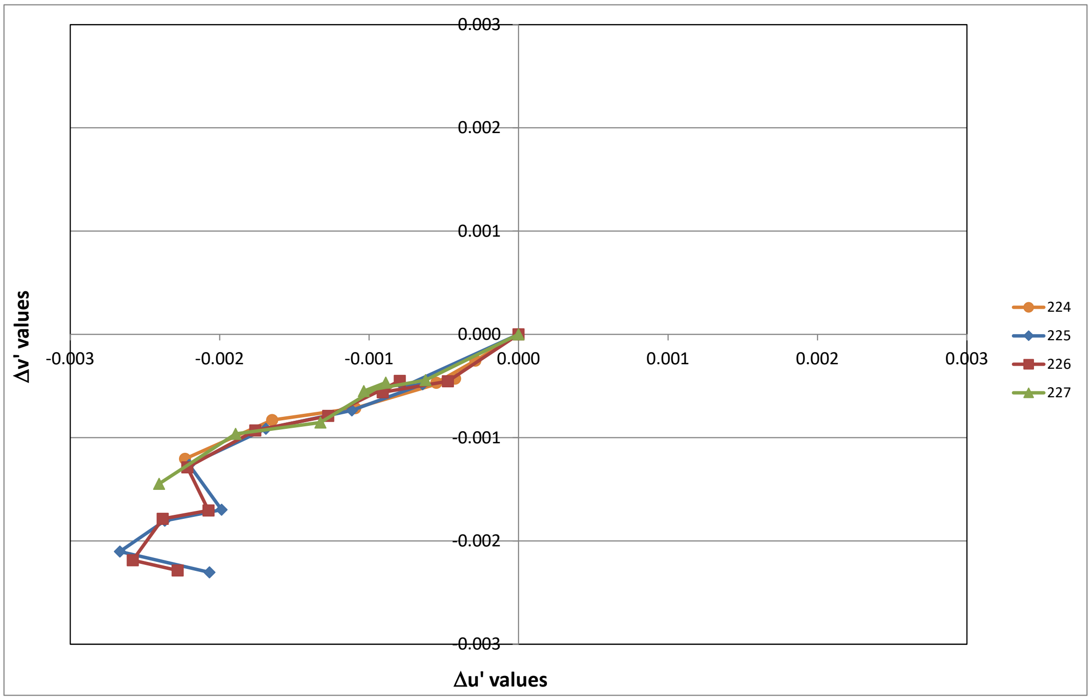

Figure 26. Graph of Δv’ vs. Δu’ for OLED luminaires subjected to elevated ambient conditions of 45°C.

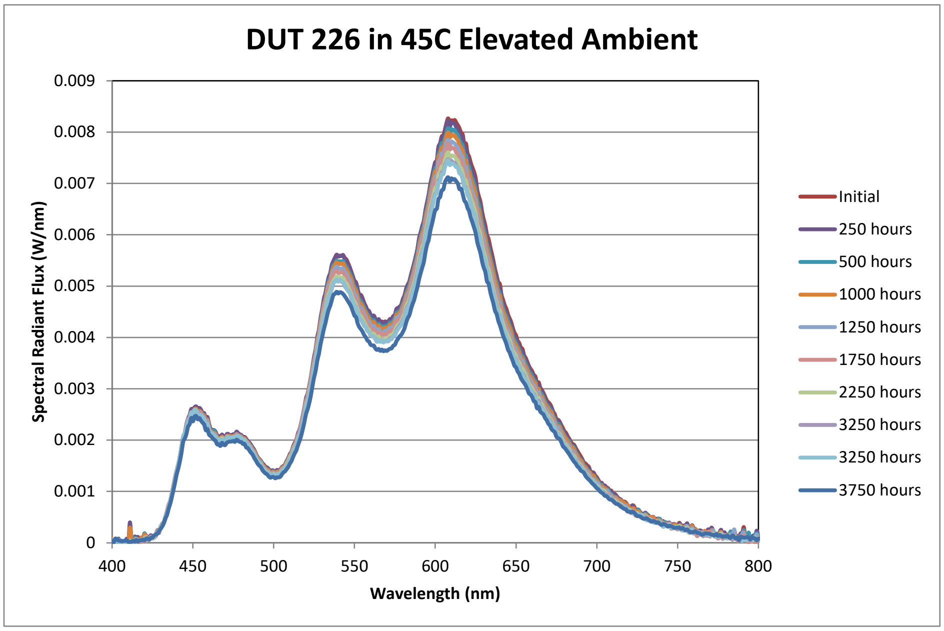

Figure 27. SPD measurements for DUT 226 at different stages of elevated ambient exposure at 45°C.

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[23] John W. Curran, “OLEDs: An introduction to the other solid-state lighting technology.” Presentation at the 2015 National Electrical Contractors Association (NECA) conference.

75°C and 75% RH (75/75) AST Results
A single luminaire (DUT #306) was subjected to 75/75 and examined after each 250 hours of exposure. Abrupt failure of the DUT occurred sometime between 500 and 750 hours. The driver for this device was examined first since this failure was an abrupt failure instead of the loss of individual panels as observed in the 45°C bake. The driver for DUT #306 was tested with another OLED luminaire and was found to be functional, ruling out driver failure as the cause of the abrupt failure.

Then, the OLED panels themselves were examined in an effort to explain the cause of the abrupt failure. A visual examination of the individual OLED panels indicated that the metallized back plane on one panel had disappeared and the panel had become translucent. (One possible explanation is that the organic material in the layer changed state with the heat and flowed to one edge of the panel, carrying the reflective cathode layer with it, leaving the panel translucent. Another explanation is that the metal backplane was completely oxidized, since it is very thin, probably less than 50 nm thick. More investigation is needed.) A comparison of this failed panel with a good panel in shown in Figure 26.

Figure 28. Photo of a surviving OLED panel (left) with a failed OLED panel (right). The failed panel's ELE layer has been partially removed to study the unexpected transparency of the backplane. Both panels were housed in the luminaire subjected to 75/75 AST protocol. (The crack in the glass panel occurred during removal of the ELE film.)

Electrical measurements were performed on all panels from the DUT #306 subjected to 75/75 testing, and the results are shown in Table 6. The electrical impedance of the failed panel is significantly higher than the functional ones indicating that the panel failed open. Since the panels are connected in series, an open circuit would result in none of the panels illuminating, as was observed. Further, since the metal layer on the backplane changed from a specular reflector to a translucent layer over most of the panel, it is speculated that the 75/75 environment resulted in oxidation of the thin aluminum layer comprising the backplane, which turned it translucent.

Table 9. Average impedance of individual OLED panels from the control luminaires, fully operational panels from the 75/75 test, and the failed panels from the 75/75 test.

Frequency	**100 Hertz**	**1000 Hertz**	**10,000 Hertz**
Panels from Control	2,375 ± 10 ohms	248 ± 1 ohms	25.9 ± 0.1 ohms
Operational Panels from 75/75 Test	2,426 ohms	256 ± 6 ohms	26.6 ± 0.6 ohms
Failed Panel 75/75 Test	4,682,000 ohms	524,000 ohms	51,590 ohms

Conclusions of RTI International accelerated lifetime testing

The AST results for the Acuity Brands Lighting, Inc. CHALINA™ OLED product provide information about the failure modes, as well as chromaticity and luminous flux maintenance of the current generation of products. Among the findings were:

- OLED panels can fail in a low impedance (i.e., near electrical short) condition that results in the luminaire providing some illumination from series-connected panels even when the shorted panel is not operational.
- Chromaticity shifts observed for these OLED products was in the blue direction due primarily to the reduction in luminous flux from phosphorescent red and green emitters while the fluorescent blue emitter decays at a slower rate.
- Through 4,500 hours of testing, the reduction of luminous flux appears to proceed in a nearly linear fashion.
- One driver failed during 45°C testing and the failure was traced to the MOSFET in the switched-mode power supply. However, the luminaire containing this driver also exhibited two panel failures and it is unknown whether the changes in the driver load resulted in the MOSFET failure, or if there were other factors.
- One OLED luminaire was subjected to elevated ambient (75/75) and this device exhibited abrupt failure in less than 750 hours of exposure. The failure was traced to a single panel which exhibited a high impedance and turned translucent.

7 Discussion

How realistic are the testing conditions used in the different forms of testing described above? The CALiPER photometric testing done by an independent commercial laboratory followed the IES LM-79-08 procedures. An OLED Working Group (S0404-10) within the IES Testing Procedures Committee concluded in 2013 that the principles for photometric testing of OLEDs followed the same principles as for LEDs. Like LEDs, OLEDs must be tested as a luminaire, since the thermal conditions of the system will affect its performance, and like LEDs the testing results are in absolute photometric quantities rather than relative quantities. These are appropriate because at this point in time there is no interchangeability of OLED panels, so it is not possible to separate the performance of the panel from the performance of the full luminaire. The ambient temperature for LM-79-08 testing is 25°C, which is similar to the temperature experienced by an OLED luminaire mounted close to the ceiling, although the ambient temperature might be 1-3° C lower for wall sconces and task lights. The OLED luminaires were run through a warm-up period until they were stable in output before formal testing began. In short, the photometric testing performed for the OLED luminaires in this CALiPER study is expected to be appropriate and accurate.

The accelerated lifetime testing operated OLED luminaires, with drivers mounted outside of the heating chamber, in four test modes, to simulate extreme conditions and also to accelerate failure modes. Three of the modes used 150 mA current, that would produce the design luminance of 3000 cd/m^2; one used 200 mA current, that would be expected to increase the panel luminance and light output by 33%, and shorten the expected operating life[24]. Two operating temperatures were tested, 45°C and 75°C, both above the manufacturer-recommended operating range of 0° to 40°C, and also well above the ambient temperature that an interior residential or commercial luminaire is likely to encounter during its lifetime, unless it is being stored in an unventilated warehouse or transported in hot cargo containers. One test also subjected the panels to both high ambient heat and very high (75%) RH, knowing that OLEDs are sensitive to moisture. All tests were run with the OLED panels energized continuously, so there were no heating-cooling cycles that usually occur with non-continuous operation in most buildings and applications.

The results of this extreme condition testing point to the weaknesses in the OLED systems, but do not directly indicate what the failure modes will be, or when they might happen. Reduced impedance, electrical shorts indicated by blackened pixels, greatly accelerated lumen maintenance, chromaticity shifts toward the blue, and changes in translucency are potential outcomes under normal operating conditions, but if they occur, are likely to occur much later in the panel's life. Panel manufacturers will be interested in these results, since they may guide R&D decisions on OLEDs, but more long-term testing is needed to know if these accelerated tests are predictive of OLED long-term performance and failure modes.

Questions for Future Testing Standardization

There are no standards for testing of OLED lighting panels and systems, although IES Testing Procedures subcommittee has been tasked with developing these. (It is inactive at this time.) Based on the testing summarized in this report, it is clear that some OLED-specific procedures need to be developed.

- Photometric testing. What changes in LM-79-08 methods are needed to accurately test OLED luminaires?

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[24] LG Chem OLED Light Panel User Guide, v.1.0.

- Luminance testing of panels. What instrument, what angle of measurement, and at what point(s) on the panel is the luminance tested? How is uniformity of luminance determined? This will be important for consistent results among laboratories.
- Color performance from different viewing angles. What instrumentation is needed, how is it reported, and how much variation is acceptable for different applications?
- OLED panel characteristics of transparency, specularity, or translucency. How are those measured and reported?
- OLED panel and system life. Since LM-80-15 and TM-21-11 do not apply to OLEDs, can standardized testing and estimating methods be developed for consistent reporting by manufacturers? How will external temperature influence the lifetime of the panel?
    - One possible approach is to drive the OLED at different current densities and have the manufacturer provide a plot of current density (or luminance) vs. lifetime (to L_{70}) at 25° C, using three different luminance levels (e.g., 1250, 3000, and 6000 cd/m^2), or the maximum rated luminance, whichever is greater.
    - A method for providing similar lifetime estimates at higher and lower ambient conditions would be helpful for more demanding applications (e.g., military, etc.)

8 Conclusions

OLEDs are a solid-state lighting product that is new to the architectural lighting marketplace, and this is the first DOE CALiPER report evaluating their performance based on independent procurement and testing of the products. Although IES LM-79-08 protocols were followed in the goniophotometer and integrating sphere testing, LM-79-08 was developed for LEDs, and may need to be modified for accurate and consistent testing of OLEDs.

Overall, efficacy of the OLED luminaires was low compared to contemporary LED luminaires, ranging from 23 lm/W up to 45 lm/W. OLED panels range between 42 and 55 lm/W according to panel manufacturer data, and much of the efficacy reduction in the luminaire performance is due to very inefficient transformer and driver selections and combinations. The wider availability of dedicated OLED drivers should improve efficacies in the near future. Drivers are also responsible for some poor performance in THD and power factor, although that will not be a major issue until OLEDs become a larger portion of the lighting load in buildings.

Color quality of the OLED luminaires depends on the panels used. CALiPER 15-13 used OLEDWorks panels, with color quality metrics (R_a, R_9, R_f, R_g, and R_f - Hue Bin 1 (red)) that are lower than those of the LG Display panels used in CALiPER 15-14, 15-15, and 15-16. The CCT of both sets of panels were about 2900 K, although the nominal CCT for the LG panels was 3000 K, according to manufacturer data.

No significant differences were noted due to orientation of luminaire 15-14. Whether it was wall-mounted or ceiling-mounted, the lumen output, input power, efficacy, power factor, color characteristics, and THD were within 1% variation. This simplifies photometry and luminaire design considerations for manufacturers, unlike using compact fluorescent lamps, for example, where performance can vary widely based on orientation.

A spectrophotometer gonio test of one pair of CALiPER 15-16 luminaires showed minor Δu’-v’ variations over a full range of viewing angles from orthogonal to the plane of the panel. These white OLED panels have an extraction layer which minimizes variation across different viewing angles. (Without the extraction layer, the color variation due to viewing angle is much more pronounced, and can be employed as an intentional design element, but at a cost in efficacy.)

Light distribution was consistent among the tested products, a soft, diffuse, roughly Lambertian emission, moderated only by the physical configuration of the luminaire hardware. This is expected to produce very soft shadows from objects in the path of the light, and patterns of light on surfaces with very soft gradients at the edges of the “beam.”

The CALiPER OLED luminaires performed very closely to the manufacturers’ published technical data, where available.

Teardown testing was done in the PNNL Lighting Metrology Laboratory, in order to examine a failed OLED panel from sample 15-15A, and to examine driver efficiency. In the damaged panel, a compromise in the OLED seal along one edge of the glass was the likely cause of the discoloration. Such a compromise can allow air and moisture to penetrate the panel and interact with the organic layers.

The drivers for all four CALiPER luminaire types were different, with some luminaires using a single driver, and others using a combination of electronic components for voltage transformation, conversion from AC to DC, and voltage/current control. Luminaire 15-13’s power electronics were estimated at 80% efficiency, with additional losses likely due to the addition of a cell phone charging circuit. 15-14 is a larger luminaire with 5 panels, and its power control electronics efficiency was estimated at a respectable 85%. 15-16 and 15-15 are one- and two-panel wall sconces, with tandem drivers, operating at a low estimated efficiency of 47% to 58%. The low driver electronics efficiencies are a concern because they directly affect system efficacy.

All OLED panels in luminaires studied for this CALiPER testing round had light extraction film applied in the panel factory to increase lumen output and reduce losses from light trapped in the glass panel, to increase diffusion, and to mask a gridded appearance in the panel.

Accelerated lifetime testing of OLED luminaires performed by RTI International yielded the following results: some failures occurred from degradation due to operations under continuous elevated ambient conditions, at 45°C and 150 mA, 75°C at 150 mA, 75°C with 75% RH at 150 mA, and high current operation (200 mA) at 45°C. One failure mode was breakage of the small gauge wires between the driver and panel, suggesting that the wiring and connectors may need closer attention.

In testing at 45°C, panel impedance was observed to increase with time, which helps to explain the higher drive voltages that are required when operating the panels under constant current conditions. In addition, it became clear over the testing that panels tested under elevated ambient temperature conditions may fail as electrical shorts, allowing multi-panel luminaires to continue operating even when less than the full number of panels is operating properly. Impedance of failed panels was found to be much lower than that of operational panels, and a close visual inspection revealed that failed panels all had a dark spot indicating a short. Therefore, it is postulated that panel impedances rises until a short-circuit failure occurs, which is a terminal failure mode for a panel but allows the luminaire to continue operating, albeit at a lower lumen output.

Decay in light output under elevated ambient conditions was steeper than expected at room temperature, with a steady decline over operation. After 4250 hours of continuous operation at 45°C, lumen maintenance averaged 87%. Using the general rule of thumb that a 10°C increase in temperature results in a doubling of the rate of decay processes, the decay rate at 25°C is estimated to be approximately one-fourth of that measured at 45°C. In the study at 45°C, chromaticity shifted toward the blue at a nearly linear rate, likely explained by a reduction in output from red and green organic layers while the blue layer was steady.

High heat and high humidity tolled the death knell for OLEDs. Under 75°C and 75% RH, one tested luminaire panel (not the driver) failed between 500 and 750 hours of operation, and the panel became translucent. However, there is not enough long-term data to know whether this accelerated testing is predictive of OLED long-term performance and failure modes. Until more is known, it would be well to assume the 45° C testing results are more predictive than the 75° C and 75% RH results.

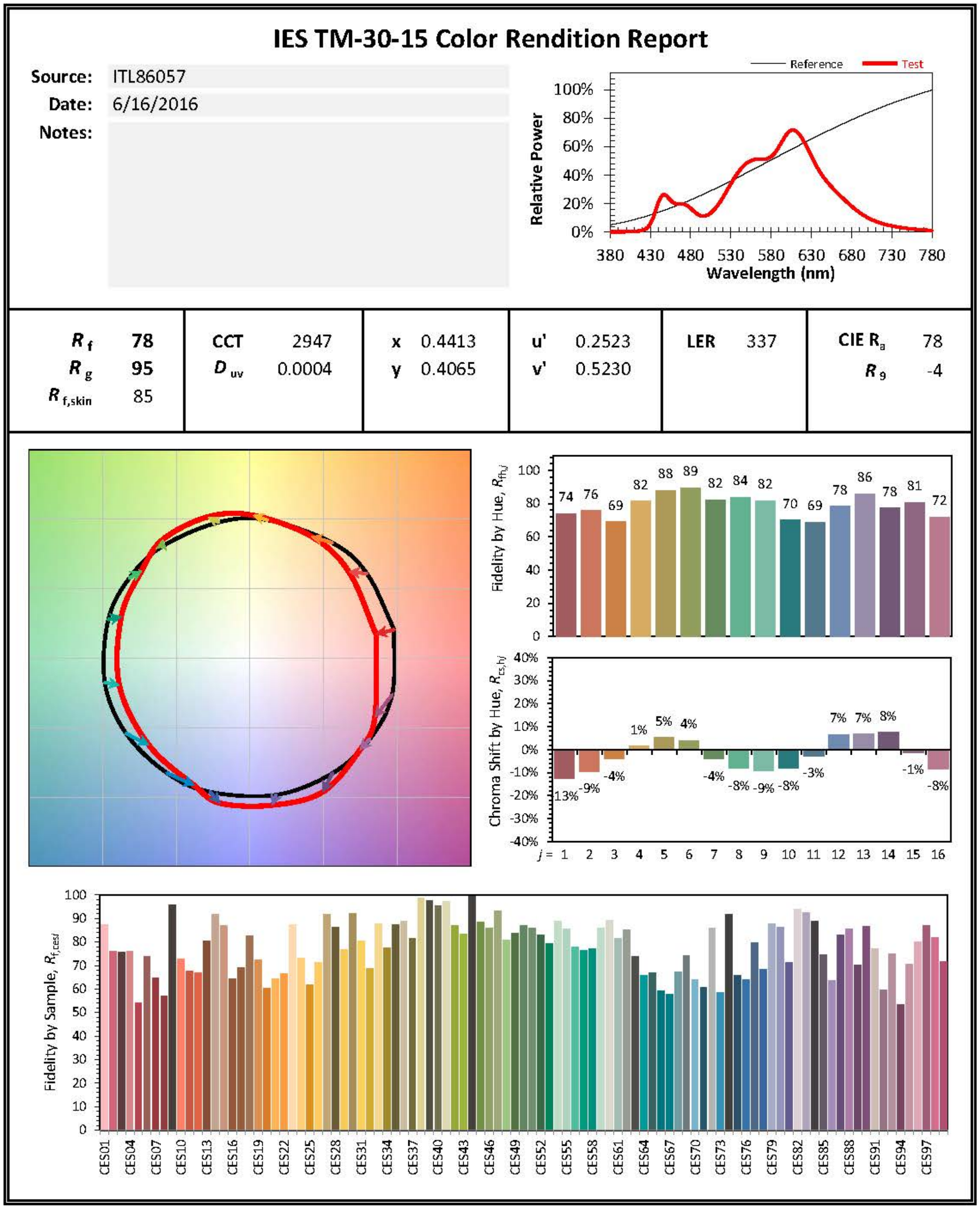
OLED panels, drivers and transformers are still in a steep curve of development. Goals are higher efficacy; longer life before panel replacement on the jobsite is needed; better lumen maintenance over time; even better color quality and wider CCT options; higher efficiency drivers; and robustness under high temperature, high humidity, and rough handling from shipping and installation. Improvements in these areas will make OLED luminaires more accepted in the architectural marketplace, and adopted as a trusted lighting solution.

Appendix A: Definitions

$\Delta u'v'$	A measure of color difference or color changed, calculated as Euclidian distance between two chromaticity coordinate pairs in the CIE 1976 (u', v') uniform chromaticity scale (UCS).
Correlated Color Temperature (CCT)	The absolute temperature of a blackbody radiator having a chromaticity that most nearly resembles that of the light source. CCT is used to describe the color appearance of the emitted light in units of kelvin (K).
Color Rendering Index (CRI or R_a)	A measure of color fidelity that characterizes the general similarity in color appearance of objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for eight color samples illuminated with the test and reference source. See also: *Special Color Rendering Index* R_9.
D_{uv}	The distance from the Planckian locus on the CIE 1960 (u, v) chromaticity diagram (also known as u', 2/3 v'). A positive value indicates that the measured chromaticity is above the locus (appearing slightly green) and a negative value indicates that the measured chromaticity is below the locus (appearing slightly pink). The American National Standards Institute provides limits for D_{uv} for nominally white light.
Fidelity Index (R_f)	The fidelity index from IES TM-30-15 measures the similarity of object colors under a test light source and a reference light source. The maximum value (perfect fidelity) is 100, and the minimum value is 0. For more information, see https://www.osapublishing.org/oe/abstract.cfm?URI=oe-23-12-15888
Gamut Index (R_g)	The gamut index from IES TM-30-15 measures the saturation of object colors under a test source compared to a reference source. A score of 100 indicates the same average level of saturation, a score greater than 100 indicates increased average saturation, and a score less than 100 indicates decreased average saturation. For more information, see https://www.osapublishing.org/oe/abstract.cfm?URI=oe-23-12-15888
Input Power Watts (W)	The power required to operate a device (e.g., a lamp or a luminaire), including any auxiliary electronic components (e.g., ballast or driver).
Luminous Efficacy Lumens per watt (lm/W)	The quotient of the total luminous flux emitted and the total input power.
Luminous Efficacy of Radiation (LER) (lm/W_{rad})	The quotient of the total luminous flux emitted and the total radiant flux emitted. This is a measure of the efficiency of the SPD, expressing the amount of lumens generated per watt of emitted optical radiation.
Light Output Lumens (lm)	The amount of light emitted by a lamp or luminaire. The radiant energy is weighted with the photopic luminous efficiency function, V(λ).
Power Factor	The quotient of real power (watts) flowing to the load (e.g., lamp or fixture) and the apparent power (volt-amperes) in the circuit. Power factor is expressed as a number between 0 and 1, with higher values Indicating less waveform distortion or displacement.

Spectral Power Distribution (SPD)	The power per unit wavelength of radiant energy. The light may be that emitted by a source or reflected from a surface.
THD-I	A measure of the level of harmonic distortion present in a current waveform, defined as the ratio of the sum of all harmonic components of the waveform to the value at the fundamental frequency.

Appendix B: SPDs



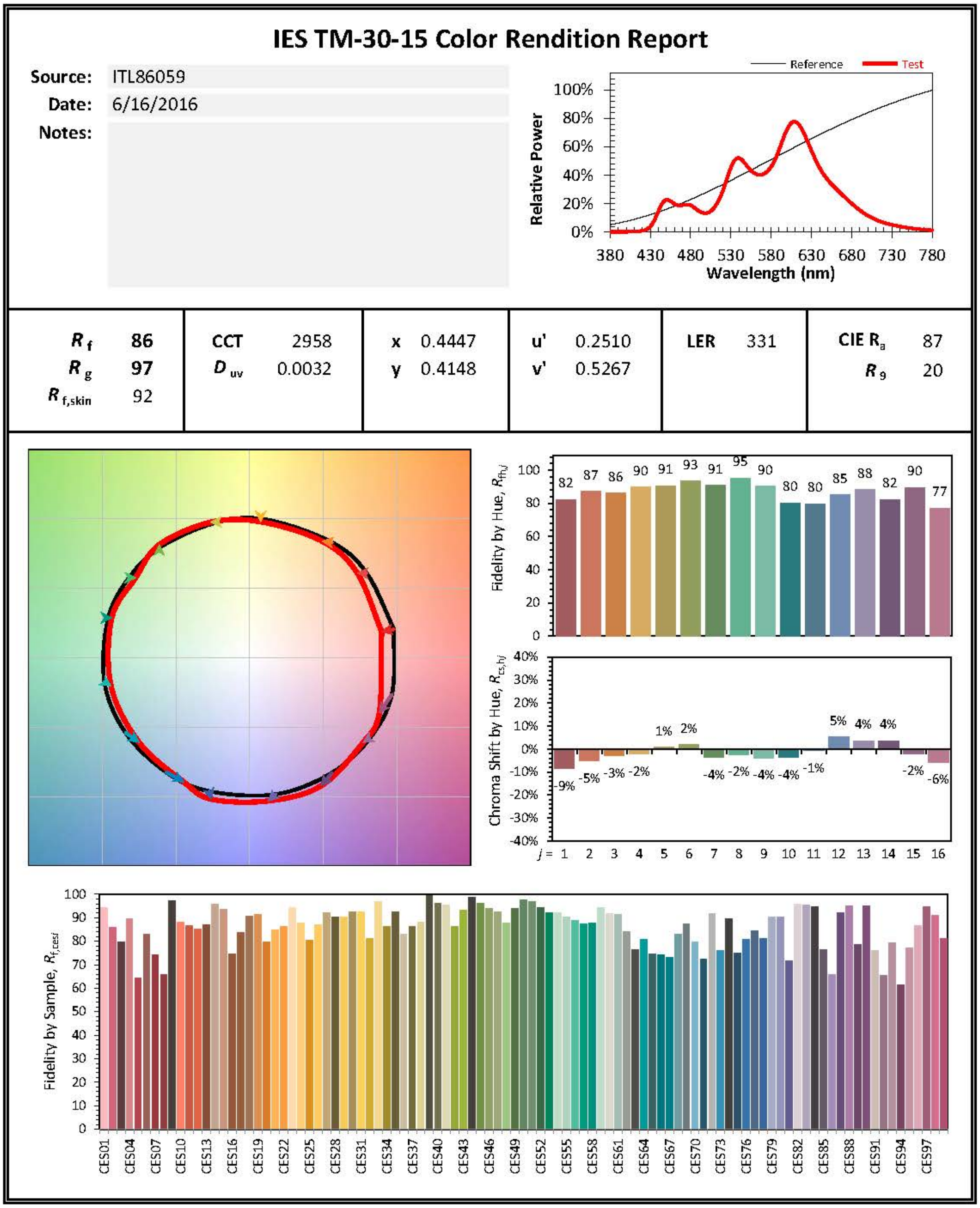
IES TM-30-15 Color Rendition Report

Source: ITL86057
Date: 6/16/2016
Notes:

R_f 78 R_g 95 $R_{f,skin}$ 85	CCT 2947 D_{uv} 0.0004	x 0.4413 y 0.4065	u' 0.2523 v' 0.5230	LER 337	CIE R_a 78 R_9 -4

Created with the IES TM-30-15 Advanced Calculator Version 1.01

Figure B 1. Color data for CALiPER 15-13A, per IES TM-30-15.



IES TM-30-15 Color Rendition Report

Source: ITL86059

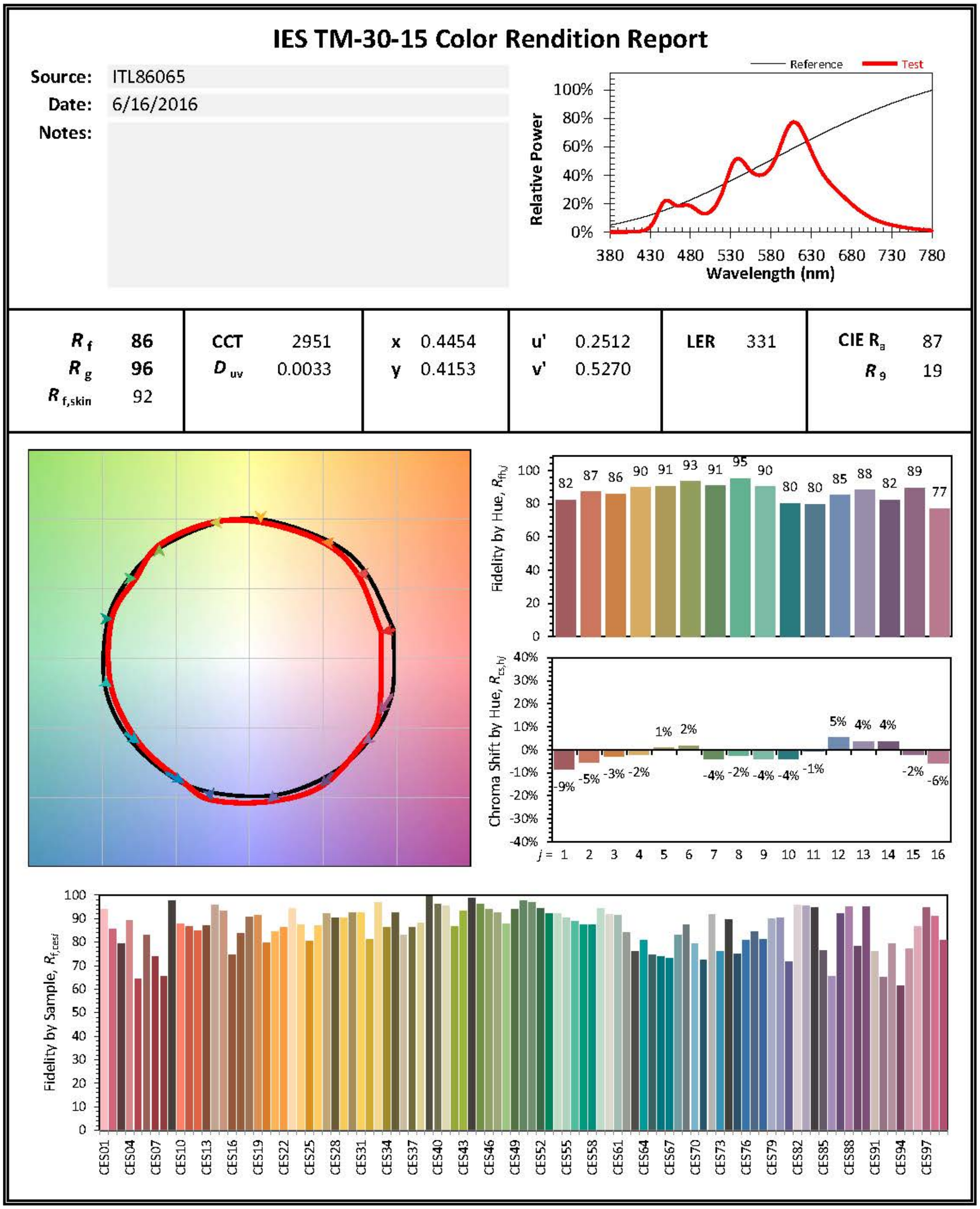
Date: 6/16/2016

Notes:

R_f 86	CCT 2958	x 0.4447	u' 0.2510	LER 331	CIE R_a 87
R_g 97	D_{uv} 0.0032	y 0.4148	v' 0.5267		R_9 20
$R_{f,skin}$ 92					

Created with the IES TM-30-15 Advanced Calculator Version 1.01

Figure B 2. Color data for CALiPER 15-14A ceiling mounted, per IES TM-30-15.



IES TM-30-15 Color Rendition Report

Source: ITL86065

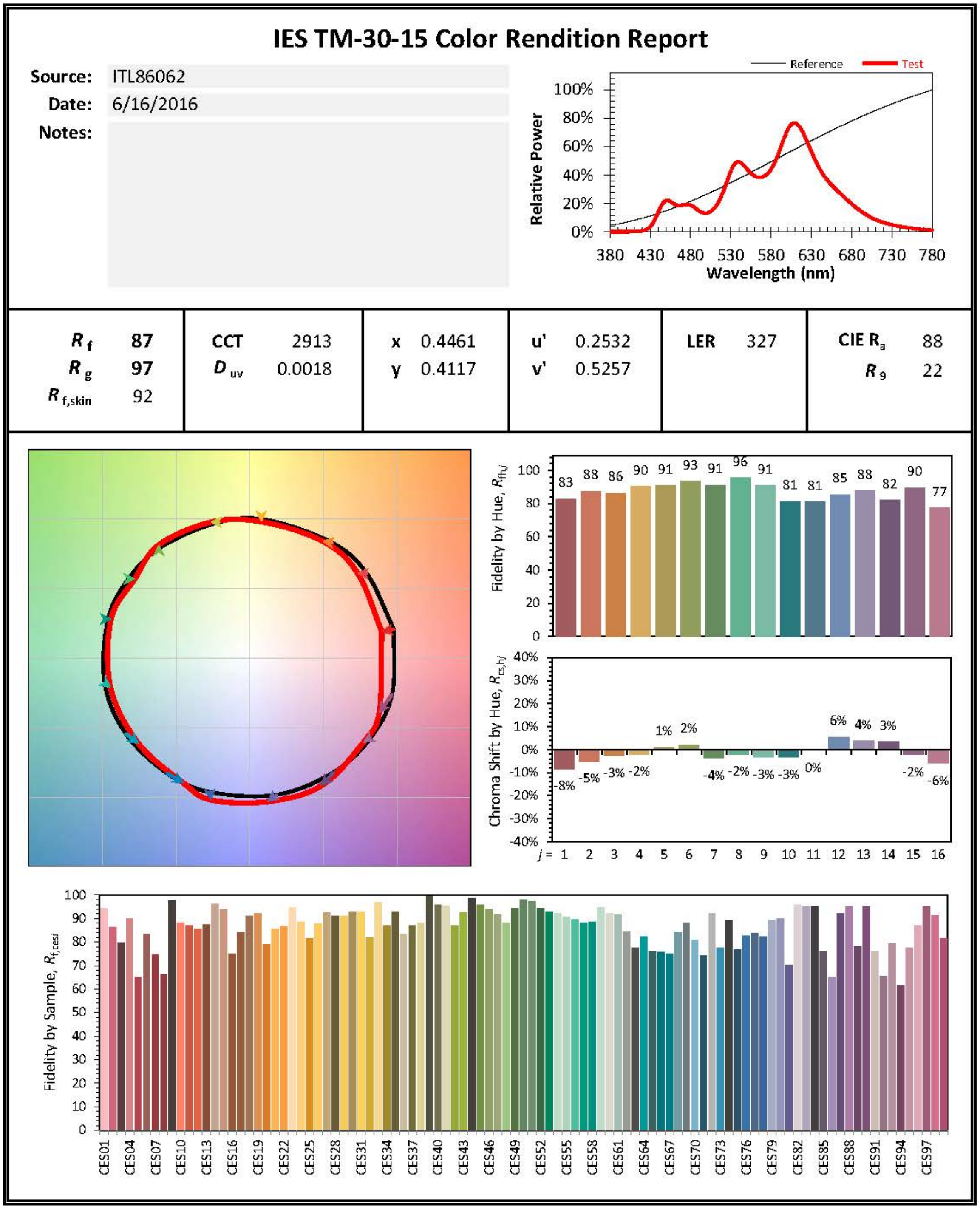
Date: 6/16/2016

Notes:

R_f	86	CCT	2951	x	0.4454	u'	0.2512	LER	331	CIE R_a	87
R_g	96	D_{uv}	0.0033	y	0.4153	v'	0.5270			R_9	19
$R_{f,skin}$	92										

Created with the IES TM-30-15 Advanced Calculator Version 1.01

Figure B 3. Color data for CALiPER 15-14A wall mounted, per IES TM-30-15.



IES TM-30-15 Color Rendition Report

Source: ITL86062

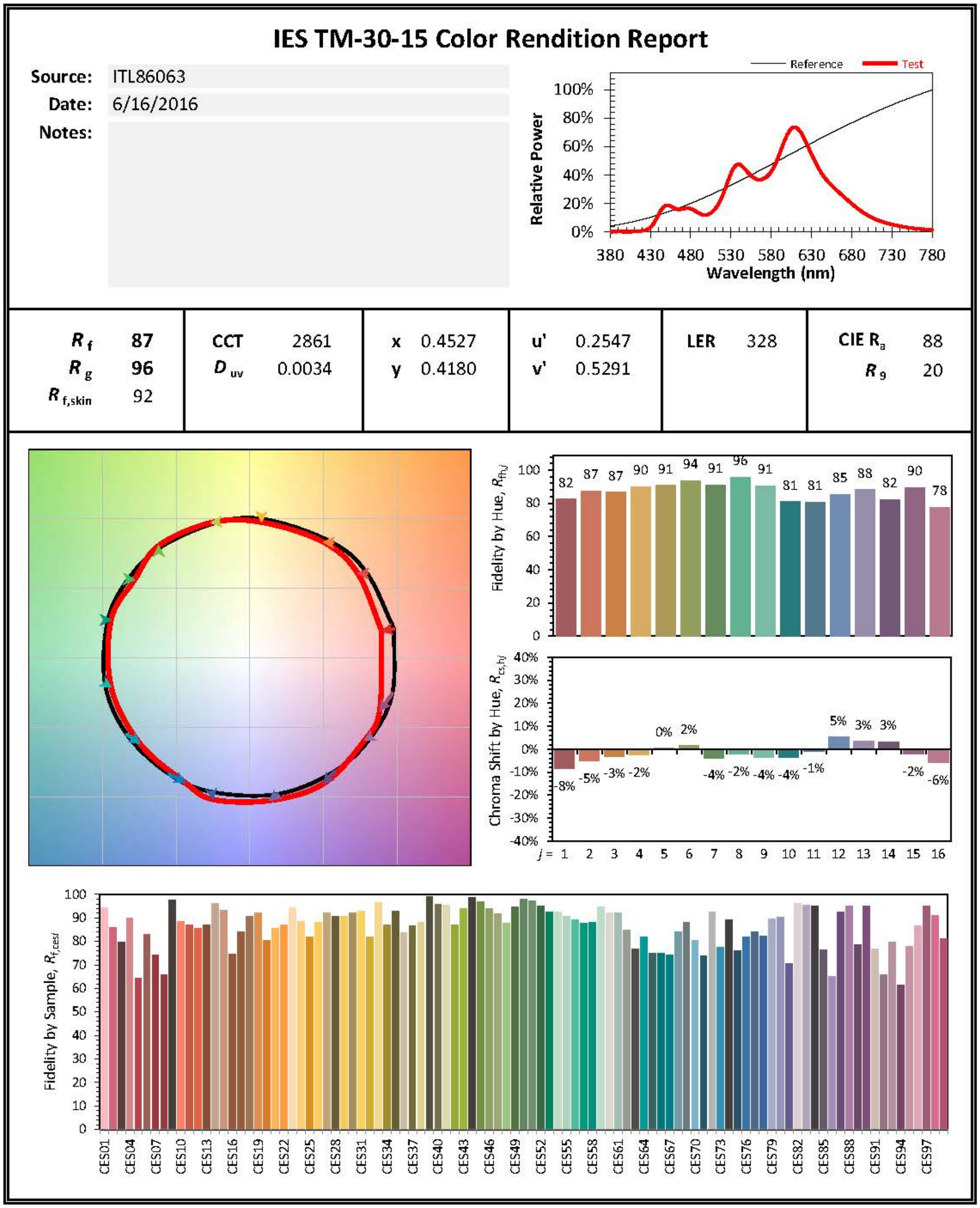
Date: 6/16/2016

Notes:

R_f	87	CCT	2913	x	0.4461	u'	0.2532	LER	327	CIE R_a	88
R_g	97	D_{uv}	0.0018	y	0.4117	v'	0.5257			R_9	22
$R_{f,skin}$	92										

Created with the IES TM-30-15 Advanced Calculator Version 1.01

Figure B 4. Color data for CALiPER 15-15B, per TM-30-15.



IES TM-30-15 Color Rendition Report

Source: ITL86063
Date: 6/16/2016
Notes:

R_f	87	CCT	2861	x	0.4527	u'	0.2547	LER	328	CIE R_a	88
R_g	96	D_{uv}	0.0034	y	0.4180	v'	0.5291			R_9	20
$R_{f,skin}$	92										

Created with the IES TM-30-15 Advanced Calculator Version 1.01

Figure B 5. Color data for CALiPER 15-16A, per TM-30-15.