U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Round 3 Update of Stress Testing Results for Organic Light-Emitting Diode Panels and Luminaires

U.S. Department of Energy—Solid-State Lighting Technology Area

March 2020

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RTI Project Number
0215939.001.001

Round 3 Update of Stress Testing Results for Organic Light-Emitting Diode Panels and Luminaires

March 2020

Prepared for

Client Name: U.S. Department of Energy

Through contract with
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Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-FE0025912.

Disclaimer

Nomenclature or List of Acronyms

35OL	operational life test conducted at 35°C
45OL	operational life test conducted at 45°C
6590	life test conducted at 65°C and 90% relative humidity
°C	degrees Celsius
α	decay rate constant in TM-28-14 model
α_1	decay rate of initial processes in double exponential model
α_2	decay rate of long-term processes in double exponential model
γ	degradation rate in stretched exponential model
$\Delta u'$	change in the *u'* coordinate of chromaticity
$\Delta v'$	change in the *v'* coordinate of chromaticity
µm	micrometer
τ_0	time required for performance to degrade to 63% of the initial value in stretch exponential model
Φ_0	initial luminous flux
$\Phi(t)$	luminous flux at time, *t*
ψ	phase angle
Ω	ohms
A	amperes or amps
A	maximum radiant flux of the emitter in a skewed Gaussian model
ac	alternating current
A_{dc}	direct current amps
AST	accelerated stress test
B	pre-exponential factor in TM-28-14 model
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	correlated color temperature
CIE	International Commission on Illumination
CRI	color rendering index
dc	direct current

DOE	U.S. Department of Energy
DUT	device under test
EERE	Office of Energy Efficiency and Renewable Energy
eV	electron volts
F	F-test metric
hrs	hours
Hz	Hertz or cycles per second
IES	Illuminating Engineering Society
K	Kelvin
L60	time required for the luminous flux to decay to 60% of the initial value
L70	time required for the luminous flux to decay to 70% of the initial value
LCR	inductance, capacitance, and resistance
LED	light-emitting diode
L_{max}	maximum measured luminance across the panel
L_{min}	minimum measured luminance across the panel
mm	millimeter
mm^2	square millimeters
NIST	National Institute of Standards and Technology
nm	nanometer
NW	neutral white
OLED	organic light-emitting diode
p	the probability of obtaining the observed results if the null hypothesis is correct
PI	polyimide
p_0	wavelength at which maximum emission occurs in skewed Gaussian model
R^2	correlation coefficient
RT	room temperature
RTOL	room temperature operational life
s	asymmetry (skewness) parameter in skewed Gaussian model
SPD	spectral power distribution

SSL	solid-state lighting
t	time
TM	technical memorandum
u'	chromaticity coordinate in the CIE 1976 color space
V	volt
v'	chromaticity coordinate in the CIE 1976 color space
V_{dc}	direct current volts
w	width at half-maximum radiant flux in skewed Gaussian model
W	watt
W_{dc}	direct current watts
W/eV	watts per electron volt
W/nm	watts per nanometer
WHTOL	wet high-temperature operational life
WW	warm white
Z	impedance

Executive Summary

Organic light-emitting diode (OLED) sources are an emerging solid-state lighting (SSL) technology for use in indoor lighting applications. Some of the advantages that OLED technologies could potentially provide to the general lighting market include thin light fixture profiles, low light source glare, uniform diffuse lighting, and excellent color rendering. The U.S. Department of Energy (DOE) has released six technical reports focused on OLED technologies to provide information and analysis to the lighting industry [1–6]. These reports include the evaluation of two different field deployment sites [1, 4], a market analysis [2], a tear-down analysis [3], and two independent assessments of the performance of select commercially available OLED products [5, 6].

This report builds on earlier DOE efforts with OLED technology by updating information about previously benchmarked commercial OLED products. Specifically, this report provides updated findings about the robustness and reliability of commercial OLED products. The information presented in this report is gained from more than 1 year of accelerated stress tests (ASTs). The commercial products covered in this report include a luminaire containing five separate three-stack tandem panels and individual OLED panels that use a six-stack tandem structure. In this report, the three-stack tandem devices are referred to as **Type A** panels, and the six-stack tandem devices are referred to as **Type B** panels. In addition to evaluating the two OLED panel structures, this report also provides information about three different generations of the Type A panel (termed GEN-1, GEN-2, and GEN-3) and two different generations of the Type B panels (termed GEN-2B and GEN-3B). The luminaires employing the Type A panels were purchased at three different times from 2015 to 2017, whereas the Type B panels were purchased at two different times in 2017 and 2018.

Advancements in OLED product reliability can be assessed through an examination of the relative performance of the different generation of products. In addition, RTI has developed a methodology to assess the luminous flux maintenance of OLED products that is a modified version of the TM-28-14 standard used for light-emitting diode (LED) lamps and luminaires. This modified TM-28-14 method allows a comparison of the performance of OLED products with LED products.

The AST procedures used in this study included room temperature operational life (RTOL) test, 35°C operational life (35OL) test, 45°C operational life (45OL) test, and a wet high-temperature operational life (WHTOL) test performed at 65°C and 90% relative humidity (6590). The 6590 test was only performed on the newest product (GEN-3B panels) because changes in encapsulation technologies have reportedly improved the robustness of these OLEDs against temperature and humidity. During the ASTs described herein, populations of each product were subjected to continuous operation at mildly elevated ambient temperature environments during RTOL, 35OL, or 45OL testing. All ASTs have completed a minimum of 6,000 hrs, and some have completed 19,000 hrs.

The key findings from this report and the earlier efforts detailed in previous DOE reports [5, 6] include the following:

- The luminous flux of the (4,000 K) Type B neutral white panels has reached the point where predicted lifetimes to L70 exceed the maximum allowed projected lifetimes according to the "modified" TM-28-14 method in testing at room temperature. These maximum allowed values were 36,000 hrs for GEN-2B Type B panels and 21,000 hrs for GEN-3B Type B panels, and these values would likely increase with additional testing. Specifically, the decay rate constant (α) for the GEN-3B Type B neutral white panels was 7.6×10^{-6}—the lowest value measured in this OLED testing study. The LM-28-14–projected limits of this study were based on 12,000 hrs of testing of three samples of GEN-2B neutral white panels and 7,000 hrs of testing of three samples of GEN-3B neutral white panels.
- Although the test duration was different for the GEN-2B and GEN-3B Type B panels, the luminous flux maintenance was generally found to be higher for the GEN-3B neutral white panels than for GEN-2B

panels in comparable test environments. In contrast, the luminous flux maintenance of the GEN-2B warm white panels was higher than GEN-3B panels in comparable test environments.

- The luminous flux maintenance of luminaires using the Type A panels improved significantly when progressing from GEN-1 to GEN-2 and GEN-3 of the luminaires. This improvement was attributed to improved heat spreading in the OLED panels, achieved through the application of a metallized polyimide (PI) film on the back of the OLED panel.
- Differential loss of light emission from the organic light-emitting molecules that compose the OLEDs produced chromaticity shifts that were large in early Type A products. The differential loss of light emission was much-improved in the later products where more stable materials and better thermal management were used. Type A GEN-1 products exhibited a strong shift in the blue direction, whereas Type A GEN-3 products exhibited a much smaller shift in a generally green direction.
- The chromaticity shift direction was approximately the same for both generations of Type B neutral white panels (i.e., GEN-2B and GEN-3B), but the amount of shift was less in equivalent tests for the newer GEN-3B panels. Using spectral deconvolution, the increased chromaticity maintenance of the GEN-3B neutral white panels (relative to GEN-2B) was attributed to the improved stability of the organic emitters. For the Type B warm white panels, the chromaticity shift behavior was slightly different, suggesting some changes in structure and/or device composition.
- The GEN-3B Type B panels exhibited good performance in WHTOL testing, with all panels surviving at least 2,000 hrs of testing. One device experienced multiple driver failures during early testing—the panel itself remained operational—and so it was removed from testing after 2,000 hrs. Another panel experienced its second driver failure at the end of testing, but its panel remained operational. Three out of the five GEN-3B Type B panels survived 6,000 hrs of testing at 6590 without driver failure; however, the luminous flux was below 0.60 for the four surviving panels in this test. In addition, one panel failed because of handling issues; therefore, it was not included in this analysis. This finding marks a significant improvement over the performance of earlier OLEDs products in WHTOL testing [3].
- Panel impedance stability of Type A panels improves markedly when progressing from GEN-1 to GEN-2 and GEN-3. Power consumption of Type A panels increased over time, and the rate of change in power consumption was correlated to the test temperature, suggesting more accelerated degradation at higher temperatures.
- The voltage required to maintain constant current in Type B panels also increased over time for both types of GEN-2B neutral white and warm white panels. However, the voltage change (and power consumption) of the GEN-3B neutral white samples through at least 7,000 hrs of temperature-only AST studies was not statistically different from the control. In contrast, the applied voltage of the GEN-3B warm white samples increased by a statistically significant amount during temperature-only AST studies. During 6590 testing, both correlated color temperature (CCT) values of GEN-3B panels exhibited large increases through 6,000 hrs.

An examination of the technology progression of the devices under test (DUTs) demonstrates that the performance of OLED panels continues to improve. Both luminous flux maintenance and chromaticity maintenance have made notable gains, and the finding that the luminous flux lifetime to L70 of OLED panels operated at ambient room temperature is now limited by the projection limits of TM-28-14 is a significant milestone. The power requirements of OLEDs do increase slowly with aging, so the overall luminous efficacy declines over time, as happens with LED technologies. These findings indicate that steady gains continue to be made in OLED technologies for lighting applications and that continued improvement of the technology may open new opportunities for SSL in the indoor space that cannot be addressed with LED-based light sources.

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1 Introduction

Organic light-emitting diode (OLED) technologies have seen significant utilization in mobile devices and have now become the dominant display technology for flagship smartphone and television products [7]. OLEDs are attractive for these applications because OLEDs 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. The prominence of OLEDs in mobile devices is 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, but their use is in relative decline as OLEDs expand their foothold in display applications [8, 9].

More than one decade ago, continued improvement of LED technologies, especially the ability to produce bright long-lasting sources, ultimately resulted in their use in general lighting applications, which is a larger market than mobile device applications. Following a similar technology progression, there can be significant benefits from research that improves the performance of OLED technologies to the point where they can provide the illuminance and reliability needed 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 [CRIs]), 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 still exist, including reducing costs, improving reliability, and commercializing the high-efficacy performance that has been demonstrated in the laboratory [10].

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. One of the main differences between the challenges that were experienced by LED lighting technologies more than a decade ago and those currently facing OLED lighting technologies is that LED lighting is now an established technology with a significant market presence and is a major competitor of OLEDs. In short, LEDs have now set the standard for efficiency and reliability of a lighting product. However, there are potential benefits to OLED lighting that may not be easily addressed with inorganic LED technologies, making the two potentially complementary lighting technologies.

To continue providing the industry with information about the state of OLED technology, this report updates findings from more than 2 years of life testing on some commercial products and provides benchmarks regarding the latest commercial OLED products. This report builds on previous testing on these products [3, 5, 6] and provides results from an additional year of AST.

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 [11]. Because OLED technologies are still being researched for lighting applications, there are no existing standard methods for such accelerated tests, and a myriad of approaches are used by researchers, in contrast to established methods for LEDs [12]. The absence of standardized OLED test methods creates confusion in the marketplace and obscures the performance of OLEDs relative to competitive technologies. However, testing standards for OLED lighting products will ultimately need to comply with the existing testing infrastructure for LED lighting, which relies on environmental stresses of temperature, vibration, and power cycling. Current research about OLED testing methods points to the use of mildly elevated ambient temperatures (e.g., 35°C to 65°C) as being appropriate for accelerated stress tests (ASTs) [5, 6, 13, 14].

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 [10]. Through a series of technical reports, demonstration projects, and market analysis [1–6], a general conclusion from DOE-sponsored studies of OLED lighting technology is that the cosine emission profile of 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 efficacy, reliability, driver performance, and initial costs, which are all potential market impediments requiring additional research.

Commercially available OLED lighting panels from several manufacturers have been the primary focus of DOE studies because of their use in luminaires by multiple luminaire manufacturers. All of the panels from major OLED suppliers that are built for the commercial lighting market use fluorescent blue-emitting organic molecules and phosphorescent organic molecules emitting in the green to red spectral regions. Panel construction can be divided into two broad classes: those built with a three-stack tandem structure [15] and those that incorporate a six-stack tandem structure [16]. In this report, the panel classes are labeled **Type A** (three-stack tandem) and **Type B** (six-stack tandem). This report will discuss the performance of three different generations of the Type A panels and the two newest generations of the Type B panels [17]. These OLED panels have been used in a broad range of luminaire types examined in DOE studies, including both GATEWAY and CALiPER (Commercially Available LED Product Evaluation and Reporting) reports [1, 3–6].

1.3 Scope of This Report

This report is a continuation of previous research reports about the performance of OLED technologies. The results presented in this report build on findings from the earlier OLED reports [3, 5, 6], but provide additional test results, new analyses, and new findings. Because all of the products discussed in this report have been tested for at least 6,000 hrs, this is likely to be the last update about these specific OLED products. Future OLED testing reports will be released as appropriate.

The scope of this research report is to provide updates about OLED technologies regarding the following key areas:

- Updating laboratory test results, including AST results, for three different generations of luminaires that use the Type A panels
- Providing updated laboratory test results, including AST findings, for two generations of Type B panels.

The evaluations described in this report include examinations of the luminous flux, chromaticity maintenance, power consumption, and lighting uniformity of the OLED samples after operation in mildly accelerating stress conditions. The AST techniques used in developing the findings reported herein typically involved lower ambient temperatures than used for inorganic LEDs [12], but they provide sufficient lifetime acceleration, without changing the failure mechanism, for reliability analysis of OLED panels. This report also contains findings from wet high-temperature operational life (WHTOL) testing of some panels to assess improvements in thermal stability and panel encapsulation technologies.

2 Experimental and Analytic Methods

This report builds on our previous DOE reports about commercial OLED technologies [3, 5, 6] and uses many of the same AST protocols and measurement methods. Although this report provides cumulative findings from the AST studies of the devices under test (DUTs), this document focuses on the recent experimental findings that have not been previously disclosed and long-term trends. For convenience, comparisons of the testing protocols and test durations used in the earlier reports are provided in **Table A-1** of **Appendix A** of this report.

2.1 Samples

There were two basic configurations of the DUTs, as described in previous DOE reports [3, 5, 6]: luminaires with several Type A OLED panels and individual Type B OLED panels. Luminaires containing five Type A OLED panels with a nominal correlated color temperature (CCT) of 2,800 K comprised one group of DUTs. These DUTs used a driver directly connected to the alternating current (ac) mains to power and operate all five OLED panels.

Individual OLED panels chosen from two different CCT values, nominally 3,000 K (warm white) and 4,000 K (neutral white), were tested for the Type B panels. These panels used a power supply to convert the ac mains to direct current (dc) power, and the dc output from the power supply was fed to a driver, which, in turn, powered the OLED panel. In the tested configuration, each panel had an associated driver. Power supplies were used interchangeably between panels during AST. The same model of driver was used for both generations of Type B panels that were tested.

The structure of the DUTs used during ASTs varied slightly, depending on whether the DUTs were luminaires or individual panels. The luminaires with Type A panels were tested as received, and the only testing accommodation was that the driver was placed outside the test chamber. As a result, the drivers experienced only room temperature conditions throughout the test, whereas the remainder of the device experienced elevated ambient temperature.[1] The Type B panels were mounted on individual aluminum plates, with the driver placed on the aluminum plate 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.[2] Photographs of the DUT configurations are presented as **Figure 2-1** and **Figure 2-2**.

[1] Note: As previously described, three different generations of luminaires (henceforth referred to as GEN-1, GEN-2, and GEN-3) were examined during these tests [5, 6]. The primary differences between the three generations of the product were the date of purchase and the incorporation of a metallized polyimide film on the back of each panel for GEN-2 and GEN-3 products to provide additional heat spreading.

[2] For the Type B panels, only the two newest generations (henceforth referred to as GEN-2B and GEN-3B) were examined during these tests. The primary differences between these generations are thought to be improvements in materials and construction to improve product reliability.

Figure 2-1. Test configuration for the luminaires with Type A panels examined during this study.

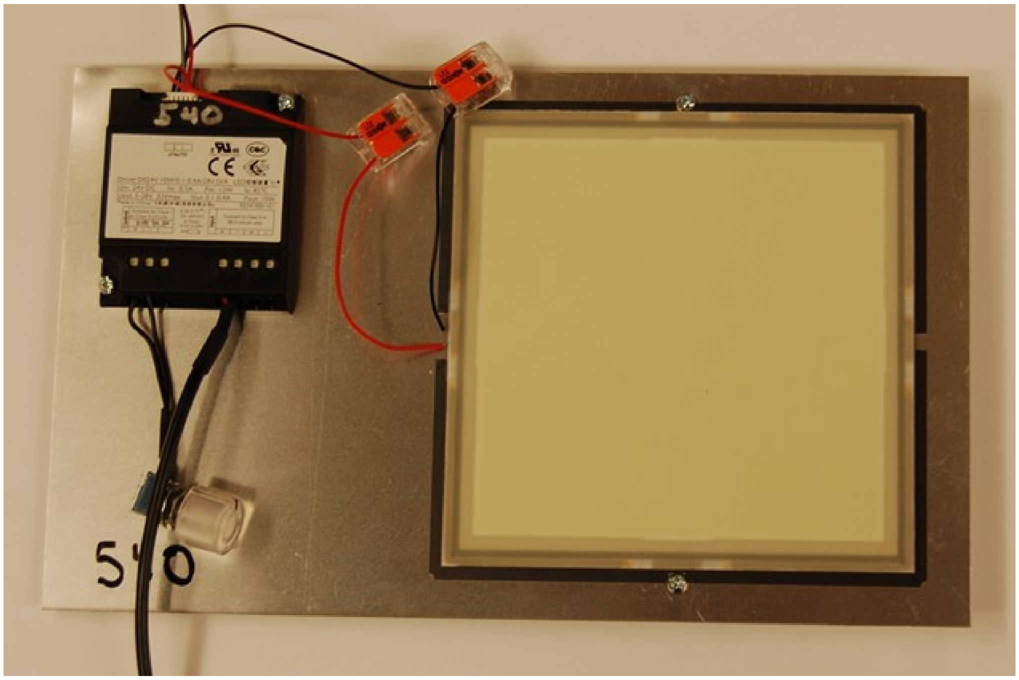

Figure 2-2. Test configuration for the Type B panel DUTs examined during this study.

2.2 Stress Testing Methods

As summarized in **Table 2-1.**, this report presents findings from room temperature operational life (RTOL) and ASTs involving temperature bakes at mildly elevated temperatures of either 35°C or 45°C (35OL and 45OL, respectively). Either a temperature oven or a temperature-humidity environmental chamber was used for these tests. Humidity was not explicitly controlled when a temperature oven was used, and the ambient humidity was determined by the air handling system of the building. Because of this, the ambient humidity varied between 20% and 80%, depending on the time of year, for the RTOL test. This equates to a variation in humidity of 10% to 42% in 35OL and 6% to 25% in 45OL. The sample size at each condition for the Type A panels varied between conditions and product generation while the sample size at all conditions for the Type B panels was three unless otherwise noted. In addition, a temperature and humidity soak at 65°C and 90% relative humidity (6590) was only used for the latest generation of Type B panels. 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 (the power conditions were within the OLED panel manufacturer specifications) 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 the devices.

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 ambient temperature of 35°C and ambient humidity
45OL	Continuous operation at a constant ambient temperature of 45°C and ambient humidity
6590	Continuous operation 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). Background corrections were applied prior to calibration. Self-absorption corrections were made for all samples by using an auxiliary lamp mounted inside the sphere, which is in accordance with procedures in LM-79-19 [18].

2.3.2 Luminance Uniformity

Panel luminance was measured by using a fiber-optic spectrometer that had been calibrated by using NIST-traceable radiometric standards. The fiber optic (400-µm cladded silicon fiber diameter) was attached to a vertical riser from an optical breadboard, and the manual xy stage with 1 per 1,000-inch precision was used to position the sample to different locations. In this setup, the fiber optic was placed 5 mm above the DUT. Assuming the acceptance angle of the fiber optic was ±12.7 degrees, this experiment arrangement measured the total luminance from an area of 3.99 mm^2 on the panel. A photograph of this arrangement is presented as **Figure 2-3**.

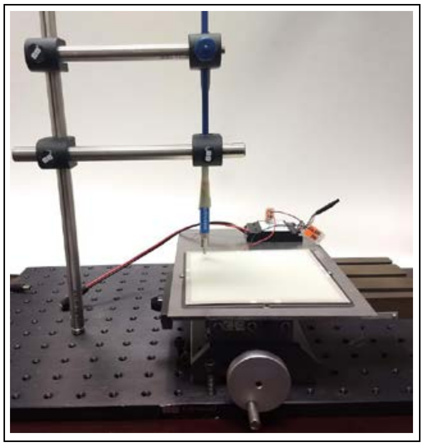

Figure 2-3. Testing configuration for luminance measurements.

For each sample, the stage was manually moved to one of nine different pre-set positions for the Type B 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) was only measured once. Once the luminance was measured at these locations, the luminance uniformity variation could 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 an electrical usage monitor on the ac mains. When more accurate electrical measurements were required, a two-channel power analyzer was used. The power analyzer measures many electrical parameters, including voltage, current, power, power factor, and total harmonic distortion. Impedance measurements of the OLED panels were made at every time interval by using a 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

The Illuminating Engineering Society (IES) technical memorandum (TM)-28-14 is the established method for modeling and projecting the long-term luminous flux maintenance of LED lamps and luminaires by using data acquired according to the guidelines of LM-84 [19]. The direct extrapolation rule of TM-28-14 provides for projections to future times of the luminous flux maintenance for an LED lamp or a luminaire by using data acquired at equal time intervals from three or more samples. The projection time is limited by the sample size, and if only three samples are used in the testing, then projections of luminous flux maintenance cannot exceed more than three times the test duration (in hours). LM-28-14 also stipulates that when a predetermined luminous flux value (e.g., L70) is reached experimentally during the course of testing, the reported value shall be obtained by a linear interpolation between the two nearest test points. and this value takes precedence over any projected value [19]. A similar procedure (i.e., IES TM-21-11) can be used to model and project the luminous flux maintenance of inorganic LEDs acquired by using the test procedures in LM-80; however, the applicable devices and the rules for sample size and project limits are different in TM-21-11 than in TM-28-14 [20]. Unfortunately, no corresponding standard method has been approved for use with OLEDs.

One procedure that has been widely used by researchers to model the degradation of OLEDs over time is the double-exponential model, consisting of the two components presented in Equation 2 [13] as follows:

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

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 Equation 2, the first exponential component describes the processes that occur early in device operation (typically less than 1,000 hrs), and the second exponential component describes the long-term degradation processes that occur thereafter. One advantage of using the double-exponential model is that if the testing time is sufficiently long (e.g., greater than 2,000 hrs), then the first exponential component 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 so that the OLED degradation model can be simplified to 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 [13] as follows:

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

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 experimental time must be long enough for a reasonable value of τ_0 to be obtained, which places a significant burden on test duration especially if the luminous flux maintenance is high.

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 standard method for modeling luminous flux in OLEDs, we decided to modify the double-exponential model for OLEDs to make it align with the methods used in TM-28-14.[3] This standard does not use data collected during early operation of the device, which can be 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 also TM-21-11), the ratio of the luminous flux at time t, $\Phi(t)$, 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-28-14 also uses Equation 4 to model luminous flux maintenance and project values at future times, comparisons of the α values of data derived from these measurements provide some relative measures of the OLED light source performance to that of inorganic LED technologies. 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.

Elements of the Single-Exponential Model Used in This Report	Comparison with the Direct Extrapolation Method of IES TM-28-14
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.
For test durations between 6,000 and 10,000 hrs, only data from the last 5,000 hrs of testing are used for the model. For test durations time greater than 10,000 hrs, only the last 50% of the data are used.	Same.
Typically, 2 to 4 samples are used in the models given here.	Somewhat different. TM-28-14, which is the basis for TM-28-14 projections, requires at least 3 samples for the direct projection method. Projection times are limited by sample size (e.g., 3 times the test duration for a sample size of 3).
The ambient test temperatures for OLED models were either room temperature (i.e., 25°C), 35°C, or 45°C. These test temperatures are justified because of the expected indoor use of the OLED panels.	Somewhat different. The methods given in LM-84 describe the data acquisition [19]. LM-84 does not specify a test temperature, but does allow for testing at ambient temperatures of 25°C.
All data, with equal time spacing, after the minimum modeling time were used for the OLED model.	Same. TM-28-14 requires equal test time increments (typically between 500 and 1,000 hrs) for modeled data.

[3] Note: TM-28-14 is not approved for use with OLED data; therefore, the approach used here is referred as a “modified TM-28-14 method.”

2.4.2 Emission Spectra Deconvolution

The OLED technologies tested during the study and the corresponding data are discussed in this report. The OLED technologies 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 help model chromaticity shift.

The Type A panels employ a three-stack tandem device structure with two combined phosphorescent layers that emit light in the green to red spectral regions, as well as and one fluorescent emissive layer that produces blue light [15]. Type B panels incorporate a six-stack tandem structure consisting of two fluorescent emissive layers that produce blue light, as well as four phosphorescent emissive layers that produce green- to red-colored light [16]. The chemical identity of the emitters used in the tested OLED technologies is 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 [21]. 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 [22] and is shown in Equation 5 as follows.

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

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 an s close to zero, the skewed distribution tends toward a symmetric Gaussian).

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

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

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 was often a better fit to the data for each emitting peak or region (e.g., blue, green-yellow, and red-orange emitters, as shown in **Figure 2-4**). Although many factors play into the overall SPD produced by an OLED lighting device (e.g., organic emitters, dopants, diffusers, uniformity), the SPD presented in this report was estimated 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 individual organic emitters was subsequently calculated as the sum of the radiant power of their respective skewed Gaussian.

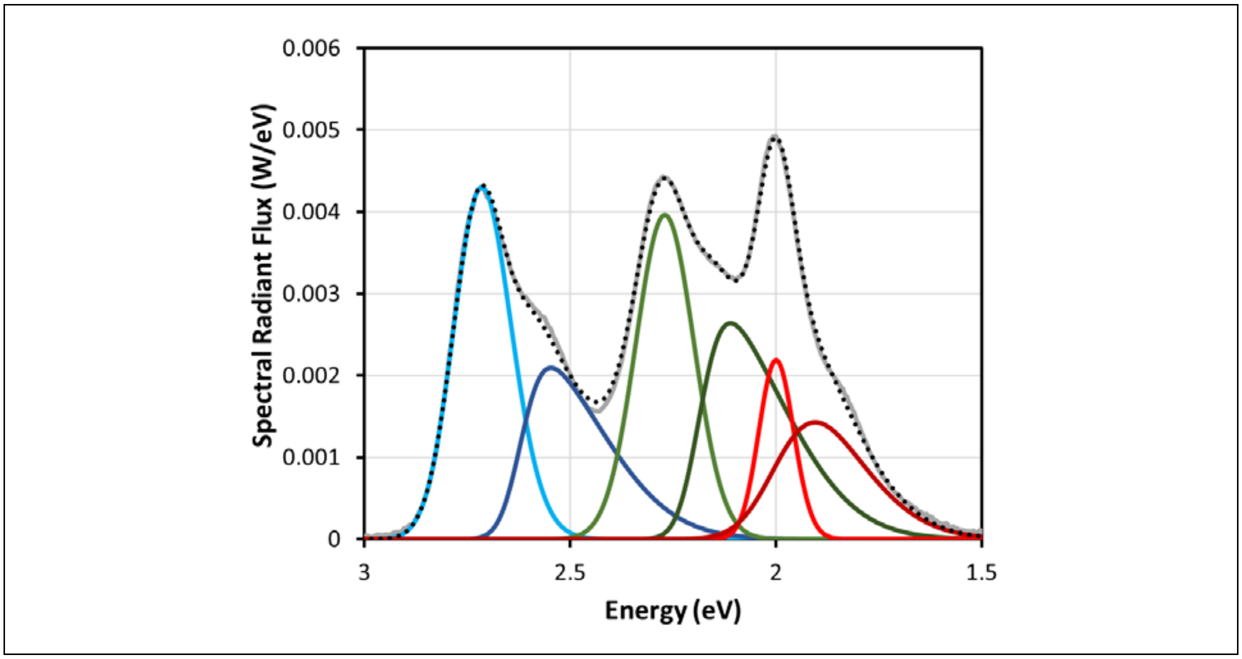

Figure 2-4. Spectral emission deconvolution from a Type B neutral white panel with two skewed Gaussian used to model each organic emitter.

Deconvolution of the spectral emissions from an OLED panel allows a determination of the chromaticity points for the individual emitters by using the sum of their respective skewed Gaussians. In this analysis, we chose to lump the two curves for the blue emissions together to obtain a single blue emitter chromaticity. A similar procedure was followed for the two phosphorescent emitters. The chromaticities of the fluorescent blue emitters for Type A and Type B panels are similar as shown in **Figure 2-5**. For the Type A panels, the two phosphorescent emitters correspond to green and amber colors, whereas the chromaticity points of the two phosphorescent emitters in Type B panels corresponded to green-yellow and red-orange colors as shown in Figure 2-5.

A closer examination of Figure 2-5 **i**llustrates the changes in total light emission produced by the OLED panel that correspond to the observed shift in chromaticity values. Starting from a typical white light chromaticity point on the blackbody locus (e.g., 3,000 K, 4,000 K), a shift in a generally blue direction involves moving toward the chromaticity point of blue emitters (i.e., wavelengths between 440 nm and 490 nm) and corresponds to a reduction in the value of *v*' (i.e., $\Delta v' < 0$) with much less change in *u'*.[4] Likewise, from a typical white chromaticity point, a shift in the generally yellow direction involves moving toward the chromaticity point of yellow emitters (i.e., wavelengths between 560 nm and 590 nm) and corresponds to an increase in the value of *v'* (i.e., $\Delta v' > 0$) with much less change in *u'*. In a similar manner, if starting from a typical white chromaticity point, a shift in a generally green direction (i.e., wavelengths between 520 nm and 560 nm) corresponds to a decrease in the value of *u*' (i.e., $\Delta u' < 0$) with much less change in *v'*, and a shift in a generally red direction (i.e., wavelengths between 630 nm and 700 nm) corresponds to an increase in the value of *u*' (i.e., $\Delta u' > 0$) with much less change in *v'*. These general changes in emitted light color are represented by the arrows in the lower right corner of Figure 2-5**.**

[4] $\Delta u'$ represents the change in the *u*' chromaticity value from the initial (or reference) point. Likewise, $\Delta v'$ represents the change in the *v'* chromaticity value from the initial (or reference) point)

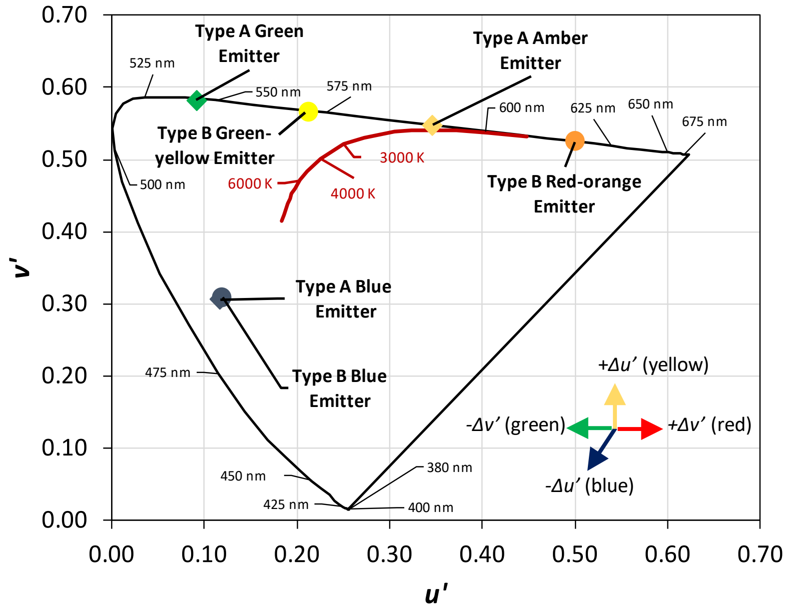

Figure 2-5. Chromaticity points of the blue, green-yellow, and red-orange organic emitters in a Type B OLED panel.

3 Results and Discussion

3.1 Luminaires with Type A Panels

As originally reported, the luminaires with Type A panels used in this study were purchased at three different times (at approximately 1-year intervals), and the design of the DUTs changed during this time. The DUTs are accordingly designated in this report as belonging to GEN-1, GEN-2, or GEN-3, depending on when they were purchased. The most visible difference between the three generations of luminaires was that the reflective back surface of the Type A OLED panels was visible for GEN-1 products [5], whereas the back surface of the Type A OLED panels for both the GEN-2 and GEN-3 products was covered by a metallized polyimide (PI) film that was applied by the manufacturer presumably to improve heat spreading [3, 5]. Because of the limited quantities and different purchase times of these DUTs, only select samples were subjected to each AST. The three different generations of 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 Luminaires with Type A Panels Examined During These Tests.

Designation	Purchase Date	Characteristics	Testing Environments
GEN-1	September 2015	No extra heat spreader on the OLED panels	450L
GEN-2	September 2016	Metallized PI film heat spreader on the panels	RTOL
GEN-3	July 2017	Metallized PI film heat spreader on the panels	350L and 450L

The initial SPDs from the GEN-1, GEN-2, and GEN-3 products are shown in **Figure 3-1**. Although there is some variation in peak intensities, the major peak locations are similar in all three generations of products. This finding suggests that the base chemistry of the organic emitter materials is similar in all three product generations. Prior to AST, the five Type A panels in the luminaire produced a combined average of 335 lumens and the luminaire system (i.e., Type A OLED panels and driver) consumed roughly 7.5 watts for a luminous efficacy of 45 lumens per watt.

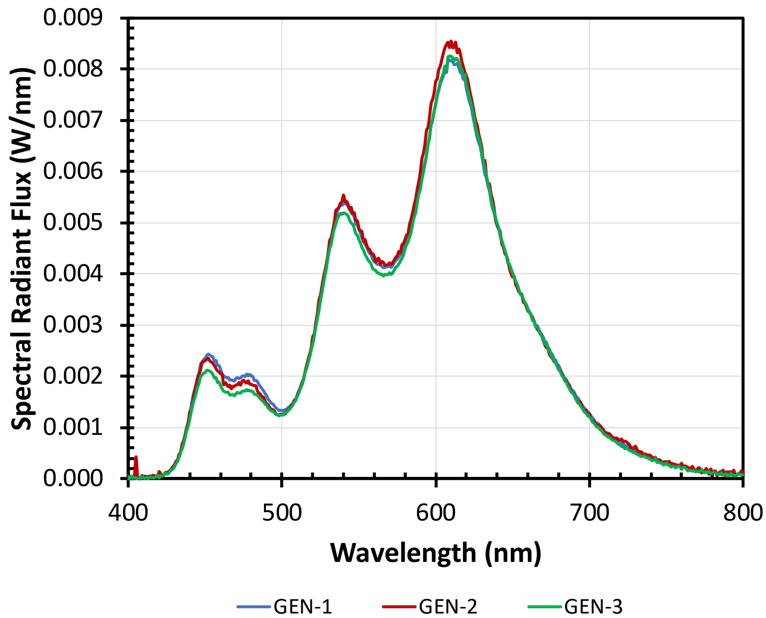

Figure 3-1. Initial SPDs obtained for GEN-1, GEN-2, and GEN-3 DUTs with Type A panels.

Panel failures were observed during 45OL testing of the GEN-1 products and were attributed to shorting within the OLED panels. Two out of the four original GEN-1 DUTs in the 45OL test were removed from testing because of excessive loss of luminous flux arising from panel shorting and abrupt failure of the entire device [3, 5]. However, the remaining two DUTs continued to operate properly and have now achieved 15,000 hrs of operation during the 45OL test, albeit at luminous flux maintenance levels below 0.5. As previously reported [5], one panel on a surviving GEN-1 device failed because of shorting after 7,000 hrs of operation at 45°C, and the total luminous flux produced by the device dropped suddenly, as shown in **Figure 3-2**. In contrast, no panel failures were observed on the GEN-2 and GEN-3 products that were tested in RTOL, 35OL, and 45OL during the testing period presented in this report.

3.1.1 Luminous Flux Maintenance

The luminous flux maintenance of the luminaires was correlated with the temperature of the test environment (see Figure 3-2), which suggests a thermal degradation mechanism. The samples in the RTOL test exhibited the best luminous flux maintenance, and the maintenance was statistically lower for the 35OL test. In contrast, the luminous flux maintenance was noticeably lower for both GEN-1 and GEN-3 DUTs operated during the 45OL test. The data presented in Figure 3-2 are an average of the population for each test condition. The test conditions are as follows: two DUTs for the RTOL test, four DUTs for the 35OL test, the two surviving DUTs of GEN-1 products for the 45OL test, and two DUTs of GEN-3 products for the 45OL test. Data for the GEN-1 and GEN-3 products in the 45OL test are presented separately in Figure 3-2 in part to illustrate the impacts of the failure of one GEN-1 panel after 7,000 hrs.

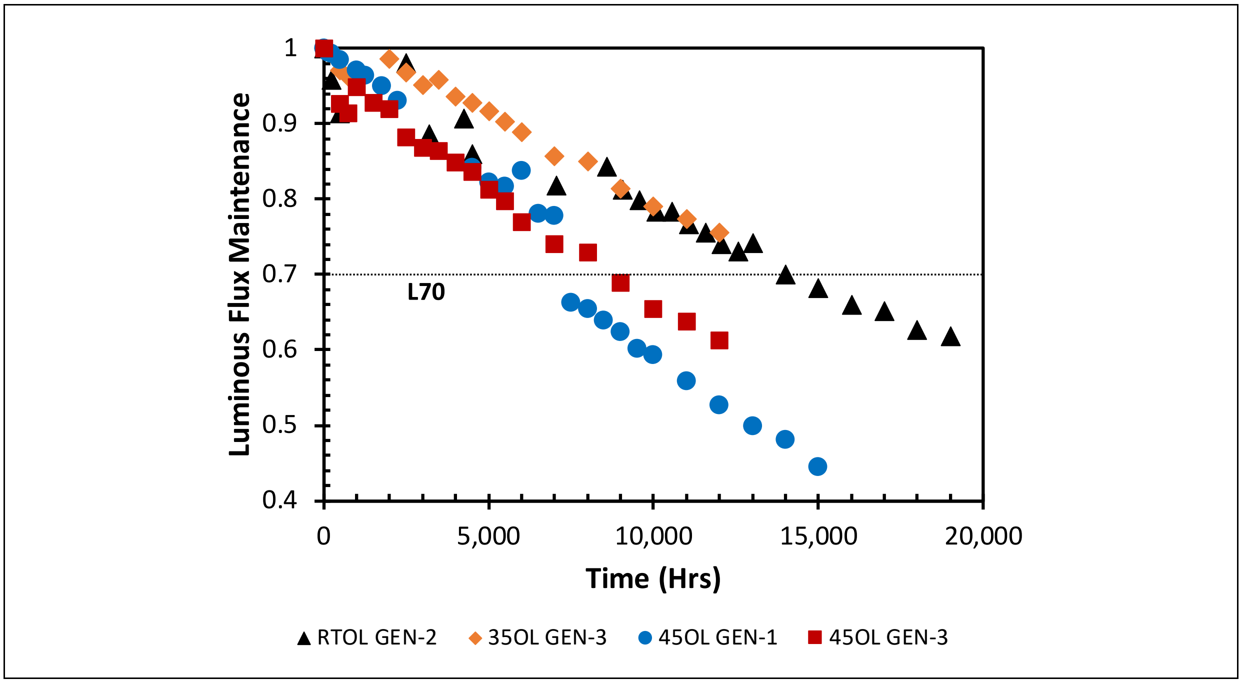

Figure 3-2. Average luminous flux maintenance for the populations of luminaires with Type A panels operated continuously in the RTOL, 35OL, and 45OL test environments. The performance results of both GEN-1 and GEN-3 products at 45 °C are provided separately.

Most test conditions were sufficient to reduce the luminous flux values of the DUTs to below the L70 level within the experimental time frame, and this allowed L70 to be determined experimentally by using linear interpolation consistent with TM-28-14. The experimentally derived L70 values for the luminaire are presented in **Table 3-2**.

Table 3-2. Experimentally Derived L70 Values for Luminaires with Type A Panels in Different Tests.

Test	DUT Generation	Experimentally Determined L70 Value
RTOL	GEN-2	19,500 hrs
35OL	GEN-3	Not observed during testing time
45OL	GEN-1	7,333 hrs due to panel failure
45OL	GEN-3	8,750 hrs

Using the modified TM-28-14 method described in Section 2.4 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 3-3**. Separate averages were calculated for the room temperature and 35°C test populations. Only one DUT was used for RTOL testing because the other DUT suffered a cracked panel when it was inadvertently dropped. Otherwise, no other panel failures occurred for these DUTs throughout the test period, and all panels were fully operational at the end of testing. For the RTOL DUT that was modeled, only the data between 9,069 and 19,000 hrs were used, as shown in Figure 3-3, in accordance with the guidelines listed in Table 2-2. A single-exponential fit of this data produced an α value of 1.7×10^{-5} and showed an excellent correlation coefficient (R^2) of 0.97. For the DUTs in the 35OL test, 12,000 hrs of operation have been completed. Consequently, data between 6,000 and 12,000 hrs were used for the model (see Figure 3-3). The α was calculated to be 2.7×10^{-5} with an excellent R^2 value of 0.98. This value can be projected to an L70 time of 14,700 hrs by applying the modified IES TM-28-14 method. Based on a statistical analysis of the raw data, the

α values for RTOL and 35OL are highly correlated to luminous flux maintenance ($F[1,63] = 104$, $p < 0.001$), and they are statistically different ($p = 0.014$) from each other.

Performing a similar analysis for the DUTs in the 45OL test was complicated by the shorting of one panel in a single GEN-1 device, which resulted in a sharp drop in luminous flux at 7,000 hrs (see Figure 3-2**)**. To compensate the total luminous flux was divided by the number of fully functional panels, for each time interval, and this ratio was reported. The results are presented in **Figure 3-4**. Because the two surviving luminaires with GEN-1 OLED panels have reached 15,000 hrs during the 45OL test, the luminous flux maintenance model can be calculated by using the average readings between 7,000 and 15,000 hrs. For the GEN-1 DUTs, the α value was calculated to be 5.4×10^{-5}, and the R^2 value was excellent (1.00). A similar procedure was followed for the GEN-3 DUTs in the 45OL test, and the α value was calculated to be 3.9×10^{-5}, and the R^2 value was excellent (0.99). A statistical analysis of the raw data used to create these models demonstrated that these α values are statistically different, at the 95% confidence level, from those measured in DUTs subjected to 35OL ($p < 0.001$ for the 45OL GEN-1 DUTs and $p = 0.006$ for the 45OL GEN-3 DUTs). In addition, the 45OL α values obtained from GEN-1 and GEN-3 DUTs were found to be statistically significant from each other ($F[1,28] = 16$, $p < 0.001$). The difference in luminous flux maintenance between GEN-1 and GEN-3 products could be due to the use of the metallized PI film on the back of the GEN-3 OLED panels to increase thermal stability.

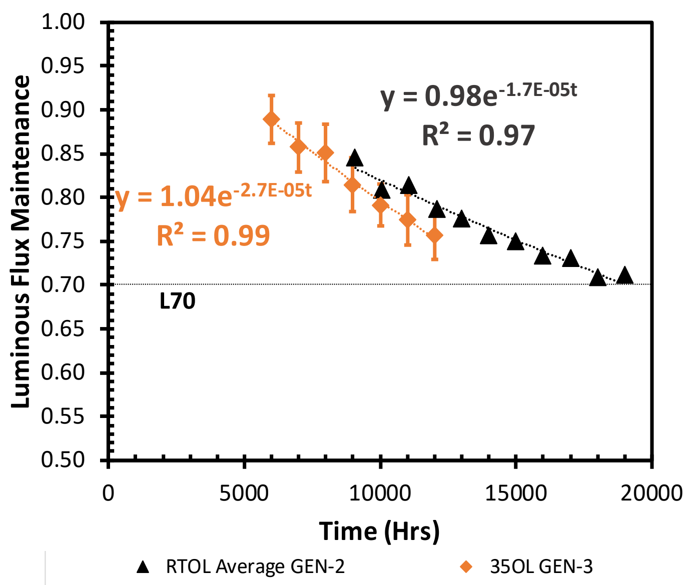

Figure 3-3. Luminous flux maintenance for luminaires with Type A panels subjected to RTOL testing (GEN-2 panels) and average luminous flux maintenance for those operated during the 35OL test (GEN-3 panels). Single-exponential fits for the latter parts of the data are shown. The error bars that are shown represent one standard deviation.

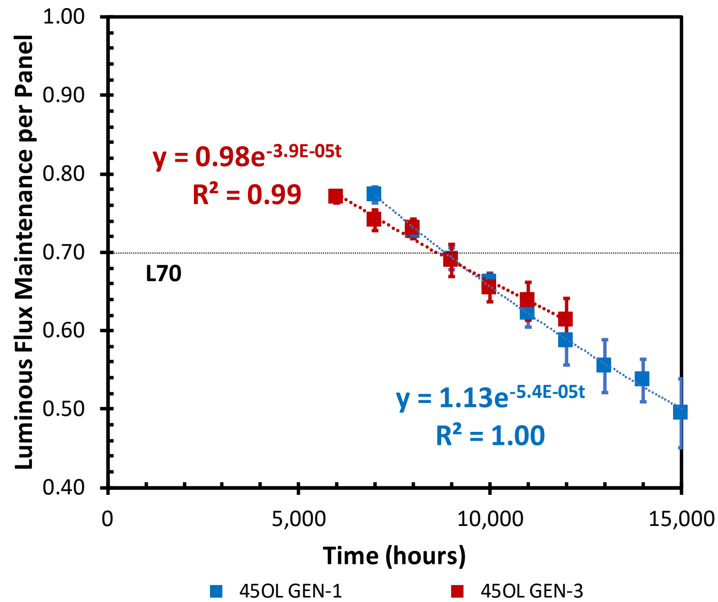

Figure 3-4. Average luminous flux maintenance models for luminaires with Type A panels in the 45OL test. Data for luminaires containing only GEN-1 panels and those containing only GEN-3 panels are provided separately. The error bars that are shown represent one standard deviation.

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 three generations of OLED luminaires with Type A panels. These results are summarized in **Figure 3-5** for the samples containing either GEN-1 panels or GEN-3 panels. Figure 3-5A provides the absolute chromaticity values, at different 45OL test times, and Figure 3-5B shows the change in chromaticity from the initial point. This change is defined as $\Delta u'$ (the difference between u' at a given time and the initial value of u') and $\Delta v'$ (the difference between v' at a given time and the initial value of v′). As can be clearly seen in both figures, there is a difference in both the direction and magnitude of the chromaticity shift between the GEN-1 and GEN-3 DUTs in 45OL, even though the initial emission spectra are similar (see Figure 3-1). 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 [23, 24].

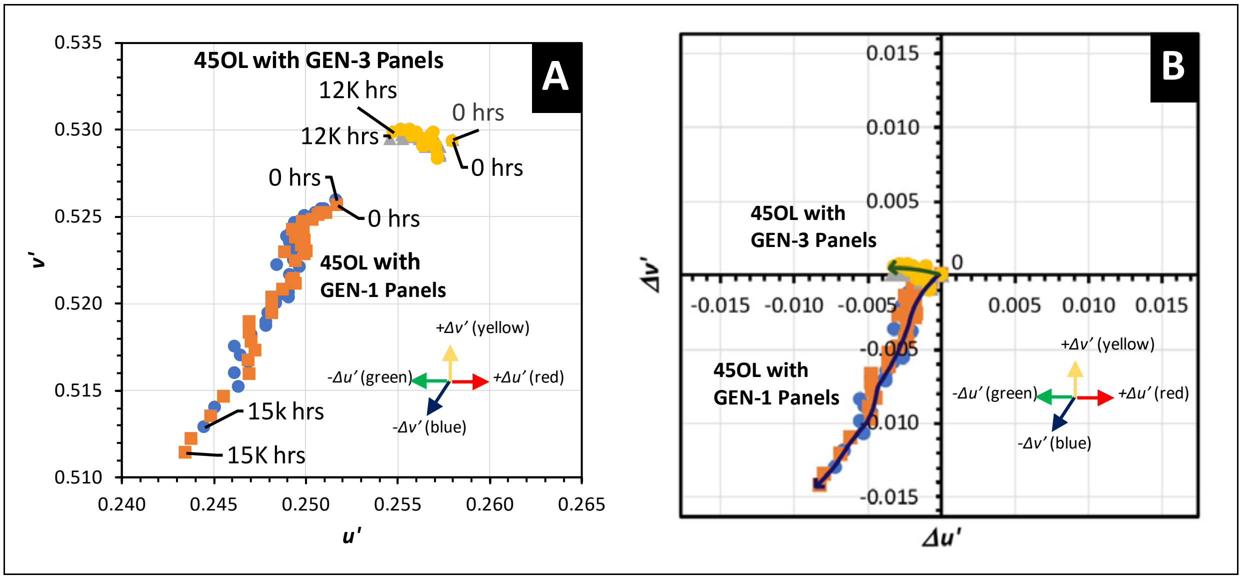

Figure 3-5. Chromaticity shifts for luminaires with GEN-1 and GEN-3 Type A OLED panels in the 45OL stress test. (A) The change with time in the absolute chromaticity is given in *u′* and *v′*. (B) The chromaticity shift over time given in *Δu′* and *Δv′* is calculated from the initial chromaticity values.

During the 45OL test, the chromaticity shift for the luminaires with GEN-1 Type A panels proceeded strongly in the generally blue direction, which agrees with previous findings [5, 6]. This trend proceeded at approximately the same rate after 4,000 hrs of testing, and the change in the -*Δv′* direction was almost twice that in the -*Δu′* direction. 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 (i.e., the SPD is increasing in the relative amount of blue emissions), which is in agreement with the examination of the SPD changes previously given [5, 6]. The magnitude of this change (as shown by the blue arrow in Figure 3-5B) is significant (*Δu′v′* = 0.0165) and will be noticeable to the viewer. That color shift is confirmed by a visible change in the appearance of the light produced by the luminaire and the corresponding increase in the CCT value.

However, the behavior of the luminaires with the GEN-3 Type A panels was significantly different as shown in Figure 3-5. The chromaticity of these devices shifted in the green direction, which is signified by a chromaticity change predominately in the -*Δu′* direction with minimal change in the ±*Δv′* direction. This shift occurred rapidly and reached a plateau of *Δu′* = -0.002 and *Δv′* = -0.001 before 4,000 hrs of operation during the 45OL test. After 7,000 hrs, the chromaticity began to change at a slower rate than the GEN-1 panels, with the change occurring in the predominantly green direction. Because the rate of chromaticity shift is significantly higher for the GEN-1 panels than for the GEN-3 panels, the chromaticity stability of the GEN-3 DUTs is judged to be higher.

3.1.3 Electrical Analysis

The updated average impedance values of all fully operational Type A OLED panels across all testing regiments are provided in this report. The impedance of each panel was measured at three frequencies—100 Hz, 1,000 Hz, and 10,000 Hz—and the average values and standard deviations for all panels of a given generation and AST protocol are presented in **Table 3-3**. 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 95% confidence level. In addition, the impedance values have increased since the last report [6], but this change was found to be statistically significant only for the 100-Hz measurement (*p* = 0.0037).

In general, GEN-2 and GEN-3 Type A panels continue to show both lower and more stable impedance values, relative to their initial panel impedances, suggesting a change in structure compared with GEN-1 panels. The panel impedance for the GEN-2 samples in RTOL did not change by a statistically significant amount during testing. In contrast, the GEN-3 panel impedances decreased by a statistically significant amount during the course of testing ($p < 0.0001$ at 95% confidence level) for both DUTs subjected to 35OL and those subjected to 45OL. However, the change in mean impedance for the DUTs is not statistically different from the last report value for GEN-3 panels in either 35OL or 45OL after 8,000 hrs of testing [6]. This finding suggests that although there may be some changes in impedance in the GEN-3 panels, the changes are likely to occur at a faster rate early in the AST protocol and the overall change stabilizes over time.

Table 3-3. Impedance of Type A Panels in 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 (≥15,000 hrs)	LG Display—GEN-1	2,843 ± 34 Ω	299 ± 3 Ω	30.8 ± 0.3 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 (19,000 hrs)	LG Display—GEN-2	2,702 ± 29 Ω	296 ± 4Ω	30.8 ± 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 (12,000 hrs)	LG Display—GEN-3	2,226 ± 15 Ω	244 ± 2 Ω	25.7 ± 0.2 Ω
Operational panels from the 45OL test (12,000 hrs)	LG Display—GEN-3	2,179 ± 11 Ω	239 ± 1 Ω	25.3 ± 0.1 Ω

Note: The reported uncertainties represent one standard deviation.

Although the average impedance of the GEN-3 panels in luminaires decreased through 12,000 hrs, their average power consumption increased across both 35OL and 45OL tests as shown in **Figure 3-6**. The power increase can be modeled with a linear regression with a good R^2 value (0.83). The findings from a statistical analysis of the complete data set that is summarized in Figure 3-6 indicate that there was a statistically significant difference between the slope of the power increase for DUTs tested in 35OL and 45OL at the 95% confidence level ($p < 0.001$). 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. The net result is that the luminous efficacy of the OLED lighting system (including Type A OLED panels and driver) decreased from an initial value of 45 lumens per watt to 28 lumens per watt after 12,000 hours of 45OL.

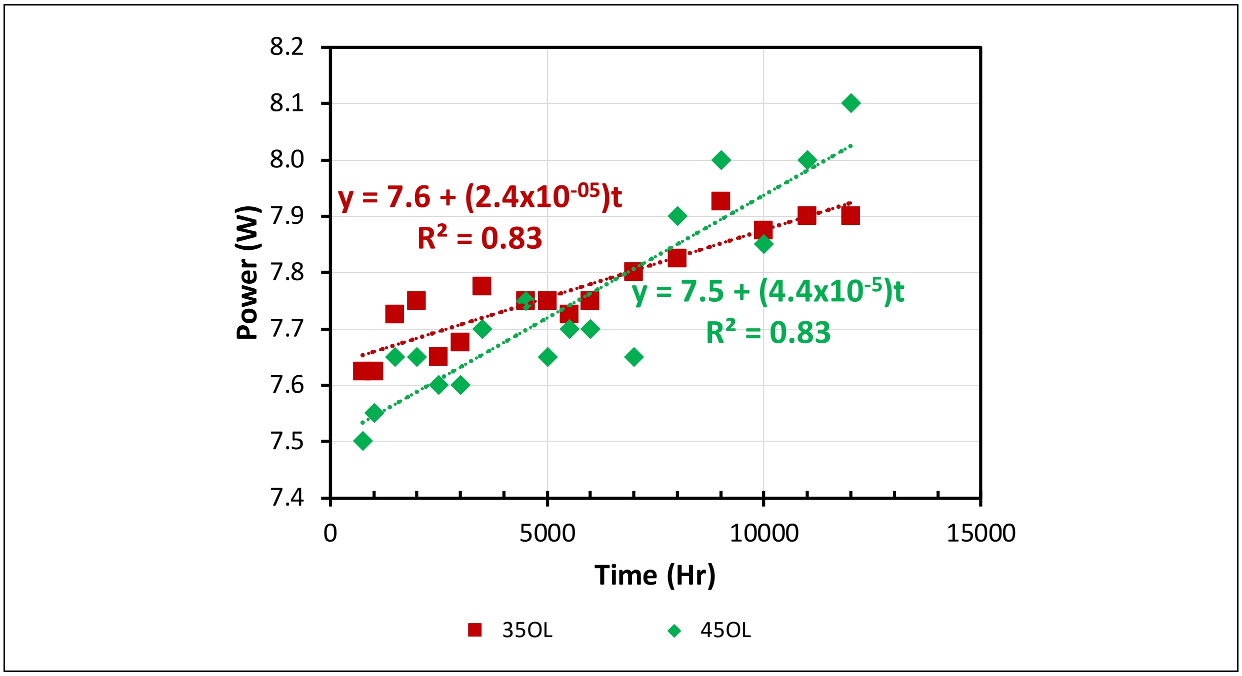

Figure 3-6. Average power increase for GEN-3 luminaires through 12,000 hrs.

3.2 Type B Panels

Three different generations (labeled GEN-1B, GEN-2B, and GEN-3B) of the Type B panels have been previously studied during DOE tests [4, 5, 6]. The first generation (GEN-1B) panels were characterized as part of a GATEWAY study [4] and will not be discussed here. Initial results for second generation (GEN-2B) and third generation (GEN-3B) were presented in earlier rounds of the AST studies [5, 6]. As shown in **Table 3-4**, the GEN-2B and GEN-3B products were purchased at two different times approximately 1 year apart. Both products are built as six-stack tandem structures [16], and there is no difference in the physical appearance of the two, although the GEN-3B products are reported to have better performance [17]. Both warm white (nominal CCT of 3,000 K) and neutral white (nominal CCT of 4,000 K) panels were included in these tests. The active area of the emitter surface of each GEN-2B and GEN-3B panel is 105 cm^2.

Table 3-4. Characteristics of the Two Generations of Type B Panels Examined During These Tests.

Designation	Purchase Date	Testing Environments
GEN-2B	August 2017	RTOL, 35OL, and 45OL
GEN-3B	October 2018	RTOL, 35OL, 45OL, and 6590

Prior to testing, the neutral white GEN-2B panels produced an average of 247 lumens when the electrical power supplied to the panel was 5.8 watts. For the warm white GEN-2B panels, the average luminous flux output was 285 lumens when the electrical power supplied to a new panel was 5.6 watts. Similarly, prior to AST, the neutral white GEN-3B panels produced an average of 245 lumens when the electrical power supplied to the panel averaged 4.7 watts. For the warm white GEN-3B panels, the average luminous flux output was 306 lumens when the electrical power supplied to the panel was 4.2 watts. Operating the driver and power supply required an additional 1.8 – 2.0 watts which lowered the overall system efficiency, as discussed in Sections 3.2.4 and 3.2.9 below.

3.2.1 Photometric Analysis of GEN-2B Panels

The initial SPDs of the GEN-2B neutral white and warm white panels are presented in **Figure 3-7**. Although the radiant fluxes of the two CCT types differ significantly at each wavelength over the range from 470 nm to 780 nm, the locations of the major emission peaks are similar. This finding suggests that the same organic emitter chemistry is used in both warm white and neutral white DUTs, but the relative concentrations or layer thickness of the emitters are different. The SPDs were used to calculate the color rendering of these light sources by using the TM-30 method [25], and these findings have been reported previously [5].

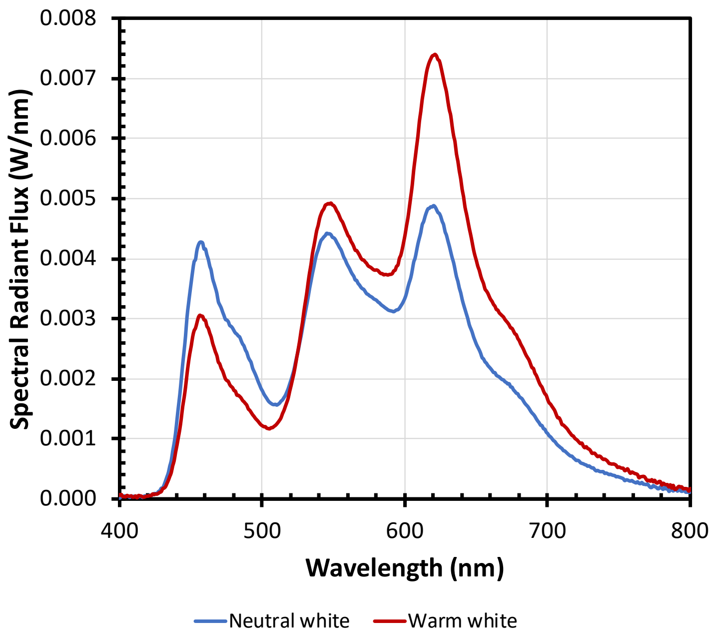

Figure 3-7. Initial SPDs of the GEN-2B Type B neutral white and warm white panels.

3.2.2 Luminous Flux Maintenance of GEN-2B Panels

Through 12,000 hrs of testing, the average luminous flux maintenance for the GEN-2B neutral white panels remained greater than 0.80 for DUTs during all three stress protocols. For all AST protocols, the luminous flux maintenance experienced two regions of decay: a fast, initial decay that leveled off 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 as it decayed, as shown in **Figure 3-8A**. The similarity in initial luminous flux decay could have resulted from comparable levels of residual contaminants (e.g., water) present during the device fabrication process. The luminous flux decay rates of blue phosphorescent emitters have been found to be greatly influenced by water content in the OLED panel [26], so we are postulating that a similar mechanism may be occurring here. After 2,000 hrs, the rate of luminous flux decay changed and exhibited greater correlation with the AST protocols; lower luminous flux maintenance was observed for AST protocols with higher temperature stresses.

The modified IES TM-28-14 method was used to model luminous flux maintenance for OLED light sources as explained in Section 2.4.1 of this report. Because there are 12,000 hrs of data, the data between 6,000 and 12,000 hrs were used to calculate the luminous flux maintenance models for each test condition. The single-exponential least squares fits of the GEN-2B neutral white panel data produced small residuals over the test duration (6,000 to 12,000 hrs), suggesting good fits as shown in Figure 3-8B. Perhaps the most significant finding is that the α value for the RTOL was 8.9×10^{-6}—a reasonable value for many lighting products as explained in the remainder of this subsection.

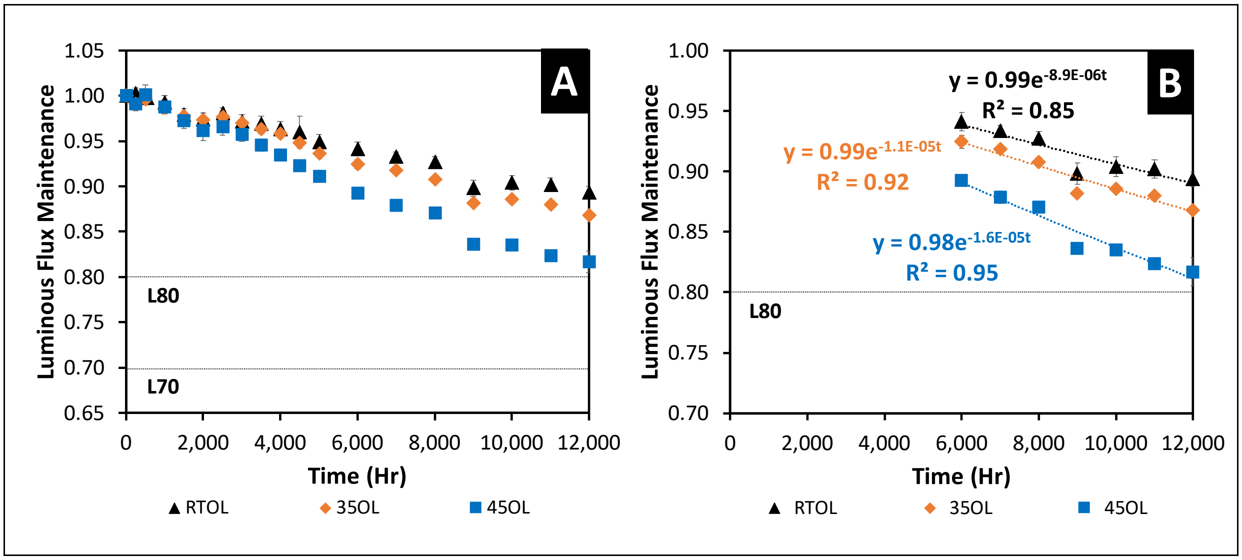

Figure 3-8. Average luminous flux maintenance for GEN-2B neutral white panels (A) and exponential fits of the latter portion of the data (B).

The average luminous flux maintenance for the GEN-2B warm white panels remained greater than 0.70 through 12,000 hrs of exposure to the three different AST protocols as shown in **Figure 3-9A**. Within each AST protocol, the warm white panels had lower levels of luminous flux maintenance compared with the neutral white panels, as indicated by higher α values. For example, the α value for the RTOL test was 1.3×10^{-5}, a nearly 50% increase over the value for neutral white panels in the same test. The GEN-2B warm white panels also exhibited two regions of decay: a fast, initial decay that was similar for the RTOL, 35OL, and 45OL populations and leveled off at approximately 2,000 hrs, followed by another slower decay period after 2,000 hrs.

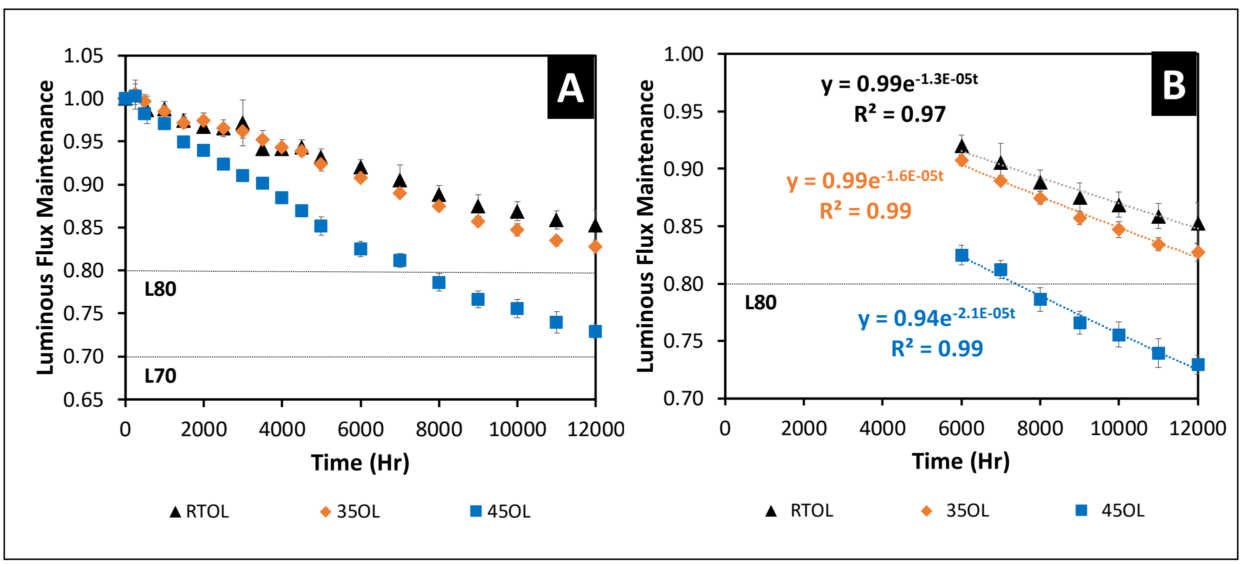

Figure 3-9. Average luminous flux maintenance for the GEN-2B warm white panels (A) and exponential fits of the latter part of the data (B).

Applying the modified IES TM-28-14 method to OLED light sources (see Section 2.4.1), the decay rate constants of the DUTs can be calculated and are shown in Figure 3-8.B and Figure 3-9.B. It should be noted that none of the testing protocols produced a sufficient drop in luminous flux maintenance for L70 to be measured experimentally. Therefore, this value must be projected by using the modified TM-28-14 method. The projected times to L70 for both types of GEN-2B neutral white and warm white panels in the various ASTs are presented in **Table 3-5**. In general, the time to L70 is longer for the neutral white panels than for the warm white panels. Because only three samples were used during this testing, projection times were limited to three times the actual test time per the rules of the modified TM-28-14 method. Only the neutral white panels evaluated during the RTOL test exceeded this threshold, and the L70 time reported for these devices was set to 36,000 hrs.

Table 3-5. Average Time to Reach L70 for the GEN-2B Panels in Different Test Conditions Based on 12,000 Hrs of Testing.

Light Color	Test	Time to L70 (12,000 hrs)	Method
Warm white	RTOL	26,700 hrs	Modified TM-28-14 method projection
Neutral white	RTOL	36,000 hrs[a]	Modified TM-28-14 method projection
Warm white	35OL	21,700 hrs	Modified TM-28-14 method projection
Neutral white	35OL	31,500 hrs	Modified TM-28-14 method projection
Warm white	45OL	14,000 hrs	Modified TM-28-14 method projection
Neutral white	45OL	21,000 hrs	Modified TM-28-14 method projection

[a] Limited by the three times total test duration limit in TM-28-14.

3.2.3 Chromaticity Shifts of GEN-2B Panels

Within the GEN-2B OLED panel series, the neutral white panels experienced the largest chromaticity shift through 12,000 hrs of testing (but also the highest luminous flux maintenance as previously discussed in Section 3.2.2). The GEN-2B neutral white panels subjected to the 45OL test had chromaticity shifts ($\Delta u'v'$) \ in excess of 0.007 in the yellow direction (i.e., chromaticity change is primarily along the $+\Delta v'$ axis, as shown in **Figure 3-10**). The initial chromaticity coordinates of representative blue, green-yellow, and red-orange organic emitters of a GEN-2B neutral white panel are shown in **Figure 3-11**, along with the chromaticity points (determined by spectral deconvolution [see Section 2.4.2]) of the GEN-2B neutral white (4,000 K) and warm white (3,000 K) panels.

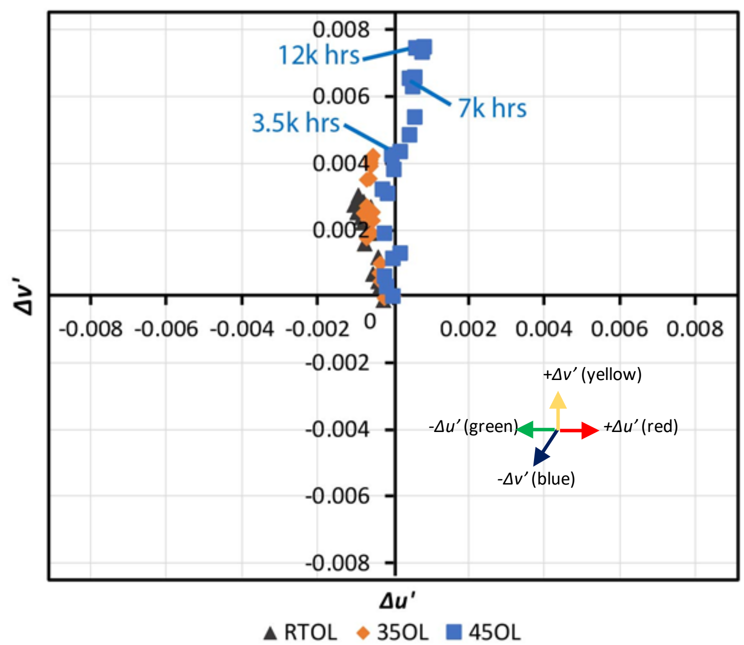

Figure 3-10. Chromaticity diagram for GEN-2B neutral white panels through 12,000 hrs of testing.

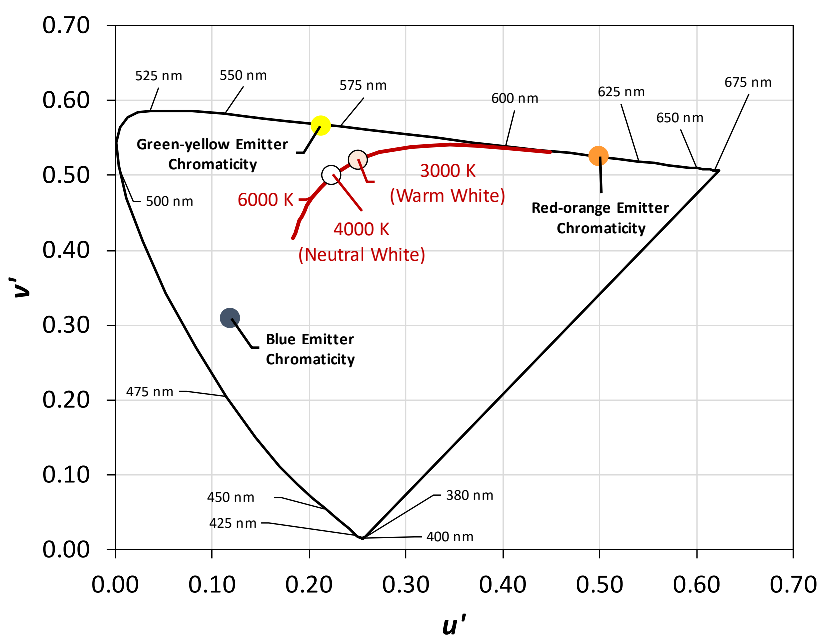

Figure 3-11. Chromaticity points of the organic emitters (from spectral deconvolution) and GEN-2 neutral white and warm white OLED panels.

To better understand the long-term chromaticity behavior of GEN-2B neutral white panels, a component analysis of the emission spectra was performed for each 45OL panel as previously described in Section 2.4.2 of this report. The absolute radiant power of each organic emitter was calculated and normalized before averaging and plotting over time as shown in **Figure 3-12**. Single-exponential least squares fits were performed on the latter half of the normalized radiant power data for each emitter to provide a general way to compare the individual emitter decay rates (α) to the decay rate determined with the modified IES TM-28-14 method for OLED light sources. The exponential fits showed that by 12,000 hrs, the blue emitter decayed at the fastest rate followed by the red-orange emitter, and the green-yellow emitter had the lowest decay rate. The decay rates for the blue and red-orange emitters were higher than the decay rate for luminous flux (Figure 3-8), and the decay rate for the green-yellow emitter was lower than the decay rate for luminous flux. Although the decay rates for each organic emitter influences the chromaticity shift, it is erroneous to assign color shifts based solely on the radiant flux α values as demonstrated in our previous report [6]. Instead, it is the relative change in the SPD that must also be examined, and the impacts of the eye's photoreceptors (i.e., the photopic response curve) must be taken in account.

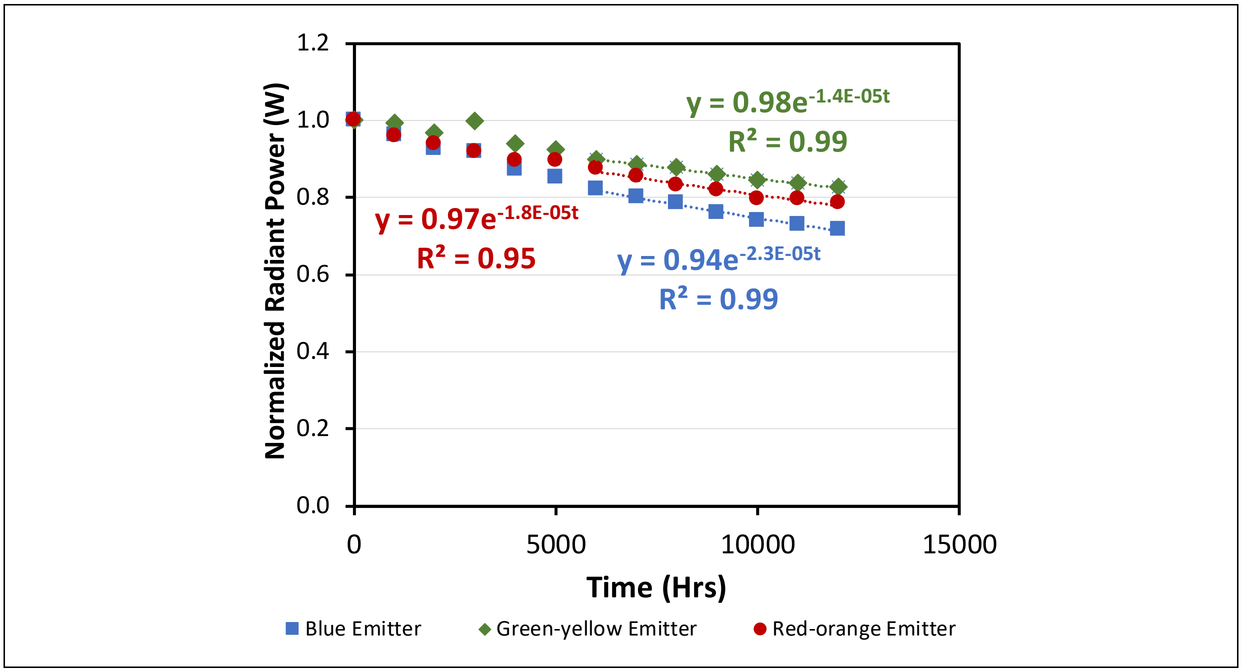

Figure 3-12. Average normalized radiant power of the GEN-2B neutral white panels at 45OL, determined from the skewed Gaussian fits of each component during the spectral emission modeling.

An example of the relative contribution of each organic emitter to the total radiant power (expressed as a percentage) of a 45OL GEN-2B neutral white panel is shown in **Figure 3-13**. In our previous report, the largely yellow chromaticity shift through 7,000 hrs was explained by the continued decrease in blue emitter contribution to the SPD, the initial increase and then relative plateauing of green-yellow emitter's relative contribution to the SPD after 3,500 hrs, and the initial decrease followed by a subtle increase of the red-orange emitter's relative contribution to the SPD through 3,500 hrs. After 7,000 hrs, the chromaticity coordinates shift almost entirely in the yellow direction for the neutral white panel because of the increasingly lower relative blue emitter contributions and higher relative green-yellow emitter contributions to the SPD. Figure 3-11 shows that such a change would pull the chromaticity point toward that of the green-yellow organic emitter and produce a change along the $+v'$ axis. In addition, such a change would actually help to keep the luminous flux maintenance high because the photopic response for green-yellow light is much greater than that for blue.

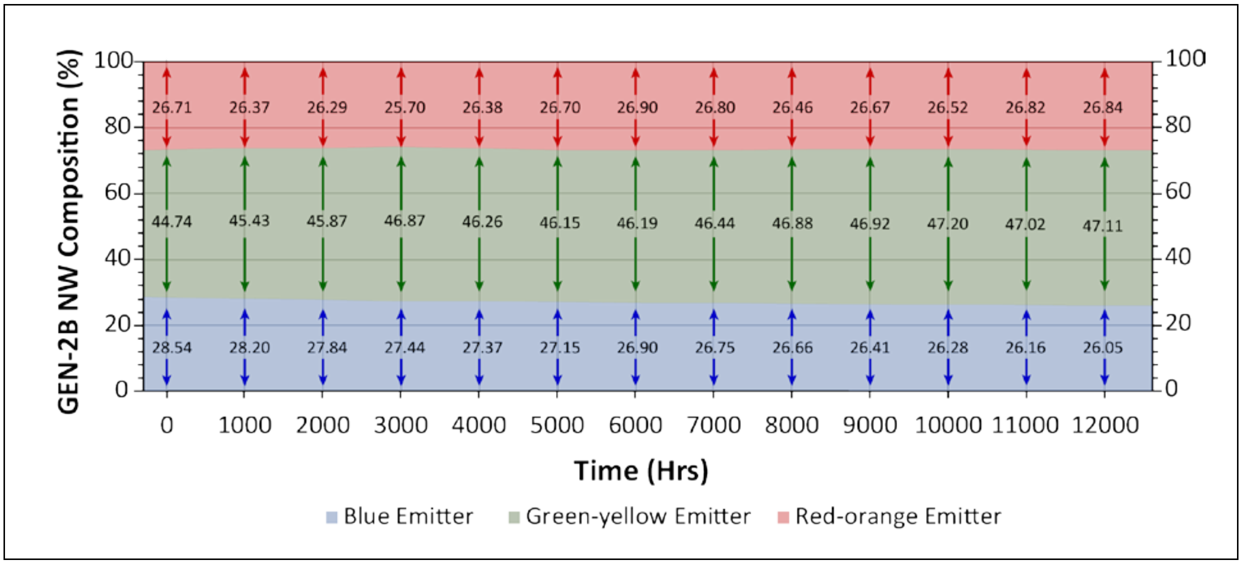

Figure 3-13. As the emitters of the GEN-2B neutral white (NW) panels age at different rates, the relative composition of the radiant power emission spectrum contains fewer blue emissions, more green-yellow emissions, and variable red-orange emissions. The data shown are for a 45OL panel.

Through 12,000 hrs, the GEN-2B warm white panels experienced a modest chromaticity change in the green-yellow direction as shown in **Figure 3-14**. GEN-2B warm white panels operated at less aggressive AST protocols (i.e., RTOL and 35OL tests) experienced a chromaticity shift ($\Delta u'v'$) of less than 0.003 in both $\Delta u'$ and $\Delta v'$, whereas GEN-2B panels operated at the most aggressive AST protocol (i.e., 45OL test) experienced chromaticity change of approximately 0.0045 in the $\Delta v'$ direction and 0.0025 in the $\Delta u'$ direction. To better understand the chromaticity changes, a component analysis of the emission spectra was performed for each panel. The absolute temporal change in radiant power of the blue, green-yellow, and red-orange emitters was then normalized and averaged for the GEN-2B warm white panels operated at 45OL as shown in **Figure 3-15**. Exponential fits of the normalized data show that by 12,000 hrs, light emissions from the blue emitter in the GEN-2B warm white panels decayed at a faster rate than that from the green-yellow and red-orange emitters, with the green-yellow emitter decaying the slowest, which is the same trend observed for the GEN-2B neutral white panels. This loss of blue emissions could be due to several factors, including the generally lower stability of blue organic emitters or increased absorbance of the blue light within a component of the OLED stack. In comparison with the neutral white panels, the decay rates for the individual emitters of the GEN-2B warm white panels were larger (causing lower luminous flux maintenance), but were more similar in magnitude (i.e., the α values varied between 2.0×10^{-5} and 2.6×10^{-5}). This smaller variation in α values resulted in smaller chromaticity shifts (as shown in Figure 3-14), but could also cause the lower levels of luminous flux maintenance.

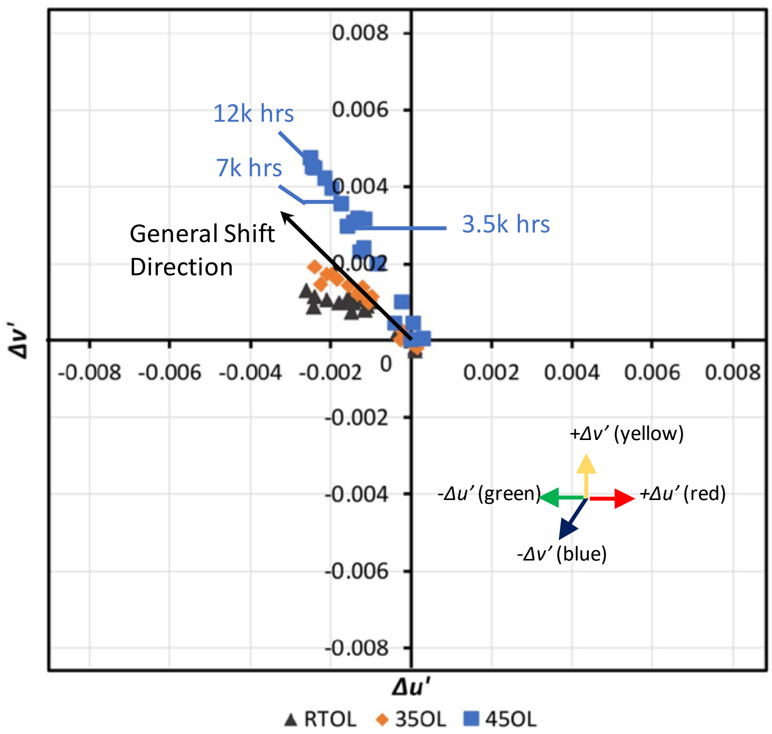

Figure 3-14. Chromaticity diagram for GEN-2B warm white panels after 12,000 hrs of testing.

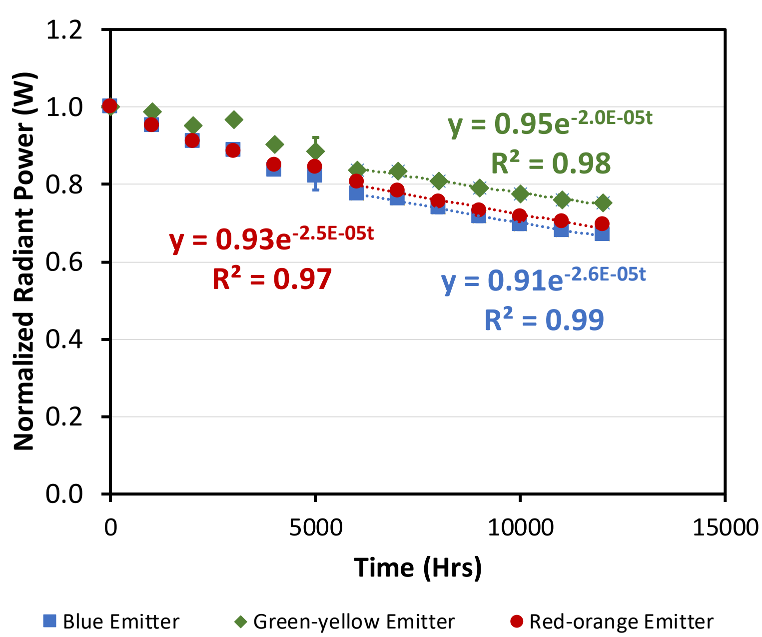

Figure 3-15. Radiant power of the GEN-2 warm white panels at 45OL determined from the skewed Gaussian fits of each component during the spectral emission modeling.

The contribution of each emitter in the GEN-2B warm white panel to the total radiant power (expressed as a percentage) is shown in **Figure 3-16**. Similar to the neutral white panels, the GEN-2B warm white panels experienced a steady decrease in the blue emitter's relative contribution to the emission spectrum throughout the entire test. However, the GEN-2B warm white panels differed from the neutral white panels in that the chromaticity shift experienced by the warm white panels did not change much after 9,000 hrs, suggesting a stabilization of the chromaticity. The details of the relative contribution of each emitter through 7,000 hrs were provided in our previous report. The relative contribution of the green emitter after 9,000 hrs was relatively stable, but the relative contribution of the blue emitter slightly declined, and the relative contribution of the red emitter slightly increased after 9,000 hrs. The overall magnitude of these changes in relative spectra composition were very small and did not produce noticeable chromaticity shifts.

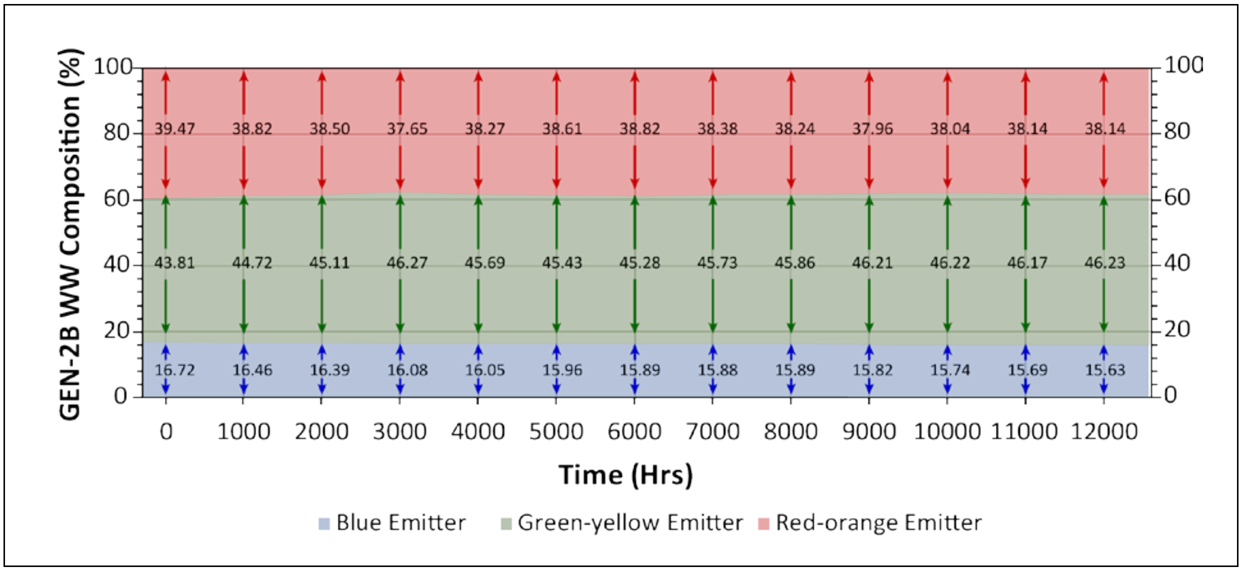

Figure 3-16. As the emitters of the GEN-2B warm white (WW) panels age at different rates, the relative composition of the radiant power emission spectrum contains fewer blue emissions, more green-yellow emissions, and fewer red-orange emissions relative to the initial emission spectrum. The data shown are for a 45OL device.

The results from this analysis demonstrate that the light emissions from the GEN-2B warm white panel contain relatively higher percentages of green-yellow emissions and relatively fewer blue emissions over time. These findings would be expected to move the chromaticity point toward the green-yellow emission source and away from the blue organic emitter. By examining Figure 3-11, it can be seen that such a change in a warm white panel (i.e., 3,000 K) would produce a chromaticity shift exactly in the direction observed experimentally (see Figure 3-14).

The greater loss of light from all emitters (as shown by the α values) used in the warm white panels relative to the neutral white panels explains the luminous flux maintenance difference observed at 12,000 hrs for the panels subjected to 45OL testing (73% versus 82%, respectively). The identities of the emitters for the GEN-2B panels are unknown, but the same values for the skewness, peak position, and width parameters provided good fits for both types of panels (just the amplitudes of the skewed Gaussian were modified). In addition, good fits were observed over the entire test duration by only changing the amplitude for both neutral white and warm white panels, implying that the emitters did not decay to form new emitting compounds, nor is it likely that the emitters decayed to form light-absorbing compounds. Therefore, we believe it is very likely that the two panels use the same emitters but in different concentrations, layer thicknesses, or with slight modifications that do not greatly affect emission spectra. 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. We postulate that differences in the transport layers or non-emitting additives to produce more equal degradation rate (thereby creating less chromaticity shift) were responsible for the greater emission loss of the warm white panels relative to the neutral white panel.

3.2.4 Electrical Analysis of GEN-2B Panels

The GEN-2B panels were periodically evaluated with a power analyzer to measure the power supplied to the OLED panel from the driver. The power supplies were set to deliver a constant current of 0.263 A to the panels; therefore, changes in driver output could be monitored through changes in voltage and power. During this analysis, higher powers were consumed by the panels subjected to an AST relative to the controls for both neutral white (**Table 3-6**) and warm white panels (**Table 3-7**). An increase in voltage was necessary to maintain the pre-set constant current for the panels (both neutral white and warm white) across all ASTs, and this voltage increase (relative to the control panel) was found to be statistically significant at 12,000 hrs (95% confidence level) by using Student's *t*-test with pooled variance. For the neutral white panels, the voltage increases across the 35OL and 45OL panels (relative to the RTOL panels) were found to be statistically significant at the 95% confidence level, but the 35OL and 45OL panels were not statistically different from each other. For the warm white panels, the voltage increases across the 45OL panels (relative to 35OL and RTOL panels) were statistically significant at the 95% confidence level, but no statistical difference was observed between the 35OL and RTOL panels. No statistical difference was found between the measurements taken at 6,000 hrs and those collected at 12,000 hrs for both neutral white and warm white panels, suggesting that the voltages stabilized by 6,000 hrs across all ASTs. The stabilization of voltage was further supported by the stabilization of impedance values that 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 (not shown). The changes in power consumption and luminous flux maintenance resulted in a decrease in luminous efficacy of the warm white OLED lighting system (Gen-2B panels, driver, and power supply) from 38 lumens per watt to 25 lumens per watt after 12,000 hrs of 45OL. Although the performance of the OLED panels degraded, a significant contributor to the low luminous efficacy of these devices was the driver and power supply, which combined had an efficiency of 67%.

Table 3-6. GEN-2B Neutral White Panel Electrical Data After Aging.

Stress Test Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel[a]	22.08 ± 0.12	0.263 ± 0.000	5.81 ± 0.03
RTOL (6,000 hrs)	22.94 ± 0.43	0.263 ± 0.001	6.04 ± 0.11
RTOL (12,000 hrs)	23.00 ± 0.14	0.262 ± 0.001	6.04 ± 0.02
35OL (6,000 hrs)	23.14 ± 0.24	0.264 ± 0.001	6.11 ± 0.07
35OL (12,000 hrs)	23.54 ± 0.63	0.265 ± 0.003	6.25 ± 0.23
45OL (6,000 hrs)	23.89 ± 0.96	0.264 ± 0.001	6.31 ± 0.25
45OL (12,000 hrs)	24.56 ± 0.96	0.264 ± 0.001	6.47 ± 0.23

[a] Data are the average of the control panel taken over time.

Table 3-7. GEN-2B Warm White Panel Electrical Data After Aging.

Stress Test Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel[a]	21.31 ± 0.01	0.264 ± 0.001	5.62 ± 0.02
RTOL (6,000 hrs)	22.94 ± 0.43	0.263 ± 0.001	6.04 ± 0.11
RTOL (12,000 hrs)	23.02 ± 0.59	0.264 ± 0.002	6.08 ± 0.15
35OL (6,000 hrs)	23.14 ± 0.24	0.264 ± 0.001	6.11 ± 0.07
35OL (12,000 hrs)	22.97 ± 0.23	0.266 ± 0.004	6.11 ± 0.10
45OL (6,000 hrs)	23.89 ± 0.96	0.264 ± 0.001	6.31 ± 0.25
45OL (12,000 hrs)	24.72 ± 0.34	0.264 ± 0.002	6.52 ± 0.12

[a] Data are the average of the control panel taken over time.

3.2.5 Luminance Uniformity Variation of GEN-2B Panels

The luminance of the GEN-2B panels was measured at nine locations (as described in Section 2.3.2), and the luminance uniformity was calculated for each panel. The average luminance uniformity for each AST and its respective standard deviation were then calculated and tabulated in **Table 3-8**. For both neutral white and warm white panels, there was no statistical difference (95% confidence level) for the luminance uniformity variation between measurements taken at 6,000 hrs and measurements taken at 12,000 hrs. The neutral white panels experienced the largest dispersion in luminance uniformity as ASTs progressed. Although the average luminance uniformity of the neutral white panels operated at 45OL was lower than the average luminance uniformity of the neutral white panels operated at RTOL, the luminance uniformity variations were not found to be significantly different at the 95% confidence level. There was a statistically significant increase in luminance uniformity variation (95% confidence level) for the warm white panels operated at 45OL relative to the warm white panels operated at RTOL at both 6,000 and 12,000 hrs. The increase in luminance uniformity variation for the 45OL panels was accompanied by a decrease in luminous flux, and this finding might indicate that the degradation pathways responsible for the luminous flux loss produces a statistically significant change in luminance uniformity variation.

Table 3-8. Average Luminance Uniformity Variation of GEN-2B Panels During Different Stress Tests.

Panel	RTOL	45OL
GEN-2B neutral white (6,000 hrs)	8.1% ± 0.2%	6.8% ± 1.4%
GEN-2B warm white (6,000 hrs)	9.8% ± 0.5%	14.1% ± 2.5%
GEN-2B neutral white (12,000 hrs)	16.0% ± 6.4%	10.5% ± 4.0%
GEN-2B warm white (12,000 hrs)	9.9% ± 2.3%	16.6% ± 1.4%

3.2.6 Photometric Analysis of GEN-3B Panels

The initial SPDs of the GEN-3B neutral white and warm white panels are presented in **Figure 3-17**. The radiant fluxes of the two sample types differ significantly at each wavelength over the range from 470 nm to 780 nm, a finding consistent with what was observed in the GEN-2B panels. The GEN-3B neutral white and warm white panels have similar peak locations of their respective major emitters, but there are subtle differences in the peak shape of the emitter that produces light in the green-yellow region. This finding suggests that similar organic emitter chemistries are used in both warm white and neutral white DUTs, but the relative concentration or layer thickness of the emitters is different.

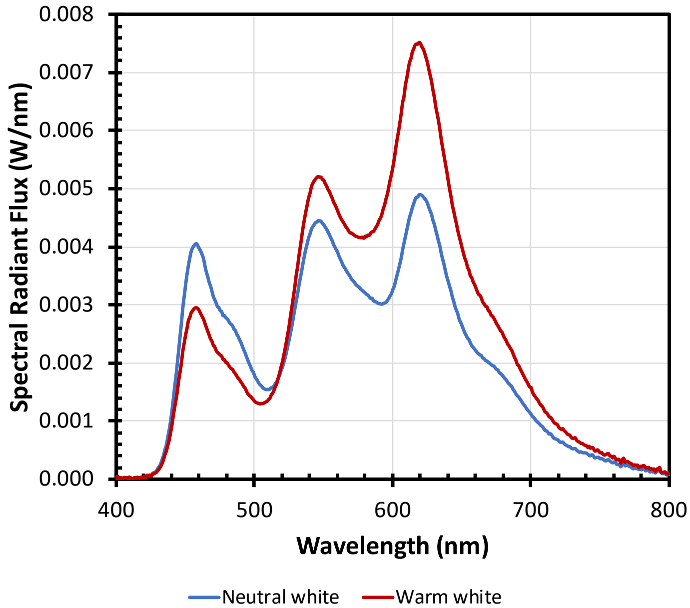

Figure 3-17. Initial SPDs of GEN-3B neutral white and warm white DUTs.

The differences in the light spectra between the GEN-2B and GEN-3B panels are shown in **Figure 3-18**. Minimal differences were found between the neutral white spectra, whereas more differences were observed in the emission spectra of the warm white DUTs.

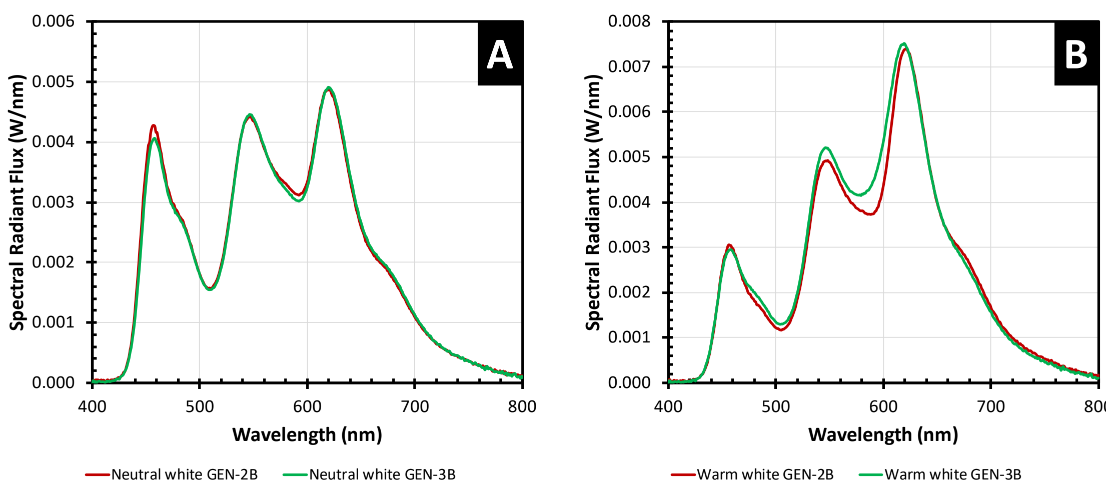

Figure 3-18. Comparison of the SPDs of GEN-2B and GEN-3B neutral white (A) and warm white panels (B).

3.2.7 Luminous Flux Maintenance of GEN-3B Panels

In agreement with findings for the GEN-2B panels, the luminous flux maintenance of the GEN-3B panels remained well above 0.70 throughout the test interval for most of the AST protocols, as shown in **Figure 3-19** and **Figure 3-20**. The one exception was the very aggressive 6590 protocol where the luminous flux dropped below the 0.70 level at 2,936 hrs for warm white DUTs and at 4,311 hrs for neutral white DUTs (determined using linear interpolation). However, it is important to note that the performance of these panels in WHTOL testing exceed that of earlier tests of OLED panels in 7575 environments [3], demonstrating an improvement in stability against environmental stressors such as high heat and humidity. All GEN-3B panels survived at least

2,000 hrs in the 6590 environment with their original drivers. Three panels completed 6,000 hrs of testing without incident, albeit at luminous flux levels below L60. Two panels experienced multiple driver failures during testing, but the panels themselves were operational. One of these panels with multiple driver failures eventually reached 6,000 hrs of testing in 6590. An additional panel was inadvertently damaged during testing; therefore, it was not included in this analysis.

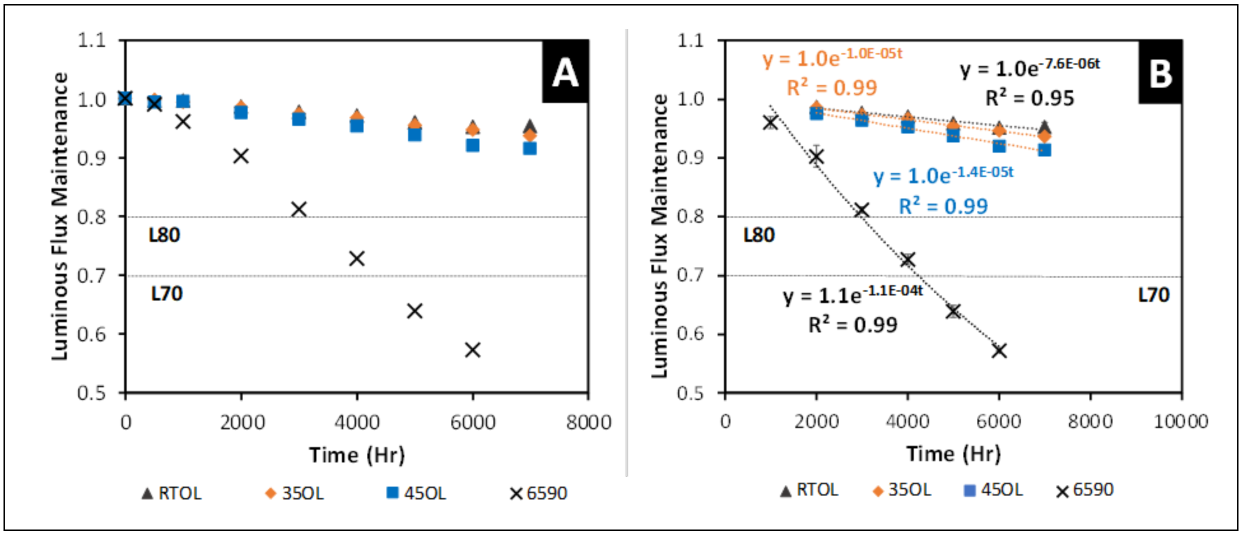

Figure 3-19. Average luminous flux maintenance with error bars (B only) for GEN-3B neutral white panels during different ASTs.

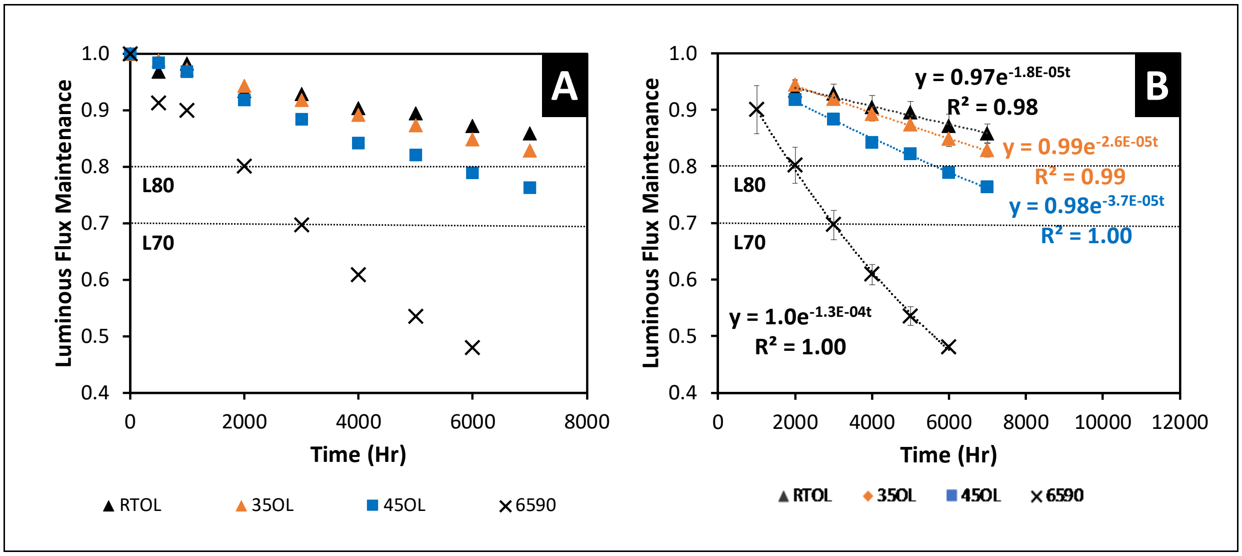

Figure 3-20. Average luminous flux maintenance with error bars (B only) for GEN-3B warm white panels in different ASTs.

Through 7,000 hrs, the average luminous flux maintenance for the GEN-3B neutral white panels remained above 0.90 for DUTs in RTOL, 35OL, and 45OL. The luminous flux decay in 6590 was significantly more rapid, as shown in Figure 3-19A and Figure 3-20A, possibly because of combined effects of higher temperature and moisture ingress into the panels. Moisture ingress was evidenced in the panels operated at 6590 by darkening (i.e., no light emission) at the edges of the emitting area. The luminous flux maintenance values for the GEN-3B neutral white panels were slightly better in these tests than equivalent GEN-2B panels at the corresponding test times. These differences were found to be statistically significant for the 35OL (p =

0.014) and 45OL ($p < 0.001$) tests; however, they were not statistically different to the 95% confidence in RTOL ($p = 0.139$).

A generally lower luminous flux maintenance was found for the GEN-3B warm white DUTs in equivalent ASTs. The luminous flux maintenance was above 0.80 for RTOL and 35OL after 7,000 hrs of testing and above 0.75 for 45OL testing as shown in Figure 3-20. The luminous flux maintenance in 6590 testing was also lower for the warm white DUTs than for the neutral white DUTs. When comparing the performance of the GEN-2B and GEN-3B warm white panels, the luminous flux maintenance of the warm white GEN-2B panels was higher than that of the GEN-3B warm white panels, and the differences were found to be statistically significant for 35OL ($p < 0.001$) and 45OL ($p = 0.001$), but not for RTOL ($p = 0.312$).

For all GEN-3B DUTs in the various AST protocols, the luminous flux maintenance experienced two regions of decay: a fast, initial decay that usually leveled off between 1,000 and 2,000 hrs, followed by another decay period after 2,000 hrs. This observation is consistent with a double-exponential model discussed in Section 2.4.1. For the first 2,000 hrs, the average luminous flux maintenance for RTOL, 35OL, and 45OL were very similar. The similarity in initial luminous flux decay could result from comparable levels of residual contaminants (e.g., water) present during the device fabrication process. After 2,000 hrs, the rate of luminous flux decay changed and exhibited a strong correlation with the AST protocols; lower luminous flux maintenance was observed for AST protocols with higher temperature stresses.

Using the modified TM-28-14 method for OLED light sources (see Section 2.4.1), the decay rate constants of the DUTs can be calculated and are shown in Figure 3-19B and Figure 3-20B. Of particular significance is the finding that the α value for the neutral white DUTs under RTOL conditions was 7.6×10^{-6}—the lowest value observed in testing to date and is 368% better than the measured α value for Type A GEN-2 panels in RTOL. Because only the 6590 test conditions produced a sufficient drop in luminous flux maintenance for L70 to be determined experimentally, the test times necessary for the other panels to drop below the L70 threshold must be projected by using the modified TM-28-14 method. Of course, projections of L70 are subject to the three times rule because of the sample size (i.e., times to reach L70 cannot be projected past three times the actual test interval). The projected times to L70 are presented in **Table 3-9**, along with the experimentally derived values for DUTs in 6590. In general, the time to L70 is longer for the neutral white panels than for the warm white panels, which indicates higher reliability; and the projected times for GEN-3B neutral white panels to reach L70 exceeded the maximum value of 21,000 hrs permitted by the three times rule for RTOL and 45OL. There was an early failure of a neutral white DUT in 35OL, so the remaining two samples were used to estimate luminous flux maintenance. Because of the lower luminous flux maintenance of the warm white panels, the time to L70 of the GEN-3B panels was less than the extrapolation limit and was also less than the projections for the neutral white panels at equivalent test conditions.

Table 3-9. Average Time to Reach L70 for the GEN-3B Panels in Different Test Conditions.

Light Color	Test	Time to L70 (7,000 hrs)	Method
Warm white	RTOL	18,200 hrs	Modified TM-28-14 method projection
Neutral white	RTOL	21,000 hrs[a]	Modified TM-28-14 method projection
Warm white	35OL	13,200 hrs	Modified TM-28-14 method projection
Neutral white	35OL	21,000 hrs[a]	Modified TM-28-14 method projection
Warm white	45OL	9,150 hrs	Modified TM-28-14 method projection
Neutral white	45OL	21,000 hrs[b]	Modified TM-28-14 method projection
Warm white	6590	2,936 hrs	Linear interpolation of experiment
Neutral white	6590	4,311 hrs	Linear interpolation of experiment

[a] Limited by the three times total test duration limit in TM-28-14.

[b] Only two samples completed 7,000 hrs of testing in 35OL, and time to L70 was set to three-times the test duration based on the performance of these two samples.

3.2.8 Chromaticity of GEN-3B Panels

Through 7,000 hrs of testing, the average chromaticity shift (*Δu′v′*) for the GEN-3B neutral white panels was less than 0.005 for DUTs in the three temperature-only stress protocols (i.e., RTOL, 35OL, 45OL tests), as shown in **Figure 3-21**. The shift proceeded in the generally yellow direction (i.e., chromaticity changed primarily along the +*Δv′* axis with minimal change along the *Δu′* axis), and the magnitude of the shift increased with temperature. The same trends—only larger in magnitude—were found for the GEN-3B neutral white panels operated in the more aggressive 6590 conditions. This finding suggests that the same chromaticity shift mechanism is likely operating in all four AST conditions, but at different rates (consistent with thermal activation). The chromaticity shifts observed during the 45OL test of the GEN-3B neutral white panels are in the same general direction but smaller in magnitude than the chromaticity shifts observed for the GEN-2B neutral white panels, suggesting an improvement in chromaticity maintenance for the newer GEN-3B panels.

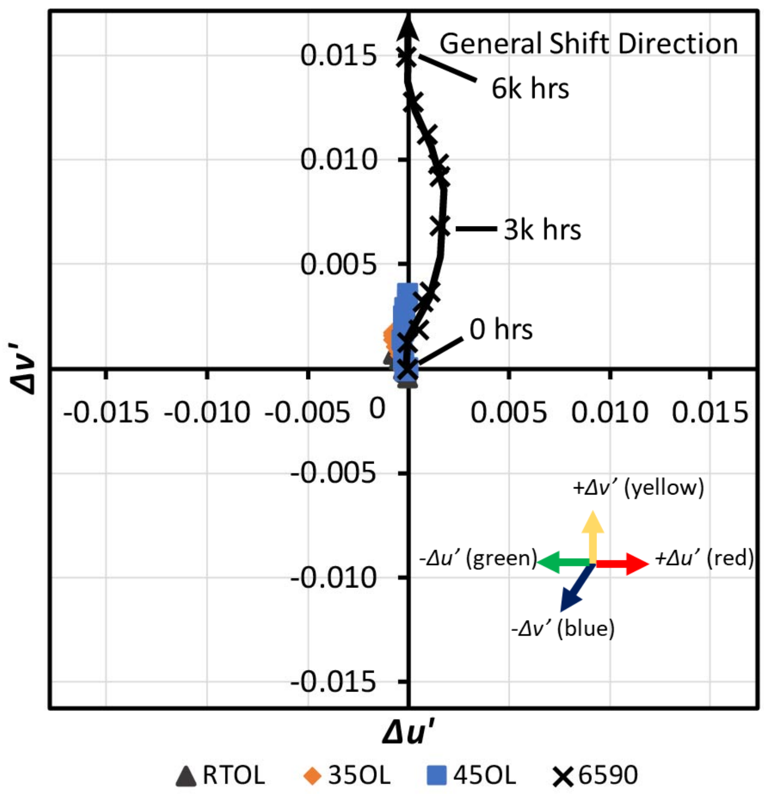

Figure 3-21. Chromaticity shifts for GEN-3B neutral white panels during different AST protocols.

The initial chromaticity coordinates of the blue, green-yellow, and red-orange organic emitters of a GEN-3B neutral white panel were determined by spectral deconvolution and are shown in **Figure 3-22**. In addition, the initial experimentally measured chromaticity coordinates for neutral white (4,000 K) and warm white (3,000 K) GEN-3B panels are also included. Based on the chromaticity of the organic emitters and the chromaticity points of the neutral white and warm white panels, it can be seen that the chromaticity shift shown in Figure 3-21 is indicative of a time-based increase in the relative contribution of the green-yellow emitter in the overall SPD for the different AST protocols.

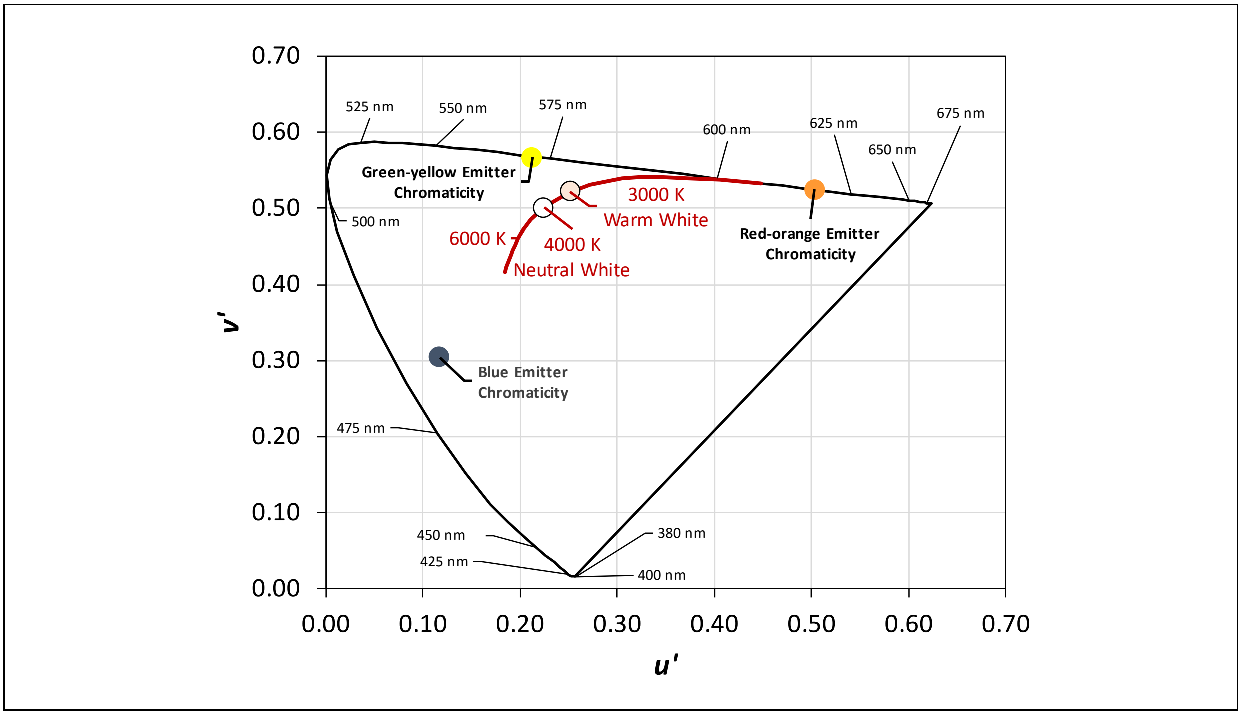

Figure 3-22. Chromaticity points of the organic emitters (from spectral deconvolution) and GEN-3 neutral white and warm white OLED panels.

A component analysis of the emission spectrum for each panel was conducted to determine the temporal absolute radiant power of the blue, green-yellow, and red-orange emitters of the GEN-3B neutral white panels and to provide further insights regarding the cause of the chromaticity shift. The radiant power for each emitter was normalized and averaged, and the temporal change in normalized radiant power for the 45OL and 6590 panels is shown in **Figure 3-23**. The decay rates for the 45OL GEN-3B neutral white panels (Figure 3-23A) follow similar trends to the GEN-2B neutral white panels (Figure 3-12). Specifically, the blue emitter decays at the fastest rate, and its decay rate is greater than the luminous flux decay rate of the GEN-3B neutral white panel. In contrast, the green-yellow and red-orange emitters decay at a slower rate, and their decay rates are lower than the luminous flux decay rate. Furthermore, the decay rates for the blue, green-yellow, and red-orange emitters of the 45OL GEN-3B neutral white panels were all lower than the respective decay rates of the 45OL GEN-2B neutral white panels. Although the least square fits used to model the emitters of the GEN-2B neutral white and GEN-3B neutral white panels were very similar, there were small changes made to the skewness, peak position, and width parameters between the two emission spectra. The magnitudes of these changes are not substantial enough for the authors of this report to believe that different emitters were used between the two generations of panel. It is more likely that improvements in encapsulation and other techniques provided the enhanced luminous flux performance of the GEN-3B neutral white panels over the GEN-2B neutral white panels at 45OL.

At the most aggressive testing conditions (6590, Figure 3-23B), the observed decay rates for each emitter were approximately one order of magnitude greater than the rate of decay in 45OL, but the relative rate of decay between emitters remained essentially the same, with the blue emitter decaying the fastest and the green emitter decaying the slowest. This finding is consistent with the same chromaticity shift occurring in all four ASTs, but the rate of chromaticity shift was higher in 6590 than in the other tests.

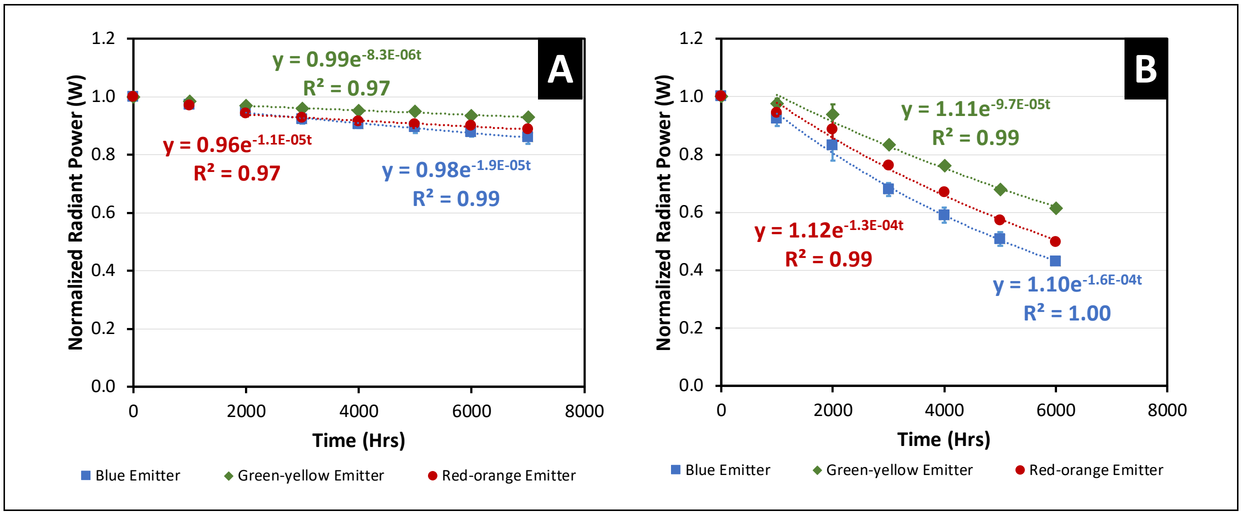

Figure 3-23. Findings from the component analysis (determined by emission spectra modeling) of the GEN-3B neutral white panels show larger impacts on the radiant power of green-yellow and red-orange emitters relative to blue emitters when heat and humidity are accelerated from 45OL (A) to 6590 (B).

The contribution of each emitter of a 6590 GEN-3B neutral white panel to the total radiant power (expressed as a percentage) is shown in **Figure 3-24**. The GEN-3B neutral white panels operated at 6590 experienced a steady decrease in the blue emitter's relative contribution to the emission spectrum and a relatively steady increase in the green-yellow emitter's relative contribution to the emission spectrum through 6,000 hrs. The red-orange emitter contributed steadily to the emission spectra until 4,000 hrs, and then began to have a decreasing contribution (the decrease was smaller than that of the blue emitter). The overall magnitude of these changes in relative spectral composition explain the slight red shift in the primarily yellow-shifted data for the 6590 GEN-3B neutral white panels.

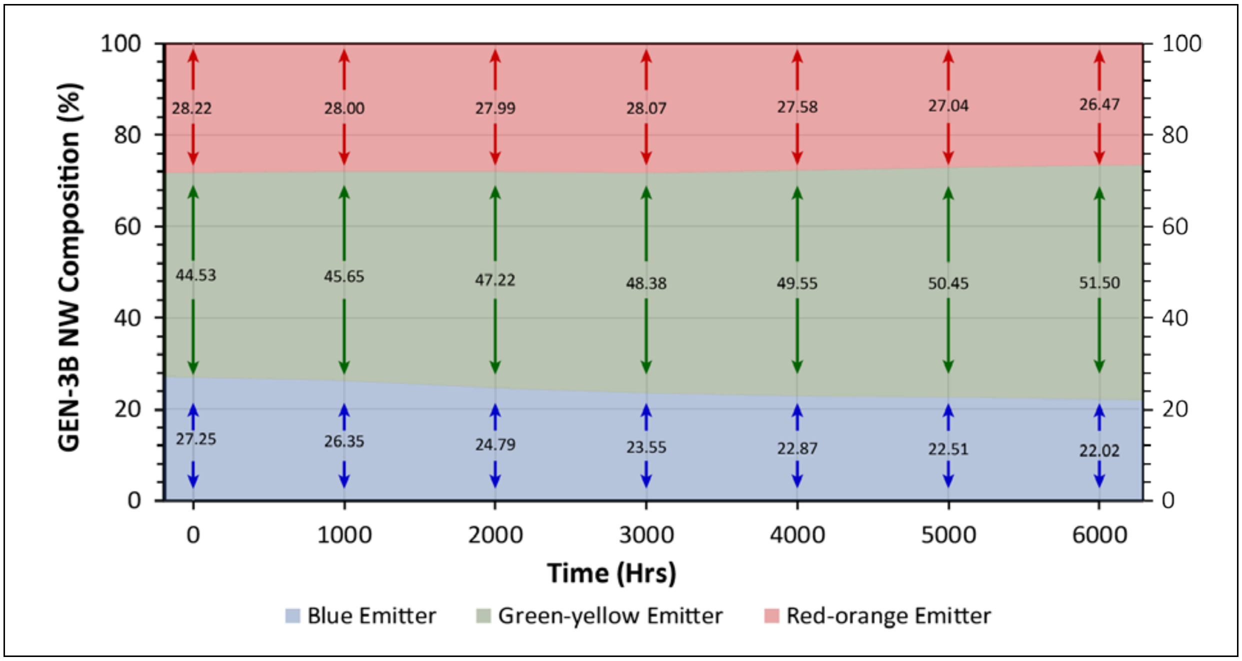

Figure 3-24. As the emitters of the GEN-3B neutral white (NW) panels aged in 6590 at different rates, the composition of the radiant power emission spectrum contains fewer blue and red-orange emissions and far more green-yellow emissions relative to the initial emission spectrum.

The chromaticity shift in the GEN-3B warm white panels is shown in **Figure 3-25**. The initial chromaticity shift for these devices is in the generally green direction ($\Delta u' \leq -0.002$) for the temperature-only ASTs. After the initial green shift, the chromaticity abruptly shifted in the generally yellow direction for the 45OL and 6590 tests. A similar effect was not found through 7,000 hrs of testing in RTOL and 35OL. It is possible that the processes responsible for this yellow shift require thermal activation and proceed slowly at temperatures below 45°C. The behavior is different from that observed for the GEN-2B DUTs. As discussed in Section 3.2.3, chromaticity shift for the GEN-2B warm white panels proceeded in the same direction throughout the test period. The reversal of chromaticity found in the GEN-3B DUTs is suggestive of a change in the chromaticity shift mechanism. An examination of **Figure 3-22** indicates that that initial chromaticity shift could be caused by equal decays of the blue and green-yellow organic emitters, which would cause a shift in the generally green direction. Then, the higher stability of the green-yellow emitter begins to dominate, and the overall light chromaticity begins to move toward the chromaticity point of the green-yellow emitter.

A component analysis of the emission spectrum for each panel was conducted to determine the temporal absolute radiant power of the blue, green-yellow, and red-orange emitters of the GEN-3B warm white panels. The radiant power for each emitter was normalized and averaged, and the temporal change in normalized radiant power for the 45OL and 6590 panels is shown in **Figure 3-26**. The decay rates for the 45OL GEN-3B warm white panels (Figure 3-26A) follow a different trend than for the GEN-2B warm white panels through 7,000 hrs [6]: the blue emitter decays at the fastest rate, and the red-orange emitter decays at the slowest rate. In addition, the decay rates for the GEN-3B warm white panels were generally larger than the decay rates for the GEN-2B warm white panels at 7,000 hrs. There were significant differences in skewness, width, and amplitude used to model the green-yellow emitter for the GEN-3B warm white panels relative to the GEN-2B warm white panels. Because the green-yellow emitter skewed Gaussian fit was very different between the two generations, the change in green-yellow emitter composition could be primarily responsible for the lower luminous flux and different chromaticity shift experienced by the GEN-3B warm white panels.

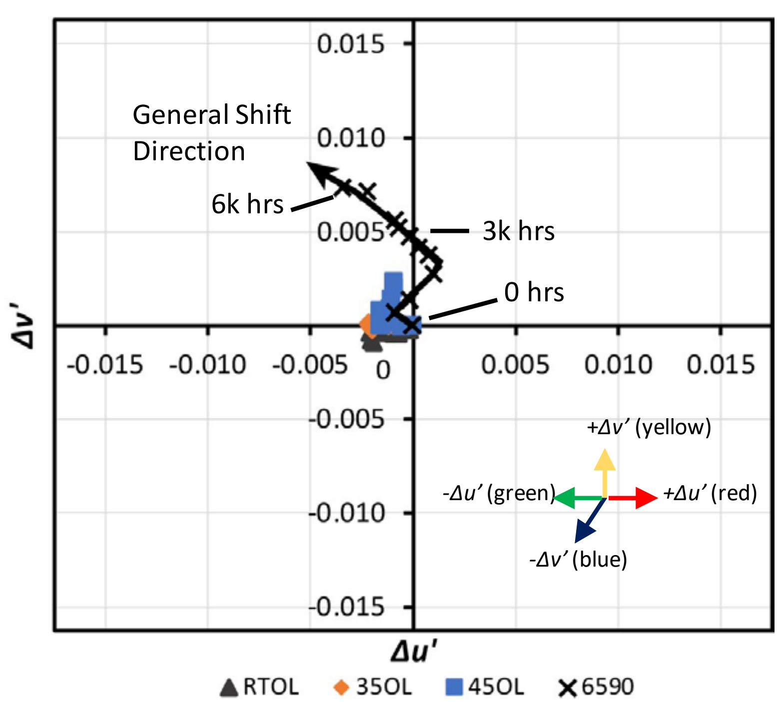

Figure 3-25. Chromaticity shifts for GEN-3B warm white panels in different AST protocols.

Similar to the GEN-3B neutral white panels, increases in temperature and humidity to 6590 resulted in decay rate increases for each emitter by an order of magnitude relative to 45OL for the GEN-3B warm white panels as shown in **Figure 3-26B**. The contribution of each emitter of a 6590 GEN-3B warm white panel to the total radiant power (expressed as a percentage) is shown in **Figure 3-27**. The relative contribution of the blue emitter decreased through 6,000 hrs, whereas the relative contributions of the green-yellow and red-orange emitters increased through 6,000 hrs for the GEN-3B warm white panels. Furthermore, the change in each emitter's relative contribution to the emission spectrum was much smaller for the GEN-3B warm white panels than for the GEN-3B neutral white panels. This finding is consistent with the smaller chromaticity shifts in the warm white panels relative to the neutral white panels.

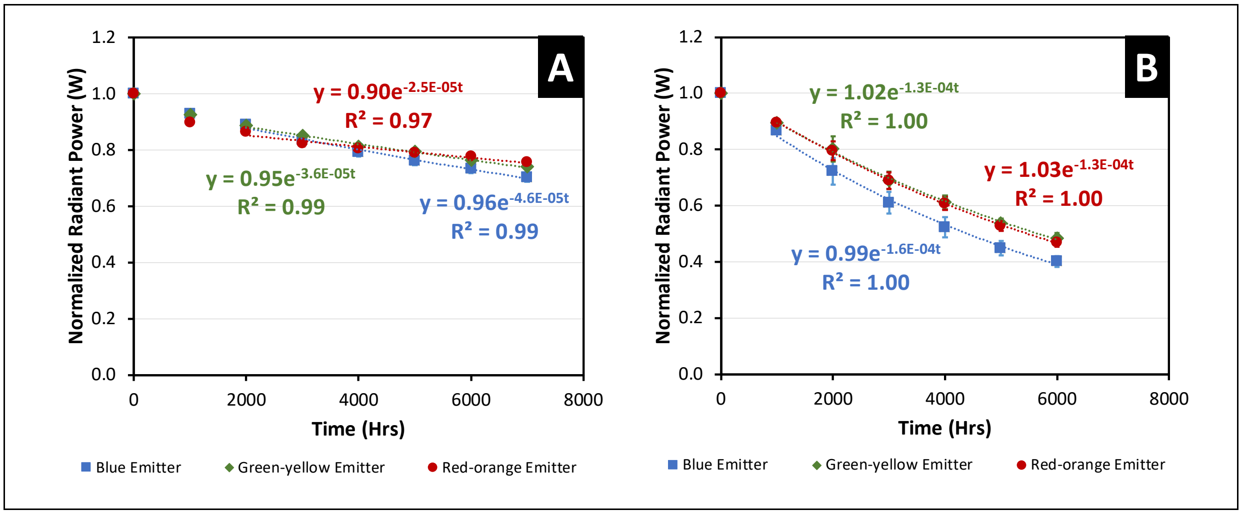

Figure 3-26. Findings from a component analysis (determined by emission spectra modeling) of the GEN-3B warm white panels show larger impacts on the radiant power of green-yellow and red-orange emitters relative to blue emitters when heat and humidity are accelerated from 450L (A) to 6590 (B).

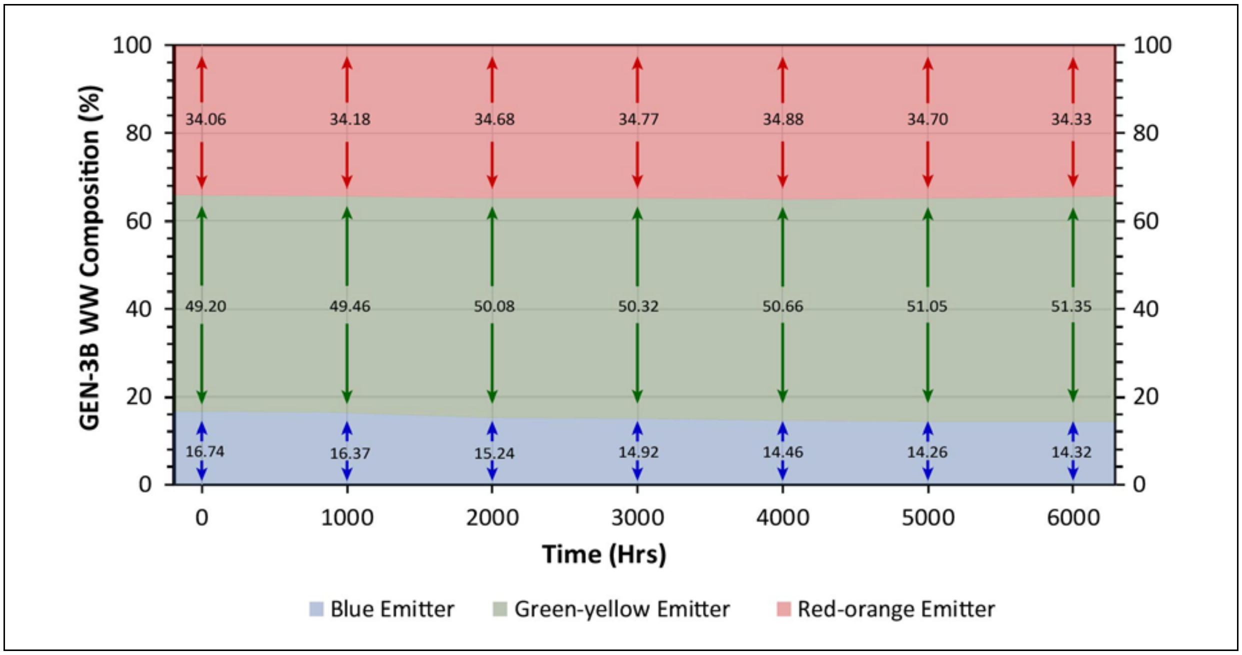

Figure 3-27. As the emitters of the GEN-3B warm white (WW) panels age in 6590 at different rates, the composition of the radiant power emission spectrum contains fewer blue emissions, more green-yellow emissions, and comparable red-orange emissions relative to the initial emission spectrum.

3.2.9 Electrical Analysis of GEN-3B Panels

Periodically, electrical characterization was performed with a power analyzer to determine the power supplied to the GEN-3B panels by their respective driver systems. The electrical drivers were pre-set to deliver 0.217 A of constant current to the panels, and most changes were monitored through voltage and power for each panel. In extreme AST conditions (e.g., panels operated in 6590 conditions), the voltage required by the panels was larger than the driver could supply, so changes in current were also observed. The average electrical data at each AST for the GEN-3B neutral white (**Table 3-10**) and warm white (**Table 3-11**) panels were calculated by using three panels, except for the neutral white panels at 35OL, the neutral white panels at 6590, and the warm white panels at 6590. In each of these exceptions, the average electrical data were calculated with two panels: a neutral white panel operated at 35OL failed by 3,000 hrs (electrical short) and a neutral white panel operated at 6590 failed by 3,000 hrs (the panel still functioned but connection to a driver resulted in premature failure of the driver). Also, the heat sink backing of a warm white panel operated at 6590 was inadvertently water damaged by the test chamber and therefore not considered for averaging throughout this report.

The voltage variations observed were much greater for the GEN-3B neutral white panels than for the warm white panels. The greater variation in electrical data could be caused by the greater variation in impedance that was observed from the onset of testing for the neutral white devices relative to the warm white devices. Specifically, the initial average impedance of the 12 test panels and control at 1,000 Hz for neutral white panels was 548.7 ± 13.3 **Ω** versus 558.8 ± 2.3 **Ω** for the same sample size of warm white panels. Throughout testing, the impedance values for both the neutral white and warm white panels did not vary significantly from the control (not shown).

The larger variation in voltage across the GEN-3B neutral white samples continued throughout testing, and statistical differences between initial and final voltages at individual AST conditions were not observed as readily for these panels. To explain, increases in voltage and power were observed for the GEN-3B neutral white panels from less aggressive AST conditions (e.g., RTOL) to more aggressive AST conditions (e.g., 45OL and 6590). However, when compared with the control sample, there was no significant statistical difference in the power or voltage supplied to the RTOL, 35OL, or 45OL panels. However, there was a significant statistical increase (95% confidence level) in the power and voltages supplied to the 6590 panels relative to the control at 6,000 hrs, and the increases in voltage and power from 1,500 hrs to 6,000 hrs were also found to be significant for these panels. The increases in voltage and power at 6,000 hrs for the panels operated in 6590 conditions were accompanied by a decrease in current supplied to the panels (though the decrease was not significant), and the decrease was likely the result of one of the panels requiring more voltage than the driver's designed maximum (28 V_{dc}). The changes in power consumption and luminous flux maintenance resulted in a decrease in luminous efficacy of the warm white OLED lighting system (Gen-3B panel, driver, and power supply) from 50 lumens per watt to 33 lumens per watt after 7,000 hrs of 45OL. Although the performance of the OLED panels degraded, a significant contributor to the low luminous efficacy of these devices was the driver and power supply, which, when combined, had an efficiency of 65%.

Table 3-10. GEN-3B Neutral White Panel Electrical Data After Aging.

Stress Test Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel[a]	21.52 ± 0.31	0.219 ± 0.001	4.72 ± 0.08
RTOL (1,500 hrs)	20.59 ± 0.70	0.217 ± 0.002	4.46 ± 0.19
RTOL (7,000 hrs)	21.38 ± 0.68	0.216 ± 0.002	4.63 ± 0.18
35OL (1,500 hrs)	21.24 ± 0.80	0.218 ± 0.002	4.63 ± 0.18
35OL (7,000 hrs)	21.98 ± 0.74	0.218 ± 0.001	4.79 ± 0.19
45OL (1,500 hrs)	21.50 ± 1.02	0.217 ± 0.002	4.68 ± 0.22
45OL (7,000 hrs)	22.52 ± 0.87	0.218 ± 0.001	4.97 ± 0.20
6590 (1,500 hrs)	22.50 ± 0.58	0.218 ± 0.001	4.91 ± 0.12
6590 (6,000 hrs)[b]	27.93 ± 0.23	0.200 ± 0.024	5.58 ± 0.72

[a] Data are the average of the control panel taken over time.

[b] Data are the averages of the two panels (i.e., DUT 522 and DUT 523). The driver used for DUT 522 had failed, so it was powered with the driver of DUT 523 for these electrical measurements.

Increases in voltage and power were observed for the GEN-3B warm white panels, and these voltage increases were significant. For all AST conditions at the end of test (6,000 hrs or 7,000 hrs), the warm white panel voltage increases were found to be statistically significant from the control panel. For the data collected at the end of test for the warm white panels, the voltage increase was highest for the most aggressive testing condition (6590), and the voltage increase was found to be second highest for the next most aggressive testing condition (45OL). A statistical difference was not observed between the 35OL and RTOL warm white panel voltages at the end of test. For all AST conditions, the warm white panel voltages increased in a statistically significant way between 1,500 hrs and the end of test.

Table 3-11. GEN-3B Warm White Panel Electrical Data After Aging.

Stress Test Protocol	Voltage Supplied to Panel (V_{dc})	Current Supplied to Panel (A_{dc})	Power Supplied to Panel (W)
Control panel[a]	19.53 ± 0.29	0.217 ± 0.000	4.24 ± 0.06
RTOL (1,500 hrs)	19.45 ± 0.02	0.217 ± 0.001	4.23 ± 0.03
RTOL (7,000 hrs)	20.98 ± 0.31	0.217 ± 0.001	4.55 ± 0.08
35OL (1,500 hrs)	19.71 ± 0.05	0.218 ± 0.001	4.30 ± 0.02
35OL (7,000 hrs)	21.46 ± 0.19	0.218 ± 0.001	4.67 ± 0.04
45OL (1,500 hrs)	19.90 ± 0.22	0.217 ± 0.002	4.32 ± 0.09
45OL (7,000 hrs)	22.52 ± 0.42	0.217 ± 0.002	4.87 ± 0.13
6590 (1,500 hrs)	21.71 ± 0.23	0.230 ± 0.014	5.00 ± 0.26
6590 (6,000 hrs) [a]	26.98 ± 0.70	0.217 ± 0.001	5.86 ± 0.14

[a] Data are the average of the control panel taken over time.

3.2.10 Luminance Uniformity Variation of GEN-3B Panels

The luminance of the GEN-3B panels was measured at nine locations (as described in Section 2.3.2), and the luminance uniformity was calculated for each panel. The average luminance uniformity for each AST and its respective standard deviation were then calculated and tabulated in **Table 3-12**. For the neutral white panels, there was no statistical difference (95% confidence level) for the luminance uniformity variation between measurements taken at 1,000 hrs and measurements taken at the end of testing for both 45OL and 6590 test panels. There was also no statistical difference between neutral white panels operated at 45OL and 6590. For the warm white panels, the increase in luminance uniformity variation at the end of test for the 45OL panels was statistically different from the luminance uniformity variation for the 45OL samples at 1,000 hrs and the 6590 panels at 6,000 hrs. Further investigation is needed to determine the cause of the high luminance uniformity variation in the 45OL warm white panels.

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

Panel	45OL	6590
GEN-3B neutral white (1,000 hrs)	7.9% ± 1.4%	14.5% ± 5.4%
GEN-3B warm white (1,000 hrs)	9.4% ± 3.1%	10.1% ± 4.2%
GEN-3B neutral white (6,000 hrs)	9.8% ± 5.3%[a]	20.2% ± 8.4%
GEN-3B warm white (6,000 hrs)	22.1% ± 3.7%[a]	5.5% ± 0.3%

[a] Data were collected at 7,000 hrs.

4 Conclusions

The data in this report lead to a definitive conclusion that the performance of commercial OLED devices intended for use in general lighting application has improved significantly over the past 4 years. At typical ambient temperatures encountered in indoor offices (e.g., 25°C to 35°C), the newest generation of OLED devices can be expected to last for tens of thousands of hours in normal operation. For example, applying a modified TM-28-14 methodology to the data presented in this report, the time required for a neutral white panel to reach L70 was found to be on the order of 36,000 hrs, and this value is limited by the projection limits of the technique and the available data, not necessarily the performance of the DUT. The level of performance of warm white devices was somewhat less than that of the neutral white devices. Chromaticity stability has also improved over the past 4 years, resulting in much greater chromaticity maintenance. The findings demonstrate that the technical performance of OLED technologies is moving in the right direction for the technology to become a viable option for segments of the indoor lighting market. Further technological advances are still needed such as reducing costs, improving overall system efficiency, matching performance of warm white panels to at least that of neutral white panels, and delivering high volumes of product to the markets. Once these issues are addressed, OLED technologies may be poised to become an important part of the indoor lighting space.

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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 [3]	DOE Report 2 [5]	DOE Report 3 [6]	This Report
Luminaires with Type A panels	RTOL	Not applicable	6,500 hrs	15,000 hrs	19,000 hrs
	350L	Not applicable	2,000 hrs	8,000 hrs	12,000 hrs
	450L	4,250 hrs	9,000 hrs	12,000 hrs	15,000 hrs
	Temperature and humidity	Yes (7575)	Not applicable	Not applicable	Not applicable
Type B panels—GEN-2	RTOL	Not applicable	1,500 hrs	7,000 hrs	12,000 hrs
	350L	Not applicable	1,500 hrs	7,000 hrs	12,000 hrs
	450L	Not applicable	1,500 hrs	7,000 hrs	12,000 hrs
	Temperature and humidity	Not applicable	Not applicable	Not applicable	Not applicable
Type B panels—Amber	RTOL	Not applicable	1,500 hrs	7,000 hrs	Not applicable
	350L	Not applicable	1,500 hrs	7,000 hrs	Not applicable
	450L	Not applicable	1,500 hrs	Not applicable	Not applicable
	Temperature and humidity	Not applicable	Not applicable	Not applicable	Not applicable
Type B panels—GEN-3	RTOL	Not applicable	Not applicable	1,500 hrs	7000 hrs
	350L	Not applicable	Not applicable	1,500 hrs	7000 hrs
	450L	Not applicable	Not applicable	1,500 hrs	7000 hrs
	Temperature and humidity	Not applicable	Not applicable	1,500 hrs (6590)	6000 hrs (6590)

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