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Stress Testing of Organic Light-Emitting Diode Panels and Luminaires

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Stress Testing of Organic Light-Emitting Diode Panels and Luminaires

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List of Acronyms

ac	Alternating current
AST	Accelerated stress test
CALiPER	Commercially available LED product evaluation and reporting
CCR	Constant current reduction
CCT	Correlated color temperature
CRI	Color rendering index
dc	Direct current
DOE	U.S. Department of Energy
DUT	Device under test
IES	Illuminating Engineering Society
LED	Light-emitting diode
LPW	Lumens per watt
OLED	Organic light-emitting diode
PWM	Pulse-width modulation
RT	Room temperature
RTI	Research Triangle Institute
RTOL	Room temperature operational life
SPD	Spectral power distribution
SSL	Solid-state lighting
TM	Technical memorandum

Executive Summary

Luminaires and other lighting devices using organic light-emitting diode (OLED) sources have many advantages over their competitors for indoor lighting, including thin form factors that produce highly diffuse, potentially low-glare, lighting with excellent color rendering properties. However, several significant issues with OLED products have limited their commercial acceptance to date, including source efficacy, source lifetime, driver performance, and initial costs. The U.S. Department of Energy (DOE) has released four reports on OLED technologies to provide the lighting industry with information on the state of the technology. These reports include the evaluation of two different field deployment sites, a market analysis, and an independent assessment of the performance of several commercially available OLED products.

This report builds on previous DOE efforts with OLED technology by updating information on a previously benchmarked OLED product (the Chalina luminaire from Acuity Brands) and provides new benchmarks on the performance of Brite 2 and Brite Amber OLED panels from OLEDWorks. During the tests described here, samples of these devices were subjected to continuous operation in stress tests at elevated ambient temperature environments of 35°C or 45°C. In addition, samples were also operated continuously at room temperature in a room temperature operational life test (RTOL). One goal of this study was to investigate whether these test conditions can accelerate failure of OLED panels, either through panel shorting or an open circuit in the panel. These stress tests are shown to provide meaningful acceleration of OLED failure modes, and an acceleration factor of 2.6 was calculated at 45°C for some test conditions. In addition, changes in the photometric properties of the emitted light (e.g., luminous flux and chromaticity maintenance) was also evaluated for insights into the long-term stability of these products compared to earlier generations. Because OLEDs are a lighting system, electrical testing was also performed on the panel-driver pairs to provide insights into the impact of the driver on long-term panel performance.

The Chalina luminaire from Acuity Brands uses OLED panels made by LG Display. These panels utilize a 3-tandem stack structure with one layer containing a blue fluorescent emitter and two layers containing combined green and red phosphorescent emitters. In this study, three different generations (denoted as Gen 1, Gen 2, and Gen 3) of OLED panels were found to be used in the tested Chalina luminaires. Gen 2 and Gen 3 OLED panels are characterized by a copper foil adhered to the back of the panel, whereas Gen 1 OLED panels have a mirror-like finish on the back. Chalina luminaires with Gen 1 panels were previously discussed in CALiPER 24.

While the light emission characteristics of the OLED panels in the Chalina luminaire were the same regardless of the generation of the light source, the thermal stability of the emitter materials was found to have improved over previous benchmarks. Stress tests described in CALiPER 24 demonstrated that the phosphorescent green and red emitters used in the Gen 1 OLED panels have lower thermal stability than the fluorescent blue emitter. As a result, the chromaticity of the Gen 1 panels shifted in the blue direction, and that trend continued in the additional testing reported here. Furthermore, the impedance increase in the Gen 1 panels was also significant in an elevated ambient temperature of 45°C, resulting in the need for progressively higher driver voltage to maintain a constant current. In the benchmark testing reported here, the thermal stability of the phosphorescent emitters was much better in the Gen 2 and Gen 3 OLED panels used in the Chalina luminaires, and there was minimal change in the impedance of the OLED panels, even at an elevated ambient temperature of 45°C for 2,000 hours. These findings demonstrate a significant improvement in the thermal performance of OLED panels, although the luminous flux maintenance improved little.

Likewise, the color rendition properties of the Brite 2 FL300 panels from OLEDWorks has been improved significantly over that of the Brite 1 panels benchmarked in earlier DOE studies. This improvement has been produced by a new mix of phosphorescent emitters that include significant emission in the far red. As a result, the color rendering metrics including color fidelity (R_f), color gamut (R_g), red color rendering (R_9), and the color rendering index (CRI) are generally improved over that of the Brite 1 panels benchmarked in earlier DOE studies. It appears that the same organic emitters are used for both neutral white and warm white Brite 2

panels with the ratio of blue, green, and red emitters altered to achieve a desired color point. As a result, the luminous efficacy of the commercial Brite 2 lighting system was 32 lumens per watt (LPW) for the neutral white product (including OLED panel, power supply, and driver) and 38 LPW for the warm white product (including the OLED panel, power supply, and driver). The efficiency of the power supply and the driver were measured to be 70.5%. As a result, the luminous efficacy of the OLED panels alone was 45 LPW for the neutral white panel and 54 LPW for the warm white panel, at driver currents of 263 mA. These values are slightly below the manufacturer's specification of 46 LPW (neutral white) and 57 LPW (warm white). Both the Brite 2 warm white and Brite 2 neutral white panels were found to render red colors in a manner comparable to the reference sources; however, the Brite 2 panels produced some desaturation in green colors, and this effect was larger for the neutral white panels than for the warm white. To date, samples of the Brite 2 panels described in this testing have been through 1,500 hours of testing at 45°C, 35°C, and room temperature with no failures; however, black spots have appeared on two samples operated continuously at room temperature.

OLEDWorks also manufactures an amber emitter, consisting of a 2-tandem stack of mixed red and green phosphorescent emitters. The intended application of this light source is melanoptic lighting. These samples have generally fared well through 1,500 hours of testing at 35°C and room temperature; however, at 45°C, all three samples failed as electrical shorts before 1,500 hours had elapsed. Because this device operates at only 6 volts direct current (dc), finding an appropriate driver for consistent operation may be difficult. Based on this result, additional testing is needed to determine whether the failure of the Brite Amber panels in the 45°C test is due to an issue with the OLED panel or with the driver.

The results demonstrate that the performance of OLED panels continues to improve. Additional gains are necessary to increase the system efficiency of OLEDs to be more comparable to that of inorganic LEDs. Gain in the luminous efficacy of OLED panels will help to improve overall system efficiency, but attention must be paid to the drivers used in OLEDs as well. The driver for the Chalina luminaire demonstrated good efficiency (83.9%) and a high power factor (0.99). In contrast, the drivers used for the Brite 2 and Brite Amber products was less efficient, and the power factor was significantly lower. These findings reinforce conclusions from earlier DOE studies that developing custom power supplies for OLED products is imperative for the industry.

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1 Introduction

Lighting using organic light-emitting diodes (OLEDs) is still in its infancy, and the technology faces several notable challenges, including reducing costs and commercializing the high-efficacy performance that has been demonstrated in the laboratory [1]. Especially in some indoor lighting applications, OLED technologies have the potential to offer intriguing benefits including brightness, thin form factor, high light quality (with excellent color rendering indices [CRI]), and the delivery of diffuse light that can be deployed close to the task without creating uncomfortable glare.

Some of the challenges faced by OLED technologies in lighting application are analogous to those faced by inorganic light-emitting diodes (LEDs) during the early stages of technology development. In an effort to provide the industry with information on the state of the technology, this report documents findings from a follow-up investigation on a commercial OLED luminaire product and recent testing results on the performance of commercial OLED panels using new breakthroughs. Test results on the performance of OLED panels will depend upon the match between the panel and the driver supplying the panel. Consequently, OLED lighting products, even at the panel level, need to be considered an entire system comprised of OLED panel(s), a driver, and a luminaire frame (for assembled products).

1.1 Previous DOE Efforts with OLEDs

The U.S. Department of Energy (DOE) has supported the development of OLED technologies as an integral part of the solid-state lighting (SSL) program. Recently, DOE published four reports highlighting OLED technologies including two field evaluations [2, 3], a Commercially Available LED Product Evaluation and Reporting (CALiPER) study as part of a laboratory evaluation [4], and a market analysis [5]. A general conclusion from these studies is that the cosine emission profile of the light produced by OLED devices is beneficial, especially for indoor lighting, and provides the product with a unique look and functionality. However, issues with the efficacy, lifetime, driver performance, and initial costs of OLED devices are analogous to the early years of inorganic LEDs used for lighting applications. One goal of this report is to update benchmark information on OLED products to document any improvement in OLED technologies since the CALiPER 24 study was completed.

While there are several manufacturers of OLED panels for lighting applications [5], panels made by LG Display and OLEDWorks have been the primary focus of DOE studies to date due to their use in commercial luminaires. While panels from both manufacturers use fluorescent blue emitters and phosphorescent red and green emitters, LG panels employ a 3-tandem stack device structure [6], whereas panels from OLEDWorks incorporate a 6-tandem stack structure [7]. Panels from LG Display have been used in a broad range of luminaire types examined in DOE studies including both Gateway and CALiPER reports [2–5]. The luminaires in these DOE reports that incorporated panels from OLEDWorks mainly used the older Brite 1 technology [2 – 4], although the newer Brite 2 panel was examined in the most recent DOE report [3]. Previous DOE reports provide a snapshot of the manufacturer's specified performance for these OLED panels, and relevant parameters are collected from these previous reports and provided in **Table 1**–1. Spectral power distributions (SPDs) and Illuminating Engineering Society (IES) Technical Memorandum-30 (TM-30) calculations for these panels were included in previous DOE studies using data from CALiPER studies and the manufacturers [2–5].

Table 1–1. Comparison of OLED panel performance given in DOE studies [2, 5].

	LG Display N65 Series	OLEDWorks Brite 1 FL300	OLEDWorks Brite 2 FL300	OLEDWorks Brite Amber
Color (CCT, CRI)	3,000 K, 90 CRI	2,900 K, 79 CRI	3,000 K, > 90 CRI	1,867 K
L70 panel life, panel lumens	40,000 hours @ 3,000 cd/m²	10,000 hours @ 8,300 cd/m²	10,000 hours @ 8,300 cd/m²	25,000 hours
Panel efficiency (new)	55 LPW	42 LPW	57 LPW	40 LPW
Panel luminance, panel wattage	3,000 cd/m², 2.5 W	8,300 cd/m², 7.4 W	8,300 cd/m², 5.3 W	2,000 cd/m²

CCT = correlated color temperature

Initial reliability studies were performed by RTI International on the Chalina luminaire from Acuity Brands, and these results were included in the CALiPER 24 report [4]. The Chalina luminaire uses panels made by LG Display. Initial studies of this product confirmed the excellent quality of the light produced by the OLED panels but also found a higher rate of luminous flux depreciation (as measured by the value of the exponent in an exponential decay least squares fit of lumen maintenance) than is currently found with inorganic LEDs. This finding likely reflects the early stage of OLED technology development. An additional finding from these studies was that the decrease in the rate of emission from green and red phosphorescent emitters was faster than that found for blue fluorescent emitters. As a result, the chromaticity of the panels in this initial study shifted in the blue direction over time, and the correlated color temperature (CCT) values of this product increased.

Previous studies from DOE also highlighted several issues with the drivers used in OLED panels. Drivers that power OLED panels are typically constant current devices, and dimming of the OLED panel is best accomplished with a constant current reduction (CCR) dimmer as compared to a pulse-width modulation (PWM) dimmer [2]. CCR dimmers adjust the driving current for the OLED and have minimal impact on photometric flicker. In contrast, PWM dimmers adjust the on/off duty cycle of power to the OLED. While this method works well with LEDs, it often causes increased flicker with OLEDs [2]. Previous DOE reports have also indicated the importance of maintaining sufficient headroom in the driver voltage to accommodate the expected increase in panel impedance during use [4]. An additional finding of previous DOE studies has been a wide range in driver efficiency, often caused by the dearth of commercial OLED driver products and the tendency for most OLED luminaires use an LED driver that may not have the optimal voltage and power efficiencies for use in the OLED device [4].

1.2 Scope of This Report

The scope of this report is to provide updates on the status of OLED technologies in four key areas:

- Updating laboratory test results for the Chalina luminaire, which uses three different generations of OLED panels from LG Display;
- Providing laboratory test results, including stress testing results for the Brite 2 and Bright Amber panels from OLEDWorks;
- Compare stress testing results for panels from both LG Display and OLEDWorks to room temperature operational life (RTOL) testing results;
- Providing additional information on the drivers used with these products including laboratory measurements of their electrical performance and parameters such as efficiency and power factor.

2 Comparison of LED and OLED Reliability Studies

A recent investigation of the reliability of LED-based lighting systems, performed by the Research Triangle Institute (RTI), used both accelerated stress test (AST) methods and failure models to assess entire luminaires and key system components, such as LEDs, drivers, and optical elements [8]. A systems-level view of reliability has been shown to be important in understanding the expected lifetime of SSL devices [8, 9]. OLED luminaires are different in many ways from LED luminaires, but in the current study, OLED panels and drivers are examined together as a system to understand lifetime expectations.

OLED lighting systems differ from LED luminaires in several ways. Most significantly, OLED lighting systems contain one or more emission panels at a scale size of centimeters as opposed to the packaged LED die in LED luminaires that have a scale size of millimeters. OLED panels are planar light sources made up of layered chemistries, sandwiched between two electrodes. As a result, OLED lighting systems do not typically use additional secondary optical components such as diffusers and lenses. OLED lighting systems mainly consist of the OLED panel(s), one or more drivers, and a frame; components such as lenses, diffusers, and reflectors, which are common among luminaires with inorganic LEDs, are incorporated into the OLED panels or not used at all. Consequently, an OLED lighting system can fail during stress testing differently than an LED luminaire does. For example, an entire OLED panel may not fail at once; instead, pixels may fail within the OLED panel, reducing luminous flux and becoming visible to the end user. In addition, the multiple emitters used to produce white light in OLEDs may exhibit significantly different lifetime characteristics, which can cause chromaticity shifts through different mechanisms and at different rates than inorganic LED devices do [4]. Other failure modes that can occur in OLED lighting systems include panel shorting, moisture ingress, and driver failure [4].

Previous stress testing studies of LED luminaires showed the robustness of LEDs themselves was high and any fragility most likely resides in luminaire components, such as the driver and optics [8, 9]. LED luminaires have been exposed to high temperature and high humidity conditions (e.g., 75°C and 75% relative humidity) and withstood several thousands of hours, on average, in such conditions before failure occurred. However, OLEDs tested at these conditions were found to be over-stressed, thus resulting in unrealistic failure modes [4]. Since OLED devices are most likely to be used indoors, changes in temperature and electrical currents were found to be the most appropriate conditions for ASTs [10]. These findings agree with previous studies demonstrating that models built on combined degradation from temperature and electrical current can accurately capture the decay in luminous flux from OLED devices [11, 12]. Alternatively, if an OLED device is operated at a known current, such as would occur when driven by a constant current driver, the decay process of the device can be accelerated using temperature alone. This approach is analogous to accelerated tests commonly used with inorganic LEDs (e.g., IES LM-80 testing) and is likely to be pursued in standardized tests of OLEDs to keep testing duration to a practical level [10].

3 Experimental Methods

The current study focuses on OLED luminaires and panels from two commercial sources, Acuity Brands, a luminaire manufacturer, and OLEDWorks, a panel manufacturer. Luminaires from Acuity Brands contain panels from LG Display, although recent information suggests that Acuity Brands is using OLED panels from both LG Display and OLEDWorks in some products [13]. CALiPER 24 provided early results on the Chalina luminaire from Acuity Brands with panels from LG Display [4], and the findings on this product are updated here. An examination of the Brite 2 panels from OLEDWorks is also provided in this report as a complement to earlier DOE studies on Brite 1 panels [2-5].

As summarized in **Table 3**–1, this report provides findings from stress testing involving temperature bakes at mildly elevated temperatures. The findings from these tests are compared to the performance of the OLED devices during RTOL testing to gauge the acceleration factor of a temperature-only test at a constant current for device operation. During all tests, the OLED devices were continually powered, and there was no effort to power cycle the devices. In addition, all OLED devices were operated with the drivers provided by the manufacturer, and these drivers were operated at their expected maximum conditions with no dimming signals applied to the product.

Table 3–1. Testing methods used during this investigation.

Test Name	Test Description
45°C	Continuous operation at a constant temperature of 45°C
35°C	Continuous operation at a constant temperature of 35°C
RTOL	Room temperature operational life — room temperature and ambient humidity

3.1 Samples

3.1.1 Acuity Brands Chalina Luminaire with Panels from LG Display

The Chalina luminaire from Acuity Brands was one of the first commercial OLED products produced on a large scale by a major luminaire manufacturer. This product uses five square OLED panels (made by LG Display) with emission areas between 813 cm^2 and 835 cm^2, depending on the purchased population. An evaluation of this product has been given previously [4]. During the testing reported herein, the drivers supplied with the Chalina product were used to power the OLEDs, and these drivers were placed outside the temperature chamber to minimize the effects of driver degradation on panel performance.

Chalina luminaires were purchased for testing at three different times during the current work (September 2015, August 2016, and July 2017). It is apparent that some changes occurred in the OLED panel construction over this period. The OLED panels included in CALiPER 24 were of one style, hereafter termed Gen 1, that could be readily identified by the specular mirror-like appearance of the back of the panel [4]. In contrast, as shown in **Figure 3-1**, luminaires purchased in 2016 and 2017 used a metal foil on the backside of the OLED panel, presumably to help with heat dissipation. The initial impedances of the panels used in the Chalina luminaire were different depending upon the time of purchase, and a comparison of the initial impedance values (taken at 100 Hz and 1,000 Hz) is given in **Table 3-2**. To facilitate this discussion, the sample populations were designated as Gen 1, 2, and 3, depending on purchase date. It is unknown whether these changes in impedance were the result of process changes in panel manufacturing or whether they arise from naturally occurring process variation with time. For all devices, regardless of the purchase date, the driver used with the Chalina luminaire remained the same part number.

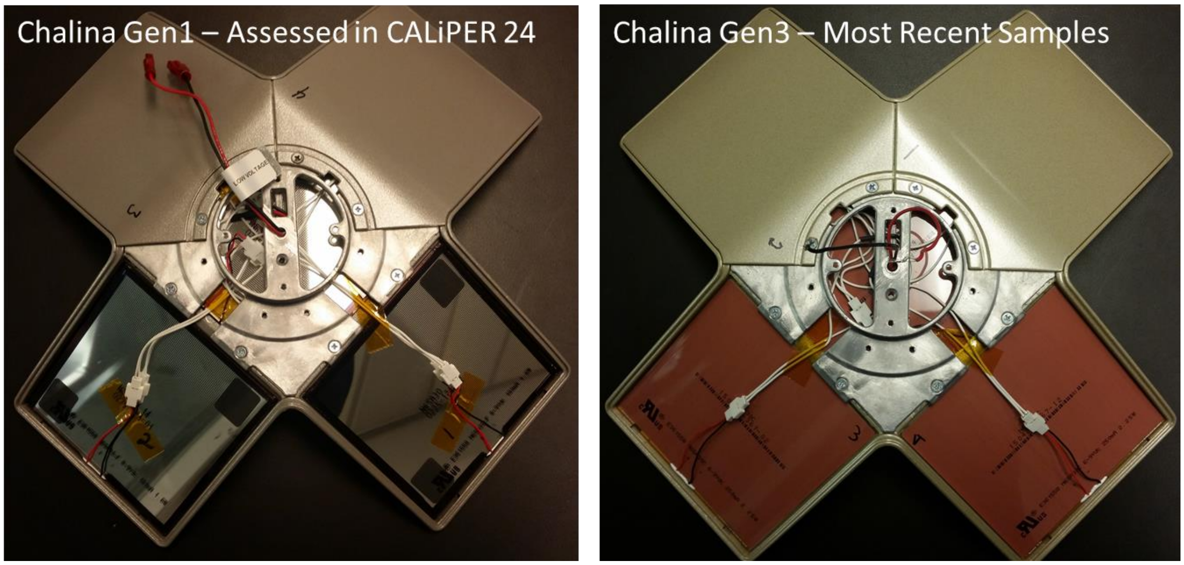

Figure 3–1. View of the backside of Chalina OLED luminaires from Acuity Brands.

Table 3–2. Comparison of the initial impedance of OLED panels in the Chalina luminaire with purchase date.

Purchase Date	Population ID	Initial Impedance (ohm) @ 100 Hz	Initial Impedance (ohm) @ 1,000 Hz
September 2015	Gen 1	2375 ± 10	248 ± 1
August 2016	Gen 2	2721 ± 30	296 ± 4
July 2017	Gen 3	2246 ± 12	237 ± 2

3.1.2 OLED Panels from OLEDWorks

OLEDWorks panels and associated drivers were purchased directly from the company, and the tested products included the Brite 2 FL300 neutral white, Brite 2 FL300 warm white, and Brite Amber products. The neutral white and warm white products were the recently introduced Brite 2 panels [14], whereas the amber OLED products were the Brite Amber OLED panels introduced in May 2017 [15]. A comparison of the panel sizes for the samples examined in this study is given in **Table 3–3**, and pictures of these samples are shown in **Figure 3–2**.

Table 3–3. Comparison of OLED panel areas.

OLEDWorks Panel	Emissive Area	Overall Dimensions
Brite 2 FL300 warm white	10.3 cm x 10.3 cm	12.8 cm x 12.8 cm
Brite 2 FL300 neutral white	10.3 cm x 10.3 cm	12.8 cm x 12.8 cm
Brite Amber	2.5 cm x 8.7 cm	4.1 cm x 11.1 cm

Figure 3–2. Neutral white, warm white, and amber panels from OLEDWorks.

The measured impedance for these samples differed between the Brite 2 and Brite Amber panels, with the latter having a significantly higher impedance as shown in **Table 3-4**. The higher impedance for the Brite Amber product likely reflects the different construction. The measured impedances for the Brite 2 panels were statistically the same for the neutral white and warm white products.

Table 3–4. Impedance of panels from OLEDWorks.

OLEDWorks Panel	Impedance (ohm) @ 100 Hz	Impedance (ohm) @ 1,000 Hz
Brite 2 FL300 neutral white	5,542 ± 19	565 ± 2
Brite 2 FL300 warm white	5,556 ± 43	566 ± 4
Brite Amber	12,059 ± 9	1,234± 0.1

The panels from OLEDWorks used different approaches to provide the necessary voltage and current for operation. The Brite 2 panels, which employ a 6-tandem stack structure [7], used a 24 volt driver that was powered by a power supply providing the alternating current (ac) to direct current (dc) conversion stage. The driver was custom-designed by Philips Lighting for OLED panels [16]. In contrast, the Brite Amber panels, which employ a 2-tandem stack structure [7, 17], used a driver that converts electrical mains to the dc power required to drive the panel. This driver was a stock device designed for use with inorganic LED products and the low voltage output needed for a 2-tandem stack device. These configurations are shown in **Figure 3**–3 for the Brite 2 and Brite Amber panels, and additional details on these products are provided in **Table 3–5.** During stress testing exposure, the drivers were included in the test ovens with the panels, so there is a potential for degradation in the driver.

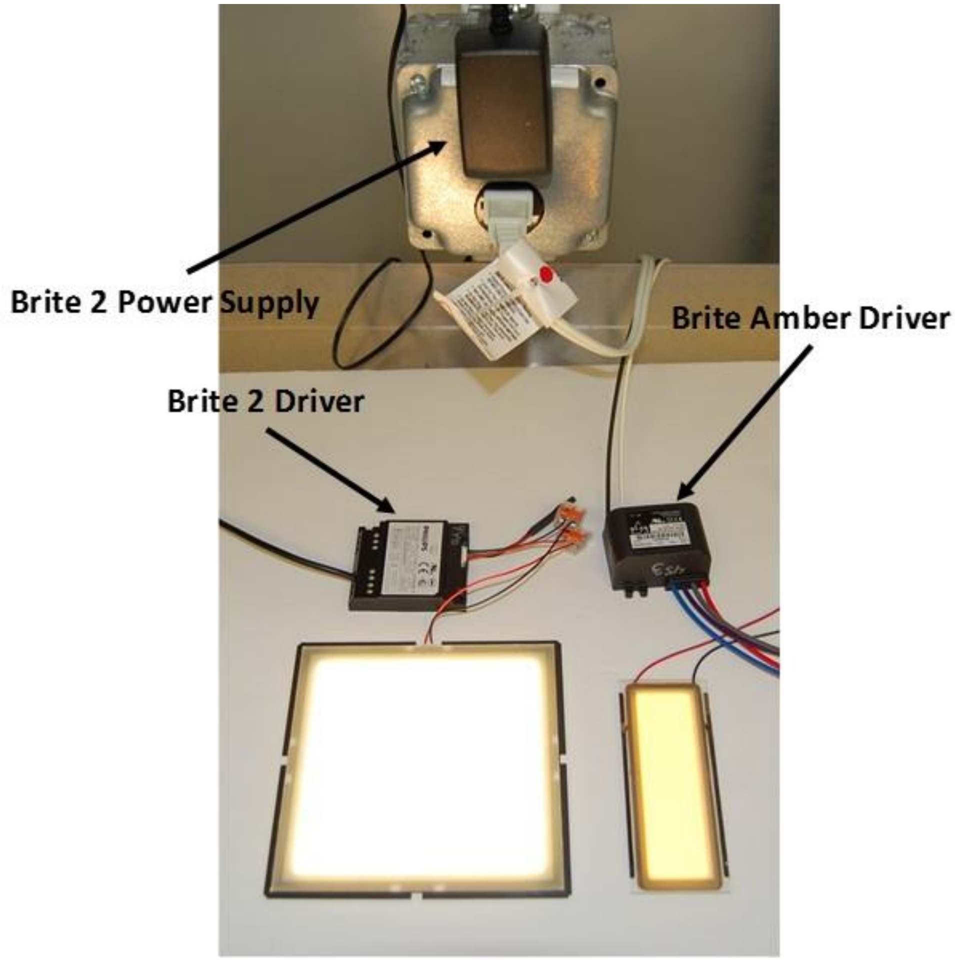

Figure 3–3. Wall power supply and driver for Brite 2 panels and driver for Brite Amber panels.

Table 3–5. Part numbers for the power supply and drivers used with OLEDWorks panels in this study.

Panel Technology	Wall Power Supply	Driver	Reference
Brite 2 Panels (both neutral white and warm white)	Triad WSU240-0500 Maximum Power: 12 W Output Voltage: 24 Vdc Output Current: 500 mA η = ≥ 83%	Philips D024V 10W/0.1-0.4/28V D/A Maximum Power: 10 W Output Voltage: 1–28 Vdc Output Current:100–400 mA η = ≤ 83%	16, 18
Brite Amber Panels	None	Bias BPWXLD 6-21-U-004 Maximum Power: 6 W String Voltage: 3–21 Vdc Output Current: 0 – 44mA η = ≤ 54%	19

3.2 Stress Testing Methods

The 45°C elevated ambient was chosen as a stress testing protocol because of its use in previous CALiPER testing of LED products, including A19 and PAR38 lamps [20, 21]. Performance in this test environment can provide some comparison of the performance of OLEDs to conventional LED products made from 2011 to 2013. Additional stress testing protocols were chosen to examine the behavior of the devices under lower and higher stress levels, and further details on the findings from the higher stress exposures are given in the CALiPER 24 report [4].

In this report, findings from five testing protocols are given:

- 35°C elevated ambient bake of Chalina luminaires operated at 150 mA,
- 35°C elevated ambient bake of OLEDWorks warm white and neutral white panels operated at 263 mA and Brite Amber panels operated at 43 mA,
- 45°C elevated ambient bake of Chalina luminaires operated at 150 mA,
- 45°C elevated ambient bake of OLEDWorks warm white and neutral white panels operated at 263 mA and Brite Amber panels operated 43 mA,
- Operation of Chalina luminaires and OLEDWorks panels at ambient room temperature (25°C ± 2°C).

Two groups of Chalina luminaires, one with the Gen 1 and the second with Gen 3 OLED panels, were subjected to the 45°C elevated ambient temperature (2 samples in each group); four Chalina luminaire samples with Gen 3 panels were used in the 35°C testing; and two Chalina luminaire samples with Gen 2 panels were used in the RTOL testing. One Chalina luminaire sample, containing Gen 1 panels, was kept as a control and was only operated during photometric testing.

For simplicity, all devices under test (DUTs) were operated continuously during stress testing, and there was no power cycling of the DUTs. All DUTs that were operated at the elevated ambient temperature of 45°C were monitored thermally using chromel-alumel thermocouples multiplexed to a data acquisition module that recorded temperature every 10 minutes. In all cases, the temperature of both the OLED panel and the driver were monitored separately with different thermocouples. The temperatures of DUTs operated at an elevated ambient of 35°C were monitored on a weekly basis using chromel-alumel thermocouples.

After completion of each stress test cycle, photometric measurements were performed individually on each DUT using a calibrated 65-inch or 10-inch integrating sphere. In addition, electrical properties of luminaires and the individual panels were checked with an Agilent handheld LCR meter (Model U1733) and Kill-A-Watt EZ power meter. Additional power measurements were made, as necessary, using a Xitron 2802 two-channel power analyzer.

The photometric measurement setup for each DUT model was designed to maximize lumen capture and ensure measurement accuracy. The luminous flux from both the Chalina luminaire and the OLEDWorks white panels were sufficient for them to be measured in a 65-inch integrating sphere. Due to the lower luminous flux of the Brite Amber panels, we chose to measure them in a 10-inch integrating sphere. Chalina luminaires were measured in the 65-inch integrating sphere and mounted to the center post using a secured screw and minimal wiring. Likewise, the Chalina and OLEDWorks panels were mounted to the 65-inch sphere center post, and each panel was secured, facing up, using a low-profile bracket that did not affect light emission. OLEDWorks Brite Amber panels were mounted in a similar fashion in the 10-inch integrating sphere. In all cases, integrating sphere measurements were taken using a 4π geometry with the device at the center of the sphere. Pictures of the test configuration of the different samples in the integrating spheres are shown in **Figure 3–4**.

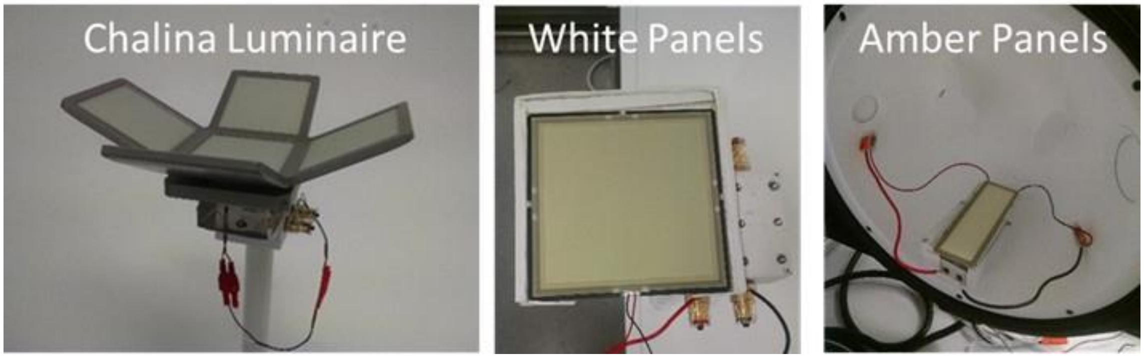

Figure 3–4. OLED devices mounted for photometric testing.

4 Results

4.1 Chalina Luminaires

As originally reported in CALiPER 24, four Chalina OLED luminaires (labeled DUTs 224–227), containing Gen 1 OLED panels, were tested by RTI at an elevated ambient temperature of 45°C [4]. While there were early failures in DUT-224 (≤ 250 hours) and DUT-226 (between 5,000 and 5,500 hours) due to panel shorting, DUT-225 and DUT-227 are still in testing as of the date of this report. Two additional Chalina luminaires (purchased July 2017) containing Gen 3 OLED panels were added to the 45°C elevated ambient test and have now reached 2,000 hours. Thus, a total of six Chalina luminaires have been tested at the elevated ambient temperature of 45°C. Because two luminaires have failed during the initial 45°C testing, the findings for the four operational luminaires will be provided here as an update on the testing reported in CALiPER 24.

To provide additional insights into the performance of the Chalina luminaire and the panels from LG Display in the luminaire, two additional tests were initiated on Chalina luminaires and are described here. First, two luminaires (with Gen 2 panels) were continuously operated at room temperature in RTOL testing. These luminaires have now reached over 9,000 hours of testing. Second, four Chalina luminaires (with Gen 3 panels) were subjected to an elevated ambient temperature of 35°C, and these DUTs have now reached 2,000 hours of exposure.

4.1.1 Photometric Measurements

The SPDs of the Chalina luminaires with Gen 2 and Gen 3 OLED panels are given in Figure B-1 and Figure B-2 of Appendix B, respectively. The color rendition of these sources was calculated from the respective SPDs using IES TM-30-15 [22], and the results are also included in Figure B-1 and Figure B-2. The color vector graphic demonstrates that the Chalina luminaire with Gen 2 and Gen 3 OLED panels does a good job of reproducing the color rendition properties of the reference source, although the OLED panels desaturate red and orange colors. In addition, the chroma shifts produced by these light sources is generally small, often 4% or less.

In comparing the SPD and source color rendition of the Chalina luminaires with Gen 2 and Gen 3 panels with that reported in CALiPER 24 for Chalina luminaires with Gen 1 OLED panels [4], only minor differences can be discerned. For the three generations of light sources, the color fidelity (R_f) and color gamut (R_g) scores are very similar as are the CRI and R_9 values. This finding indicates that the overall emission properties of the OLED panels remained the same among the different generations of Chalina luminaires even though there were changes in the physical appearance of the panels (see **Figure 3**–1) and different initial impedance values (see **Table 3**–2) for three generations of products.

4.1.2 Luminous Flux Maintenance

As expected, the luminous flux maintenance of the Chalina luminaires in RTOL testing is better than that of equivalent luminaires operated at elevated temperatures. While there is no accepted standard method to fit the luminous flux maintenance of an OLED, a simple exponential decay is used in this report. For the RTOL samples, the fit was started at 250 hours due to anomalous data in the initial measurement. For the rest of the samples in this report, the fit begins with the initial measurement. The raw data for the RTOL measurements along with an exponential fit are shown in **Figure 4–1**.

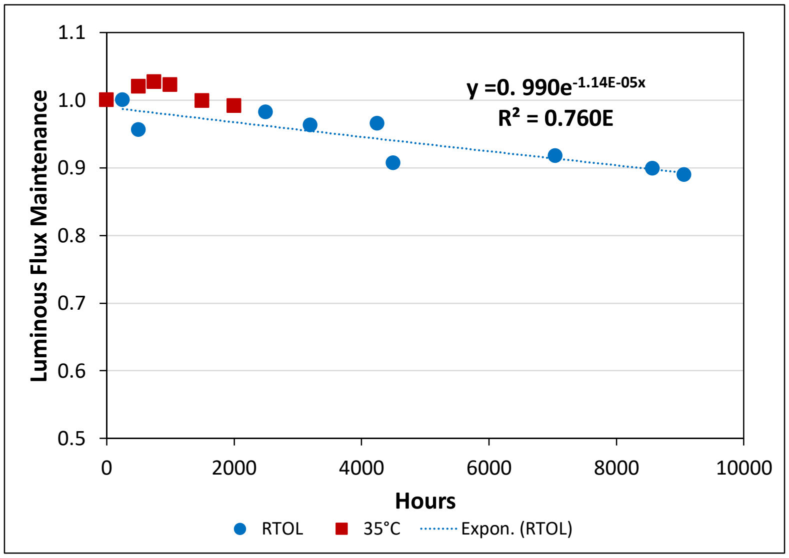

Figure 4–1. Luminous flux maintenance for the Chalina luminaire during continuous operation at room temperature (in RTOL) testing and at 35°C.

Using this approach, the luminous flux of the RTOL samples can be seen to decrease by roughly 9.5% per year when operated continuously at an ambient environment of 25°C. In contrast, the luminous flux of the samples tested at 45°C was shown to decrease by roughly 24.5% per year in CALiPER 24 [4]. From this limited sample set, we can calculate an acceleration factor for the 45°C test (relative to 25°C) of approximately 2.6, which agrees with earlier studies of OLED panels operating at the same current [11]. For the DUTs operated at an elevated ambient temperature of 35°C, there was a slight initial increase in luminous flux followed by a decrease. Unfortunately, the 35°C measurements have not progressed a sufficient amount of time to allow a meaningful model of the luminous flux decay to be created; however, we expect the acceleration factor to be lower than that observed for 45°C.

Because the make-up of the two sets of Chalina luminaires in the 45°C elevated ambient test may be different, we chose to examine the behavior of the four operational luminaires separately. In addition, DUT-225 and DUT-227 were each removed from testing for short periods of time for maintenance reasons. For DUT-225, this break consisted of five months due to other testing priorities, whereas for DUT-227, this hiatus consisted of two separate breaks of five months each. Upon returning to the test population, the luminaires were measured before continuing stress testing and showed minimal change in both the luminous flux and the rate of luminous flux decay (see **Figure 4**–2 and **Figure 4**–3**)**. This finding provides some insight into the stability of the devices when not in use (e.g., in storage). Shortly after testing resumed, one panel in DUT-225 failed due to an electrical short, which resulted in a sharp drop in luminous flux as indicated in **Figure 4**–2. The five-month storage time is not believed to be responsible for panel failure in DUT-225 because it occurred after more than 250 hours of new testing. In addition, no panel failures have been observed to date for DUT-227, which has undergone two separate hiatuses of five-months each.

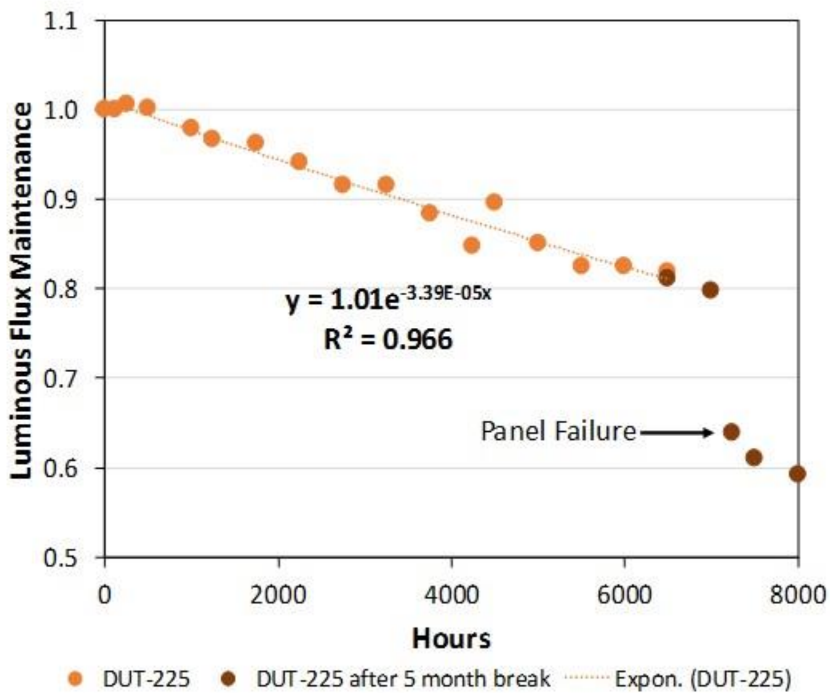

Figure 4–2. Luminous flux maintenance for DUT-225, which contains Gen 1 panels.

As shown in **Figure 4**–4, the luminous flux maintenance behavior of the two Chalina luminaires with Gen 3 panels in the 45°C test was very similar. Furthermore, the rates of luminous flux maintenance decay for these samples is in approximate agreement with that found for Chalina luminaires with Gen 1 OLED panels. These findings demonstrate that the luminous flux maintenance characteristics of the Chalina luminaires is similar regardless of the generation of OLED panel used in the product.

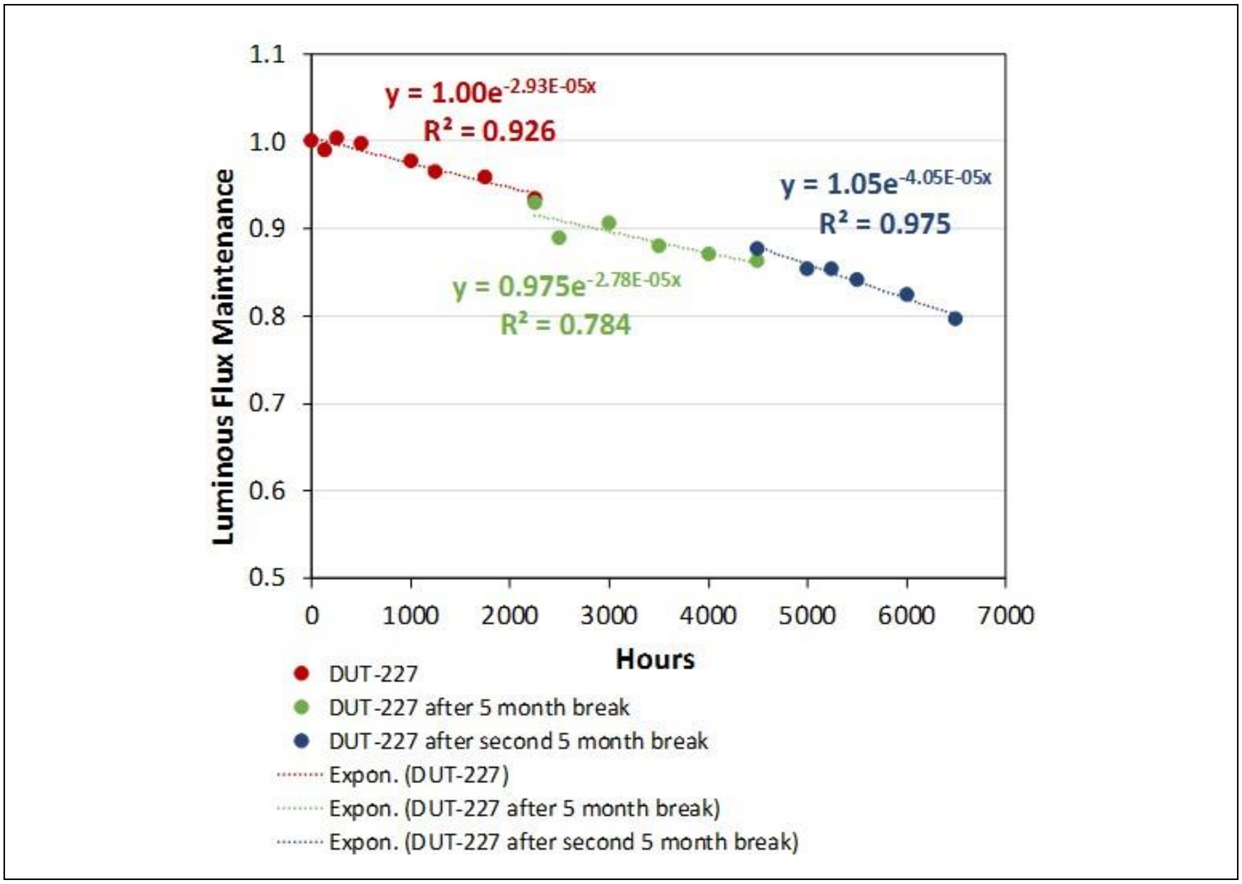

Figure 4–3. Luminous flux maintenance for DUT-227, which contains Gen 1 panels.

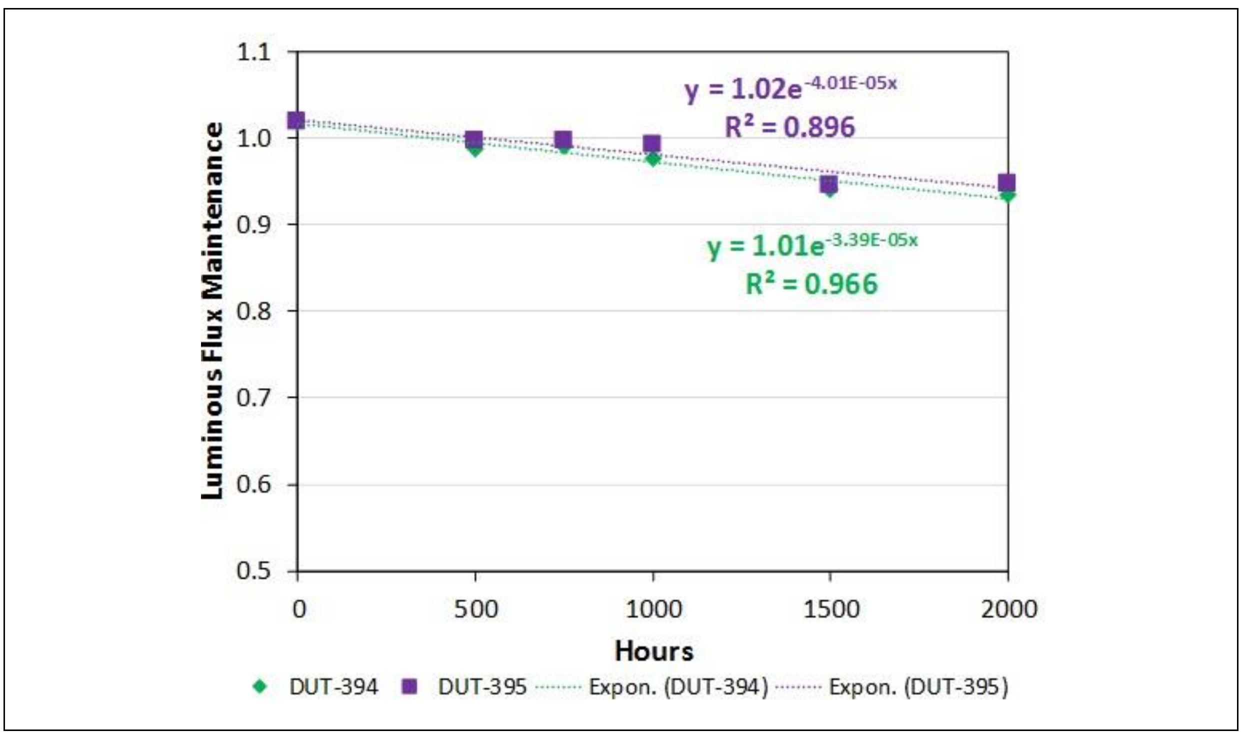

Figure 4–4. Luminous flux maintenance for DUT-394 and DUT-395, which contain Gen 3 panels.

4.1.3 Chromaticity

CALiPER 24 reported that the chromaticity shift for Chalina luminaires with Gen 1 panels proceeds in the blue-green direction during testing at an ambient environment of 45°C with both *u′* and *v′* decreasing in roughly equal proportions [4]. Additional testing reported here found that the chromaticity shift begins to move more in the blue direction (i.e., *v′* decreasing much faster than *u′*) after approximately 4,500 hours of testing as shown in **Figure 4**–5.

A representative SPD of Chalina luminaires with Gen 1 OLED panels (DUT-227) is given in **Figure 4**–6. The SPD can be deconvoluted into two different skewed Gaussians for each assumed emitter color (i.e., blue, green, red), with varying levels of skew in the calculated emission peaks. Integration of the area of the two peaks for each color provides the emission intensity for that color. By deconvoluting the SPDs measured at each test interval, the relative emission intensities of the three colors can be compared over time as shown in **Figure 4**–7. This charting can explain the observed chromaticity shift for the Chalina luminaires with Gen 1 panels through a faster reduction in emission from red and green sources while the blue emitter reduces at a slower rate. The lower stabilities of the red and green emitters found in the Gen 1 panels are characteristic of phosphorescent sources, which have higher initial efficiencies but lower stability than fluorescent emitters have [22]. In contrast, the higher stability of the blue source confirms that a fluorescent emitter was used in these samples, in agreement with the published literature [6].

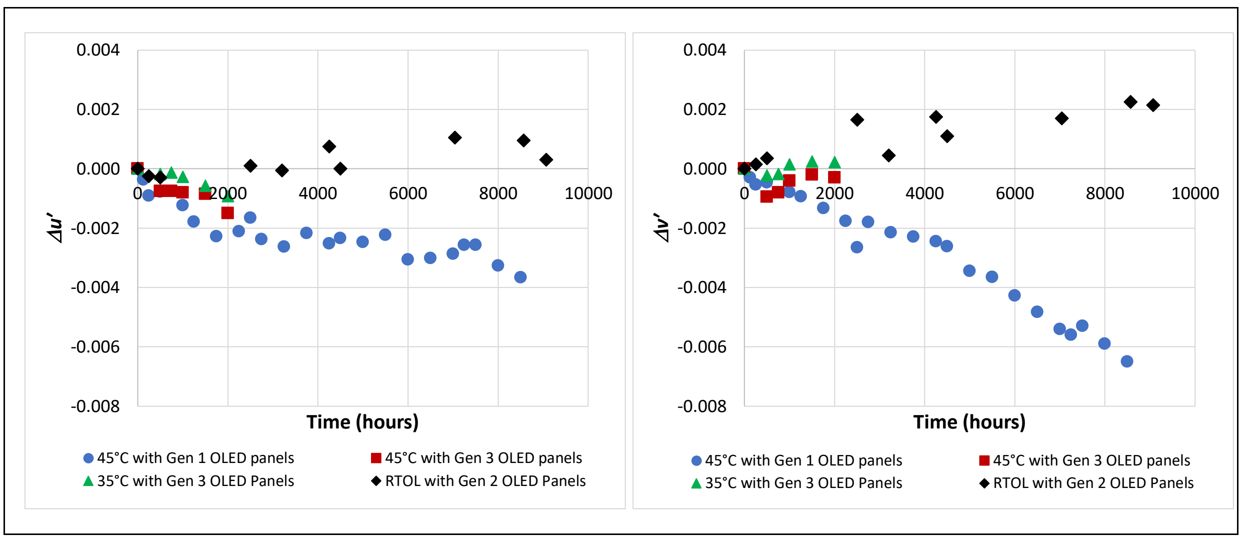

Figure 4–5. Time dependence of *Δu′* and *Δv′* for Chalina luminaires with Gen 1 OLED panels in 45°C stress testing.

While the Chalina luminaires with the Gen 1 panels exhibited a strong blue shift at 45°C elevated ambient temperature, the same behavior was not found for Chalina luminaires with Gen 2 and Gen 3 panels. As shown in **Figure 4**–5, the luminaires with Gen 2 and Gen 3 panels tended to shift in the red direction (i.e. *u′* and *v′* increasing). This finding indicates an improved thermal stability for luminaires with the Gen 2 and Gen 3 OLED panels. The chemical change responsible for the improved thermal stability changed the nature of chromaticity shift during RTOL and stress testing but does not appear to affect the rate of lumen depreciation.

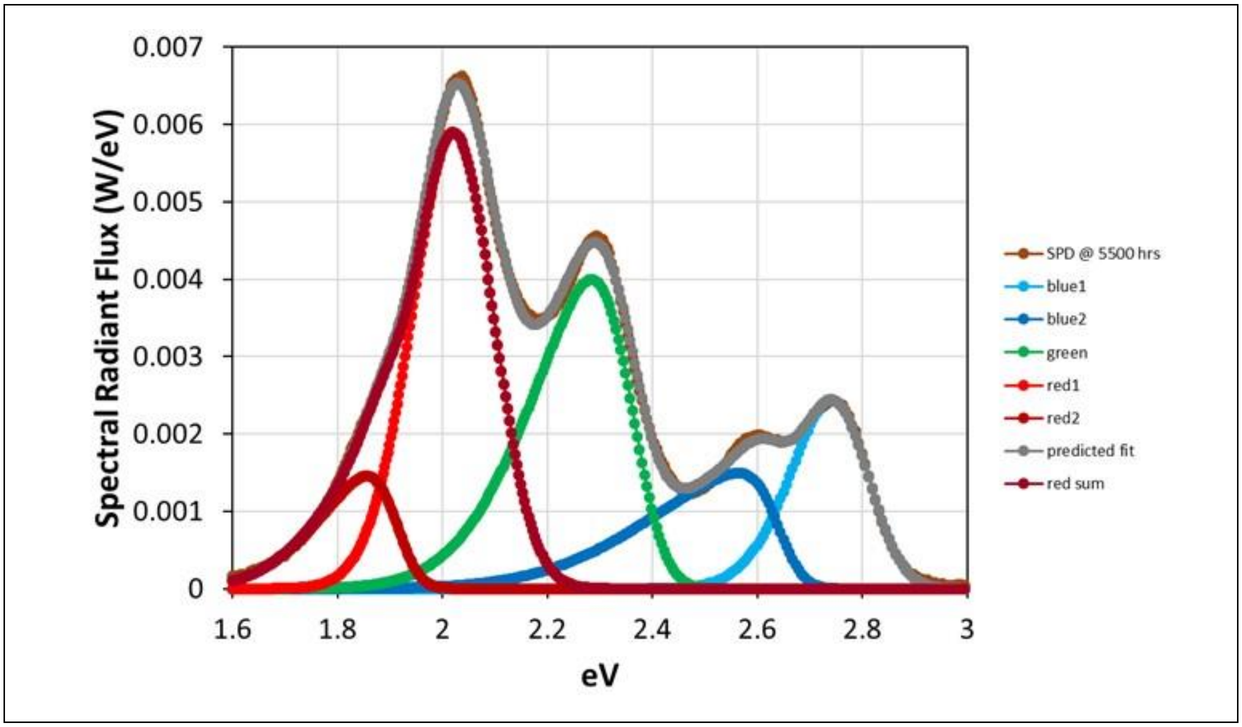

Figure 4–6. Deconvolution of the SPD for DUT-227 containing Gen 1 OLED panels.

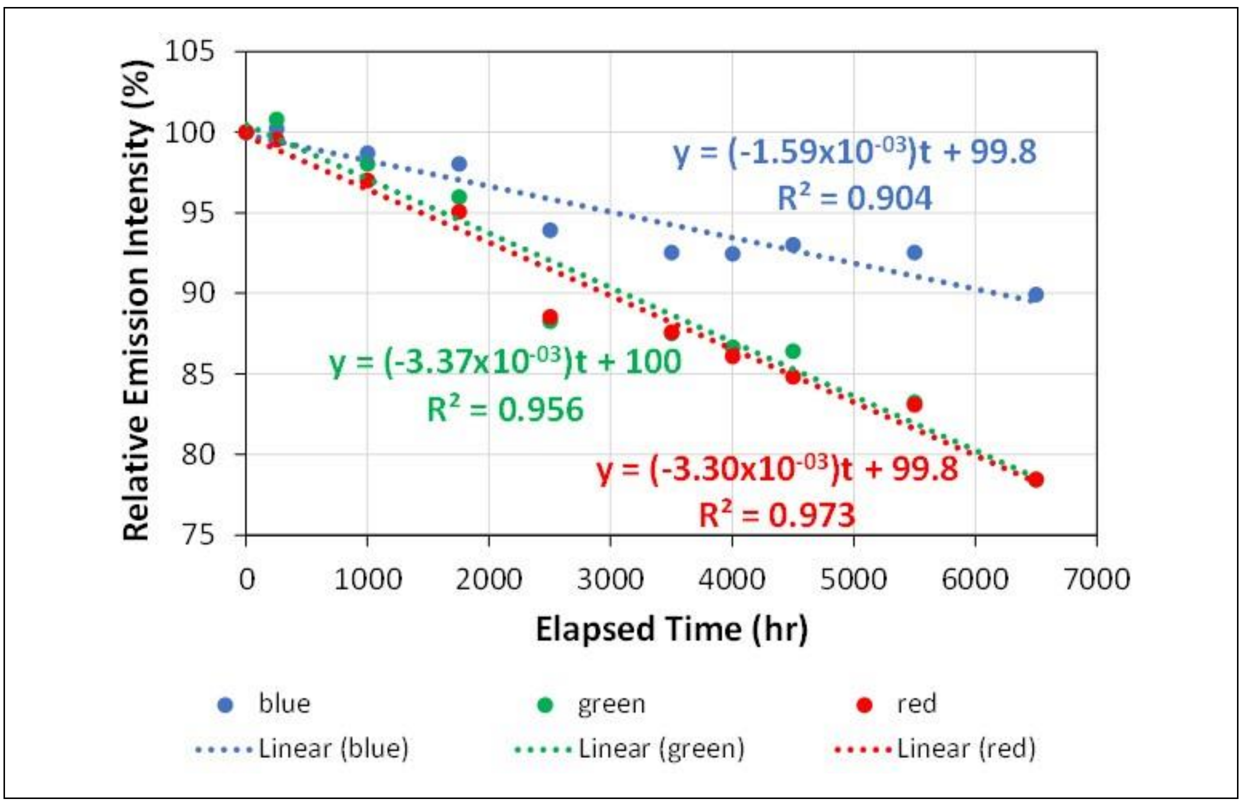

Figure 4–7. Relative emission intensity over time of the three emitters used in a Chalina luminaire with Gen 1 OLED panels.

4.1.4 Electrical Analysis

As part of the characterization of the OLED luminaires, the impedance of all fully operational OLED panels was compared across the control (Gen 1 panel), the first samples at 45°C (Gen 1 panels stress test-exposed), the RTOL samples (Gen 2 panel), and later samples (Gen 3 panels, both 45°C and 35°C exposed). The impedance of each panel was measured at three frequencies—100 Hz, 1,000 Hz, and 10,000 Hz—as shown in **Table 4**–1. A close inspection of the data reveals several main trends. First, the mean impedance of the panels from luminaires subjected to the 45°C elevated ambient temperature 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. In contrast, the measured impedance of the Gen 3 samples decreased throughout the testing performed to date (i.e., 2,000 hours) at 45°C, and this decrease is also statistically significant. A similar trend was found for the Gen 2 panels in RTOL testing (through 9,000 hours) and the Gen 3 panels subjected to the 35°C elevated ambient test. These data indicate that the changes in panel construction between the different generations of OLED panels improved the stability of the device with ageing. In CALiPER 24, we estimated the driver efficiency for these OLED luminaires as 86.8%. Using a Xitron two-channel power analyzer, measured driver efficiencies (with Gen 1 control as the load) were found to be respectable at 83.9%.

Table 4–1. Impedance of Chalina OLED luminaires.

Frequency	Panel Type	100 Hertz	1000 Hertz	10,000 Hertz
Panels from control	LG Display – Gen 1	2,375 ± 10 ohms	248 ± 1 ohms	25.9 ± 0.1 ohms
Operational panels from 45°C bake (≥ 6,500 hours)	LG Display – Gen 1	2,728 ± 41 ohms	289 ± 6 ohms	29.8 ± 0.6 ohms
Initial measurement RTOL samples	LG Display – Gen 2	2,721 ± 30 ohms	296 ± 4 ohms	30.9 ± 0.4 ohms
Operational panels from RTOL testing (9,000 hours)	LG Display – Gen 2	2,711 ± 31 ohms	295 ± 4 ohms	30.8 ± 0.4 ohms
Initial measurements	LG Display – Gen 3	2,246 ± 12 ohms	237 ± 2 ohms	25.7 ± 0.2 ohms
Operational panels from 35 °C bake (2,000 hours)	LG Display – Gen 3	2,238 ± 11 ohms	242 ± 2 ohms	25.8 ± 0.2 ohms
Operational panels from 45°C bake (1,500 hours)	LG Display – Gen 3	2,209.9 ± 15 ohms	244 ± 19 ohms	25.6 ± 0.1 ohms

Note: The reported uncertainties represent one standard deviation.

4.2 OLEDWorks Panels

Three models of OLED panels from OLEDWorks were investigated in this study and are described as warm white, neutral white, and amber. Three stress testing protocols were used to examine each OLED panel model: RTOL, 35°C elevated ambient bake, and 45°C elevated ambient bake. For each stress testing protocol, three panels of each model were investigated. The exposure time to date for all OLEDWorks panels is 1,500 hours.

4.2.1 Photometric Analysis

The SPDs of the Brite 2 FL300 Neutral White, Brite 2 FL300 Warm White, and Brite Amber OLED panels are given in Figure B-3, Figure B-4, and Figure B-5 of Appendix B, respectively. IES TM-30-15 was used to calculate the color rendition of these sources from the respective SPDs measured in this work [21], and the results are also included in Appendix B. As expected, the color rendition properties of the two white sources demonstrate their suitability for general lighting applications, whereas the Brite Amber OLED panel is more of a special application light source.

In comparing the SPDs of the warm white panels from OLEDWorks (Figure B-3) with those of the LG Display panels in the Chalina luminaires, the OLEDWorks warm white panels have more intensity in the deep red spectral region as evidenced by the presence of a small emission peak near 670 nm. As a result, the Brite 2 warm white panels were determined to have higher CRI and R_9 values than the panels from LG Display did. Consequentially, the color rendition graphic demonstrates that the Brite 2 OLED warm white source renders red and orange colors slightly more accurately than the LG Display panels; however, the Brite 2 OLED warm white source is slightly desaturated for green colors and oversaturated for blue and purple. These findings align with the manufacturer's data included in a recent DOE field study [3] and confirm the improved color rendition of the Brite 2 panels compared to the Brite 1 panels.

The SPD of the Brite 2 neutral white panel suggests that it uses the same emitters as the warm white product; however, the relative concentrations of the emitters have changed to achieve a different CCT value. Brite 2 neutral white OLED panels also provide good color rendering at a higher CCT value. The color vector graphic demonstrates that the source accurately renders red and orange colors, but there is more desaturation of green than found with the warm white source.

The SPD of the Brite Amber product confirms that it is a mix of green and red emitters [17], and these sources appear to be very similar to those used in the warm white and neutral white products. As is to be expected from such a light source targeting a specific application (e.g., melanoptic lighting), the overall color rendition properties are poor with both R_f and R_g values of 35 and 33, respectively. Ironically, the CRI of this source is 79 and the R_9 value is 10, which would make this source acceptable for some general lighting applications if only these two metrics were used. However, the color vector graphics demonstrate that this light source severely desaturates most colors, as would be expected from the absence of a blue emitter. Consequently, this light source is best suited for its intended application in melanoptic lighting.

4.2.2 Luminous Flux Maintenance

Through 1,500 hours of exposure to three different stress testing protocols, the average luminous flux maintenance for neutral white panels remains above 96%. Three samples were used for each OLED color (e.g., neutral white, warm white, and amber) in each test condition. The average luminous flux maintenance across the stress testing protocols remains very similar, except at 250 hours when the panels at room temperature (RT) experienced an increase in luminous flux maintenance due to burn-in, as shown in **Figure 4–8**. All panels started to experience a steady decrease in luminous flux after 500 hours.

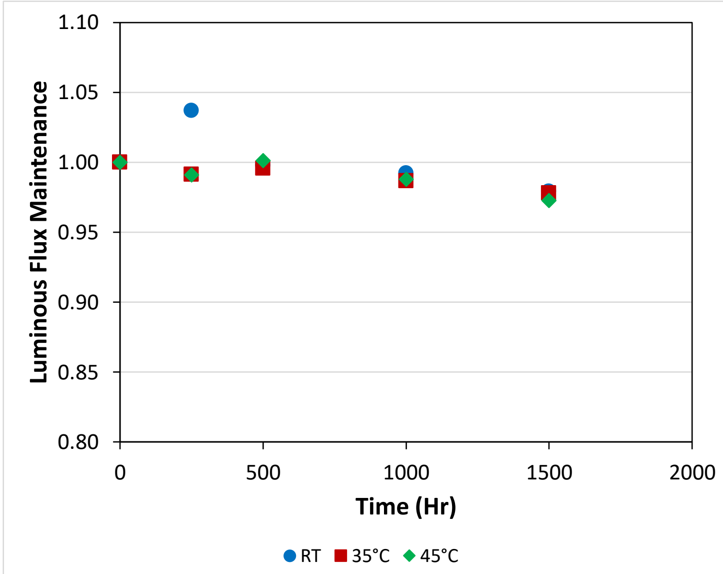

Figure 4–8. Average luminous flux maintenance for neutral white panels.

The average luminous flux maintenance for warm white panels also remained above 95% through 1,500 hours of exposure to the three different testing protocols as shown in **Figure 4–9**. This level of lumen depreciation in the first 1,500 hours of testing is comparable to that found for the LG Display panels used in the Chalina luminaires. An increase in luminous flux was also seen for the warm white panels operated at RT for 250 hours. After 250 hours, the average luminous flux maintenance in neutral white panels for all testing protocols decreased, with the largest change occurring among the panels subjected to the 45°C bake. It is anticipated that the luminous flux of the panels tested at 45°C will continue to decay at a faster rate than those at less aggressive stress testing protocols. However, additional data is needed before a meaningful projection can be made.

By 1,500 hours, the luminous flux maintenance of six Brite Amber panels remains above 95%; these panels were subjected to the RT and 35°C bake testing protocols. The three amber panels operated at RT had an average luminous flux maintenance above 1.0 through 1,000 hours (**Figure 4–10**), while the three panels operated at 35°C and 45°C had an average luminous flux maintenance above 1.0 through 500 and 250 hours, respectively. As mentioned, there were three panel failures in the samples subjected to the 45°C elevated ambient test that resulted in no light emission by 1,500 hours. The exact time to failure for each device is given in **Table 4–2.** As such, at 1,000 hours, the average luminous flux maintenance for the 45°C bake includes only the two operational panels. Of the two operational panels, one experienced a drastic reduction in luminous flux maintenance (67.8%) at 1,000 hours, accounting for the sharp decrease in average luminous flux maintenance for the 45°C bake panels. All three panels in the 45°C tests had failed by 1,500 hours.

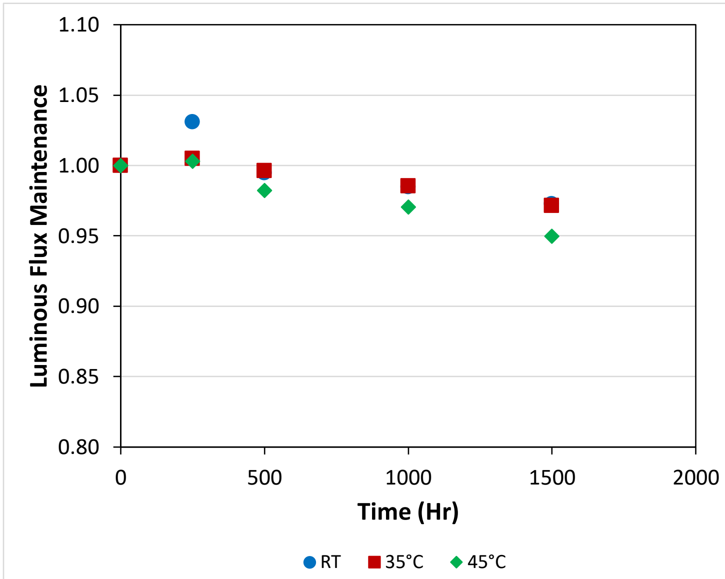

Figure 4–9. Average luminous flux maintenance for warm white panels.

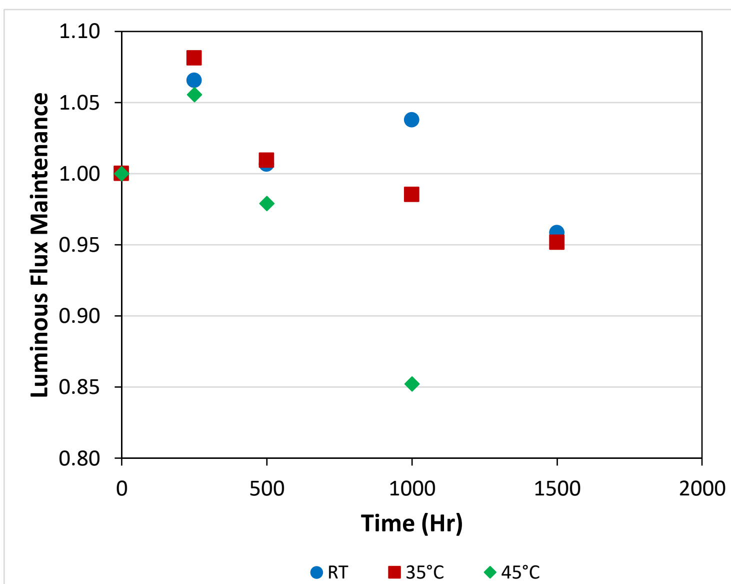

Figure 4–10. Average luminous flux maintenance for amber panels.

4.2.3 Chromaticity

Chromaticity shift for the neutral white and warm white panels remains subtle at 1,500 hours as shown in **Figure 4–11** and **Figure 4–12,** respectively. Neutral white panels experienced a small chromaticity shift in the green-yellow direction, with greater tendency toward yellow for the 45°C bake samples (Figure 4–11). There was no clear trend for the chromaticity shift in the warm white panels (Figure 4–12). Furthermore, the average chromaticity shift for the warm white panels was less than one step, and therefore, it is expected that the fluctuations in chromaticity are mostly due to the experimental variation. Further testing is needed to determine the long-term chromaticity behavior for these panels.

The Brite Amber panels experienced the largest chromaticity shift of the tested OLEDWorks panels: approximately two steps in the red direction with *u′* increasing much faster than *v′* decreases (**Figure 4–13**). To better understand this behavior, a component analysis of the emission spectra was performed. The Brite Amber panels use a 2-tandem stack phosphorescent OLED structure with two mixed red and green phosphorescent emitters [17]. In our spectral analysis of the Brite Amber panels, the red and green emitters were fit with skewed Gaussians, and a linear least squares regression was performed to estimate their individual contribution to the overall emission spectrum as shown in **Figure 4–14**. The red emitter was estimated as a sum of two skewed Gaussians due to its broader peak shape at lower energy (without knowing the identity of the red emitter, this fit serves to best estimate the spectrum of the red emitter). The intensities of the red and green emitters of the amber panel subjected to stress testing were then compared to the respective intensities of the red and green emitters from the control panel, allowing the deduction of the relative emission intensity over time for both red and green emitters. From this analysis, there is strong evidence to support that the red color shift of the amber panels is caused by a greater stability period of the red emitters relative to the green emitter during the test period.

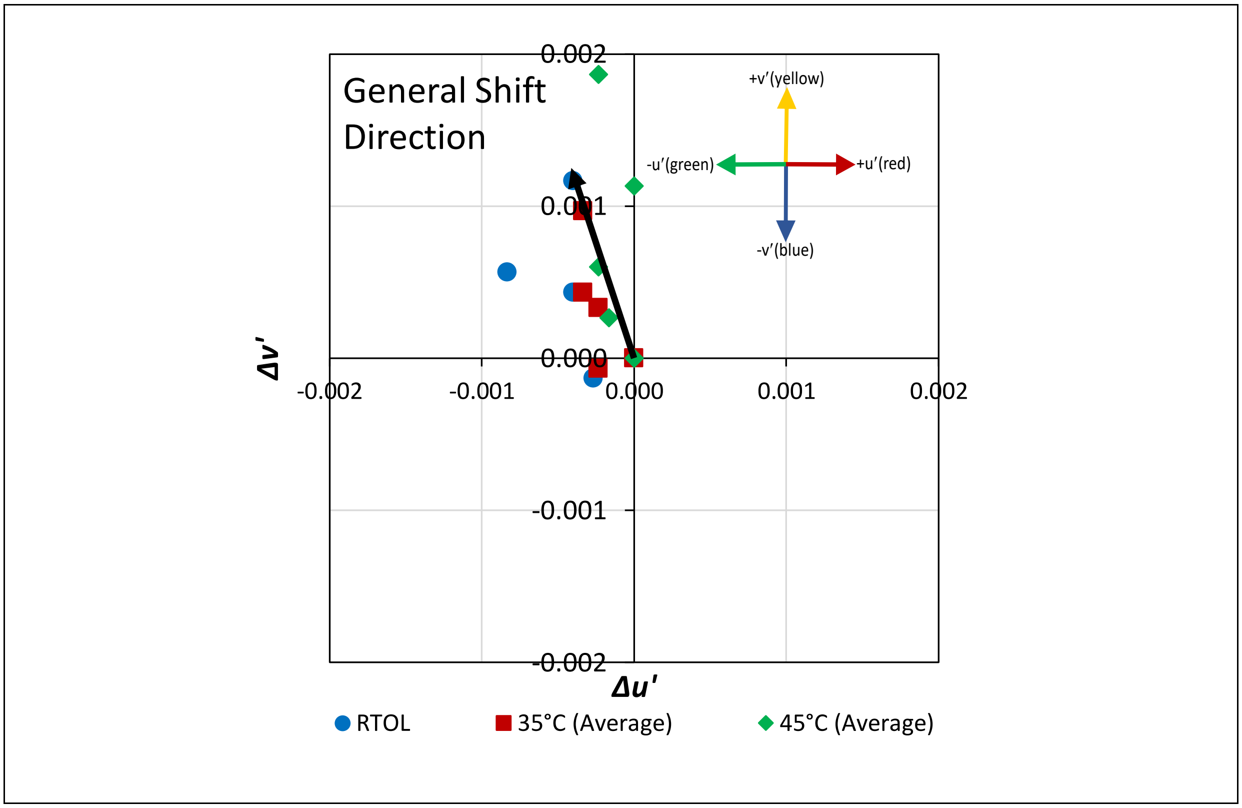

Figure 4–11. Chromaticity diagram for neutral white panels.

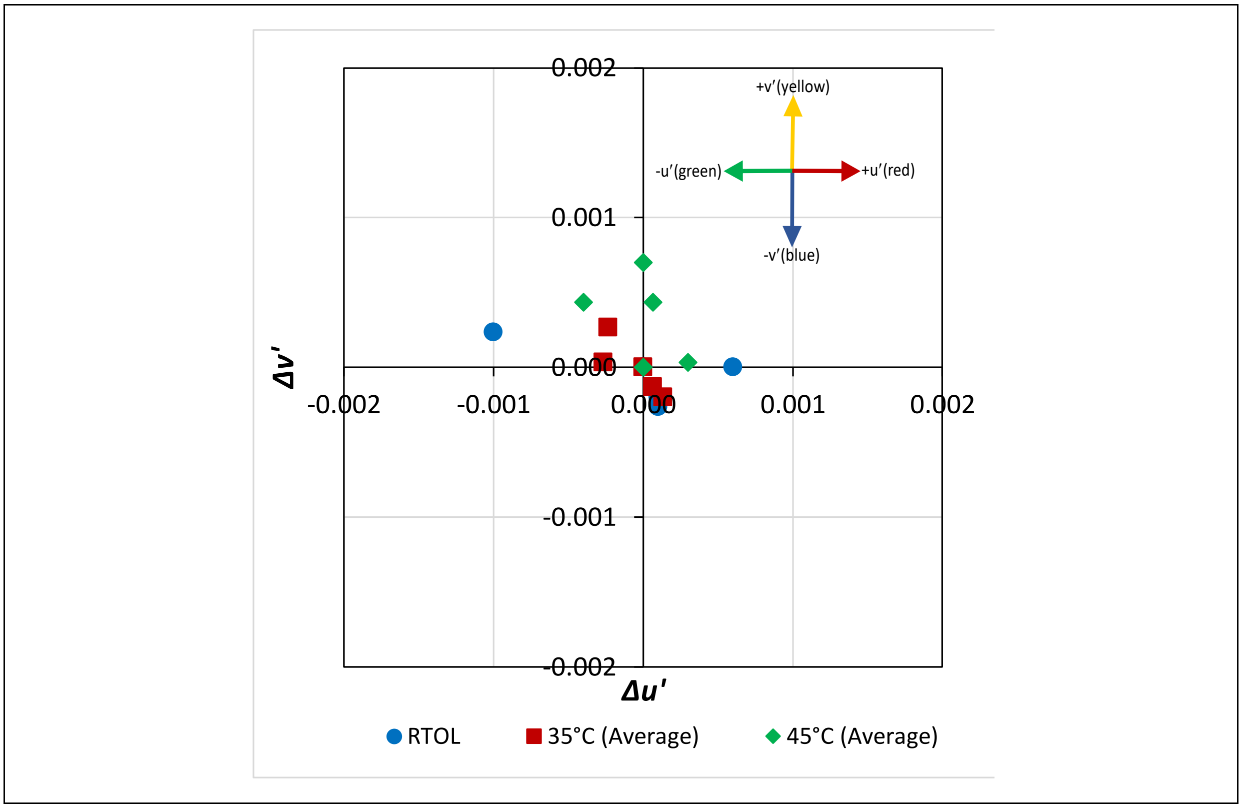

Figure 4–12. Chromaticity diagram for warm white panels.

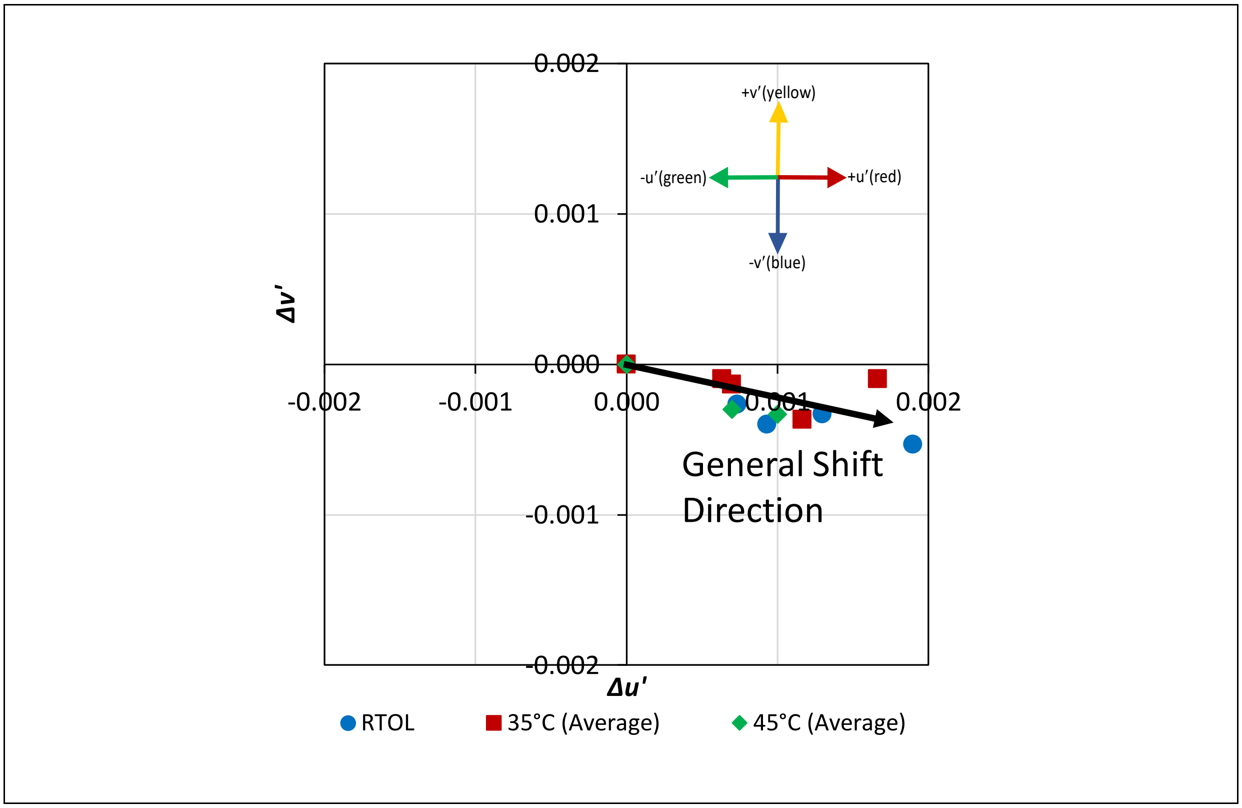

Figure 4–13. Chromaticity diagram for amber panels.

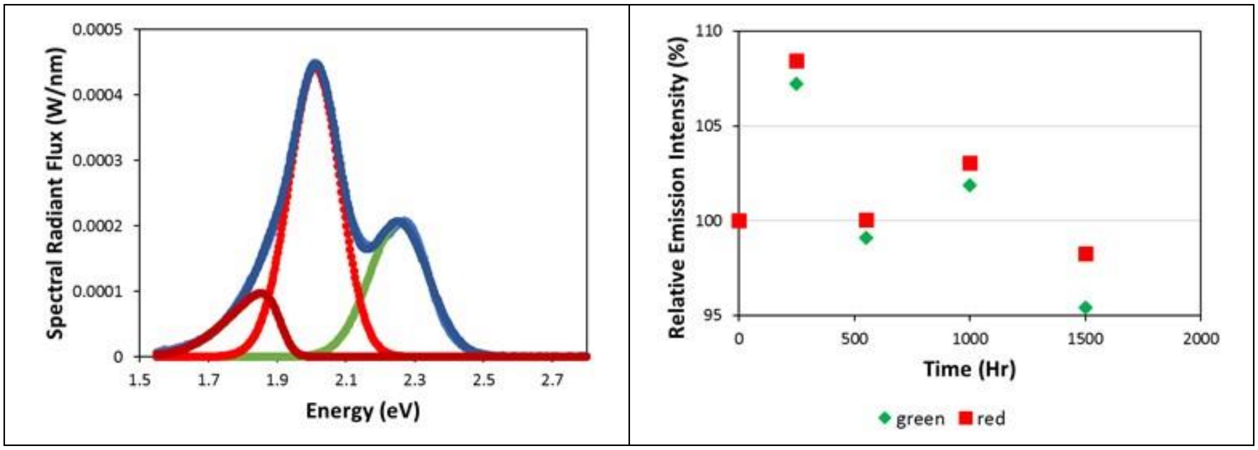

Figure 4–14. Emission spectra modeling for red and green components relative to the control sample over 1,500 hours.

4.2.4 Electrical Analysis

4.2.4.1 Neutral White

As of 1,500 hours, all neutral white panels remain in good operating condition. Electrical analysis of the average power consumed by the test panels at the end of each testing cycle revealed an increase in power consumption for all testing protocols (**Figure 4–15**). OLED panels are known to have an increase in power consumption as they age due to the increase in the voltage needed to maintain constant current across the panel as the OLEDs degrade [4]. The greatest increase in power consumption is observed for the most aggressive testing protocol (45°C), indicating that the greatest progression of OLED ageing had occurred in the panels operated at 45°C. In addition, a larger variation in panel power consumption (measured by the standard deviation) as time progresses is observed for all testing protocols, which is consistent with ageing of the panels.

Impedance values were recorded for each panel at the conclusion of each testing cycle to provide further characterization of the neutral white panels. The impedance was measured at three frequencies: 100 Hz, 1 kHz, and 10 kHz. The average impedance (measured at 1 kHz) was calculated for each testing protocol at the conclusion of each cycle as shown in **Figure 4–16**. Temporal examination of the average neutral white panel impedances shows an increase in impedance across all testing conditions. This finding supports the increase in power consumption observed for the panels; further evidence to support this claim is contained in the fact that the most aggressive testing conditions (45°C) also result in the greatest relative increase in impedance (i.e., the largest slope in the linear least squares fit). Interestingly, the standard deviation of panel impedance values did not vary significantly with time.

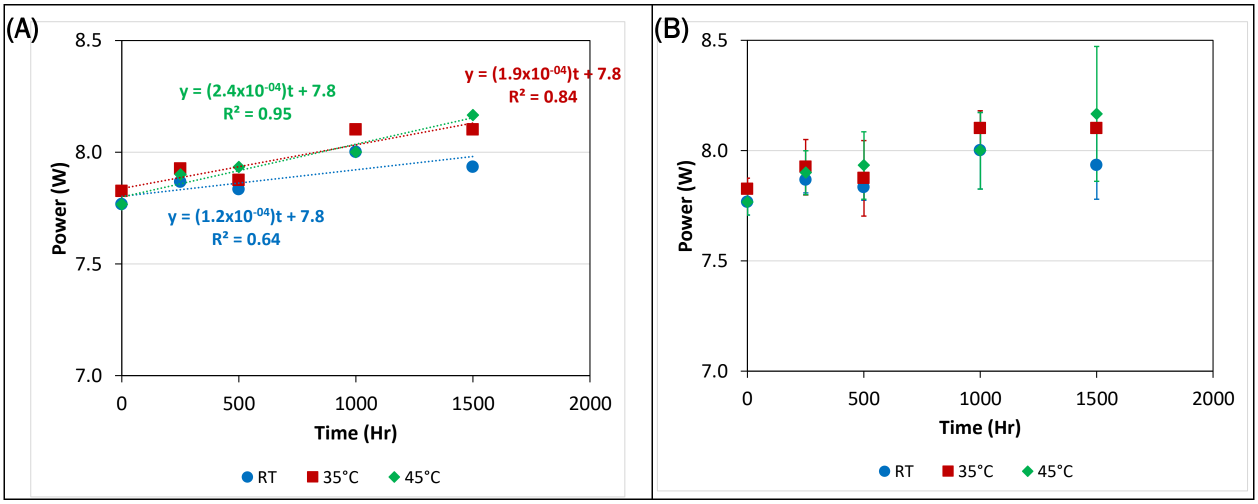

Figure 4–15. Average power consumption of neutral white panels in each testing condition (35°C, 45°C, and RT) show a greater increase in power consumption for more aggressive conditions (A) and an increase in standard deviation with ageing (B).

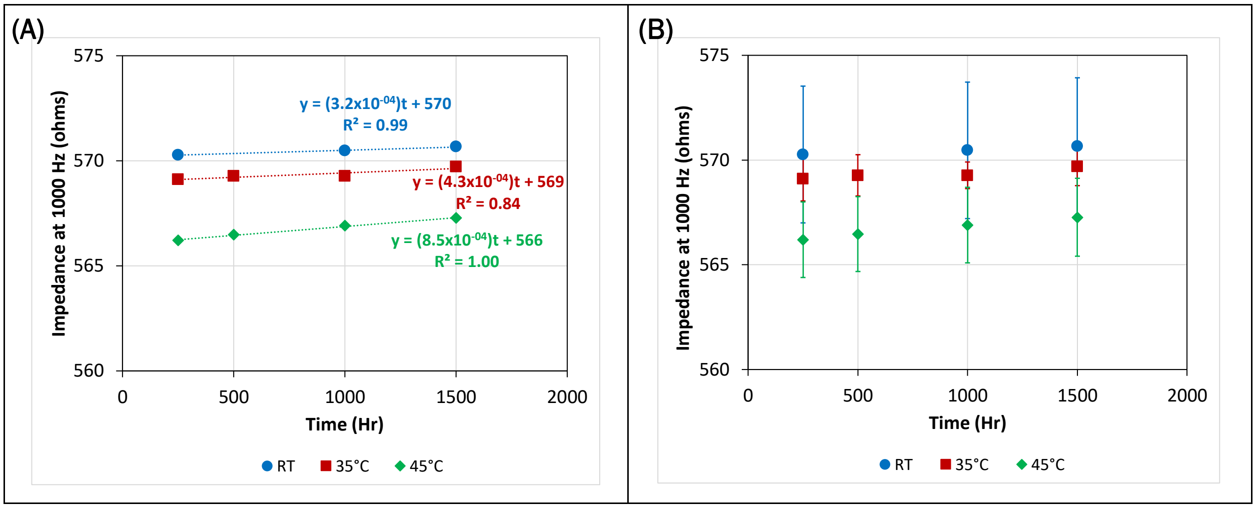

Figure 4–16. Average impedance of neutral white panels in each testing condition (35°C, 45°C, and RT) show a greater increase in impedance for more aggressive conditions (A) and an increase in standard deviation with ageing (B).

4.2.4.2 Warm White

All warm white panels remain in operation after 1,500 hours of testing; however, two of the RTOL panels have black spots where emission should occur (**Figure 4–17**). Warm white panels exhibited some of the same electrical characteristics as the neutral white panels. For instance, an average increase in power consumption was observed across panels in all testing protocols (**Figure 4–18**). There is also an increase in the variance of panel power consumption relative to the zero-time point, indicative of OLED ageing. In contrast to the neutral white panels, the warm white panels exhibit more fluctuation in power consumption and do not explicitly exhibit greater power consumption with more aggressive stress testing protocols. The panels that are operated at 45°C have the largest increase in power consumption, but the power consumption increase for the RTOL devices is higher than the power consumption increase for the panels operated at 35°C. This counterintuitive result could stem from the limited number of data points collected to date. Alternatively, the difference could be due to differing driver ability to supply constant current to the warm white panels compared to the neutral white panels (both panels use the same driver). More testing is needed to understand these differences.

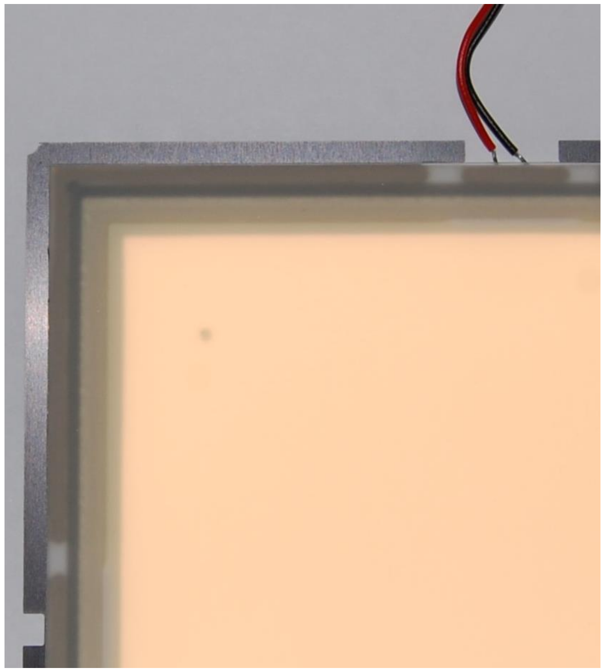

Figure 4–17. Black spot on warm white panel in RTOL testing.

The average impedance (measured at 1 kHz) of the warm white panels operated at each testing protocol is shown in **Figure 4–19**. Temporal examination of the average impedances shows an increase in impedance across all testing conditions, with the more aggressive stress testing conditions (45°C and 35°C) having a greater relative increase in impedance compared to the RTOL panels. Similar to the neutral white panels, the measured standard deviation in warm white panel impedances did not vary significantly with time. However, the standard deviation of the both the power consumed and impedance at 1 kHz was greater for the warm white samples compared to the neutral white samples.

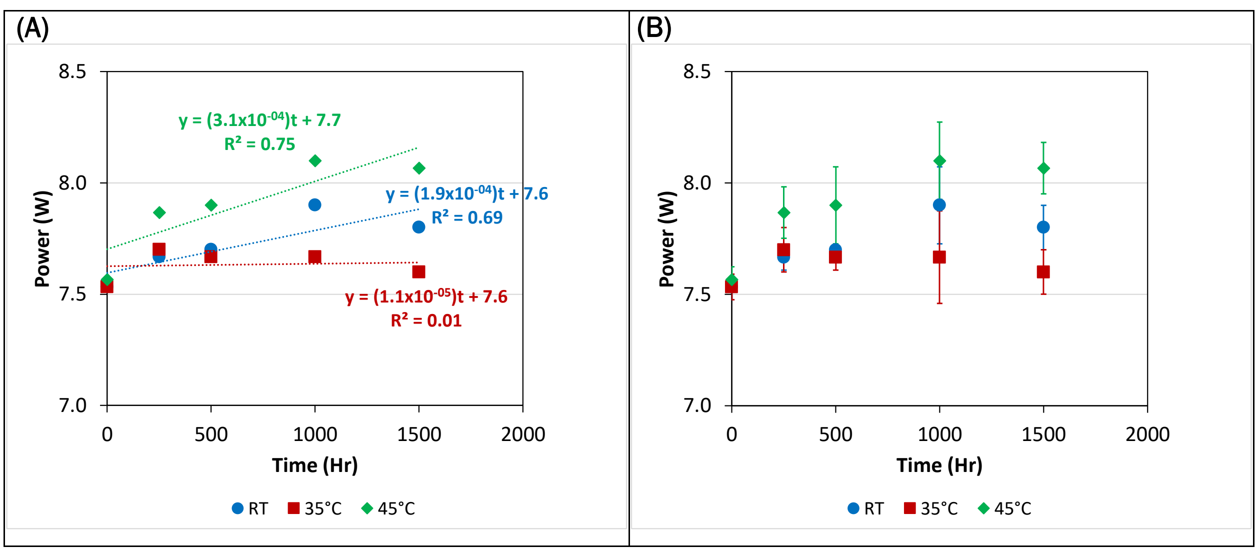

Figure 4–18. Average power consumption of warm white panels in each testing condition (35°C, 45°C, and RT) show a greater increase in power consumption for more aggressive conditions (A) and an increase in standard deviation with ageing (B).

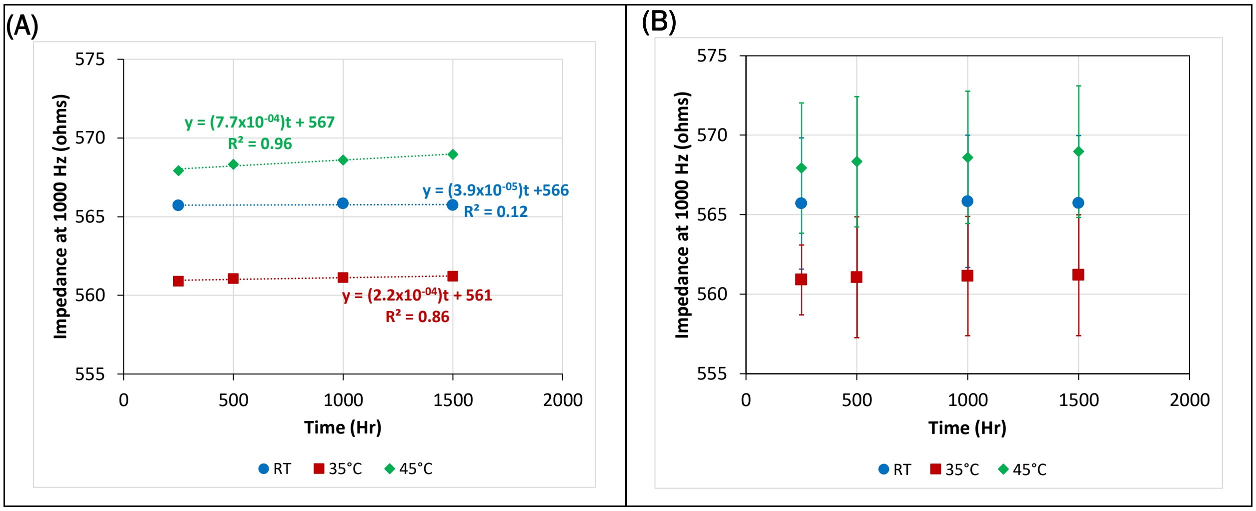

Figure 4–19. Average impedance of warm white panels in each testing condition (35 °C, 45 °C, and RT) show a greater increase in impedance for more aggressive conditions (A) and an increase in standard deviation with ageing (B).

4.2.4.3 Amber

As of 1,500 hours, the Brite Amber panels in the RTOL and 35°C bake testing protocols are still operational, but the Brite Amber panels at the most aggressive stress testing protocol (45°C bake) failed abruptly before this time. The precise failure time of an OLED panel can be captured through temporal thermal monitoring of the panel and its driver. Under normal operating conditions, lamps equilibrate to a maximum operating temperature in the elevated ambient temperature oven within a few hours. Once the equilibrium temperature has been reached, the temperature of the lamp remains constant unless an external force acts upon the lamp or the lamp experiences an internal change. Because the amber panels and drivers were maintained in a constant temperature environment during testing, any abrupt changes in temperature beyond the warm-up period are indicative of a change on the panel or driver. Furthermore, a shorting failure of a panel is often marked by a sharp increase in driver temperature accompanied by an abrupt decrease in panel temperature as shown in **Figure 4–20.** Using the thermocouple data collected every 10 minutes, time to failure during the 45°C elevated ambient test was determined and tabulated for the three failed panels in **Table 4-2.**

Table 4–2. Time to failure for the amber panels operated during a 45 °C elevated ambient test.

Amber Panel #	Time to Failure (Hours)
1	845.4
2	1384.8
3	1451.8

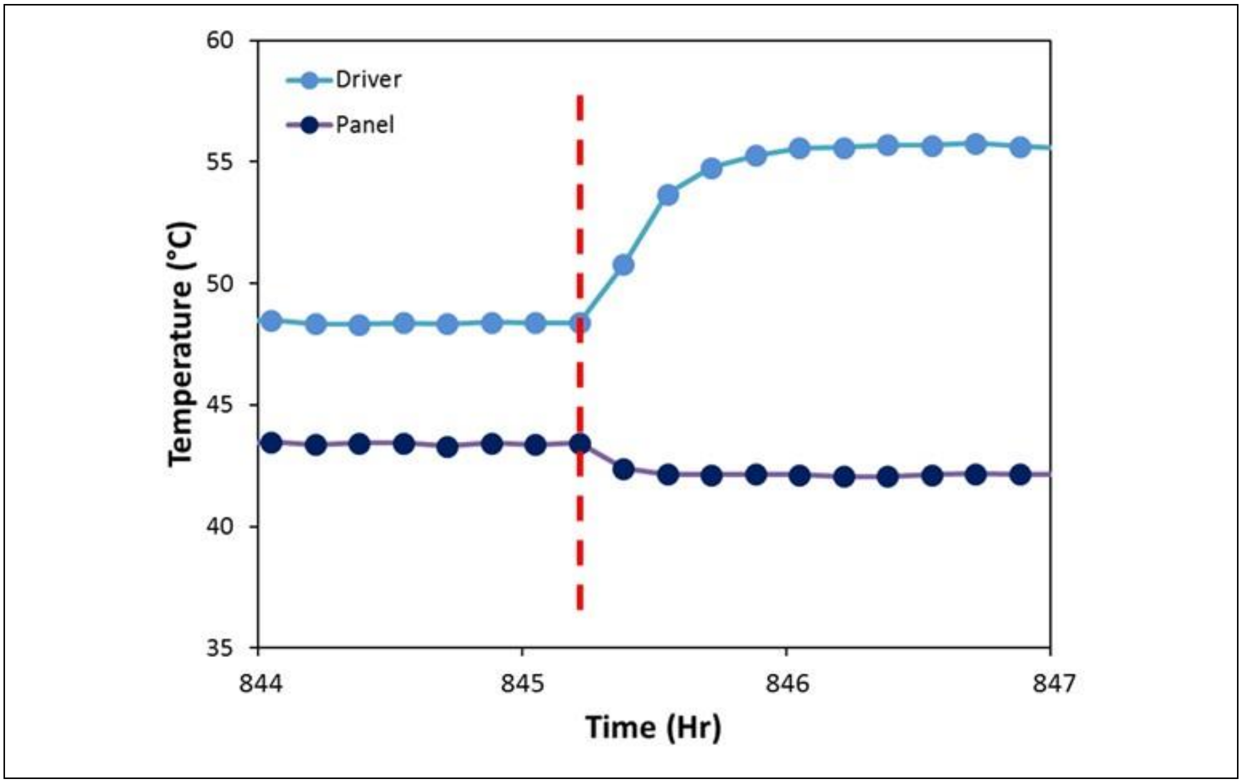

Figure 4–20. Failure is indicated by the red line for a Brite Amber panel. OLED drivers experience a temperature increase and OLED panels experience a temperature decrease when a shorting failure arises within the OLED panel.

The operational amber panels and associated drivers have not experienced a significant change in power consumption as of 1,500 hours of ageing (**Table 4**–3). However, power consumption changed for the failed panel-driver pairs from the 45°C testing protocol; the power delivered to these panels fluctuated rapidly, with increased average power consumption in comparison to the other testing protocols. The increase in power consumption for the failed panel-driver pairs can stem from the driver or panel. As part of the characterization of the amber panels, the impedance was recorded after each testing cycle at three frequencies: 100 Hz, 1,000 Hz, and 10,000 Hz. The average impedance value of the amber panels during each testing protocol after 1,500 hours is shown in **Table 4**–4.. Relative to the control panel, the aged amber panels show a decrease in impedance at all test conditions. Additionally, the average impedance of the failed amber panels is much lower than that of the operational panels, indicating the presence of an electrical short within the panels. More testing is needed to determine the location of the electrical short within each panel.

Table 4–3. Average power consumption for the amber panel-driver pairs subjected to each test protocol after 1,500 hours.

Panel	Power (W)
Control	0.7
RTOL	0.7
35°C elevated ambient temperature	0.7
45°C elevated ambient temperature (all failed)	1.4 ± 0.5

Table 4–4. Average impedance values for amber panels subjected to each test protocol after 1,500 hours.

Frequency	100 Hertz	1,000 Hertz	10,000 Hertz
Control panel	12,059 ± 9 ohms	1,234± 0.1 ohms	125.4 ± 0.04 ohms
RTOL panels	11,620 ± 151 ohms	1,225 ± 8 ohms	125.1 ± 1.4 ohms
35°C bake panels	8,807 ± 2992 ohms	1,218 ± 13 ohms	125.8 ± 0.8 ohms
Failed panels from 45°C bake	41.2 ± 14 ohms	22.1 ± 8 ohms	23.9 ± 10 ohms

Note: The reported uncertainties represent one standard deviation.

4.2.5 Uniformity of OLEDWorks Panels

Two masks were developed to measure the uniformity of the RTOL OLEDWorks panels. The mask developed for the neutral white and warm white panels enabled luminance testing of two corners, four central points, and two outer-edge locations. The mask developed for the amber panels included three locations for luminance testing (**Figure 4–21**). Absolute irradiance at each location was measured orthogonal to the panel at a fixed height using a radiometrically calibrated Ocean Optics spectrometer, and variance was calculated according the following equation:

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

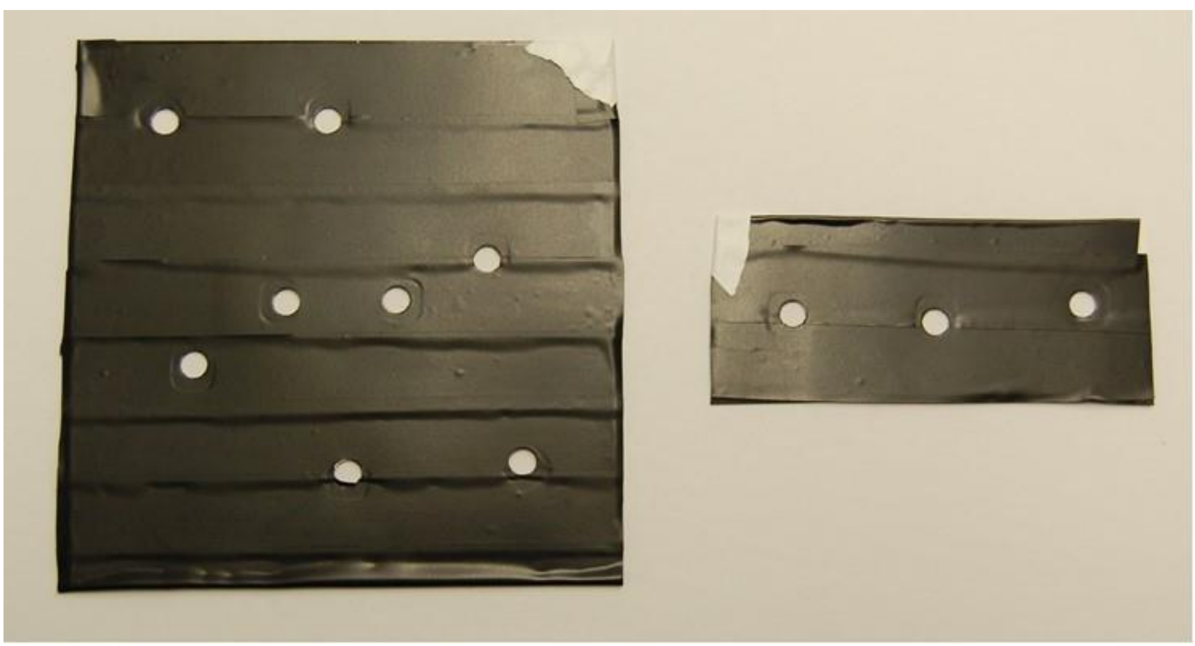

Figure 4–21. Mask used to measure neutral white and warm white panel uniformity.

The results in **Table 4–5.** show that all of the RTOL OLEDWorks panels exhibit minor variations in luminance uniformity, with the largest variance of luminance uniformity (10.0%) occurring in the warm white panels.

Table 4–5. Average luminance uniformity of OLEDWorks panels.

Panel	Variance
Neutral white	9.4%
Warm white	10.0%
Amber	3.7%

5 Recommended Next Steps

One of the main challenges facing efficacy improvement of OLED technologies is poor driver efficiency. Historically, OLED devices have been driven by constant current LED drivers (e.g., a 24Vdc power supply). Using an LED driver for OLED technologies has intrinsic pitfalls, however: (1) the impedance of OLED panels is known to increase over time, increasing the voltage necessary to produce constant current; (2) the supply voltage for OLEDs can be significantly different from that used for inorganic LEDs; and (3) the transients produced by LED drivers may affect OLEDs differently than LEDs. As OLED technologies progress, more emphasis needs to be placed on developing drivers specifically for OLEDs.

The OLED drivers used in this study were analyzed with a Xitron 2802 two-channel power analyzer, and efficiencies and other relevant power measurements are provided in **Table 5**–1. The drivers used for the Acuity Brands Chalina luminaire and the Brite Amber panel provide conversion of the ac in the electric mains into sufficient output dc voltage and current to drive the respective OLED panels. In contrast, the Brite 2 OLED panels use both a power supply (for ac to intermediate dc conversion) and a driver (for intermediate dc to final dc conversion). The parameters given in Table 5–1 detail the complete conversion of the ac in the electric mains to the output dc voltage and current. Low driver efficiencies, as seen with the Brite Amber driver, have a negative impact on overall system efficiency and need to be addressed in future products.

Table 5–1. Summary of efficiencies and other power characteristics for the Acuity Brands Chalina luminaire and OLEDWorks panel drivers.

Device Description	Output Current (A)	Output Voltage (V)	Output Power (W)	Power Factor	Efficiency (%)
Acuity Brands Chalina	0.15	42.02	6.29	0.99	83.90
Brite 2*	0.30	21.93	5.76	0.47	70.50
Brite Amber	0.04	5.82	0.25	0.43	49.40

* The reported parameters for the Brite 2 driver include both the power supply (for ac to intermediate dc conversion) and the driver (for intermediate dc to final dc conversion).

As noted in CALiPER 24, driver efficiency generally decreases as output voltage decreases, so the low efficiency of the drivers for the Brite 2 and Brite Amber product may be a consequence of the dearth of appropriate power supplies for OLED panels. Due to low market demand, availability and development of drivers that convert ac mains voltage to low voltages and currents are limited. Many low-voltage LED applications typical use batteries (e.g., flashlights) for power. Furthermore, Acuity Brands Chalina and Brite 2 drivers have respectable efficiencies, but the driver for the Brite Amber panel is much less efficient. As described in Section 3.1.2, the Philips Lighting driver used to power the Brite 2 panels was custom-designed for OLED panels, but the driver for the Brite Amber panel was designed for LEDs. The low driver efficiency for Brite Amber panels emphasizes the need for the development of custom OLED drivers to operate at low voltages. An alternative approach would be to increase the number of layers in the stack in order to raise the driver voltage. However, this approach may complicate manufacturing processes and raise costs.

The OLED panel and driver are coupled together in the OLED lighting system. Consequently, the performance of one may affect the performance of the other. Results from CALiPER 24 suggested that failure of too many OLED panels may cause the driver to operate outside its intended design voltage, which may adversely affect reliability [4]. In addition, because the three Brite Amber failures at 45°C testing occurred while the panels were operating near the lower voltage of the driver, it cannot be ruled out that the driver played a role in device failure. Future work is needed to evaluate whether the Brite Amber driver contributed to the electrical shorting within the panel.

The OLED panels evaluated in this study show improvements over previous DOE benchmarks [2–5]. The thermal stability of the OLED panels from LG Display that are used in the Chalina luminaires are more stable and do not exhibit the rapid blue color shift previously observed [4]. While this change along with an increase in the stability of device impedance are needed technical advances, additional work is also needed to raise the luminous efficacy of the panel to values measured in laboratory testing. Likewise, the Brite 2 OLED panel has significantly improved luminous efficacy and color properties over the Brite 1 panels benchmarked in previous DOE studies. Additional improvements in luminous efficacy, driver performance, and overall system efficiency are needed.

This report is the latest in a series of reports from DOE on OLED performance. We anticipate providing an update on this testing when the devices have reached approximately one year of laboratory testing.

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Appendix A

Table A-1 lists the number of samples used in each sample set for the various testing protocols.

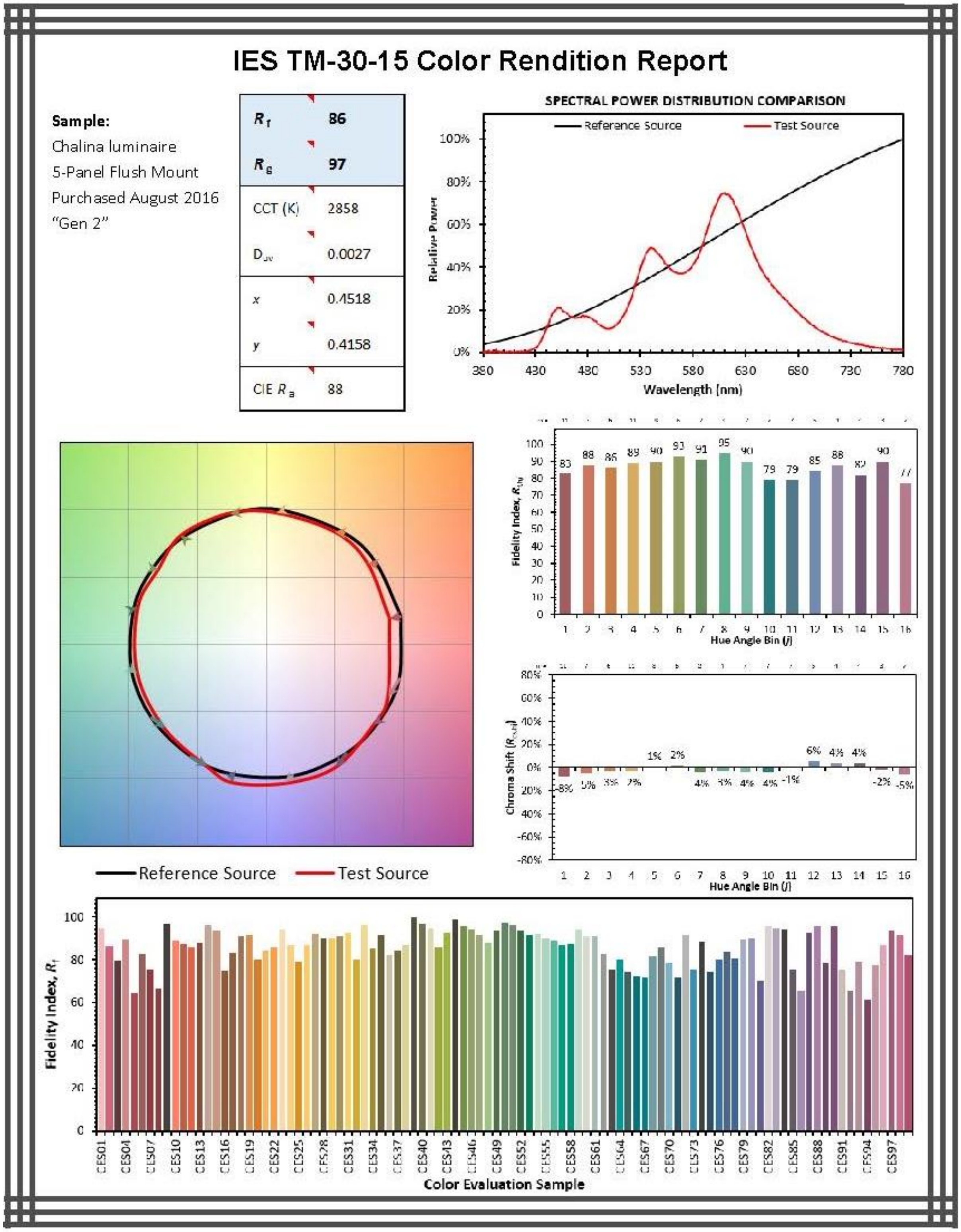
Table A-1. Test Methods developed and/or used during this investigation.

Test Description	Luminaire or Panel	Sample Description	Sample Count	Total Hours Exposed to Date
35°C dry bake	Luminaire	Acuity Brands Chalina	4	2,000
35°C dry bake	Panel	OLEDWorks Brite 2 NW	3	1,500
35°C dry bake	Panel	OLEDWorks Brite 2 WW	3	1,500
35°C dry bake	Panel	OLEDWorks Brite Amber	3	1,500
45°C dry bake	Luminaire	Acuity Brands Chalina	6	2,000-8,500
45°C dry bake	Panel	OLEDWorks Brite 2 NW	3	1,500
45°C dry bake	Panel	OLEDWorks Brite 2 WW	3	1,500
45°C dry bake	Panel	OLEDWorks Brite Amber	3	1,500
RTOL	Luminaire	Acuity Brands Chalina	2	9,000
RTOL	Panel	OLEDWorks Brite 2 NW	3	1,500
RTOL	Panel	OLEDWorks Brite 2 WW	3	1,500
RTOL	Panel	OLEDWorks Brite Amber	3	1,500

NW = neutral white

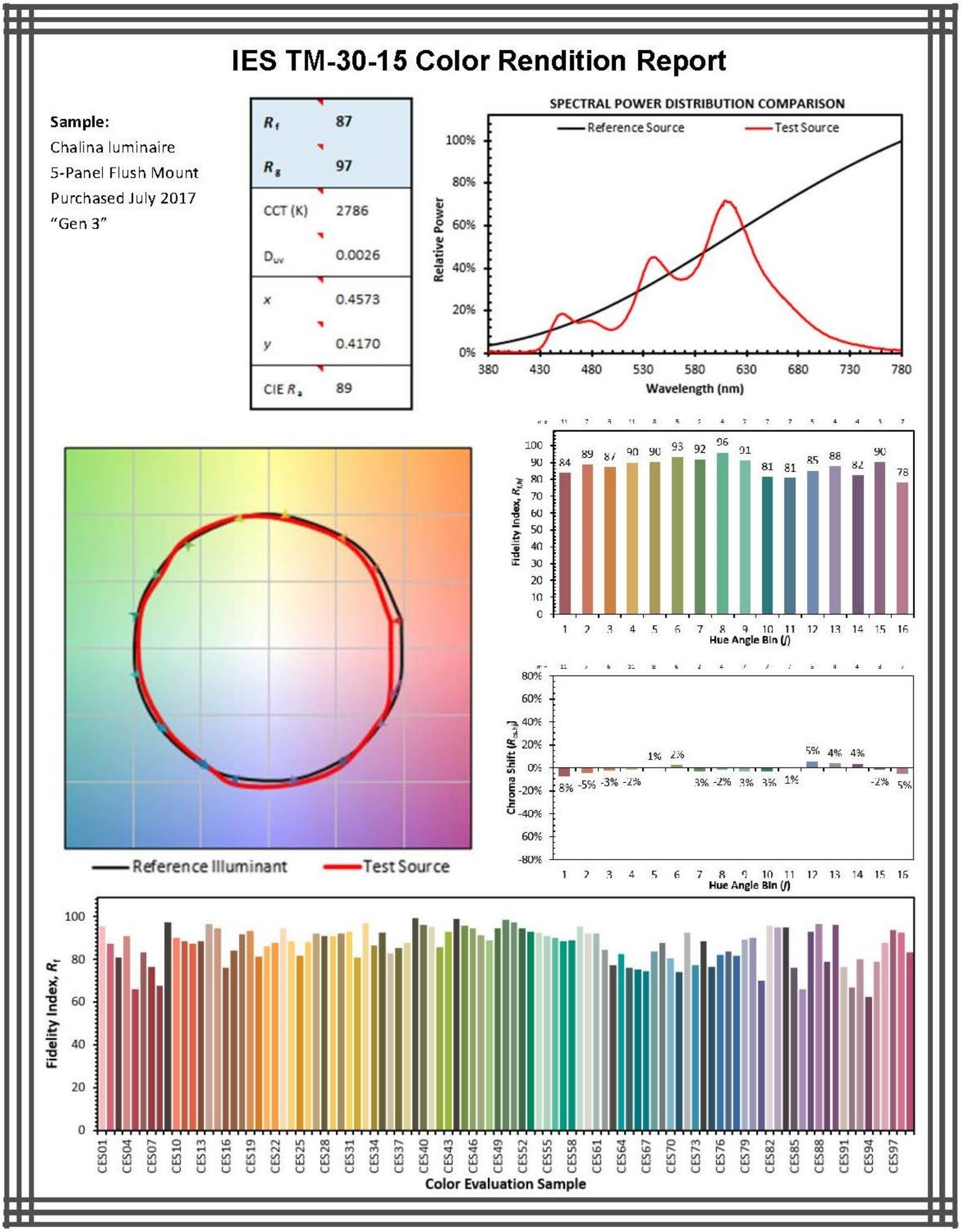
WW = Warm white

Appendix B



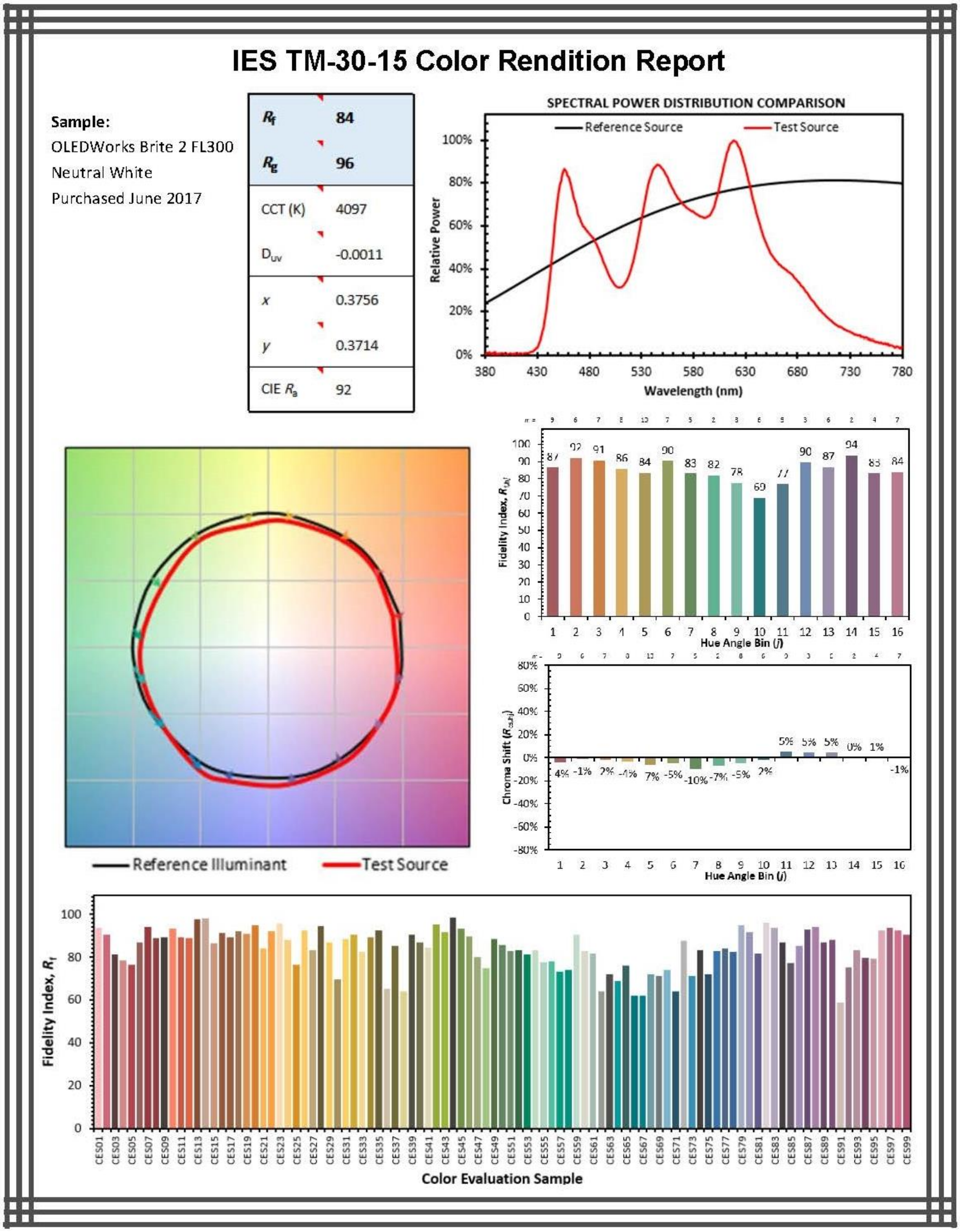
Created with the IES TM-30-15 Advanced Calculator Version 1.02.

Figure B-1. Color data for Chalina luminaire with Gen 2 OLED panels.



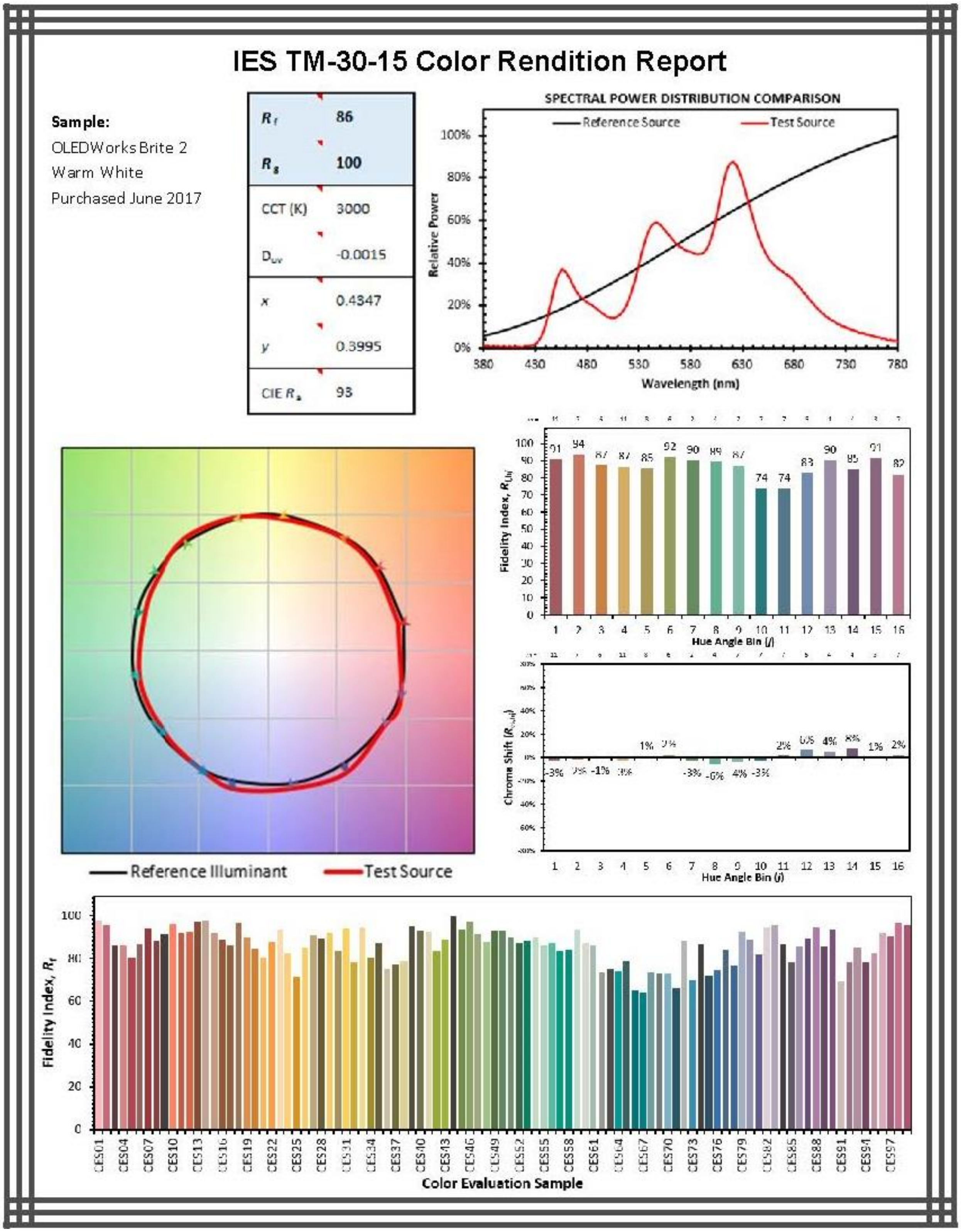
Created with the IES TM-30-15 Advanced Calculator Version 1.02.

Figure B-2. Color data for Chalina luminaire with Gen 3 OLED panels.



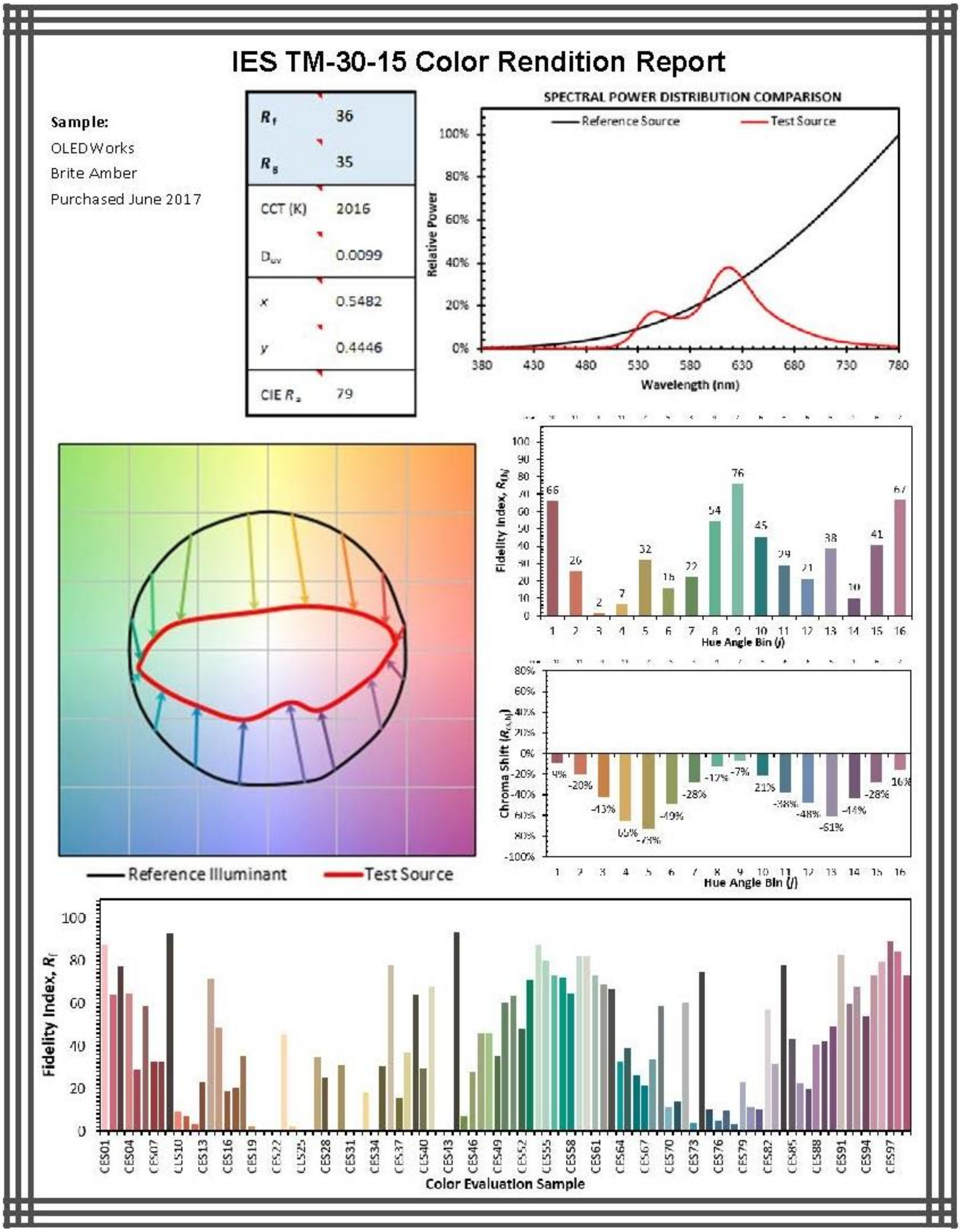
Created with the IES TM-30-15 Advanced Calculator Version 1.02.

Figure B-3. Color rendition data for OLEDWorks Brite 2 FL300 neutral white panels.



Created with the IES TM-30-15 Advanced Calculator Version 1.02.

Figure B-4. Color rendition data for OLEDWorks Brite 2 FL300 warm white panels.



Created with the IES TM-30-15 Advanced Calculator Version 1.02.

Figure B-5. Color rendition data for OLEDWorks Brite Amber panels.

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