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Round 2 Update of Stress Testing Results for Organic Light-Emitting Diode Panels and Luminaires

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Round 2 Update of Stress Testing Results for Organic Light-Emitting Diode Panels and Luminaires

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Disclaimer

Nomenclature or List of Acronyms

35OL	Operational life test conducted at 35°C
45OL	Operational life test conducted at 45°C
6590	Power cycling testing conducted at 65°C and 90% relative humidity
°C	Degrees Celsius
µm	Micrometers
Ω	Ohms
A	Amperes or amps
A_{dc}	Direct current amps
AST	Accelerated stress test
CALiPER	Commercially Available LED Product Evaluation and Reporting
cd/m^2	Candelas per square meter
CCT	Correlated color temperature
CRI	Color rendering index
dc	Direct current
DOE	U.S. Department of Energy
DUT	Device under test
eV	Electron volts
hr	Hour
hrs	Hours
IES	Illuminating Engineering Society
K	Degrees Kelvin
L70	The time required for the luminous flux to decay to 70% of the initial value
LCR	Inductance, capacitance, and resistance
LED	Light-emitting diode
LPW	Lumens per watt
mm	Millimeters
mm^2	Square millimeters
NIST	National Institute of Standards and Technology

OLED	Organic light-emitting diode
R^2	Correlation coefficient
RT	Room temperature
RTOL	Room temperature operational life
SDCM	Standard deviation color matching
SPD	Spectral power distribution
SSL	Solid-state lighting
TM	Technical memorandum
V	Volts
V_{dc}	Direct current volts
W	Watts
W_{dc}	Direct current watts

Executive Summary

Organic light-emitting diode (OLED) sources are a potential solid-state lighting technology for use in indoor lighting applications. Some of the advantages offered by OLEDs include thin profiles, low glare, diffuse lighting, and unique form factors. The U.S. Department of Energy (DOE) has released five reports about OLED technologies to provide information and analysis to the lighting industry [1]. These reports include the evaluation of two different field deployment sites, a market analysis, and two independent assessments of the performance of select commercially available OLED products [2].

This report builds on earlier DOE efforts with OLED technology by updating information about previously benchmarked OLED products (i.e., the Chalina luminaire from Acuity Brands and the Brite 2 and Brite Amber panels from OLEDWorks) in accelerated stress tests (ASTs). In addition, this report also provides an initial analysis of the performance of recently released OLED products—the Brite 3 panels from OLEDWorks.

During the ASTs described herein, populations of each products were subjected to continuous operation at mildly elevated ambient temperature environments of either 35°C or 45°C. In addition, a population of Brite 3 panels have just begun testing in a more aggressive power cycling test in a temperature and humidity environment of 65°C and 90% relative humidity (6590). These tests were performed with the goal of accelerating the aging of the devices to study their degradation pathways in a reasonable period of time. As a control, a population of each product was also operated continuously in a room temperature operational life test.

The key findings from this report and the earlier efforts detailed in previous DOE reports include the following:

- The luminous flux maintenance of the current OLED products is improving but still remains lower than that of some inorganic light-emitting diodes (LEDs) using mid-power LED packages made during the 2011 timeframe.
- Improvements in the thermal management of OLED panels tended to produce gains in the luminous flux and the chromaticity maintenance of the panels.
- Differential loss of light emission from the blue, green, and red light-emitting molecules that compose the OLEDs produced chromaticity shifts that were significant in early products but have improved in later products that use more stable materials and have better thermal management.
- A steady increase in power provided by the driver was measured in most cases. A concomitant decrease in efficiency also occurred.
- Abrupt failure of OLED panels generally occurs through a shorting mechanism that may be caused by the formation and growth of organic particles. The tendency for panels to fail abruptly is reduced in later products, and abrupt failures are less likely, but dark spots still tend to occur over time.
- Mildly accelerated conditions were found to provide meaningful acceleration of OLED failure modes and can reproduce field failures in greatly reduced time periods. Luminous flux degradation in such testing can be modeled by using standing lighting industry methods such as a single-exponential decay function after an initial period.

An examination of the technology progression of the devices under test demonstrates that the performance of OLED panels continues to improve. Both luminous flux maintenance and chromaticity maintenance have made notable gains. The power requirements of OLEDs do increase slowly with aging, which can be due in part to an increase in panel impedance, so overall luminous efficiency continues to decline. The findings indicate that steady gains continue to be made in OLED technologies for lighting applications. Continued improvement of the technology may open new opportunities for solid-state lighting in the indoor space that cannot be addressed with other LED–based light sources.

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1 Introduction

Organic light-emitting diode (OLED) technologies have made significant market penetration in mobile devices and have now become the dominant display technology for flagship smartphone and television products [3]. OLEDs are attractive display products in these applications because they provide an excellent color gamut with high luminance, properties that are derived from the light emission characteristics of the organic molecules used as light emitters in OLEDs. The OLED market gains in mobile device applications are coming at the expense of other white light-emitting technologies such as fluorescent lamps and light-emitting diode (LED) sources. Both fluorescent lamps and LEDs have historically served as backlights for active matrix displays that use white light combined with color filters to provide subtractive colors [4, 5].

White LEDs were also used in mobile device displays during their early days of commercialization, but that market has begun to shrink due to price contraction and market gains from OLEDs [4]. Approximately one decade ago, continued improvement of LED technologies ultimately resulted in their use in general lighting applications, which is a larger market opportunity. Following a similar technology progression, there can be significant benefits of research to improve the performance of OLED technologies to the point where they can be used in general lighting applications. For example, in some indoor lighting applications, OLED technologies have the potential to offer intriguing benefits, including thin form factors, 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. However, lighting using OLED technologies is still in its infancy, and several notable research challenges, including reducing costs, improving reliability, and commercializing the high-efficacy performance that has been demonstrated in the laboratory, still need to be realized [6].

Some of the challenges of using OLED technologies in lighting application are analogous to those experienced by LEDs during the early stages of technology development as LEDs progressed from display applications to general lighting. Among these challenges are improving the luminous efficacy to compete with existing lighting technologies and meeting the expectations of long-term performance and reliability established by current lighting solutions. To continue providing the industry with information about the state of OLED technology, this report updates findings from more than a year of life testing on some commercial products and provides initial benchmarks regarding the latest commercial OLED products.

1.1 Reliability Research for OLEDs

Over-stress testing and accelerated life testing have been recognized as appropriate methods to identify failure modes and to study the reliability of lighting devices [7]. Because OLED technologies are still being researched for lighting applications, there are no existing standard methods for such accelerated tests. However, testing standards for OLED lighting products will likely need to comply with the existing testing infrastructure for LED lighting, which relies on environmental stresses of temperature, vibration, and rapid power cycling. Current research about OLED testing methods point to the use of mildly elevated ambient temperatures (e.g., 35°C to 65°C) as being appropriate for accelerated stress tests (ASTs) [2, 8, 9].

1.2 Previous Studies of Commercial OLED Products

The U.S. Department of Energy (DOE) continues to support the development of OLED technologies as an integral part of the solid-state lighting (SSL) program [6]. DOE has published five reports that highlight commercial OLED technologies: two field evaluations [10, 11], a Commercially Available LED Product Evaluation and Reporting (CALiPER) study [12], initial results from ASTs of OLED panels and luminaires [2], and a market analysis [13]. A general conclusion from these studies is that the cosine emission profile of the light produced by OLED devices is beneficial for indoor lighting applications and provides OLEDs with a unique look and functionality compared with the generally directional nature of inorganic LED lighting. However, OLED technologies have experienced issues with the efficacy, reliability, driver performance, and initial costs, which are all potential market impediments requiring additional research.

Although there are several manufacturers of OLED panels for lighting applications [13], panels made by LG Display and OLEDWorks have been the primary focus of DOE studies to date because of their use in commercial luminaires. Although panels from both manufacturers use fluorescent blue-emitting organic molecules and phosphorescent red- and green-emitting organic molecules, panels from LG Display employ a three-tandem stack device structure [14], whereas panels from OLEDWorks incorporate a six-tandem stack structure [15]. 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, 10–13]. The luminaires in these DOE reports that incorporated panels from OLEDWorks mainly used the older Brite 1 technology [10–12], although the newer Brite 2 panels were examined in the most recent DOE reports [2, 12]. Recently, OLEDWorks introduced a new generation of OLED panels, the Brite 3, which provides enhanced capabilities over previous products [16]. The manufacturer's specifications for the warm white and neutral white Brite 3 products are provided in **Table 1-1**. The manufacturer's specifications for the earlier OLED products examined in DOE studies are presented in other reports [2, 12].

Table 1-1. Manufacturer's Specifications for the Brite 3 Panels.*

Panel Property	OLEDWorks Brite 3 Warm White FL300	OLEDWorks Brite 3 Neutral White FL300
Color (CCT, CRI)	3,000 K, CRI >90	4,000 K, CRI >90
L70 panel life, panel lumens	30,000 hrs at 8,300 cd/m^2	30,000 hrs at 7,000 cd/m^2
Panel efficiency (new)	75 LPW	57 LPW
Panel luminance, panel wattage	8,500 cd/m^2, 4.0 W	7,000 cd/m^2, 4.2 W

* Given specifications are for the panels only and do not include the driver efficiency.
Note: CCT = correlated color temperature; CRI = color rendering index; LPW = lumen per watt; L70 = time required for the luminous flux to drop to 70% of the initial value.

1.3 Scope of This Report

This report is a continuation of previous research reports about the performance of OLED technologies. The presented results build on findings from the earlier OLED reports [2, 12], but provide additional test results, new analyses, and new findings. The scope of this research report is to provide updates about OLED technologies regarding the following three key areas:

- Updating laboratory test results, including AST results, for three different generations of Chalina luminaires (manufactured by Acuity Brands)
- Providing updated laboratory test results, including AST findings, for the Brite 2 and Brite Amber panels (manufactured by OLEDWorks)
- Providing initial benchmarks regarding the recently released Brite 3 panels (manufactured by OLEDWorks).

The evaluation includes examinations of the luminous flux and chromaticity maintenance in mildly accelerating stress conditions. This technique, which involves lower ambient temperature than typically used for inorganic LEDs, is emerging as an appropriate test method for OLEDs [2, 8, 9]. This report also contains findings from initial temperature and humidity testing of the newly released Brite 3 panels. Temperature and humidity studies were added to the testing protocol for Brite 3 panels to assess improvement in thermal stability and panel encapsulation technologies and to examine whether the robustness of the OLED panels have improved over earlier benchmarks.

2 Experimental and Analytic Methods

This report builds on our previous DOE reports about commercial OLED technologies [2, 12] and uses many of the same AST protocols and measurement methods. This report focuses on the recent experimental findings that have not been previously reported. Previously reported results will be briefly summarized, but complete details can be found in the earlier reports. For convenience, a comparison of the testing protocols and test durations used in the earlier reports is provided in **Table A-1** of **Appendix A** of this report.

2.1 Samples

The structure of the devices under test (DUTs) used during ASTs varied slightly depending on whether the DUTs were luminaires or individual panels. The Chalina OLED luminaires were tested as received, and the only testing accommodation was that the driver was placed outside the test chamber. As a result, the Chalina drivers experienced only room temperature conditions throughout the test, whereas the remainder of the device experienced elevated ambient temperature.[1] The Brite 2 and Brite 3 panels from OLEDWorks were mounted on individual heat sinks, with the driver placed on the heat sink next to the panel. The power supply for the driver was kept external to the test chamber and experienced only room temperature environments throughout testing. A photograph of the DUT configurations is presented as **Figure 2-1**. The Brite Amber products were used without a heat sink, and the driver remained near the OLED panel within the test chamber when applicable.

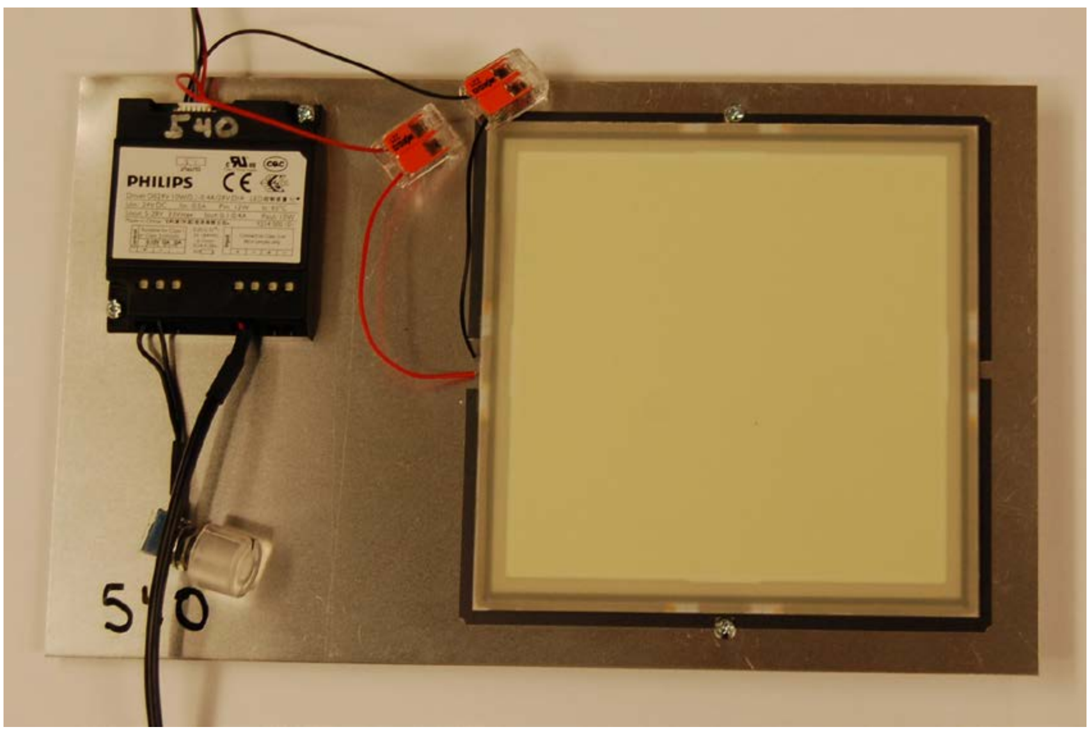

Figure 2-1. Test configuration for the OLEDWorks Brite 2 and Brite 3 DUTs examined in this study.

[1] Note: As previously described, three different generations of Chalina luminaires (henceforth referred to as GEN-1, GEN-2, and GEN-3) are examined in these tests [2]. The primary differences between the three generations of the product were the date of purchase and the incorporation of a metallized Kapton® film on the back of each panel for GEN-2 and GEN-3 products in order to provide additional heat spreading.

2.2 Stress Testing Methods

As summarized in **Table 2-1**, this report provides findings from room temperature operational life (RTOL) and ASTs involving temperature bakes at mildly elevated temperatures of either 35°C or 45°C. Either a temperature oven or a temperature-humidity environmental chamber was used for these tests. In addition, a temperature and humidity soak at 65°C and 90% relative humidity (6590) was only used for the Brite 3 panels. The findings from these tests are compared with the performance of the OLED devices during RTOL to gauge the acceleration factor of each test. For all tests, the OLED devices were continually powered at the maximum output set by the manufacturers, and there were no attempts to modify the device output. Specifically, all OLED devices were operated with the drivers provided by the manufacturer, and these drivers were operated at their expected maximum output conditions with no dimming signals applied to the product. During all operational life tests, the devices were operated continuously for the testing period, and there was no effort to power cycle. A power cycle was used during the 6590 test, and the power was applied to the panel for a 1-hr power on and 1-hr power off cycle.

Table 2-1. Test Methods Used in This Report.

Test Name	Test Description
RTOL	Continuous operation at room temperature (nominally 25°C) in ambient humidity
35OL	Continuous operation at a constant temperature of 35°C and ambient humidity
45OL	Continuous operation at a constant temperature of 45°C and ambient humidity
6590	Power cycling operation with a 1-hr power on and 1-hr power off cycle at a constant temperature of 65°C and relative humidity of 90%

2.3 Measurement Methods

2.3.1 Luminous Flux

The spectral power distribution (SPD), luminous flux, and chromaticity measurements were taken in a calibrated 65-inch integrating sphere with each sample mounted in the center of the sphere (4π geometry). Regular calibrations of the integrating sphere were performed by using a calibrated spectral flux standard that was traceable to standards from the National Institute of Standards and Technology (NIST). Self-absorption corrections were made for all samples by using an auxiliary lamp mounted inside the sphere in accordance with Illuminating Engineering Society (IES) standard LM-79 [17].

2.3.2 Luminance Uniformity

Panel luminance was measured by using an Ocean Optics USB2000 fiber-optic spectrometer that had been calibrated by using NIST traceable radiometric standards. The fiber optic (Ocean Optics QP400, 400 µm cladded silicon fiber diameter) was attached to the body of an inverted microscope, and the programmable stage of the microscope was used to position the sample to different locations. In this setup, the fiber optic was placed 1 mm above the DUT. Assuming the acceptance angle of the fiber optic is ±12.7 degrees, this experiment arrangement measures the total luminance from an area of 0.16 mm^2 on the panel. A photograph of this arrangement is presented as **Figure 2-2**.

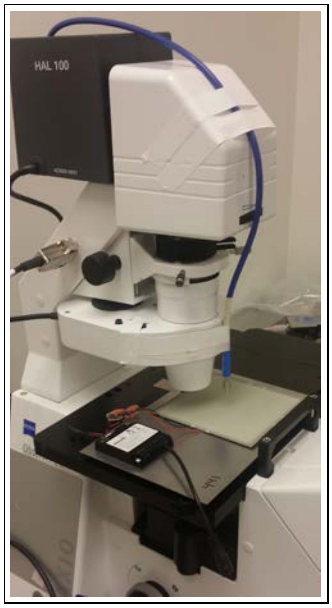

Figure 2-2. Testing configuration for luminance measurements.

For each sample, the programmable stage was moved to one of nine different pre-set positions for the Brite 2 and Brite 3 samples. These positions corresponded to areas near each corner of the display and three positions on the horizontal and vertical bisectors of the panel. The middle of the panel (i.e., the intersection of the horizontal and vertical bisectors) is only measured once. For the Brite Amber panels, the programmable stage was moved to one of three different present position along the horizontal bisector of the panel. Once the luminance was measured at these locations, the luminance uniformity variation can be calculated as shown in Equation 1 as follows:

$$Luminance\ Uniformity\ Variation\ (\%) = \frac{L_{max} - L_{min}}{L_{max}} \times 100 \qquad \text{(Eq. 1)}$$

In Equation 1, L_{max} is the maximum measured luminance and L_{min} is the minimum measured luminance across the panel.

2.3.3 Electrical Properties

Electrical properties such as power consumption and power factor were measured during photometric testing by using a Kill A Watt meter. When more accurate electrical measurements were required, a Xitron 2802 two-channel power analyzer was used. The Xitron power analyzer measures many electrical parameters, including voltage, current, power, power factor, and total harmonic distortion. Impedance measurements of the OLED panels were made by using an Agilent U1733C hand-held inductance, capacitance, and resistance (LCR) meter. Impedance (Z) and phase angle (ψ) were measured at frequencies of 100 Hz, 1,000 Hz, and 10,000 Hz.

2.4 Data Analysis Methods

2.4.1 Luminous Flux Maintenance

IES technical memorandum (TM) TM-28-14 is the established method for modeling and projecting the long-term luminous flux maintenance of LED lamps and luminaires [18]. A similar procedure (i.e., IES TM-21-11) can be used to model and project the luminous flux maintenance of inorganic LEDs [19]. Unfortunately, no corresponding standard method exists for OLEDs.

One procedure that has been widely used to model the degradation of OLEDs over time is the double-exponential model consisting of the two components given in Equation 2 [8]:

$$\varphi(t) = ae^{-\alpha_1 t} + be^{-\alpha_2 t} \qquad \text{(Eq. 2)}$$

In Equation 2, a and b are constants determined by the initial conditions, α_1 is the decay rate of initial processes, α_2 is the decay rate of long-term processes, and t is time. In this equation for the model, the first exponential component describes processes that occur early in device operation (typically less than 1,000 hrs) and the second exponential component describes long-term degradation processes that occur thereafter. One advantage of the double-exponential model is that if the time is sufficiently long (e.g., greater than 2,000 hrs), then the first term can be ignored, and the equation is analogous to that used in TM-28-14 and TM-21-11. Consequently, measurement times of 6,000 hrs or longer are preferred when using a single-exponential function.

Another approach to modeling the degradation of OLED emitters is to use the stretched exponential function as presented in Equation 3 [8] as follows:

$$\varphi(t) = e^{\left(-\frac{t}{\tau_0}\right)^{\gamma}} \qquad \text{(Eq. 3)}$$

In Equation 3, τ_0 is the characteristic time required for performance to degrade to 63% (i.e., $1 - 1/e$) of the initial value, and γ is a parameter that characterizes the degradation rate. To use this model, the experiment time must be long enough for a reasonable value of τ_0 to be obtained.

It is difficult to compare the parameters (e.g., decay rates α_1 and α_2) of a double-exponential model with the degradation rate (γ) obtained from a stretched exponential model. Therefore, in the absence of an acceptable method for modeling luminous flux in OLEDs, we decided to modify the double-exponential model for OLEDs to make it align with the models used in TM-21-11 and TM-28-14. These LED standards do not use data collected during early operation of the device, which is equivalent to dropping the short-term component (i.e., $ae^{-\alpha_1 t}$) of Equation 2 and using a single-exponential decay model to describe long-term behavior. In a single-exponential decay model such as the one used in TM-28-14 and TM-21-11, the ratio of the luminous flux at any time ($\Phi(t)$) to the initial luminous flux Φ_0 can be expressed as shown in Equation 4 as follows:

$$\Phi(t)/\Phi_0 = Be^{-\alpha t} \quad \text{(Eq. 4)}$$

In Equation 4, B is the pre-exponential factor, and α is the decay rate constant. Because TM-21-11 and TM-28-14 also use this equation to model luminous flux maintenance, comparisons of the α values of data derived from these measurements provide some relative measures of the light source. Additional modifications in the TM-28-14 test method were made in the data analysis results presented here, and the details of the modifications compared with the methods of TM-28-14 are provided in **Table 2-2**.

Table 2-2. Comparison of the Luminous Flux Maintenance Model Used in This Report with the Requirements of IES TM-28-14 and TM-21-11.

Elements of the Single-Exponential Model Used in This Report	Comparison with IES TM-28-14 and TM-21-11
A single-exponential fit is used to model luminous flux maintenance data. The decay rate constant (α) and pre-exponential factor (B) are the reported parameters for the model.	Same
A minimum of 6,000 hrs of data is required. Longer test times are preferred.	Same as the direct extrapolation method of TM-28-14 and TM-21-11.
For data collected between 6,000 and 10,000 hrs, only the last 5,000 hrs are used for the model. For data collection times greater than 10,000 hrs, only the last 50% of the data is used. The time of the first data point used for model is the minimum modeling time.	Same
Typically, 2 to 4 samples are used in the models given here.	Somewhat different. TM-28-14 requires at least 3 samples for the direct projection method, whereas TM-21-11 requires at least 10 samples.
The ambient test temperatures for OLED models were either room temperature (i.e., 25°C), 35°C, or 45°C. The lower temperatures are justified due to the expected indoor use of the OLED panels.	Somewhat different. TM-28-14 does not specify a test temperature but does allow for testing at ambient temperatures of 25°C. TM-21-11 requires testing at 85°C and 105°C.
All data after the minimum modeling time were used for the OLED model, regardless of whether the test increment was the same. This has the consequence of providing more weight to specific data points.	Significantly different. TM-21-11 requires equal test time increments (typically 500–1,000 hrs) for modeled data.

2.4.2 Emission Spectra Deconvolution

The OLED technologies tested in this report have complex structures where multiple organic layers (e.g., emissive layers, electron transport layers, hole transport layers) are sandwiched between electrodes. Therefore, the decay rate constant (α, see Section 2.4.1 of this report) that describes the degradation of OLEDs over time incorporates the rate of degradation of each emitter, charge transport layer, and all other components into a single variable. Although this information is helpful to project luminous flux maintenance, further spectral deconvolution analysis is needed to determine individual emitter contribution to the light degradation rate to subsequently predict chromaticity shift.

LG Display's panels employ a three-tandem stack device structure with two combined green and red emissive layers and one blue emissive layer [14]. OLEDWorks panels incorporate a six-tandem stack structure consisting of two blue emissive layers and four combined green and red emissive layers [15]. The identity of the emitters used in the tested OLED technologies are unknown to the authors of this report because of the proprietary formulations used by the manufacturers.

Given that the emitters are likely aromatic compounds, the emission spectra of the individual emitters contributing to the SPD of each DUT are anticipated to be asymmetric or skewed [20]. An empirical function [$f(s,A,\Delta p,p_o,p)$] to describe a skewed emission distribution (commonly called a skewed Gaussian) can be drawn from Fraser and Suzuki [21] and is shown in Equation 5.

$$f(s, A, \Delta p, p_0, p) = A * \exp\left(-\,ln(2)\left(ln\left(1 + \frac{2s(p-p_0)}{\Delta p}\right) * \left(\frac{1}{s}\right)\right)^2\right) \qquad \text{(Eq. 5)}$$

In Equation 5, *A* describes the maximum radiant flux of the emitter, p_0 describes the wavelength at which maximum emission occurs, and *s* is the asymmetry parameter, which is positive when the emission skews at wavelengths $p > p_0$ and negative when the emission skews toward wavelengths $p < p_0$ (for s close to zero, the skewed distribution tends toward a symmetric Gaussian).

The relationship between Δp and the full width of the emission distribution at half-maximum radiant flux (*w*) is described in Equation 6, as follows:

$$w = \Delta p\left(\frac{\sinh(s)}{s}\right) \qquad \text{(Eq. 6)}$$

For this report, all peaks in the SPD of the tested OLED lighting products were assumed to be separate emitting compounds and were fit with separate skewed Gaussian. Because of the broad nature of organic light-emitting compounds, the sum of two skewed Gaussian often better fit the data for each emitting peak or region (blue, green, and red emitters, as shown in **Figure 2-3**). Although many factors play into the overall SPD produced by an OLED lighting device (e.g., organic emitters, dopants, diffusers, uniformity), the SPD was estimated in this report as the sum of the individual emitters, and the sum of squared errors was minimized through a non-linear regression analysis to complete the spectral deconvolution. Radiant power was estimated by using the trapezoid rule to approximate the definite integrals of the skewed Gaussian that composed the SPD. Radiant power of the blue, green, and red emitters was subsequently calculated as the sum of the radiant power of the respective skewed Gaussian.

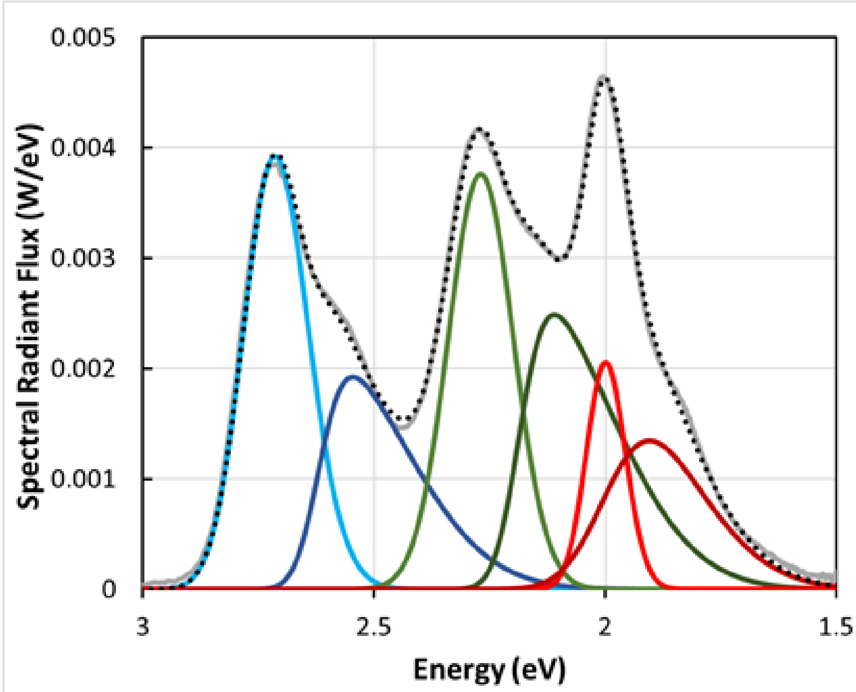

Figure 2-3. Spectral emission deconvolution of the Brite 2 neutral white panels with two skewed Gaussian used to model each blue, green, and red emitter.

3 Results

3.1 Chalina Luminaires

As originally reported, the Chalina luminaires used in this study were purchased at three different times (approximately 1 year apart), and the DUTs are designated in this report as belonging to GEN-1, GEN-2, or GEN-3, depending on the time of purchase. The most visible difference between the three generations of Chalina products is that the GEN-1 products have a reflective back surface of the OLED panels [12], whereas the back surface of the OLED panels for both the GEN-2 and GEN-3 products was covered by a metallized Kapton® film that was applied presumably to improve heat spreading [2]. Because of the limited quantities and different purchase times of these DUTs, only select samples were subjected to each test. The three different generations of Chalina luminaires and the test environments to which each was exposed are summarized in **Table 3-1**.

Table 3-1. Characteristics of the Three Generation of Chalina Devices Examined During These Tests.

Designation	Purchase Date	Characteristics	Testing Environments
GEN-1	September 2015	No extra heat spreader on the OLED panels	45OL
GEN-2	September 2016	Metallized Kapton tape heat spreader on the panels	RTOL
GEN-3	July 2017	Metallized Kapton tape heat spreader on the panels	35OL and 45OL

As previously reported, panel failures because of shorting were observed in the GEN-1 products, and two out of the four original DUTs in the 45OL test were dropped from testing because of excessive loss of luminous flux arising from panel shorting [2, 12]. However, the remaining two DUTs (i.e., DUT-225 and DUT-227) continue to operate properly and have now surpassed 14,000 hrs (DUT-225) and 12,000 hrs (DUT-227) of operation during the 45OL test. This report only presents results to 12,000 hrs because that is the longest time that both devices have been tested. As previously reported [2], one panel on DUT-225 failed because of shorting after 7,000 hrs of operation at 45°C, and the total luminous flux produced by the device dropped. In contrast, no panel failures have been observed on the GEN-2 and GEN-3 products through the 8,000 hrs of testing presented in this report.

3.1.1 Luminous Flux Maintenance

The luminous flux maintenance of the Chalina luminaires depended upon the temperature of the test environment (see **Figure 3-1**). The samples in the RTOL test exhibited the best luminous flux maintenance, and the maintenance was slightly lower for the 35OL test. In contrast, the luminous flux maintenance was noticeably lower for DUTs operated in the 45OL test. The data presented in Figure 3-1 is an average of the population for each test condition, which consists of two DUTs for RTOL, four DUTs in the 35OL test, the two surviving DUTs of GEN-1 products in the 45OL test, and two DUTs of GEN-3 products in the 45°C 45OL test. Data for the GEN-1 and GEN-3 products in the 45OL test are presented separately in Figure 3-1, and the failure of one GEN-1 panel after 7,000 hrs of testing produced a noticeable drop in luminous flux maintenance.

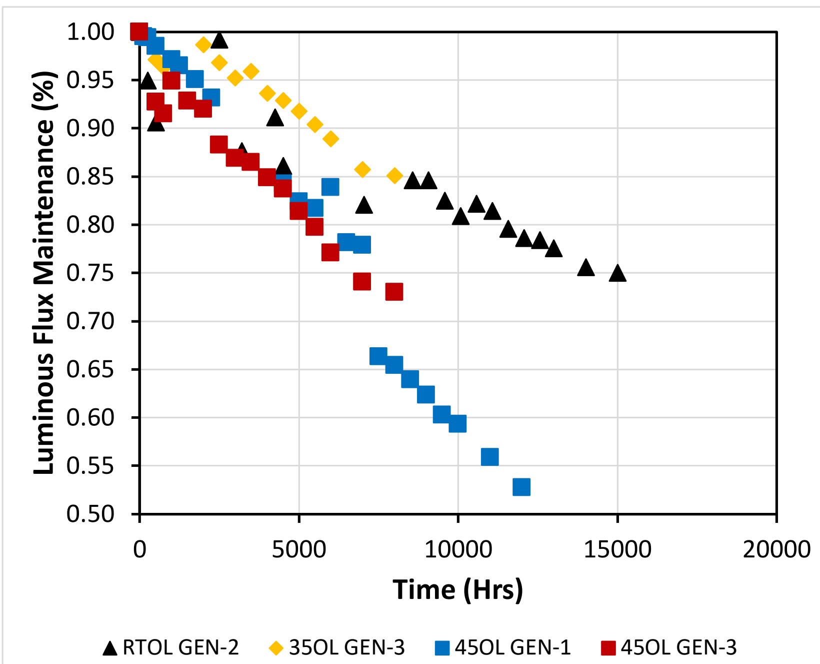

Figure 3-1. Average luminous flux maintenance for the populations of Chalina luminaire operated continuously in the RTOL, 35OL, and 45OL test environments. The performance results of both GEN-1 and GEN-3 products at 45°C are provided separately.

Using the approach described in Section 2.4.1 of this report, the luminous flux maintenance models for the DUTs subjected to RTOL and 35OL testing were determined, and the results are shown in **Figure 3-2**. Separate averages were calculated for the room temperature and 35°C test populations. Only DUT-332 was used for RTOL testing because the other device (i.e., DUT-331) suffered a cracked panel when it was inadvertently dropped. Otherwise, no other panel failures occurred for these DUTs throughout the test period, and all five panels were fully operational at the end of testing. For DUT-332 during the RTOL test, only the data between 7,044 and 15,000 hrs were used in the model, as shown in Figure 3-2, in accordance with the guidelines listed in Table 2-2. A single-exponential fit of this data produced an α value of 1.6×10^{-5}, and a good correlation coefficient (R^2) of 0.83. For the DUTs in the 35OL test, 8,000 hrs of operation have been completed. Consequently, data between 3,000 and 8,000 hrs were used for the model (see Figure 3-2). The α was calculated to be 2.6×10^{-5} with an R^2 value of 0.97.

Performing a similar analysis for the samples in the 45OL test was complicated by the shorting of one panel in a GEN-1 device (i.e., DUT-225), which resulted in a sharp drop in luminous flux at 7,000 hrs (see Figure 3-1). To compensate, we decided to divide the total luminous flux by the number of fully functional panels, for each time interval, and report this ratio. The results are presented in **Figure 3-3**. Because the two surviving luminaires with GEN-1 OLED panels have reached 12,000 hrs during the 45OL test, the luminous flux maintenance model can be calculated by using the average readings between 6,000 and 12,000 hrs. The α value was calculated to be 4.7×10^{-5}, and the R^2 value was excellent (0.97). A similar procedure was followed for the luminaires with GEN-3 panels in the 45OL test, and the α value was calculated to be 3.9×10^{-5}, and the R^2 value was excellent (0.98). The differences in these α values suggest that the use of metallized Kapton on the back of the OLED panels provides a measure of increased thermal stability.

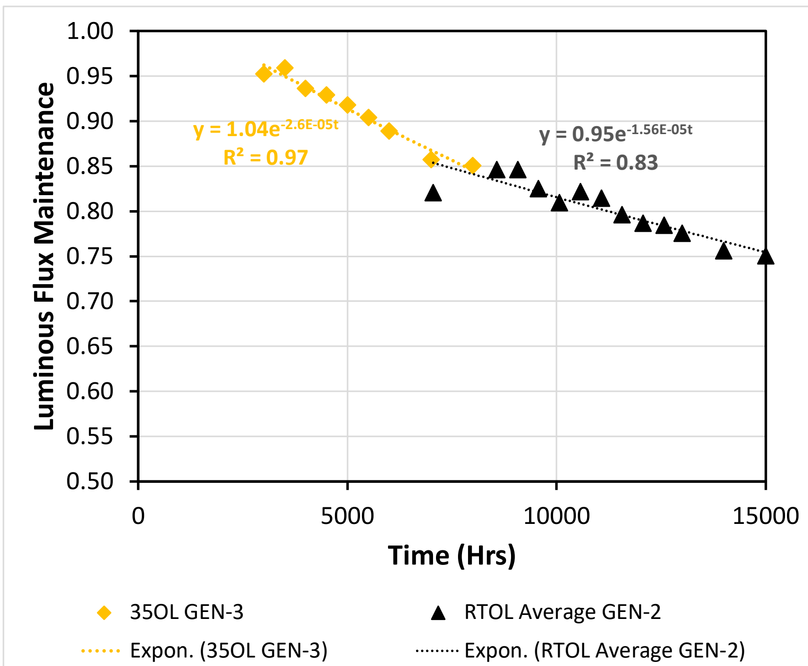

Figure 3-2. Average luminous flux maintenance for Chalina luminaires subjected to RTOL testing (GEN-2 panels) and those operated in the 35OL test (GEN-3 panels). Single-exponential fits for the latter parts of the data are shown.

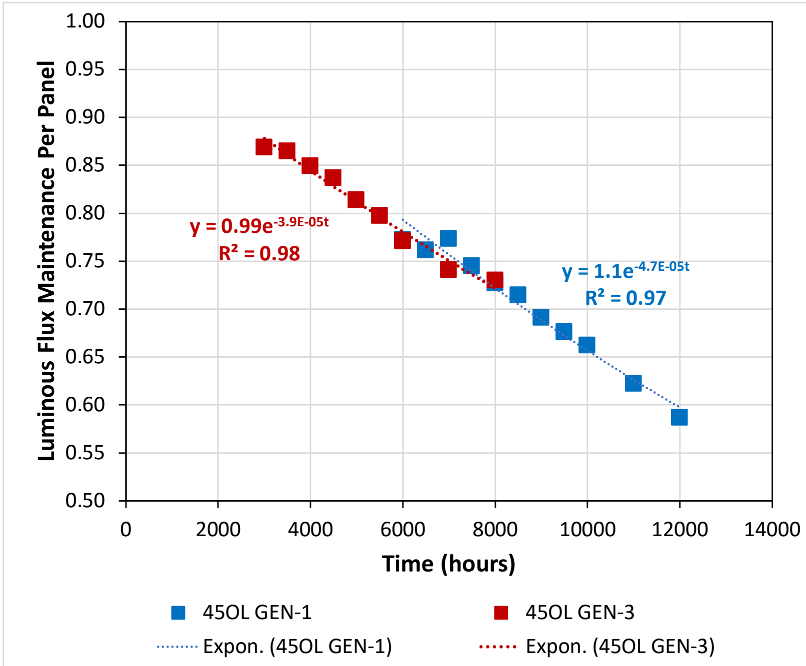

Figure 3-3. Average luminous flux maintenance models for Chalina luminaires in the 45OL test. Data for luminaires containing only GEN-1 panels and those containing only GEN-3 panels are provided separately.

3.1.2 Chromaticity

The luminaires evaluated during the 45OL test provide the clearest indication of the chromaticity shifts that can be expected to occur in the Chalina OLED devices (with panels from LG Display). These results are summarized in **Figure 3-4** for the samples containing either GEN-1 panels or GEN-3 panels. Figure 3-4 shows the change in chromaticity from the initial point, and the direction of this change can provide significant information about the relative changes in emission intensities that are responsible for the chromaticity shift as discussed in other publications [22, 23].

During the 45OL test, the chromaticity shift for the Chalina luminaires with GEN-1 panels proceeded in the generally blue direction, which is in agreement with previous findings [2]. This trend followed at approximately the same rate throughout testing over the past year, and the change in the -*Δv′* direction was almost twice that in the -*Δu′* direction. This behavior is indicative of a chromaticity shift in the blue direction that is being strongly driven by light emission loss processes. The observation of a strong blue shift for the OLED products suggests that light emission from the red and green emitters is decaying faster than that from the blue emitter, which is in agreement with the examination of the SPD changes previously given [2]. The magnitude of this change (as shown by the blue arrow in Figure 3-4) demonstrates that the chromaticity change is noticeable to the viewer, which is confirmed by the visible change in appearance of the light from the luminaire and the increase in the correlated color temperature (CCT) value. After 12,000 hrs of testing in 45OL for the luminaires with the GEN-1 panels, the magnitude of the chromaticity shift (*Δu′v′*) exceeded 7 standard deviation color matching (SDCM), which is generally viewed as a sign of excessive chromaticity shift.

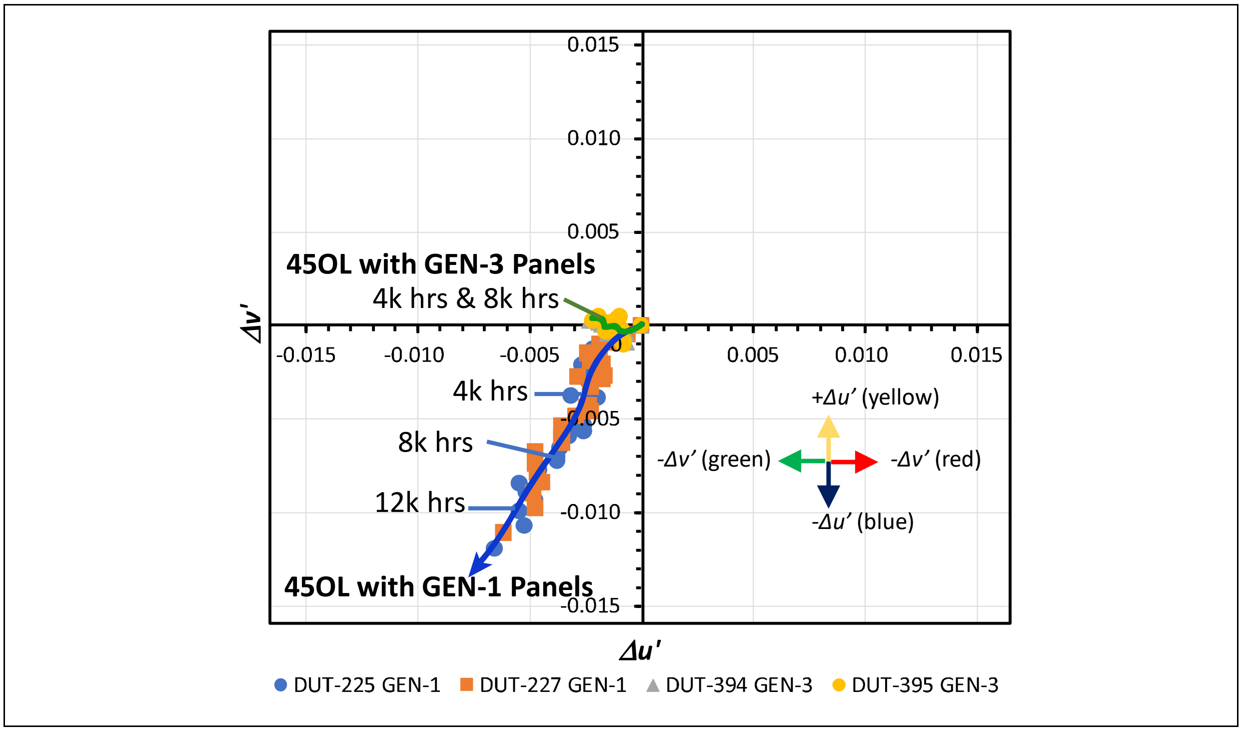

Figure 3-4. Chromaticity shifts for Chalina luminaires with GEN-1 and GEN-3 OLED panels in the 45°C elevated ambient temperature stress test.

However, the behavior of the Chalina luminaires with the GEN-3 panels (also from LG Display) was significantly different as shown in Figure 3-4. The chromaticity of these devices shifted in the green direction, which is signified by a chromaticity change predominately in the -$\Delta u'$ direction with minimal change in the $\pm\Delta v'$ direction. This shift occurred rapidly and reached a plateau of $\Delta u'$ = -0.002 and $\Delta v'$ = -0.001 before 4,000 hrs of operation during the 45OL test. As a result, there is minimal difference in the chromaticity coordinates for GEN-3 samples following between 4,000 and 8,000 hrs of operation during the 45OL test. The improved chromaticity maintenance of the newer products demonstrates significant improvements in the reliability of the panels used in the Chalina luminaires when progressing from GEN-1 to GEN-2 and GEN-3.

For GEN-2 and GEN-3 DUTs tested in RTOL or 35OL, the chromaticity shift also rose quickly and then plateaued. Once the plateau was reached, the chromaticity remained near the same coordinates (within experimental error). At room temperature, this chromaticity plateau was reached after approximately 9,000 hrs of operation, whereas it was reached after approximately 4,000 hrs of operation during the 35OL test because of the acceleration factor of the test. As shown in **Figure 3-5**, the plateau for devices during the RTOL test occurred at approximately $\Delta u'$ = 0.001 and $\Delta v'$ = 0.0025, whereas the chromaticity shifted to approximately $\Delta u'$ = -0.0007 and $\Delta v'$ = 0.0008 for the DUTs during the 35OL test. Although the chromaticity of the GEN-2 and GEN-3 devices changes over time in a similar manner, the overall differences between these DUTs is thought to be small. It is important to note that the direction of the chromaticity shift changes with environmental conditions, with the RTOL devices (GEN-2) shifting mainly in the yellow direction, the GEN-3 DUTs in the 45OL test shifting in the green direction, and the GEN-2 panel in the 35OL test shifting in the direction between the two. These behaviors suggest a temperature dependence in the degradation of green and red emitters.

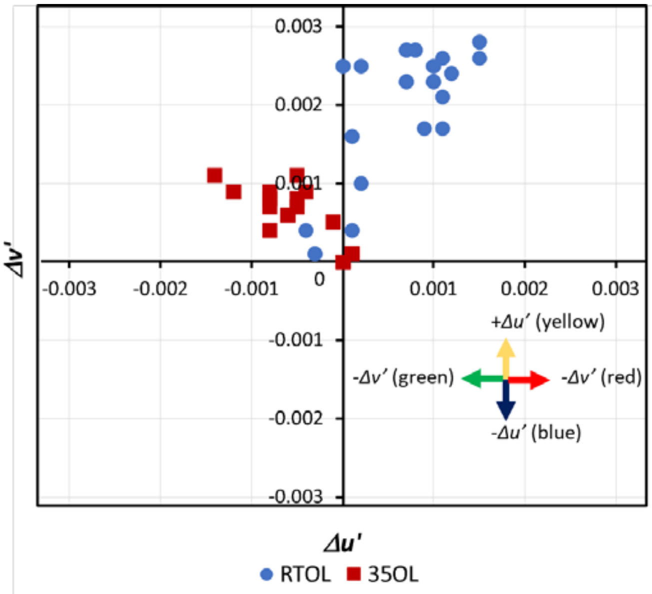

Figure 3-5. Changes in the chromaticity points for Chalina OLEDs subjected to RTOL (blue) and 35OL (red).

3.1.3 Electrical Analysis

In this report, we provide the updated average impedance values of all fully operational OLED panels across the control (GEN-1 panel), GEN-1 panels subjected to the 45OL test, GEN-2 panels subjected to the RTOL test, and GEN-3 panels subjected to either the 35OL or 45OL test. The impedance of each panel was measured at three frequencies—100 Hz, 1,000 Hz, and 10,000 Hz. The average value and standard deviation for all panels of a given generation and AST protocol are presented in **Table 3-2**. Previously discussed trends continue to maintain validity: GEN-1 panels operated during the 45OL test continue to show higher impedance values at all measured frequencies relative to the GEN-1 control; this increase is statistically significant at the 99% confidence level. In contrast, GEN-2 and GEN-3 panels continue to show lower impedance values relative to their initial panel impedances, suggesting a change in structure compared with GEN-1 panels. These changes are statistically significant (at the 90% confidence level) for the GEN-3 DUTs subjected to either the 35OL or 45OL test; however, the decrease in mean impedance for the GEN-2 DUTs subjected to the RTOL test is not statistically different.

Table 3-2. Impedance of Panels in Chalina OLED Luminaires.

Frequency	Panel Type	100 Hz	1,000 Hz	10,000 Hz
Panels from control	LG Display—GEN-1	2,375 ± 10 Ω	248 ± 1 Ω	25.9 ± 0.1 Ω
Operational panels from 45OL (≥12,000 hrs)	LG Display—GEN-1	2,809 ± 29 Ω	297 ± 3 Ω	30.6 ± 0.2 Ω
Initial measurements	LG Display—GEN-2	2,721 ± 30 Ω	296 ± 4 Ω	30.9 ± 0.4 Ω
Operational panels from the RTOL test (15,000 hrs)	LG Display—GEN-2	2,716 ± 30 Ω	297 ± 4 Ω	30.9 ± 0.4 Ω
Initial measurements	LG Display—GEN-3	2,246 ± 12 Ω	237 ± 2 Ω	25.7 ± 0.2 Ω
Operational panels from the 35OL test (8,000 hrs)	LG Display—GEN-3	2,225 ± 14 Ω	240 ± 2 Ω	25.7 ± 0.2 Ω
Operational panels from the 45OL test (8,000 hrs)	LG Display—GEN-3	2,178 ± 9 Ω	236 ± 1 Ω	25.3 ± 0.1 Ω

Note: The reported uncertainties represent 1 standard deviation.

Although the average impedance of the GEN-3 panels in Chalina luminaires decreased through 8,000 hrs, their average power consumption increased across both 35OL and 45OL tests as shown in **Figure 3-6**. The GEN-3 luminaires were purchased in two different batches, as detailed in our previous report [2], and we believe that the difference in initial power consumption is a result of purchase date (luminaires assigned to operate during the 45OL test were purchased first). The GEN-3 luminaires operated during the 45OL test demonstrated a greater increase in power consumption (as indicated by the slope of the linear least squares fit) compared with the GEN-3 luminaires operated during the 35OL test, which is consistent with higher stress conditions. Because the panel impedances actually decrease for these devices (see Table 3-2), the increase in power consumption is not likely because of impedance changes.

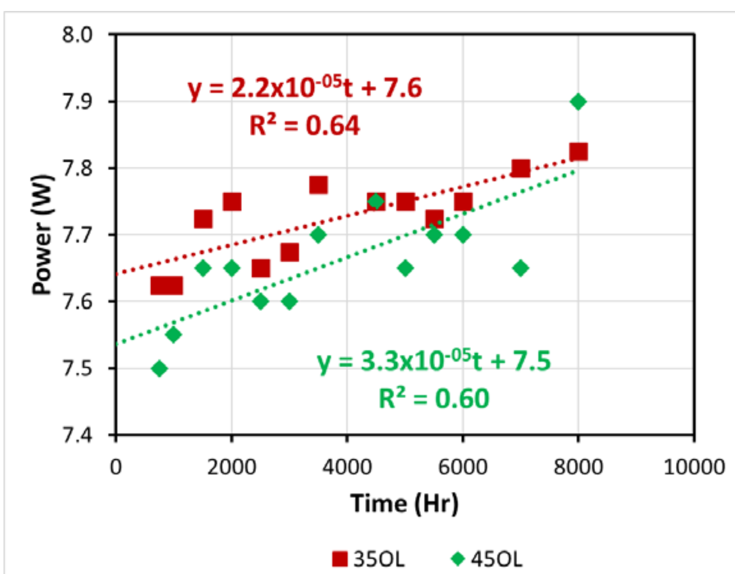

Figure 3-6. Average power increase for GEN-3 luminaires through 8,000 hrs.

3.2 OLEDWorks Lumiblade Brite 2 and Brite 3 Panels

In this report, four models of Lumiblade OLED lighting panels from OLEDWorks were investigated and are described as FL300 Brite 2 neutral white, FL300 Brite 2 warm white, FL300 Brite 3 neutral white, and FL300 Brite 3 warm white. These DUTs are simply referred to as Brite 2 neutral white, Brite 2 warm white, Brite 3 neutral white, and Brite 3 warm white. Separate populations of Brite 2 neutral white and warm white panels were used in each of three stress testing protocols (i.e., RTOL, 35OL, and 45OL). Likewise, separate populations of Brite 3 neutral white and warm white panels were used in each of the four stress testing protocols (i.e., RTOL, 35OL, 45OL, and 6590). Unless otherwise noted, the data reported herein for each population are the average of three samples within the labeled AST protocol. Updated test results through 7,000 hrs are provided for the Brite 2 warm white and neutral white OLED panels. Initial AST results from the latest Lumiblade generation—the Brite 3 series—are provided through 1,500 hrs.

3.2.1 Photometric Analysis

The SPDs of the Brite 2 neutral white and Brite 2 warm white panels were provided in our previous report [2]. The SPDs of Brite 3 neutral white and Brite 3 warm white panels are provided in **Figure B-1** and **Figure B-2**, respectively, of **Appendix B** of this report. IES TM-30-15 [24] was used to calculate the color rendition of these sources from the respective SPDs measured during this research, and the results are also included in Appendix B. In all cases, the color rendering properties of the Brite 3 neutral white and warm white OLED panels were found to be comparable with their Brite 2 counterparts.

3.2.2 Luminous Flux Maintenance

3.2.2.1 Brite 2

Through 7,000 hrs, the average luminous flux maintenance for the Brite 2 neutral white panels remains above 85% for DUTs in all three stress protocols. For all AST protocols, the luminous flux maintenance experienced two regions of decay: a fast, initial decay that leveled out at approximately 2,000 hrs, followed by another decay period after 2,000 hrs, which was consistent with a double-exponential model. For the first 2,000 hrs, the average luminous flux maintenance across the AST protocols remained very similar and decayed at a similar rate, as shown in **Figure 3-7A**. The similarity in initial luminous flux decay may result from comparable levels of residual contaminants (e.g., water) present during the device fabrication process. The luminous flux decay rates of blue phosphorescent emitters has been found to be greatly influenced by water content in the OLED panel [25], so we are postulating that a similar mechanism may be occurring here. After 2,000 hrs, the rate of luminous flux decay changed and started to correlate with the AST protocols; lower luminous flux maintenance was observed for AST protocols with higher temperature stresses.

The IES TM-28-14 adaptations for OLED light sources are explained in Section 2.4.1 of this report, but an additional stipulation was added for the Brite 2 neutral white panels. For these neutral white samples, only the data collected between 2,500 and 7,000 hrs are fit with exponential curves because of the suspected fabrication-related degradation through 2,000 hrs. The single-exponential least squares curve fits of the Brite 2 neutral white data produced small residuals over this time period, suggesting good fits, as shown in **Figure 3-7B**. The decay rate constants correlated to the AST protocols, with high stress protocols having higher decay rate constants.

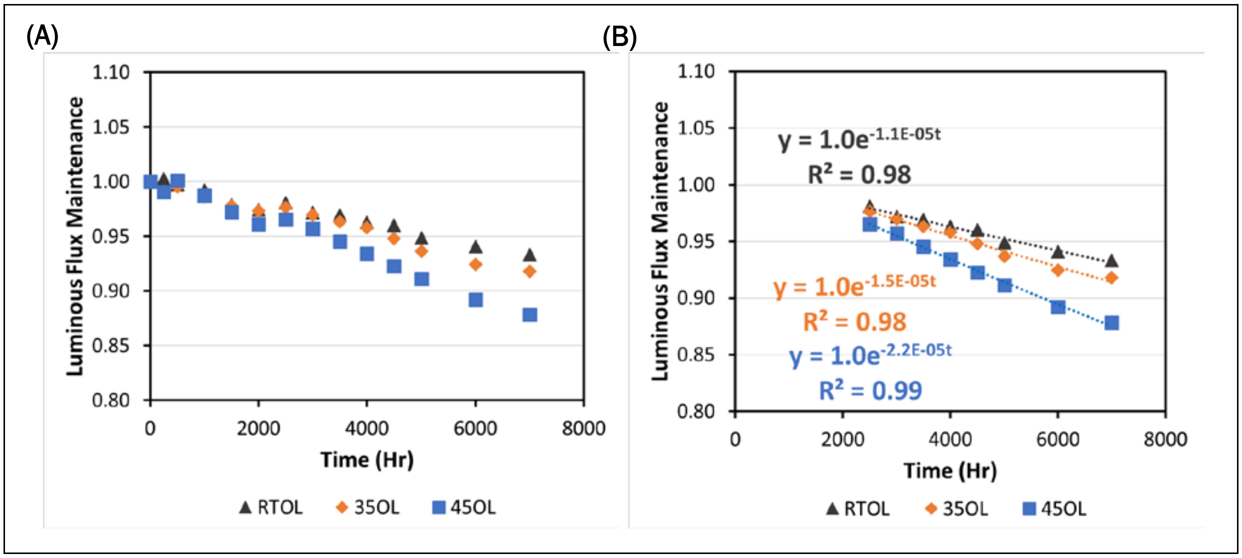

Figure 3-7. Average luminous flux maintenance for Brite 2 neutral white panels (A) and exponential fits of the latter part of the data (B).

The average luminous flux maintenance for the Brite 2 warm white panels remained greater than 80% through 7,000 hrs of exposure to the three different AST protocols as shown in **Figure 3-8A**. Within each AST protocol, the Brite 2 warm white panels had lower levels of luminous flux maintenance compared with the Brite 2 neutral white panels. Similar to the Brite 2 neutral white panels, the Brite 2 warm white panels operated during the RTOL and 35OL tests exhibited two regions of decay: a fast, initial decay that was similar for the RTOL and 35OL populations and leveled out at approximately 2,000 hrs, followed by another slower decay period after 2,000 hrs. This two-step behavior was not observed for Brite 2 warm white panels evaluated during the 45OL test. Instead, a steady decrease in luminous flux maintenance after 250 hrs was found for these samples.

To keep consistency with the Brite 2 neutral white panels, the first 2,000 hrs of LM-80 data for the Brite 2 warm white panels were discarded and subsequently, exponential least squares curve fits were applied to the remaining data as shown in **Figure 3-8B**. As expected, the decay rate constants for the panels evaluated during the 45OL test were higher than the decay rate constants for the panels evaluated during 35OL and RTOL tests. The decay rate constants within each AST protocol were also higher for the warm white panels than for the neutral white panels.

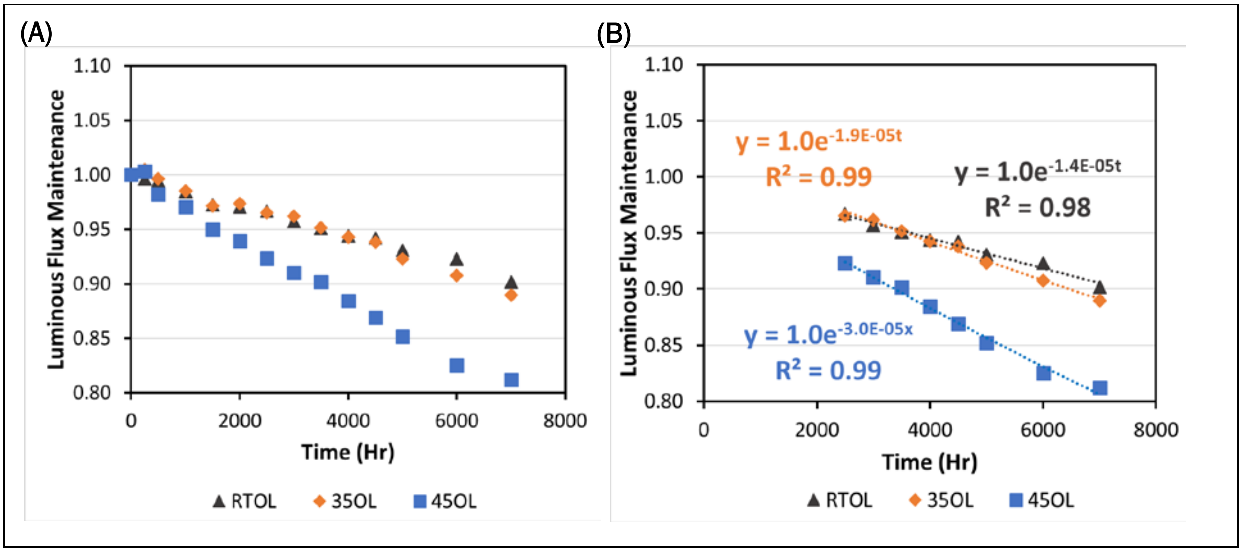

Figure 3-8. Average luminous flux maintenance for Brite 2 warm white panels (A) and exponential fits of the latter part of the data (B).

3.2.2.2 Brite 3

By 1,500 hrs, the average luminous flux maintenance of Brite 3 neutral white panels in all four testing protocols remains greater than 92%, as shown in **Figure 3-9**. Minimal decreases in luminous flux (<2%) were observed for the Brite 3 neutral white panels subjected to lower stress protocols (RTOL, 35OL, and 45OL), and these levels are comparable with or better than the performance for the Brite 2 neutral white panels through 1,500 hrs. The luminous flux maintenance of the Brite 3 neutral white panels subjected to 6590 is lower than the remainder of the DUTs, but the panels still function properly. This finding is noteworthy because panels in the Chalina luminaires subjected to cyclic power testing at 75°C and 75% relative humidity failed to operate after less than 750 hrs [12]. It is anticipated that the luminous flux of the panels tested at 6590 will continue to decay at a faster rate than those subjected to less aggressive stress testing protocols. However, the fact that the devices have survived 1,500 hrs of testing at 6590 suggests that the encapsulation technology of the device has improved resistance to environmental stress.

Through 1,500 hrs, the luminous flux maintenance of all Brite 3 warm white panels remains greater than 83%, as shown in **Figure 3-10**. The luminous flux maintenance for the Brite 3 warm white panels is comparable to that of their Brite 2 panel counterparts at 1,500 hrs for the panels subjected to the RTOL, 35OL, and 45OL tests. The Brite 3 warm white panels operated at 6590 experienced the largest drop in luminous flux (luminous flux maintenance is approximately 84%), and it is anticipated that the panels operated at this higher stress testing protocol will continue to decay at a faster rate than those subjected to the less aggressive AST protocols. Although additional data are needed before meaningful models can be made, the Brite 3 warm white panels showed greater initial decay than the Brite 3 neutral white panels. This finding is consistent with the lumen maintenance decay observed between the Brite 2 neutral white and Brite 2 warm white panels.

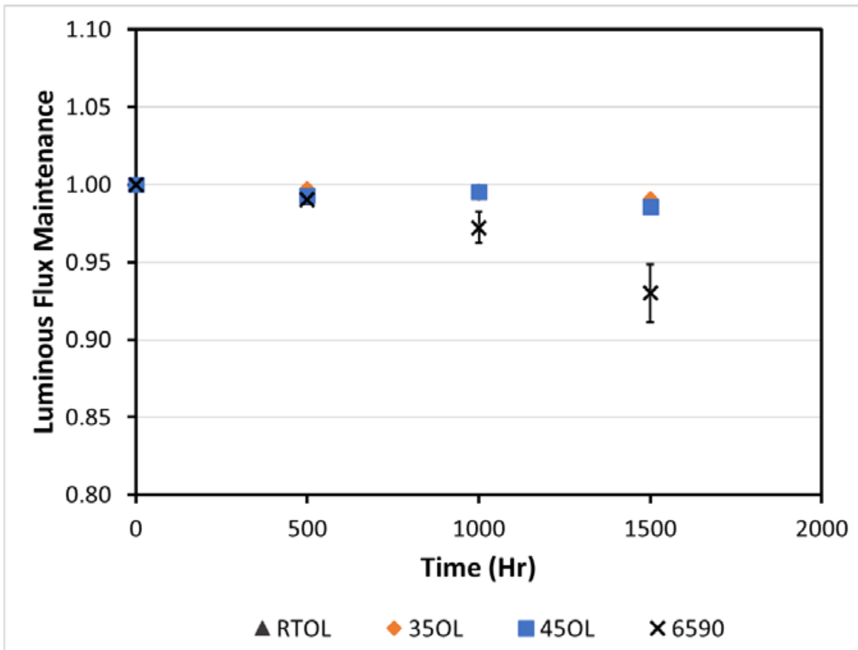

Figure 3-9. Average luminous flux maintenance with error bars for Brite 3 neutral white panels during different ASTs.

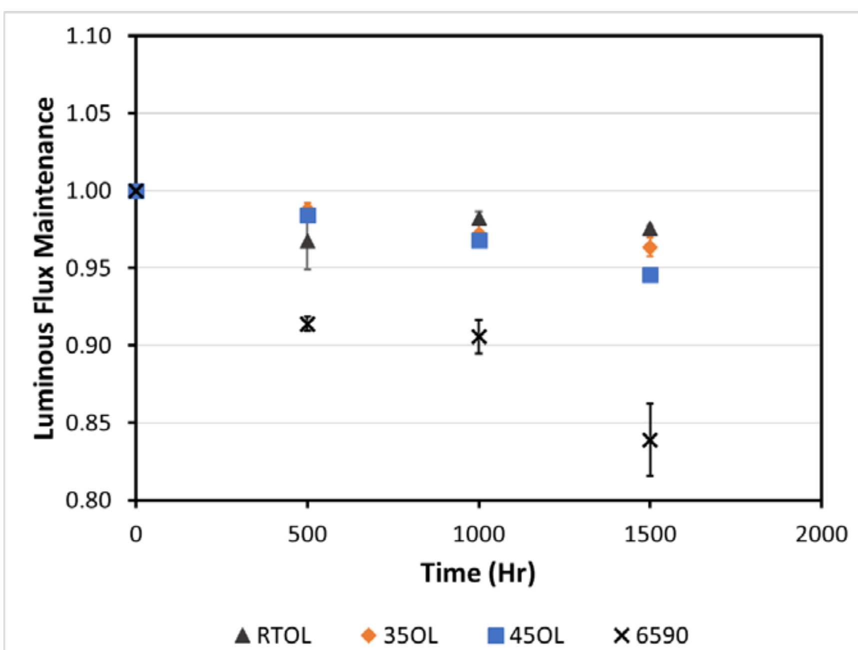

Figure 3-10. Average luminous flux maintenance with error bars for Brite 3 warm white panels in different ASTs.

3.2.3 Chromaticity

3.2.3.1 Brite 2

Within the Lumiblade Brite 2 FL300 OLED panel series, the neutral white panels experienced the largest chromaticity shift through 7,000 hrs, with the panels subjected to the 45OL test having chromaticity shifts in excess of 6 SDCM in the yellow direction (i.e., $\Delta v'$ increased much faster than $\Delta u'$, see **Figure 3-11**). To better understand this behavior, a component analysis of the emission spectra was performed as described in Section 2.4.2 of this report. From these curve fits, the absolute radiant power of each emitter was calculated and plotted over time as shown in **Figure 3-12**. An examination of the temporal radiant power revealed that the blue emitter in the Brite 2 neutral white panels decreases at a faster rate than the green and red emitters. This loss of blue emissions could be due to several factors, including lower stability of the blue emitter or increased absorbance for the blue light within a component of the OLED stack. Although the decay rates for each emitter influences the chromaticity shift, it is erroneous to assign color shifts based solely on these values. The relative change in the SPD also must be examined. To explain, if only the emitter decay rates were used, then the expected chromaticity shift of the Brite 2 neutral white panels would move in the red-yellow direction because the red emitter has the lowest decay rate; however, the initial chromaticity shift proceeds in the green-yellow direction. Further examination of the temporal radiant power reveals that the initial radiant power of the green emitter is approximately 1.7 times greater than the radiant power of the red and blue emitters. As such, a small loss of radiant power (e.g., 0.01 W) from the green emitter has less effect on the chromaticity than an equivalent loss of radiant power from the blue or red emitters.

The relative contribution of each emitter in the Brite 2 neutral white panel to the total radiant power (expressed as a percentage) is shown in **Figure 3-13**. As the panel ages, a steady decrease is observed for the relative contribution of the blue emitter to the emission spectrum. In addition, the relative contribution of the red emitter to the overall emission spectrum experienced a slight decline through 3,500 hrs, and then started to increase again, while the relative contribution of the green emitter to the overall emission spectrum increased through 3,500 hrs and then started to plateau. The combination of these events coincides with the largely yellow shift influenced by a subtle green shift through 3,500 hrs (as shown in Figure 3-11) and then a subtle red shift after 3,500 hrs.

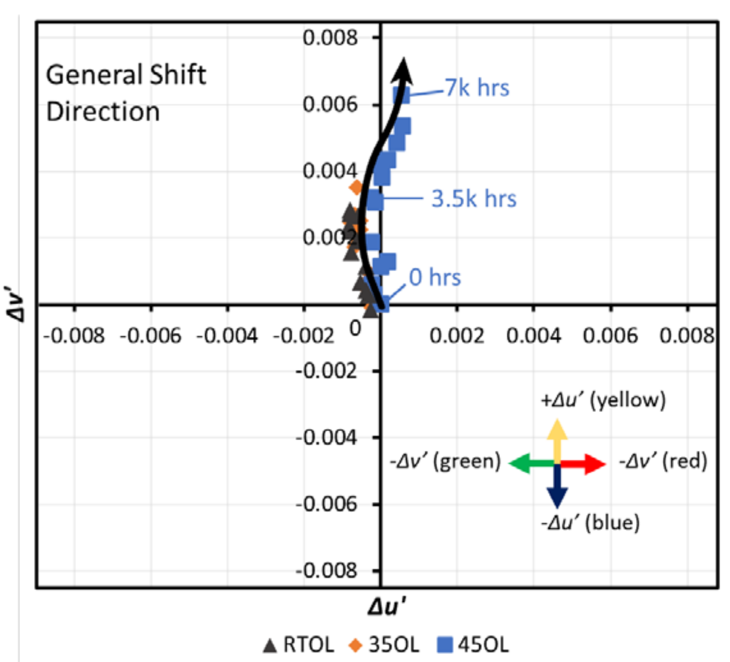

Figure 3-11. Chromaticity diagram for Brite 2 neutral white panels.

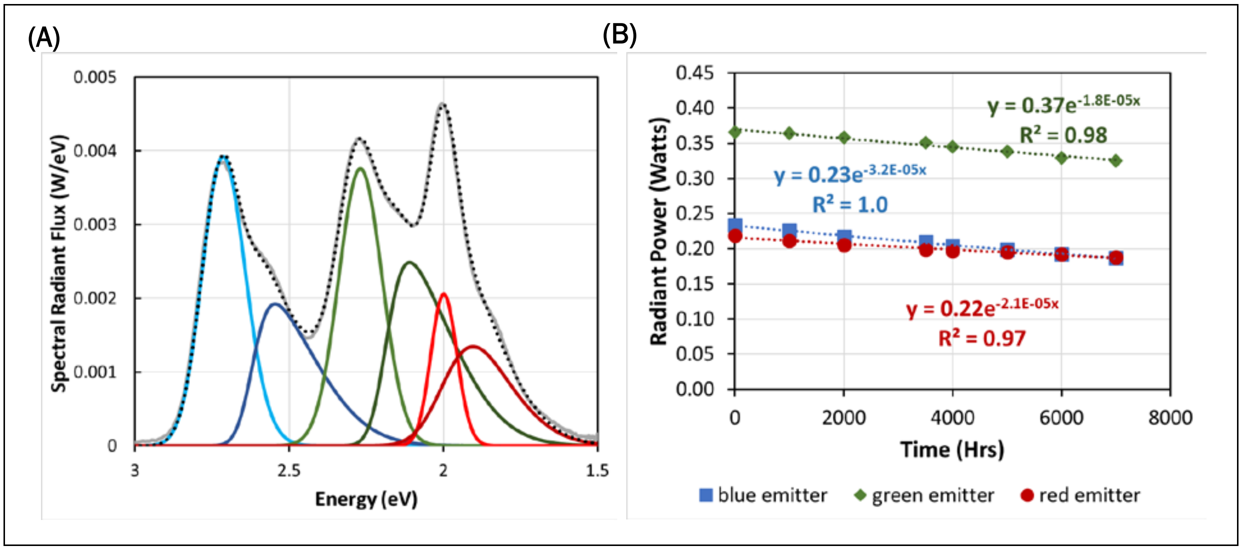

Figure 3-12. Emission spectra modeling for blue, green, and red components of a Brite 2 neutral white panel subjected to the 45OL test (A) and the radiant power determined from the skewed Gaussian curve fits of each component (B).

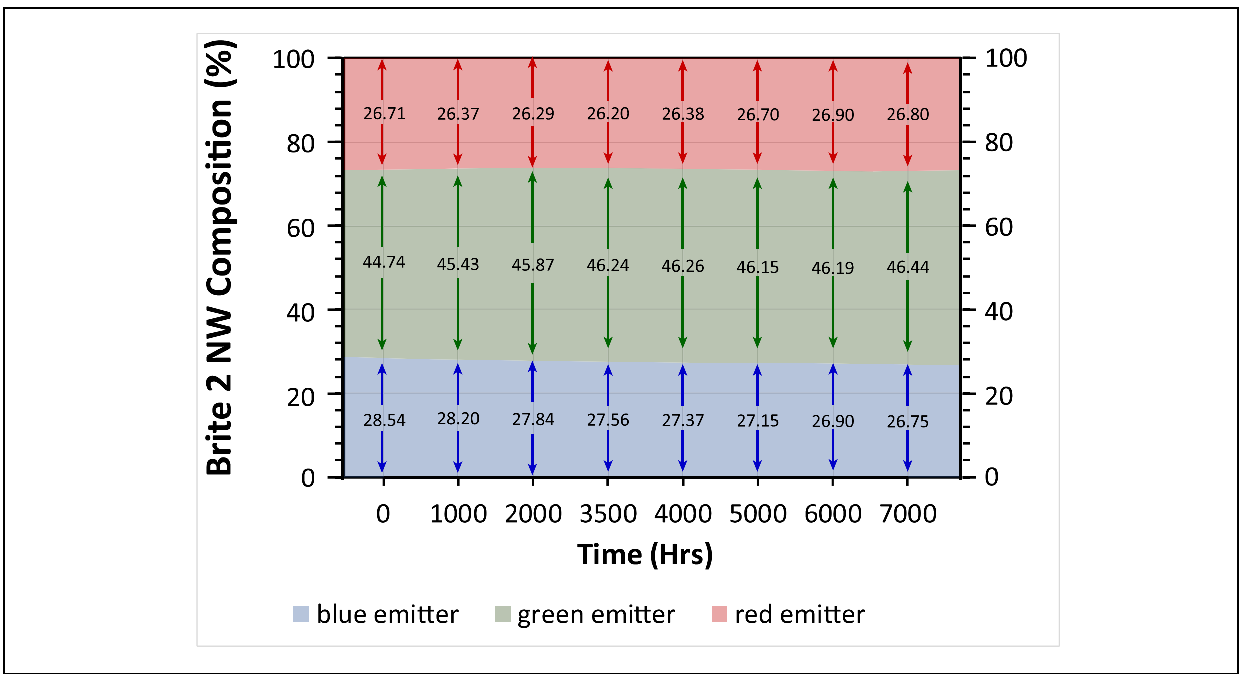

Figure 3-13. As the emitters of the Brite 2 neutral white (NW) panels age at different rates, the relative composition of the emission spectrum contains fewer blue emissions, more green emissions, and variable red emissions.

Through 7,000 hrs, the Brite 2 warm white panels experienced a modest color change in the green-yellow direction as shown in **Figure 3-14**. Brite 2 warm white panels operated at less aggressive AST protocols (i.e., RTOL and 35OL tests) experienced changes of less than 2 SDCM in both $\Delta u'$ and $\Delta v'$, whereas Brite 2 panels at the most aggressive AST protocol (i.e., 45OL test) experienced color change of approximately 4 SDCM in the $\Delta v'$ direction and only 2 SDCM in the $\Delta u'$ direction. To better understand the chromaticity changes, a component analysis of the emission spectra was performed, and the absolute temporal change in radiant power of the blue, green, and red emitters of the Brite 2 warm white panels subjected to the various AST protocols were then compared as shown in **Figure 3-15B**. This analysis shows that light emissions from the blue emitter in the Brite 2 warm white panels decay at a faster rate than that from the green and red emitters, which is the same trend observed for the Brite 2 neutral white panels. This loss of blue emissions could be due to several factors, including lower stability of the blue emitter or increased absorbance for the blue light within a component of the OLED stack. In comparison with the Brite 2 neutral white panels, the red and green emitter radiant power decay rates are approximately 1.7 and 1.6 times greater, respectively, in comparison with the red and green emitter radiant power decay rates observed in the Brite 2 neutral white panels. The radiant power decay rate of the blue emitter in the Brite 2 warm white panels was only 1.3 times greater than the radiant decay rate of the blue emitter in the Brite 2 neutral white panels.

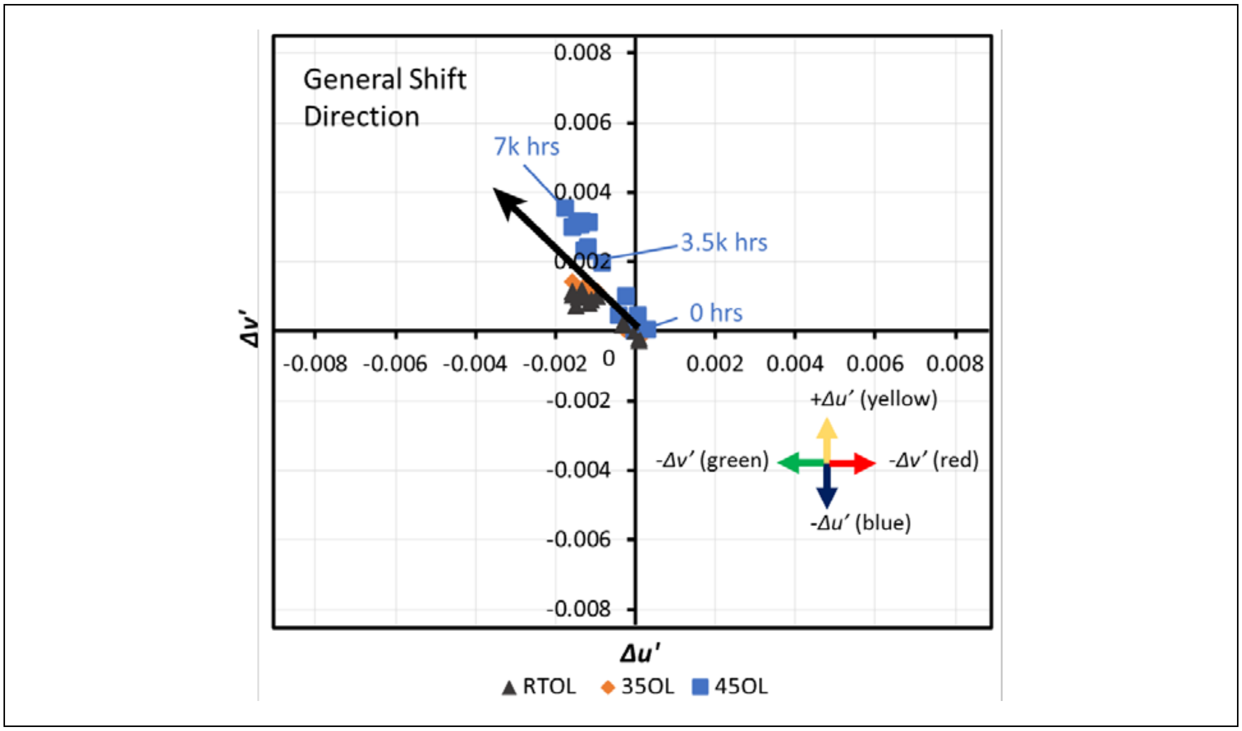

Figure 3-14. Chromaticity diagram for Brite 2 warm white panels.

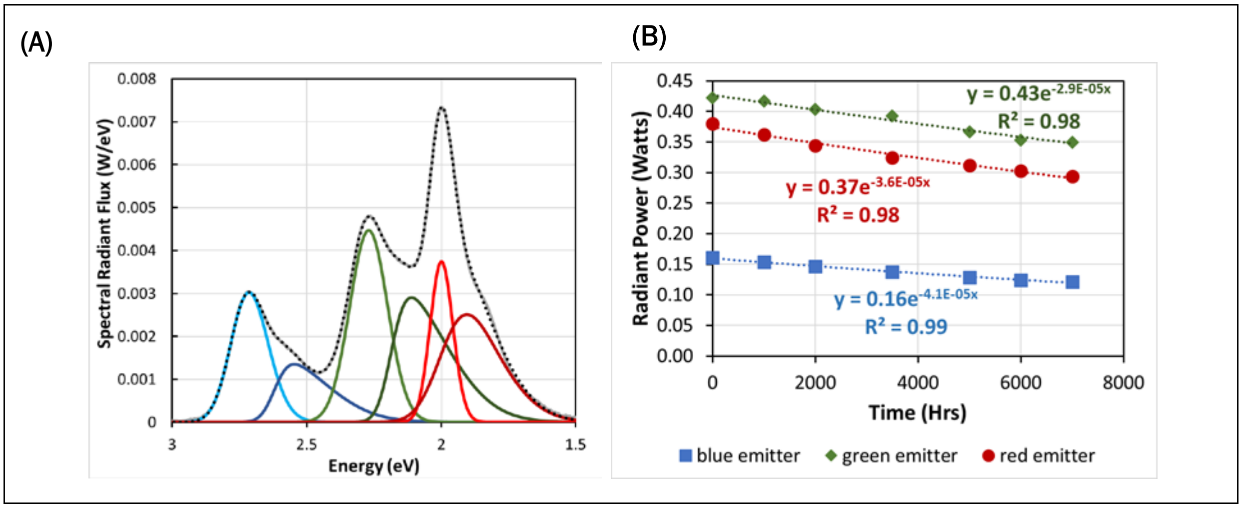

Figure 3-15. Emission spectra modeling for blue, green, and red emitters of a Brite 2 warm white panel subjected to 45OL test (A) and the radiant power determined from the skewed Gaussian curve fits of each component (B).

The contribution of each emitter in the Brite 2 warm white panel to the total radiant power (expressed as a percentage) is shown in **Figure 3-16**. Similar to the Brite 2 neutral white panels, the warm white panels experienced a steady decrease in the blue emitter's relative contribution to the emission spectrum. In addition, the relative contribution of the red emitter to the overall emission spectrum experienced a slight decline through 3,500 hrs, and then started to increase again while the relative contribution of the green emitter to the overall emission spectrum increased through 3,500 hrs and then started to level off. The overall magnitude of these changes in relative spectra composition were smaller than those observed in the neutral white panels; therefore, the green-yellow chromaticity shift of the warm white panels was smaller than the neutral white panels.

The greater loss of light from the red and green emitters used in the warm white panels relative to the neutral white panels explains the luminous flux maintenance difference observed at 7,000 hrs for the panels subjected to 45OL testing (80% versus 88%, respectively). Though the identity of the emitters for the Brite 2 panels is unknown, the same values for the skewness, peak position, and width parameters provided good curve fits for both Brite 2 panels (just the amplitudes of the skewed Gaussian were modified). Therefore, we believe it is likely that the two panels use the same emitters but in different concentrations or with slight modifications. Given that the emitters are likely the same or very similar, it is unclear why the red and green emitters of the warm white panels lose emission intensity faster than those of the neutral white panels.

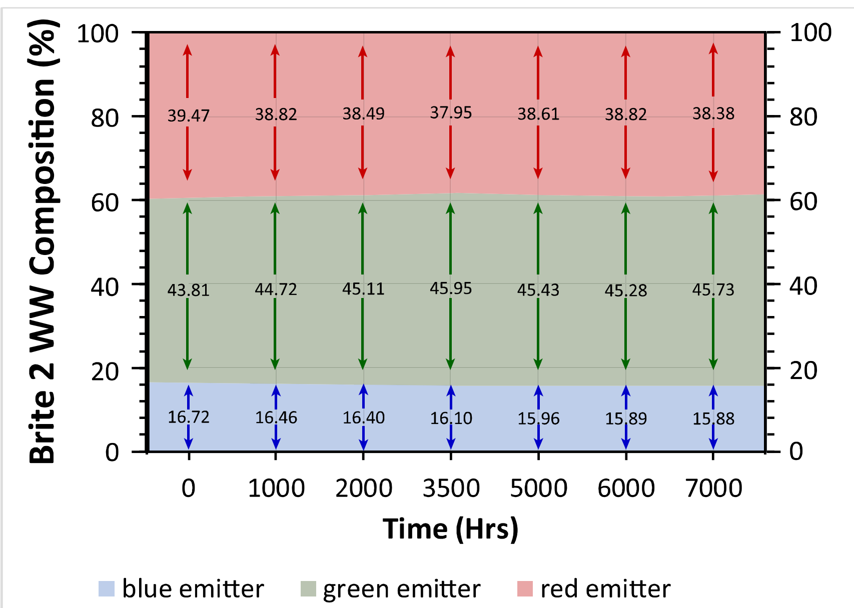

Figure 3-16. As the emitters of the Brite 2 warm white (WW) panels age at different rates, the composition of the emission spectrum contains fewer blue emissions, more green emissions, and relatively stable red emissions relative to the initial emission spectrum.

3.2.3.2 Brite 3

The chromaticity shifts for the Brite 3 neutral white and warm white panels remained subtle at 1,500 hrs as shown in **Figure 3-17** and **Figure 3-18,** respectively. The average chromaticity shift for the Brite 3 neutral white panels was less than 1 SDCM for DUTs in the three temperature-only stress protocols (i.e., RTOL, 35OL, 45OL tests), which was mostly attributed to experimental variation. For the Brite 3 neutral white panels operated in the more aggressive 6590 conditions, the chromaticity shifted in the generally yellow direction (i.e., changed primarily along the $+\Delta v'$ with minimal change along the $\Delta u'$ axis as shown in Figure 3-17). The chromaticity shifts observed during the 45OL test of the Brite 3 neutral white panels are in the same direction but smaller than the chromaticity shifts seen for the Brite 2 neutral white panels, suggesting an improvement in chromaticity maintenance for the newer Brite 3 generation.

The chromaticity shift in the Brite 3 warm white panels was generally small in the green direction ($\Delta u' \leq$ -0.002) for the temperature-only ASTs. There was a tendency for chromaticity to shift toward a generally yellow direction for the DUTs exposed to 6590 (see Figure 3-18). Through 1,500 hrs during the 45OL test, the magnitude of the chromaticity shifts in the Brite 3 warm white panels is similar to the magnitude of the chromaticity shifts experienced by the Brite 2 warm white panels; however, the direction is different—the Brite 2 panels shift mainly along the $+\Delta v$ axis (i.e., generally in the yellow direction), whereas the Brite 3 panels shifted mainly along the $-\Delta u'$ axis (i.e., generally in the green direction). More testing is needed to determine the long-term chromaticity behavior for these panels.

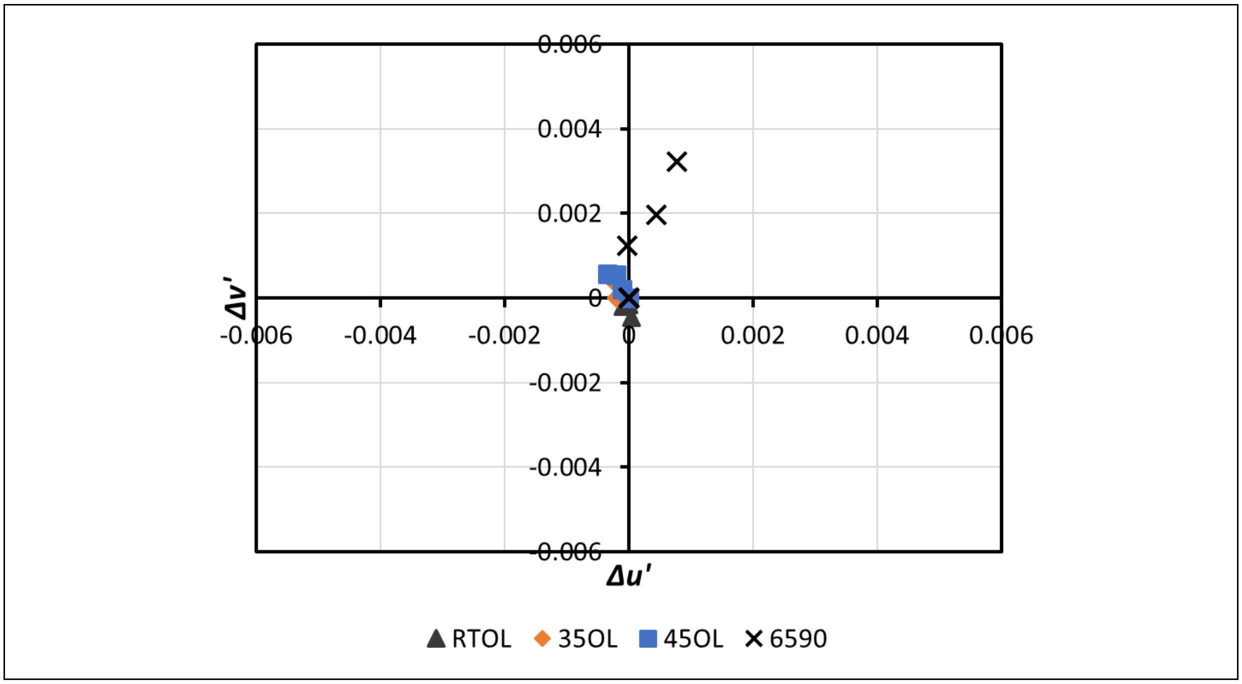

Figure 3-17. Chromaticity shifts for Brite 3 neutral white panels during different AST protocols.

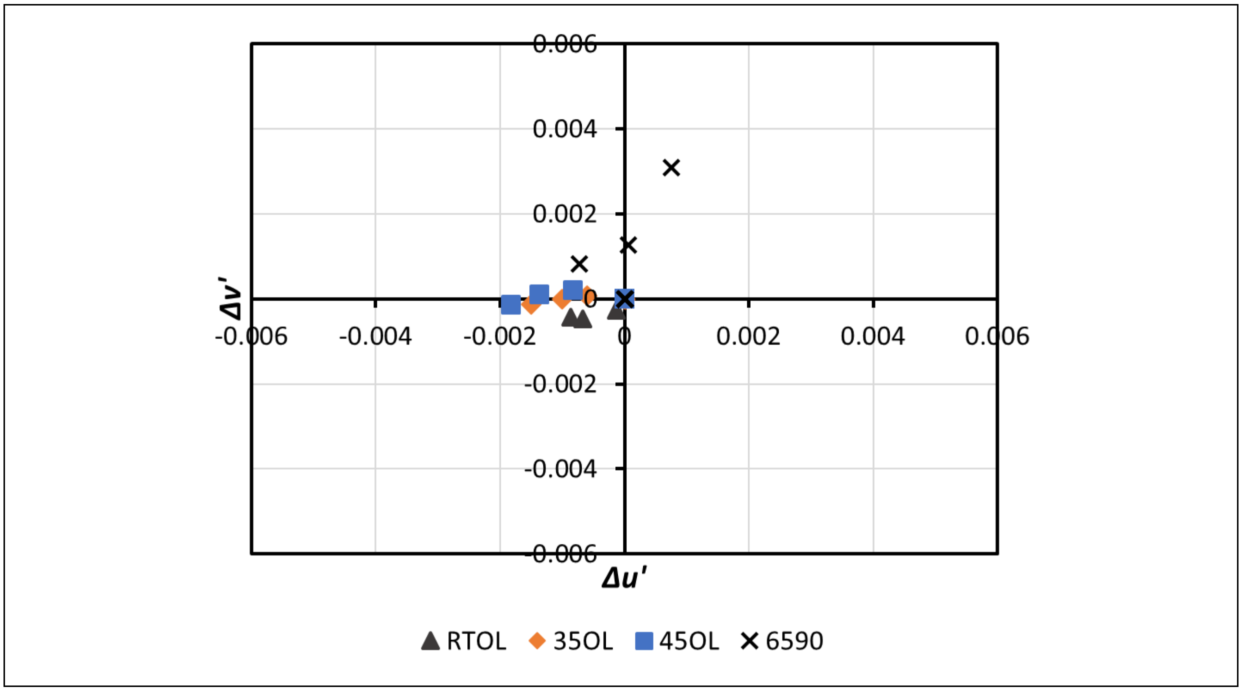

Figure 3-18. Chromaticity shifts for Brite 3 warm white panels in different AST protocols.

3.2.4 Electrical Analysis

3.2.4.1 Brite 2

The OLED lighting system was periodically evaluated with a power analyzer to measure the power supplied to the OLED panel from the driver. The power supplies delivered a fixed current of 0.263 A for the Brite 2 panel, so changes in the power delivered to the panel can be monitored through either the power or the voltage. In this analysis, higher voltages were needed to maintain the pre-set constant current across the aged test panels, a finding consistent with previous reports [2, 12]. Both neutral white (**Table 3-3**) and warm white panels (**Table 3-4)** also require increased power for DUTs subjected to the most aggressive AST protocol (45OL), and the increase in power (relative to that required for DUTs subjected to only RTOL) is significant (95% confidence level) by using Student's *t*-test with pooled variance. Compared with power consumption of DUTs subjected to the 35OL tests, the higher power consumption for both the neutral white and warm white panels subjected to the 45OL test is also statistically significant at the 95% confidence level. However, the difference between the mean power consumed by the DUTs subjected to the RTOL and 35OL tests is not statistically different.

Table 3-3. Brite 2 Neutral White Panel Electrical Data After 6,000 hrs of Aging.

Stress Test Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel*	22.17 V	0.263 A	5.83 W
RTOL	22.94 ± 0.43 V	0.263 ± 0.001 A	6.04 ± 0.11 W
35OL	23.14 ± 0.24 V	0.264 ± 0.001 A	6.11 ± 0.07 W
45OL	23.89 ± 0.96 V	0.264 ± 0.001 A	6.31 ± 0.25 W

*Control panel not aged.
Note: The reported uncertainties represent 1 standard deviation.

Table 3-4. Brite 2 Warm White Panel Electrical Data After 6,000 hrs of Aging.

Stress Test Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel*	21.30 V	0.263 A	5.60 W
RTOL	22.30 ± 0.15 V	0.263 ± 0.002 A	5.87 ± 0.00 W
35OL	22.39 ± 0.14 V	0.262 ± 0.002 A	5.87 ± 0.07 W
45OL	23.89 ± 0.47 V	0.263 ± 0.002 A	6.27 ± 0.14 W

*Control panel not aged.
Note: The reported uncertainties represent 1 standard deviation.

Impedance values were recorded at three frequencies (i.e., 100 Hz, 1,000 Hz, and 10,000 Hz) for every panel at the end of each testing cycle to provide further characterizations of the Brite 2 neutral white and warm white panels. Herein, we report the initial and latest (post-7,000 hrs of aging) average impedance values in **Table 3-5** and **Table 3-6**. Examinations of the average neutral white panel impedances (Table 3-5) and warm white panel impedances (Table 3-6) show small changes in impedance for DUTs subjected to the RTOL, 35OL or 45OL test conditions relative to the control. However, for all three AST protocols, there was not a statistically valid change in panel impedances between measurements taken after 250 hrs and those after 7,000 hrs of AST exposure.

Table 3-5. Brite 2 Neutral White Panel Impedance Data After 7,000 hrs of Aging.

Stress Test Protocol	Impedance at 1,000 Hz (t = 250 hrs)	Impedance at 1,000 Hz (t = 7000 hrs)
Control panel*	561.2 Ω	560.7 Ω
RTOL	570.3 ± 3.3 Ω	570.2 ± 2.5 Ω
35OL	569.1 ± 1.0 Ω	570.3 ± 1.3 Ω
45OL	566.2 ± 1.8 Ω	567.6 ± 1.8 Ω

*Control panel not aged.
Note: The reported uncertainties represent 1 standard deviation.

Table 3-6. Brite 2 Warm White Panel Impedance Data After 7,000 hrs of Aging.

Stress Test Protocol	Impedance at 1.000 Hz (t = 250 hrs)	Impedance at 1.000 Hz (t = 7,000 hrs)
Control panel*	569.6 Ω	568.7 Ω
RTOL	565.7 ± 4.1 Ω	565.3 ± 4.0 Ω
35OL	560.9 ± 2.2 Ω	562.2 ± 3.8 Ω
45OL	567.9 ± 4.1 Ω	571.1 ± 5.5 Ω

*Control panel not aged.
Note: The reported uncertainties represent 1 standard deviation.

3.2.4.2 Brite 3

All Brite 3 panels remain in operation after 1,500 hrs of testing. The power consumption of the entire OLED lighting system (drivers and panels) was recorded at the end of each test period, and initial efficacies of the Brite 3 neutral white and Brite 3 warm white systems were found to be higher than initial efficacies of the Brite 2 neutral white and Brite 2 warm white systems, respectively, as shown in **Table 3-7**. Further electrical characterization was completed periodically with the Xitron power analyzer to separate electrical driver power consumption from panel consumption.

For the Brite 3 neutral white panels, an average decrease in power consumption relative to the control was observed across panels in all testing protocols except for 6590, which experienced an increase in power consumption relative to the control (**Table 3-8**). Power consumption loss was the greatest for panels operated at the least aggressive testing protocols.

For the Brite 3 warm white panels, an average increase in power consumption relative to the control was observed across panels in all testing protocols, with more aggressive protocols having larger increases in power consumption (**Table 3-9**). There was also an increase in the variance of panel power consumption relative to the zero-time point (not shown), indicative of OLED aging. More testing is needed to understand the differences between the power consumption of neutral white and warm white panels and to identify the root cause of these changes.

Table 3-7. Average Initial Efficacies of Brite 2 and Brite 3 Lighting Systems (Driver Efficiency Included).

Product	Color Temperature	Efficacy (LPW)
Brite 2	Neutral white	31.7 ± 0.4
Brite 2	Warm white	37.8 ± 0.6
Brite 3	Neutral white	37.8 ± 1.1
Brite 3	Warm white	50.4 ± 1.0

Table 3-8. Brite 3 Neutral White Panel Electrical Data After 1,500 Hrs of Aging.

AST Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel*	21.87 V	0.220 A	4.81 W
RTOL	20.59 ± 0.70 V	0.217 ± 0.002 A	4.46 ± 0.19 W
350L	21.24 ± 0.80 V	0.218 ± 0.002 A	4.63 ± 0.18 W
450L	21.50 ± 1.02 V	0.217 ± 0.002 A	4.68 ± 0.22 W
6590	22.50 ± 0.58 V	0.218 ± 0.001 A	4.91 ± 0.12 W

*Control panel not aged.
Notes: The reported uncertainties represent 1 standard deviation.
The same driver and power supply are used in both the Brite 2 and Brite 3 lighting systems.

Table 3-9. Brite 3 Warm White Panel Electrical Data After 1,500 Hrs of Aging.

AST Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel*	19.2 V	0.217 A	4.18 W
RTOL	19.45 ± 0.02 V	0.217 ± 0.001 A	4.23 ± 0.03 W
350L	19.71 ± 0.05 V	0.218 ± 0.001 A	4.30 ± 0.02 W
450L	19.90 ± 0.22 V	0.217 ± 0.002 A	4.32 ± 0.09 W
6590	21.71 ± 0.23 V	0.230 ± 0.014 A	5.00 ± 0.26 W

*Control panel not aged.
Note: The reported uncertainties represent 1 standard deviation.

At the end of each testing cycle, the impedance of each Brite 3 panel (neutral white and warm white) was recorded at three frequencies: 100 Hz, 1,000 Hz, and 10,000 Hz. The initial and latest (post-1,500 hrs of aging) average impedance values are reported in **Table 3-10** and **Table 3-11**. The initial impedance values of the

Brite 3 panels are lower than the initial impedance values of their Brite 2 precursors which, in conjunction with the lower power consumption and higher efficacy observed for Brite 3 versus Brite 2 lighting systems (Table 3-7), supports manufacturer claims of enhanced capabilities from Brite 2 to Brite 3 panels. Examination of the average Brite 3 neutral white panel impedances (Table 3-10) and Brite 3 warm white panel impedances (Table 3-11) over time shows a small decrease in impedance for DUTs subjected to the RTOL and 35OL test conditions and a slight increase in impedance for DUTs subjected to the 45OL and 6590 test conditions.

Table 3-10. Brite 3 Neutral White Panel Impedance Data After 1,500 Hrs of Aging.

Stress Test Protocol	Impedance at 1,000 Hz (t = 0 hrs)	Impedance at 1,000 Hz (t = 1,500 hrs)
Control panel*	541.7 Ω	541.5 Ω
RTOL	557.5 ± 19.4 Ω	555.9 ± 19.0 Ω
35OL	548.9 ± 13.2 Ω	544.7 ± 13.1 Ω
45OL	549.8 ± 14.1 Ω	551.5 ± 13.9 Ω
6590	547.6 ± 16.7 Ω	550.1 ± 16.3 Ω

*Control panel not aged.
Note: The reported uncertainties represent 1 standard deviation.

Table 3-11. Brite 3 Warm White Panel Impedance Data After 1,500 Hrs of Aging.

Stress Test Protocol	Impedance at 1,000 Hz (t = 0 hrs)	Impedance at 1,000 Hz (t = 1,500 hrs)
Control panel*	557.5 Ω	557.4 Ω
RTOL	558.4 ± 2.3 Ω	556.6 ± 0.7 Ω
35OL	562.3 ± 0.1 Ω	557.8 ± 1.6 Ω
45OL	558.8 ± 1.9 Ω	559.3 ± 1.8 Ω
6590	557.9 ± 2.2 Ω	558.1 ± 4.2 Ω

*Control panel not aged.
Note: The reported uncertainties represent 1 standard deviation.

3.2.5 Luminance Uniformity Variation

The luminance of all Brite 2, Brite Amber, and Brite 3 OLED panels was measured as described in Section 2.3.2 of this report. Once the luminance was measured at each of the pre-determined locations, the luminance uniformity variation was calculated for each panel. The luminance uniformity variation values for the DUTs from each AST protocol were averaged and the standard deviations were calculated. These values are provided in **Table 3-12**. In general, the luminance uniformity variation was less than 10% for most measurements, and there have not been any significant deviations in uniformity observed to date in any of the ASTs.

Table 3-12. Average Luminance Uniformity Variation of OLEDWorks Panels in Different Stress Tests.

Panel	RTOL	45OL	6590
Brite Amber	4.8% ± 3.2%	Not applicable	Not applicable
Brite 2 neutral white (6,000 hrs)	8.1% ± 0.2%	6.8% ± 1.4%	Not applicable
Brite 2 warm white (6,000 hrs)	9.8% ± 0.5%	14.1% ± 2.5%	Not applicable
Brite 3 neutral white (1,000 hrs)	8.2%*	7.9% ± 1.4%	14.5% ± 5.4%
Brite 3 warm white (1,000 hrs)	8.1%*	9.4% ± 3.1%	10.1% ± 4.2%

* The control samples are reported for the Brite 3 products instead of the RTOL test samples.

3.3 OLEDWorks Brite Amber Panels

The OLEDWorks Brite Amber panels were investigated by using separate populations in each of the three AST protocols: RTOL, 35OL, and 45OL. For each AST protocol, three panels were studied, for a total of nine panels undergoing testing. In our previous report, we noted that by 1,500 hrs, all test panels exposed to the 45OL test had failed. In this current report, we provide updated test results through 7,000 hrs of testing for the remaining six panels evaluated during RTOL and 35OL tests. Three additional panels failed during this testing cycle, as described later in this section, and estimates of all the failure times observed to date are listed in **Table 3-13**.

Table 3-13. Estimated Time to Failure for the Brite Amber Panels.

AST Protocol	DUT Number	Time to Failure (hrs)
45OL	449	845.4
45OL	448	1,384.8
45OL	450	1,451.8
35OL*	446	1,693.3 < *t* < 1,757.1
RTOL*	452	3,500 < *t* < 4,000
35OL*	447	6,000 < *t* < 7,000

* A range of hrs is reported for time to failure for these panels because they were not thermally monitored because of equipment constraints.

3.3.1 Luminous Flux Maintenance

Through 7,000 hrs of exposure, only three Brite Amber panels remain in operation: two operational panels in the RTOL test and one operational panel in the 35OL test. The two Brite Amber panels in the RTOL test had an average luminous flux maintenance of 90% through 7,000 hrs while luminous flux maintenance of the panel operated at 35°C was approximately 87% as shown in **Figure 3-19**.

Because of the abrupt failures during this round of testing, the average luminous flux data for 35°C includes only two operational panels from 2,000 through 6,000 hrs and one operational panel at 7,000 hrs. Similarly, the average luminous flux data for the RTOL test only includes two operational panels from 4,000 through 7,000 hrs.

The Brite Amber data between 2,000 and 7,000 hrs from **Figure 3-19A** was fit with a single-exponential decay function using the methods described in Section 2.4.1 of this report. Although the fluctuation of the data (likely caused by instrument variability at the low illuminance levels of these panels) prevents the curve fits from having small residuals, a decreasing trend in lumen maintenance is still observed as shown in **Figure 3-19B**. The decay rate constants correlated to the AST protocols, with the higher stress protocol (35OL test) having the highest decay rate constant.

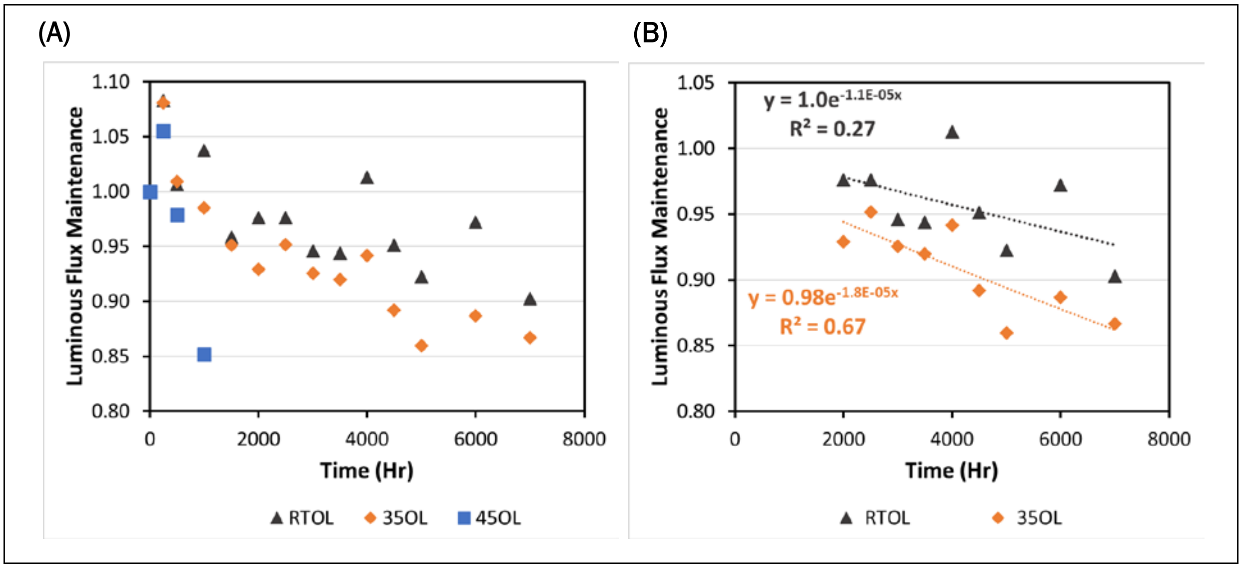

Figure 3-19. Average luminous flux maintenance for the Brite Amber panels (A) and exponential fits of the latter part of the data (B) per the rules in Table 2-2.

3.3.2 Chromaticity

In our previous report, the Brite Amber panels experienced a chromaticity shift of approximately 2 SDCM in the red direction by 1,500 hrs. From 1,500 through 7,000 hrs, virtually no additional color shift occurred in the Brite Amber panels, as shown in **Figure 3-20**. Although a minimal chromaticity shift occurred between 1,500 and 7,000 hrs, the luminous flux maintenance decreased by approximately 10% (for 35OL test panels); therefore, it was expected that the red and green emitters decayed at similar rates under these test conditions.

To verify this hypothesis, spectral analysis was performed on the individual red and green phosphorescent emitters used in the two-tandem stack Brite Amber OLED device to determine the individual contribution of each emitter to the overall emission spectrum. The methods described in Section 2.4.2 of this report was used for this analysis. To facilitate this analysis, the spectral integral (i.e., absolute radiant power) of each component at every time period was normalized to the original value, and this ratio of the normalized radiant power of the green emitters relative to the normalized radiant power of the red emitters was then calculated at each testing time period. This analysis showed that the normalized green to red emission ratio decreased the most during the first 1,500 hrs of exposure, and then the ratio stayed at approximately 0.98 from 1,500 hrs to 7,000 hrs as shown in **Figure 3-21**. The spectral analysis confirmed that after 1,500 hrs, the rate of decay for both red and green emitters was very similar, as evidenced by the constant green to red emission ratio.

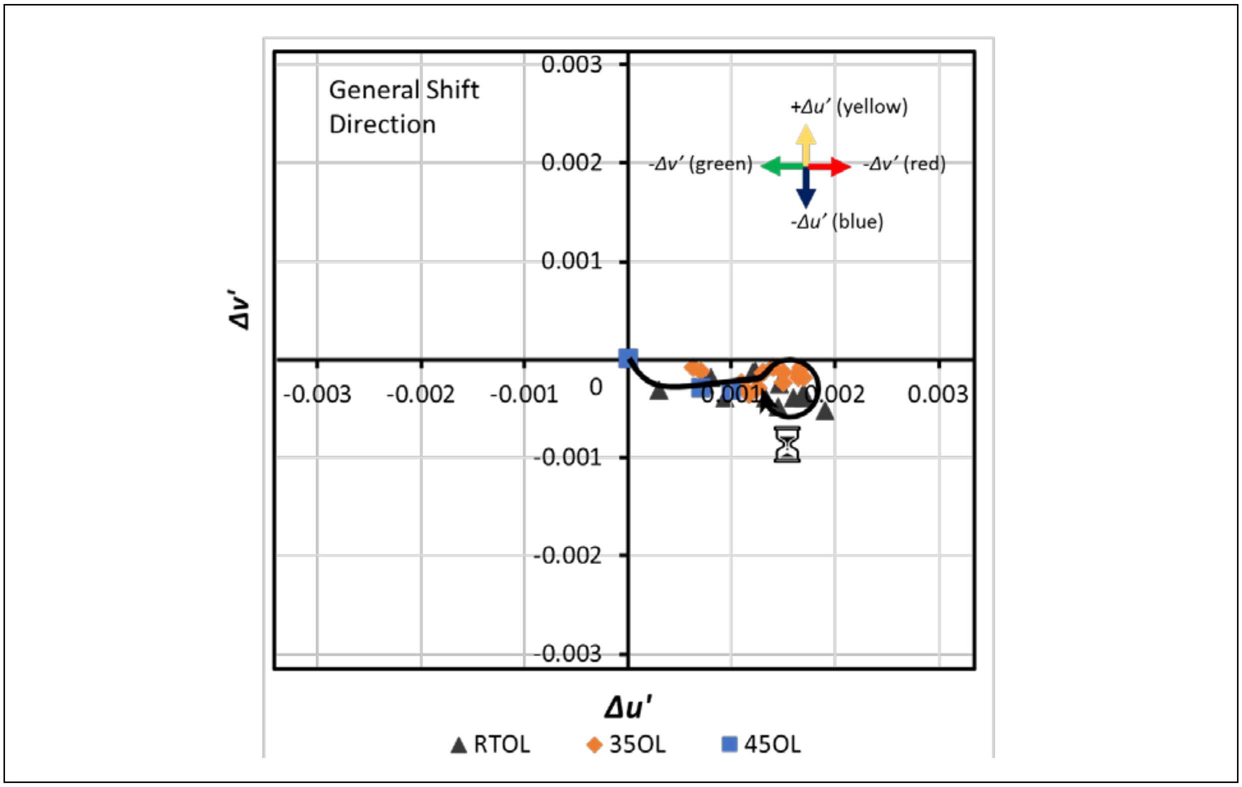

Figure 3-20. Chromaticity diagram for the Brite Amber panels.

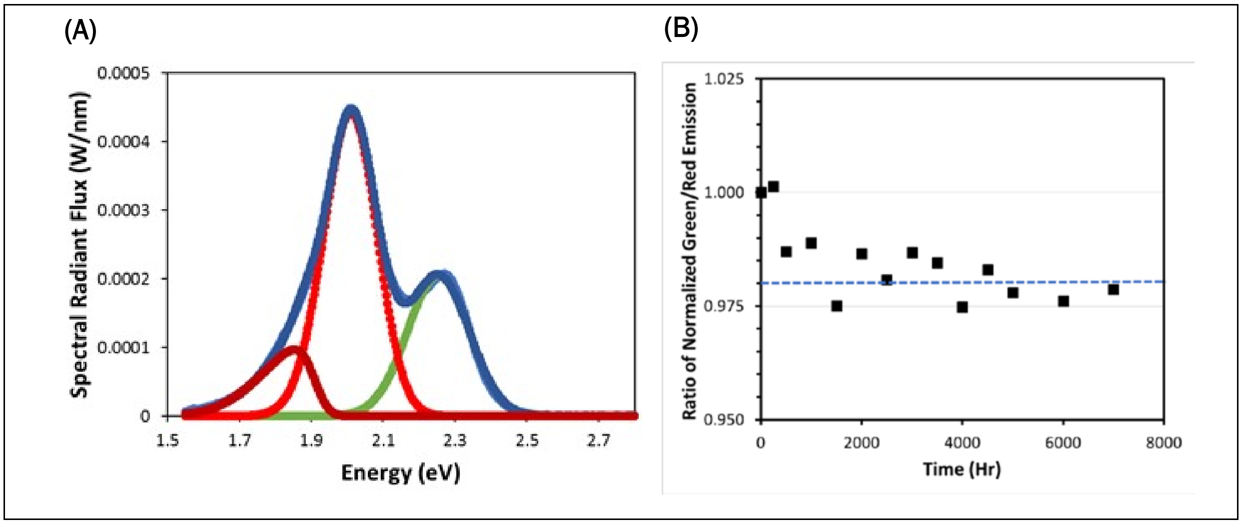

Figure 3-21. Skewed Gaussian curve fits are used to model emission spectra for red and green emission components relative to the control (A) and the average temporal ratio of the normalized green to red emission is calculated for the 35°C samples. The blue, dashed line shows the average ratio maintained after 1,500 hrs (B).

3.3.3 Electrical Analysis

As part of the characterization for the Brite Amber panels, the impedance (Z) and phase shift (ψ) of each sample were recorded after each test cycle at three frequencies: 100 Hz, 1,000 Hz, and 10,000 Hz (impedance only). A summary of these values after 7,000 hrs is provided in **Table 3-14**. Relative to the control panel, the functional Brite Amber panels from RTOL and 35OL tests showed decreases in impedance and phase shift at

100 Hz and 1,000 Hz, but the impedance and phase shift at 10,000 Hz remains relatively unchanged. These samples have retained some reactive capacitance as indicated by the Z and ψ values but have clearly degraded from the initial values. In contrast, the shorted panels have low impedances and ψ values near zero. The temporal change in average impedance at 1,000 Hz shows a decrease in impedance across both 35OL and RTOL test protocols as shown in **Figure 3-22.** In addition, a larger variation in impedance value (as measured by standard deviation) is observed for panels operated at the more aggressive test protocol (i.e., 35OL), which is consistent with aging. By 7,000 hrs, only one panel is operational in the 35OL test; therefore, no standard deviation can be calculated for this time point.

Table 3-14. Average Impedance and Phase Shift Values for Amber Panels Subjected to Each Test Protocol After 7,000 hrs.

Test Protocol	$Z_{100\ Hz}$ (Ω)	$\psi_{100\ Hz}$ (degrees)	$Z_{1,000\ Hz}$ (Ω)	$\psi_{1,000\ Hz}$ (degrees)	$Z_{10,000\ Hz}$ (Ω)
Control panel*	11,718 ± 239	-83.7 ± 1.7	1,216.2 ± 12.3	-88.0 ± 0.4	125.2 ± 0.2 Ω
RTOL panels	8,805 ± 3,736	-46.2 ± 26.4	1,191 ± 28	-81.3 ± 6.6	125.0 ± 1.0 Ω
35OL panel	3,984	-19.5	1,130	-71.5	125.9 Ω
Failed panels (35OL)	28.3 ± 5.6	-4.2 ± 5.7	28.4 ± 5.8	0.0	27.6 ± 5.4 Ω
Failed panel (RTOL)	25.3	0.0	25.3	-0.9	24.8 Ω

*Control panel standard deviations include measurements taken from populations that had been operated for 2,000 to 7,000 hrs in either RTOL or 35OL test.
Note: The reported uncertainties represent 1 standard deviation.

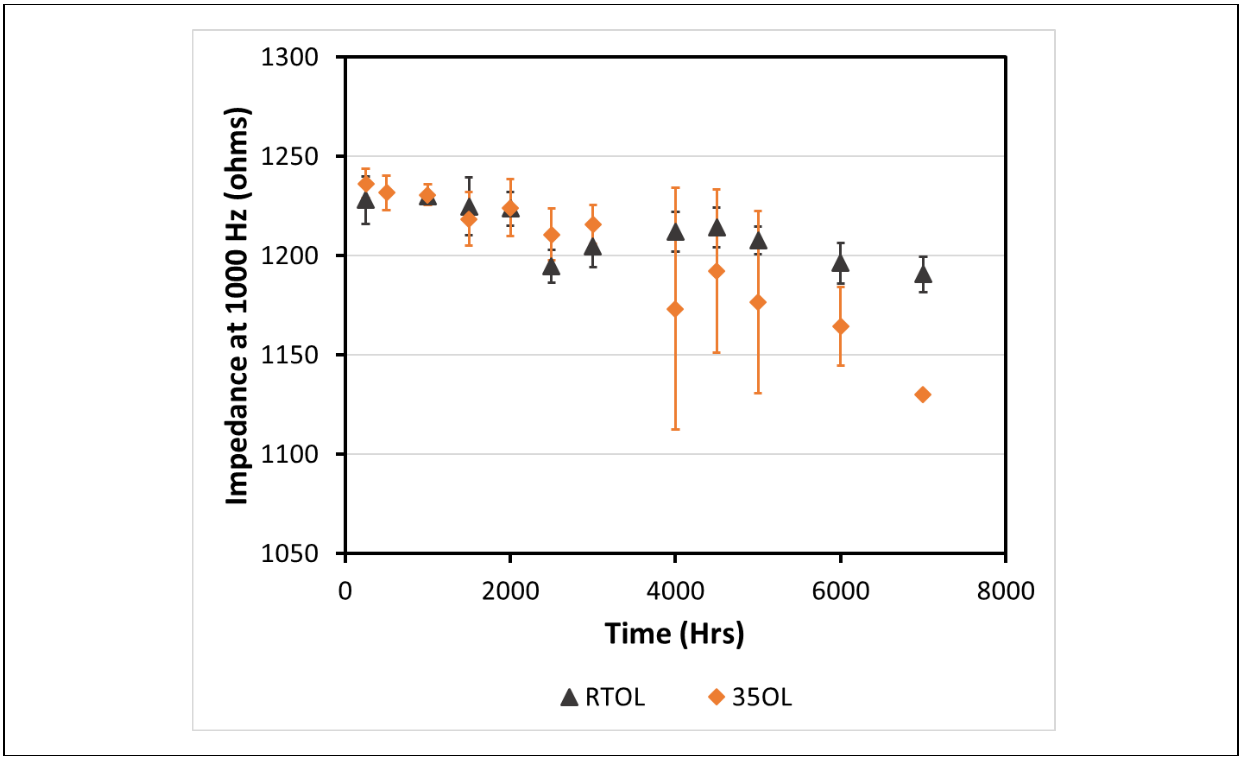

Figure 3-22. Average impedance of Brite Amber panels show a greater decrease in impedance for more aggressive conditions.

The decreases in panel impedance and phase shift at low frequencies were consistent across all panels. These decreases suggest that the OLED panel starts to deviate from capacitor-like behavior at low frequency, implying the potential development of at least one nano- or microshort. For some panels, the evidence of these microshorts can be seen first as "hot spots," and then subsequently as dark spots as shown in **Figure 3-23**. It is most likely that these dark spots consist of organic microparticles, although their composition has not been confirmed. It is also plausible that the slow decreases in impedance and phase angle track the growth of these organic microparticle clusters until a macroshort occurs [26].

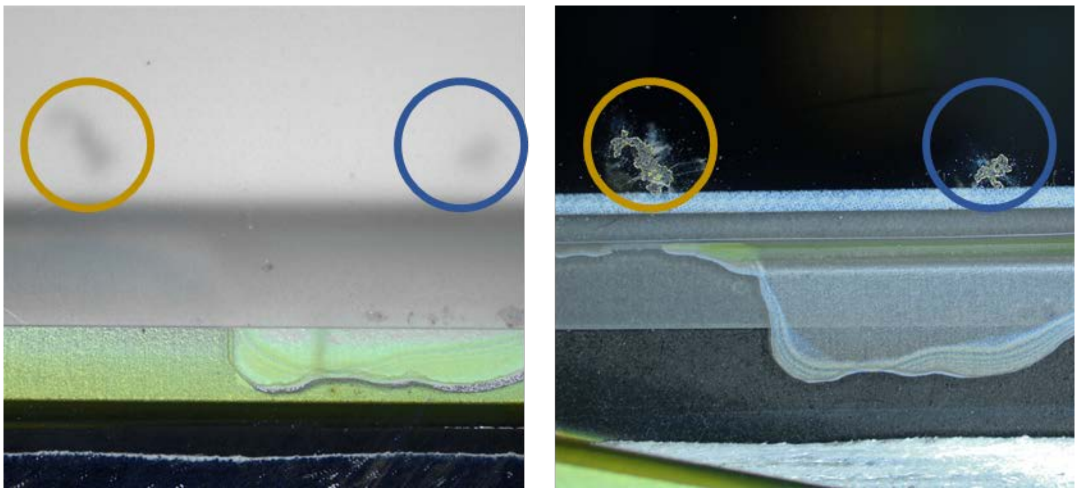

Figure 3-23. Two dark spots (yellow and blue circles) can be seen on a failed Brite Amber panel. The dark spots are viewed from the anode side of the OLED stack (left) and from the cathode side of the OLED stack (right). Imaging software was used to reflect the image of the cathode about the *y*-axis.

4 Conclusions

The findings from reliability research on OLED products have been building gradually, and this is the third DOE–sponsored report presenting AST data from OLED products. Because this research has now spanned multiple generations of the Chalina luminaire and Lumiblade Brite panels, a multi-generational comparison of the overall behavior of these products provides insights regarding recent improvements in OLED technologies.

The Chalina products use OLED panels made by LG Display. The GEN-1 products (purchased in September 2015) were found to exhibit premature failure due to panel shorting during operation in mildly elevated temperatures (e.g., during the 45OL test) [2, 12]. The four Chalina GEN-1 products that have been in the 45OL test since 2015 have experienced a cumulative total of 32,000 hrs of testing, and a total of four panels (20%) have completely failed during that time. In contrast, the Chalina GEN-3 products have survived a cumulative total of 16,000 hrs during the 45OL test without experiencing <u>any panel failures</u>. In addition, there have been no panel failures (other than an accidental breakage) for any Chalina GEN-2 and GEN-3 products. A compilation of the performance of the multiple generations of Chalina products examined during the tests reported here are provided in **Table 4-1**. Clearly, technological advances realized in progressing from the GEN-1 products to the GEN-2 and GEN-3 products have increased reliability by reducing the susceptibility of OLED panels to fail via a shorting mechanism.

Table 4-1. Summary of the Cumulative Test Exposures of the Three Generation of Chalina Luminaires.

Chalina Product Description	AST	Cumulative Test Time	Panel Failure Times (if any)
GEN-1	45OL	32,000 hrs	125–250 hrs 1,750–2,250 hrs 2,250–2,750 hrs 7,000–7,250 hrs
GEN-2	RTOL	30,000 hrs	No panel failures
GEN-3	35OL	32,000 hrs	No panel failures
GEN-3	45OL	16,000 hrs	No panel failures

In addition to improving the resistance to panel shorting, the multiple generations of Chalina products examined during this study also exhibited improved lumen and chromaticity maintenance. Even during the 45OL test, the α values of the GEN-3 OLED panels were better than those of GEN-1 panels (see Figure 3-3). Perhaps more noticeable are the improvements in chromaticity maintenance and the lifetime of the green-emitting and red-emitting organic molecules. The Chalina GEN-1 products exhibited a strong tendency for the chromaticity to shift in the blue direction because of the relative decrease in green and red emissions (see Figure 3-4). This chromaticity shift exceeded the generally accepted maximum allowable shift (i.e., $\Delta u'v' \geq 0.007$) in approximately 8,000 hrs of operation during the 45OL test. However, for the Chalina GEN-2 and GEN-3 products, the relative change of blue, green, and red emitters was more balanced, and a much smaller chromaticity shift occurred that was well within the accepted range.

Comparisons between the performance of the Brite 2 and Brite 3 products are limited at this time because of the low test duration (1,500 hrs) of the Brite 3 products. However, it is significant that no panel failures have occurred in either product, and the cumulative test exposures for Brite 2 and Brite 3 products are provided in **Table 4-2**.

Table 4-2. Summary of Cumulative Stress Test Exposures of Brite 2 and Brite 3 Products.

Product Description	AST	Cumulative Test Time	Panel Failure Times (if any)
Brite 2 neutral white	RTOL, 35OL, and 45OL	21,000 hrs each test	No panel failures
Brite 2 warm white	RTOL, 35OL, and45OL	21,000 hrs each test	No panel failures
Brite 3 neutral white	RTOL, 35OL, 45OL, and 6590	4,500 hrs each test	No panel failures
Brite 3 warm white	RTOL, 35OL, 45OL, and 6590	4,500 hrs each test	No panel failures

The findings of this research demonstrate that the performance and reliability of OLED products continues to improve. The panel shorting and chromaticity maintenance issues that readily occurred in early products are less likely in more recent ones. However, additional ASTs are needed to determine whether these failure modes have been completely eliminated or if their probability for occurrence has been reduced. However, there are still issues with OLED technologies that must be addressed, such as achieving additional gains in luminous efficacy and addressing the increasing power required for operation as the device ages, that must also be addressed for OLED products to provide high energy efficiency across the products' lifetime. The gains in OLED performance and reliability that have already been achieved are encouraging and signal the possibility for OLED technologies to become a significant lighting technology in the future. Additional research focusing on new materials with improved performance and higher reliability will help to unlock the commercial potential of this technology in indoor lighting applications.

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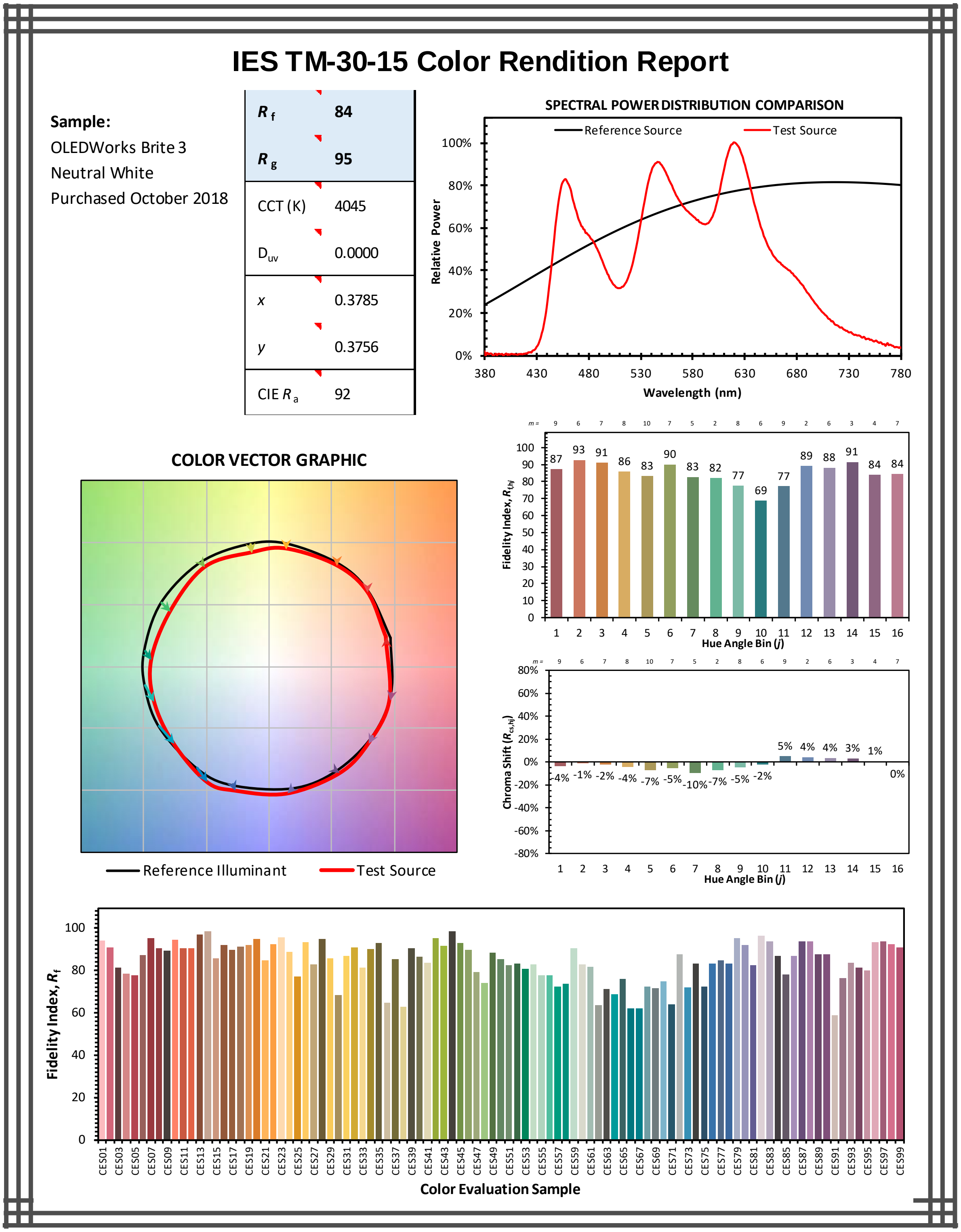
Appendix A

Table A-1. Comparison of the Testing Procedures and Test Duration Reported in Previous Studies and in This Report.

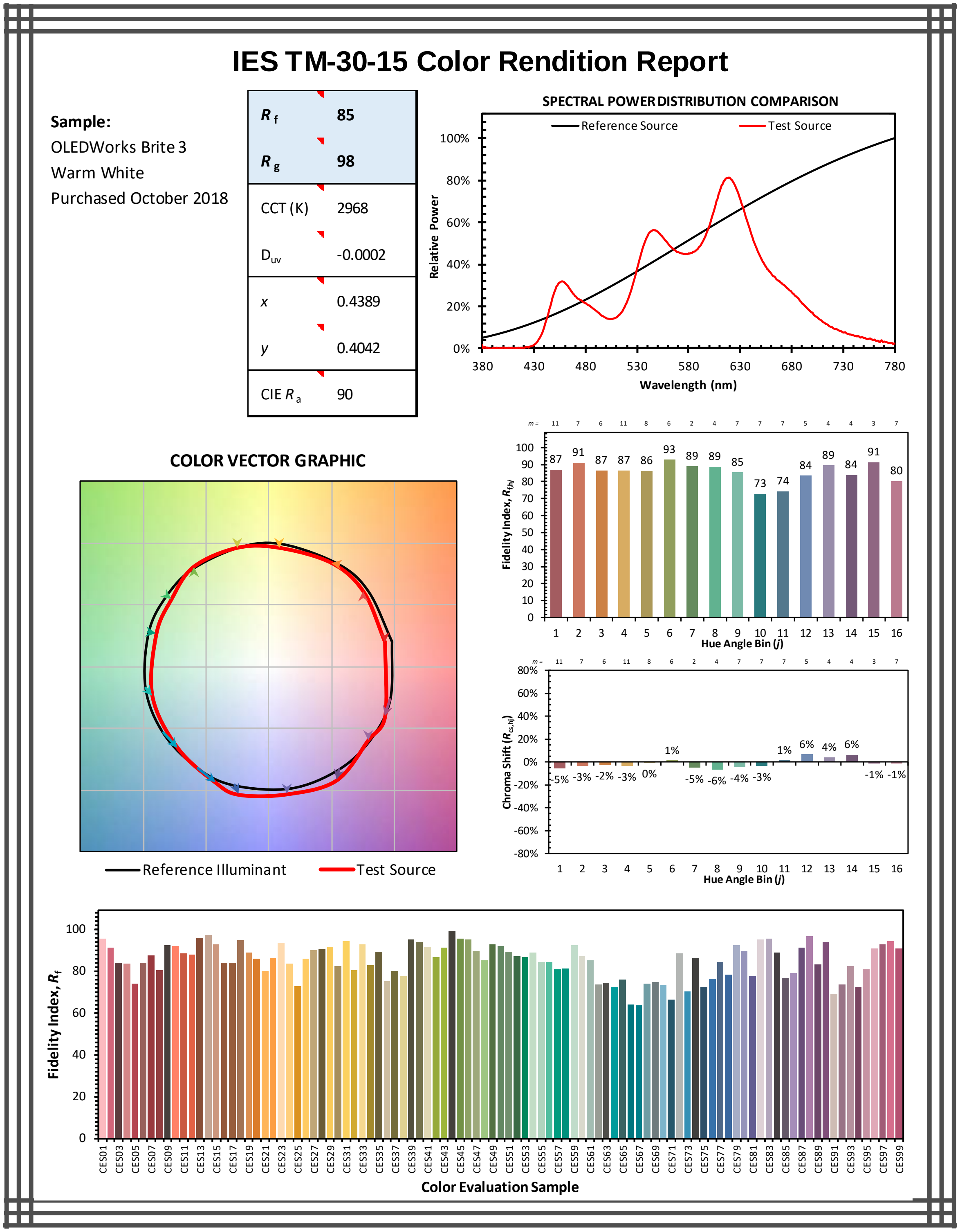
Sample	Accelerated Stress Test	U.S. Department of Energy (DOE) Report 1 [12]	DOE Report 2 [2]	This Report
Chalina Luminaire	RTOL	Not applicable	6,500 hrs	15,000 hrs
	350L	Not applicable	2,000 hrs	8,000 hrs
	450L	4,250 hrs	9,000 hrs	12,000 hrs
	Temperature and humidity	Yes (7575)	No	No
Brite 2 panels	RTOL	Not applicable	1,500 hrs	7,000 hrs
	350L	Not applicable	1,500 hrs	7,000 hrs
	450L	Not applicable	1,500 hrs	7,000 hrs
	Temperature and humidity	Not applicable	Not applicable	Not applicable
Brite Amber panels	RTOL	Not applicable	1,500 hrs	7,000 hrs
	350L	Not applicable	1,500 hrs	7,000 hrs
	450L	Not applicable	1,500 hrs	Not applicable
	Temperature and humidity	Not applicable	Not applicable	Not applicable
Brite 3 panels	RTOL	Not applicable	Not applicable	1,500 hrs
	350L	Not applicable	Not applicable	1,500 hrs
	450L	Not applicable	Not applicable	1,500 hrs
	Temperature and humidity	Not applicable	Not applicable	1,500 hrs (6590)

Appendix B



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

Figure B-1. Color rendition data for the OLEDWorks Brite 3 FL300 neutral white panels.



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

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

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