

Accelerated Stress Testing of Multi-Source LED Products: Horticulture Lamps and Tunable- White Modules

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List of Acronyms

°C	degree Celsius
ac	alternating current
CCT	correlated color temperature
Ce:YAG	cerium-doped yttrium aluminum garnet
CIE	Commission Internationale de l'Éclairage (International Commission of Illumination)
CSM	chromaticity shift mode
Cu-Sn	copper–tin
DOE	U.S. Department of Energy
DUT	device under test
DW	Durbin-Watson statistic
EERE	Office of Energy Efficiency and Renewable Energy
hr, hrs	hour, hours
IES	Illuminating Engineering Society
K	Kelvin
L80	Time required for luminous flux to decay to 80% of initial value
LED	light-emitting diode
LSG	Lighting Science Group
mA	milliAmp
MP-LED	mid-power light emitting diode
nm	nanometer
PAR	parabolic aluminized reflector
PCB	printed circuit board
pcLED	phosphor-converted light-emitting diode
R ²	R squared (correlation coefficient)
RH	relative humidity
SMT	surface mount technology
SPD	spectral power distribution
SSE	sum of squared error
SSL	solid-state lighting

Executive Summary

Solid-state lighting (SSL) technologies are bringing new capabilities to lighting products, and the growth in added functionality is driven in part by the capabilities of light-emitting diodes (LEDs). A wide variety of LED structures is readily available in a range of package sizes, luminous flux levels, emission spectra, and costs. Although these LEDs can be easily packaged together on a printed circuit board to form LED sources that are multi-functional and multi-component by using conventional electronics manufacturing technologies, the long-term performance of such systems has not been fully investigated. For example, it is unclear how differences in luminous flux and chromaticity maintenance of a product incorporating two different types of LEDs would compare with a conventional SSL product containing only a single LED type.

This report discusses the use of accelerated stress testing to provide insights into the long-term behavior of commercial products utilizing different types of mid-power LEDs (MP-LEDs) integrated into the same LED module. Test results are presented from two commercial lamps intended for use in horticulture applications and one tunable-white LED module intended for use in educational and office lighting applications. Each of these products is designed to provide a custom spectrum for their targeted applications and each achieves this goal in different ways. Consequently, a comparison of the long-term stability of these devices will provide insights regarding approaches that could be used to possibly lengthen the lifetime of SSL products.

In horticulture lighting, there is a desire to provide both blue and deep red wavelengths to promote plant flowering and growth. The Newhouse Lighting PAR38 horticulture lamp examined in this study achieves this goal through a phosphor-converted LED (pcLED) that produces only blue and deep red illumination. In contrast, the Lighting Sciences Group (LSG) Vividgro PAR38 horticulture lamp also examined in this report uses cool white pcLED packages combined with direct-emitting red LEDs to provide mainly blue and red illumination, with a small amount of green added to provide a low level of white light. These products were tested in an accelerating environment of 65 degrees Celsius (°C) and 90% relative humidity to mimic the potential conditions of heat and high humidity that are likely to occur in a greenhouse. These tests demonstrate that the direct-emitting red LEDs exhibited the greatest stability, both in terms of luminous flux and emission wavelength peak, of the MP-LEDs used in these products. Through 3,000 hours of testing there was minimal decline in luminous flux (approximately 5%) from the direct-emitting red and practically no change in the red emission wavelength peak. As a result, the luminous flux of the product incorporating the direct-emitting red LED was higher, and the device tended to undergo a chromaticity shift in the red direction through 3,000 hours of testing. In contrast, the product incorporating the deep red pcLEDs exhibited greater levels of luminous flux decline and tended to undergo chromaticity shifts along a linear trajectory between the blue LED and phosphor chromaticity point. For both products, the changes in luminous flux and chromaticity can ultimately be traced to the materials used in the LED packages and the surrounding optical structure (e.g., lenses, reflectors) in the lamp.

Regarding indoor lighting, some data suggest that tuning the lighting spectrum produced by troffers can improve the work and learning environment in schools and offices. The long-term behavior of one tunable-white LED product consisting of 40 warm white and 40 cool white MP-LEDs is presented in this report. To accelerate aging, the LED modules were subjected to an elevated ambient temperature of either 75°C or 95°C (with no added humidity), and the samples at each temperature were divided into four different groups with each group operated at one of four different current levels. Test data of up to 13,000 hours (hrs) was collected in this part of the study, and the luminous flux levels for the tunable-white LED modules were excellent and exceeded that of the horticulture lamps. The chromaticity shift behavior was also excellent, but different chromaticity shifts were observed for the cool white and warm white LED primaries. These differences can also be traced back to the materials used in the LEDs, including the phosphors and the molding resin used in the mid-power packages.

There is an indication from the tunable-white MP-LED data and other sources, that the chromaticity of pcLED devices utilizing a blue LED will ultimately shift in the blue direction. The effect was attributed to oxidation

of the molding resin over time and can be accelerated by higher currents and temperatures. In addition, this study found that the correlated color temperature (CCT) of the MP-LED played a role in the time necessary for this process to occur. The data suggest that because higher CCT devices convert less of the blue photons generated by the LED into longer wavelength photons, the blue shifts that eventually occur in most MP-LEDs are likely to occur sooner for higher CCT devices than for lower CCT devices. This study also found that direct-emitting red LEDs are unlikely to undergo these types of chromaticity shifts because of the absence of blue photons.

Although horticulture lamps and tunable-white luminaires seem to be unrelated products, the flexibility of LED sources has allowed each product to provide a spectrum tailored to a specific application and gain market share. A holistic view of the materials used in constructing these devices is essential to understanding their long-term behavior, with the characteristics of phosphors, molding resins, direct-emitter epitaxy, and secondary optics significantly impacting both chromaticity and luminous flux maintenance. By understanding these factors, the chromaticity shift of the device can be minimized over time, thereby providing greater service life.

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1 Introduction

Solid-state lighting (SSL) technologies have advanced significantly over the past decade, both in terms of increased luminous efficacy and providing new capabilities that are not possible with other lighting technologies. Light-emitting diodes (LEDs), which serve as the light source in SSL products, provide greater flexibility in generating light than is possible with using traditional products such as incandescent, fluorescent, or discharge lamps. LED-based lighting products have expanded significantly beyond traditional illumination applications, and they are now beginning to provide enhanced capabilities in a variety of applications, including horticultural lighting,¹ educational lighting,² and medical lighting.³

The inherent advantage of SSL technologies to provide greater application efficiency for light is derived from the flexibility of LEDs, which can be produced in a variety of package types, luminous flux levels, and light emission spectra. By drawing on nomenclature developed in the electronics industry, a hierarchy of packaging technologies can be described for LEDs,⁴ and the main elements of this hierarchy are shown in **Figure 1-1** and are listed as follows:

- Level 0—The LED chip
- Level 1—The LED chip package
- Level 2—The LED module, which consists of multiple Level 1 packages on a printed circuit board (PCB)
- Level 2+—The LED module combined with various higher levels of integration such as optics.

Well-established manufacturing technologies are used to integrate the different levels of the LED packages. For example, the electrical and thermal connections between Level 0 and Level 1 are often provided by either wire bonds, solder, or other chip attach technologies. The electrical and thermal connections between Level 1 and Level 2 are usually provided by surface mount technologies, including solder and, less commonly, conductive adhesives. The ability to integrate the small LED packages (Level 1) into larger LED modules (Level 2) by using established PCB manufacturing technologies provides tremendous flexibility to SSL product designs and manufacturing technologies.

LED modules can be readily manufactured with surface mount technology LED packages placed on the PCB as shown in Figure 1-1. These modules may consist of LED packages with the same nominal characteristics, including initial luminous flux and chromaticity. Alternatively, the LED packages used for the LED modules may have significantly different characteristics. In this case, the LED modules consists of two or more LED primaries with different characteristics such as emission spectra or package type. Common examples of LED modules containing different LED primaries include linear tunable-white modules (which may contain warm white and cool white LEDs), hybrid LED modules (which may contain both direct-emitting [typically either blue or red] and phosphor-converted LEDs (pcLED)), and horticulture lamps (which may contain white pcLEDs and red direct-emitter LEDs). Examples of these types of LED modules are included in Figure 1-1.

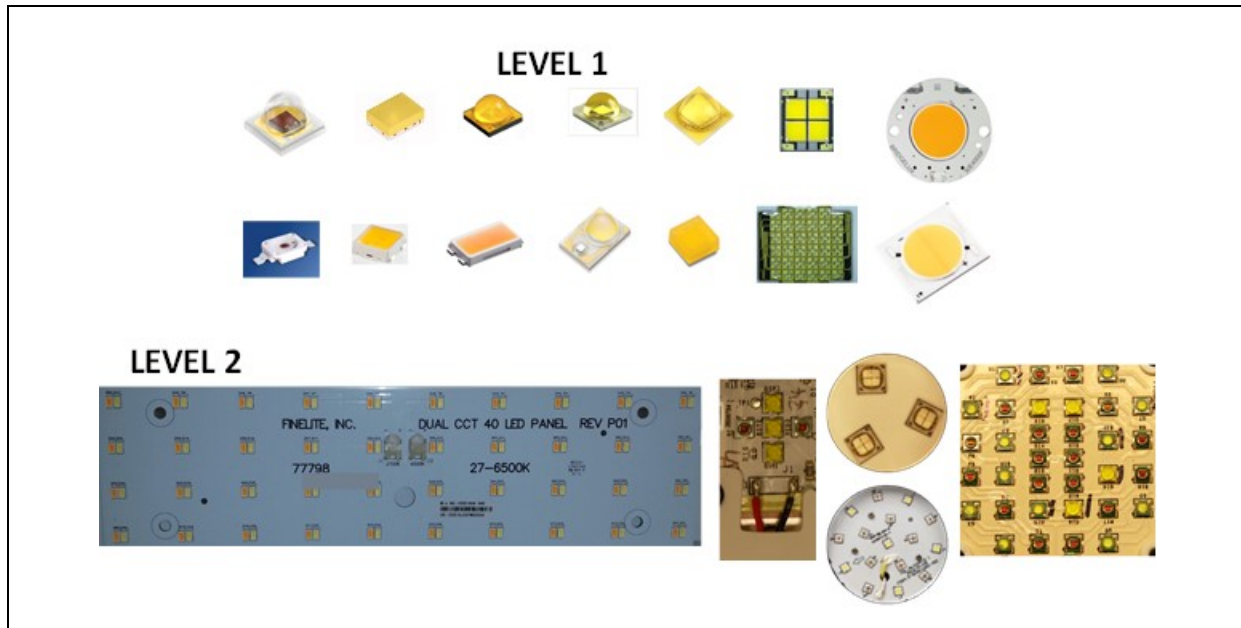


Figure 1-1. Examples of Level 1 and Level 2 LED devices.

Early SSL products were targeted at human needs for general illumination and typically provided light at only one correlated color temperature (CCT) value. The light produced by these fixed-CCT SSL sources was usually provided by pcLEDs consisting of a mixture of inorganic phosphors (chosen to achieve a desired CCT) and a blue-emitting LED.⁴ However, newer SSL products are capitalizing on the capabilities of LEDs to provide lighting that is more tailored to the needs of humans in specific situations such as education,⁵ offices,⁶ health care,³ and/or night shift work.⁷ SSL lighting technologies are also establishing a strong market for products with lighting spectra tailored to the needs of plants and animals (i.e., horticulture lighting).⁸

This report focuses on the behavior of LED devices that use light sources made with two or more LED primaries with different properties, including luminous flux and chromaticity. Such devices are termed “multi-source LED lighting products” and are providing enhanced illumination by producing spectra that can be set to application-specific needs. This report is a complement to a previous report from the U.S. Department of Energy (DOE) about multichannel drivers, because multichannel drivers are usually used to operated SSL devices with multiple LED sources.⁹ With the added capabilities provided by multi-source LED modules, the long-term behavior of these devices may be different from that of devices made with the LEDs of the same properties (e.g., SSL devices with a fixed CCT value). Understanding the underlying demands of specific lighting situations is critical to achieving acceptable lighting application efficiency in these tunable lighting products.

1.1 Chromaticity Shifts in LED Packages and Modules

Significant gains have been made in understanding the causes of chromaticity shift in LED packages and modules, and these findings are summarized in this subsection. Detailed discussions of this effect can be found in literature.^{10, 11}

The chromaticity shift of pcLEDs has been studied in PAR38 lamps and has been shown to have a strong dependence of LED package type.^{10, 11, 12} This finding has been extended beyond PAR38 lamps and appears to be broadly applicable to pcLEDs. In general, there are three likely outcomes from the chemical reactions that produce chromaticity shifts in pcLEDs.

The first potential outcome is a change in the relative radiant fluxes produced by the blue-emitting LED and the phosphor. This change will produce a shift in chromaticity that generally falls along the line that connects the chromaticity points of the two, as shown in **Figure 1-2**. Such chromaticity shifts involve larger changes in the v' chromaticity coordinate than in u' , as is apparent in Figure 1-2.

The second potential outcome is a change emission spectrum produced by either the blue-emitting LED or the phosphors. The chromaticity of a LED-based light source is sensitive to even small changes in the emission properties of the sources. Such changes will alter the dominant emission wavelength of the light source and will produce chromaticity shifts such as those shown in **Figure 1-3**. Such chromaticity shifts involve larger changes in the u' chromaticity coordinate than in v' , as is apparent from Figure 1-3.

The third potential outcome is a change in the optical properties of materials outside of the LED package. The yellowing of secondary lenses or reflectors are examples of this outcome. Depending on the design of the device, yellowing of both lenses and reflectors can alter the emission spectrum from the SSL device; however, changes in the lens usually have a much greater impact than changes in the reflector surrounding the LED packages.^{13, 15} The optical effects are discussed in Section 1.2 of this report.

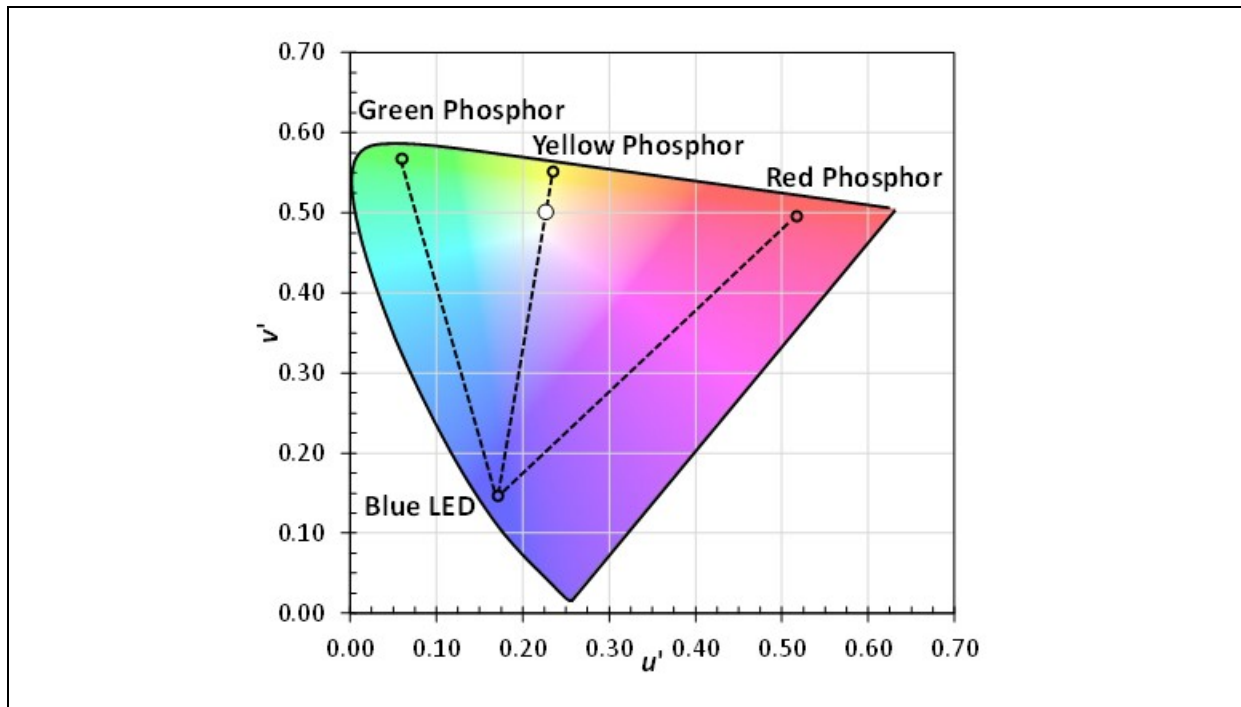


Figure 1-2. The direction of chromaticity shifts caused by relative changes in emissions from the phosphor and blue-emitting LED.

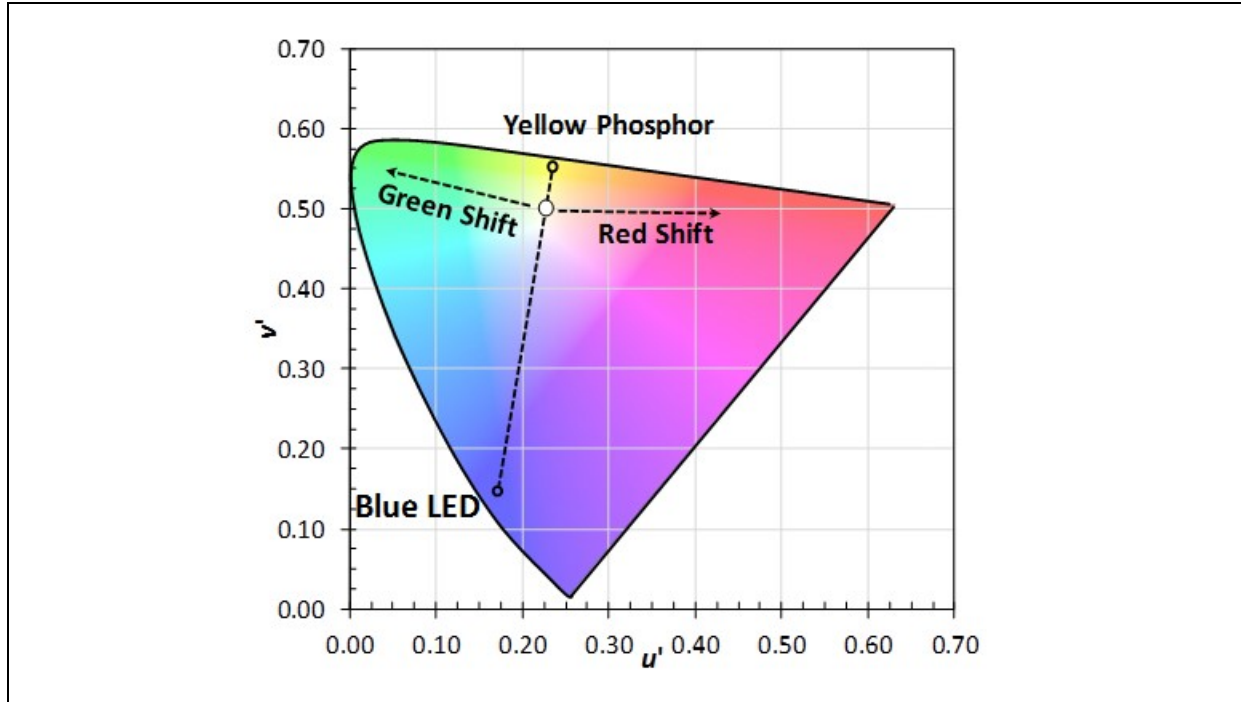


Figure 1-3. The direction of chromaticity shifts caused by changes in the emission wavelengths of either the phosphor or the blue-emitting LED.

1.2 Optical Impacts on Chromaticity Shifts

The optical materials that are commonly used in LED devices may change over time, and some common materials are more subject to change than others.¹⁴ These changes often occur over long periods of time with an incubation period that may last hundreds of hours,¹⁵ followed by a prolonged period of a nearly linear rate of change that has a strong wavelength dependence.¹³ **Figure 1-4** shows the expected change in transmittance of polycarbonate lens after exposure to 3,000 hours (hrs) of an accelerated stress testing (AST) environment conducted at 65 degrees Celsius (°C) and 90% relative humidity (RH). This condition results in an increase in light absorption at blue wavelengths, but the light absorption level at longer wavelengths changes much less. As a result, this type of degradation will typically cause emissions from a pcLED device to shift toward the phosphor emission chromaticity, analogous to the behavior shown in Figure 1-2.

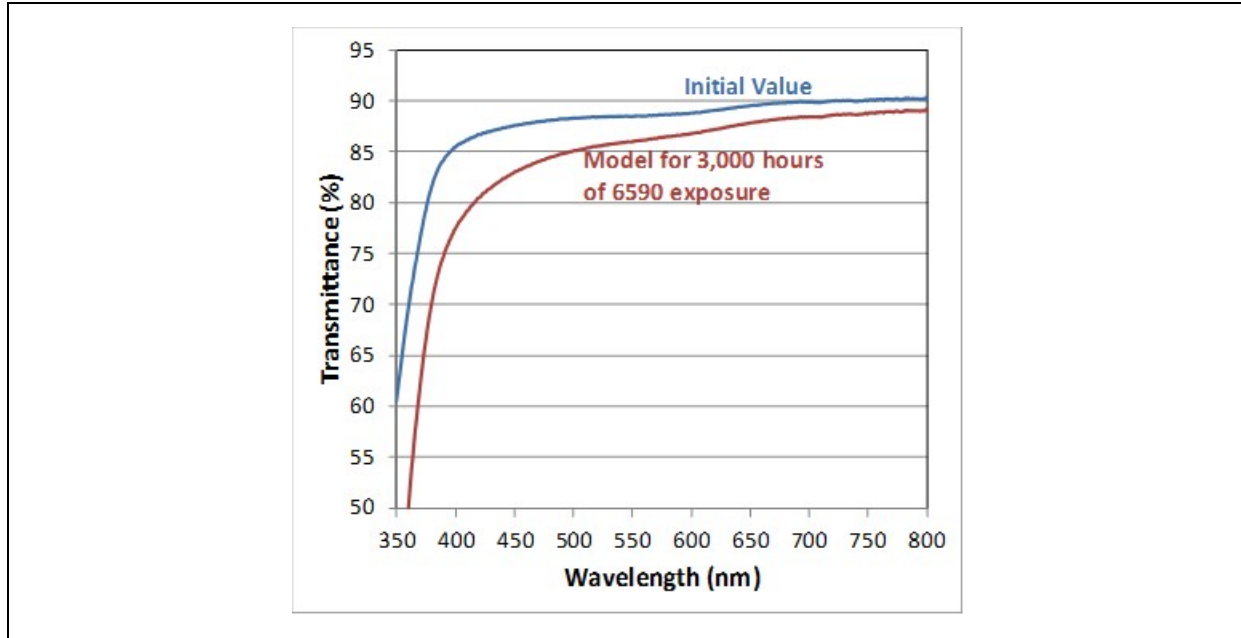


Figure 1-4. Transmittance of a polycarbonate lens when new and after 3,000 hrs of exposure to 65°C and 90% RH.

1.3 Modeling Chromaticity Shifts in LED Devices

Chromaticity shifts in LED packages, modules, and other devices are vector quantities in the color spaces typically used in lighting (e.g., Commission Internationale de l'Éclairage [CIE, the International Commission of Lighting] 1976 chromaticity diagram) and can be described by both a magnitude and a direction. The quantity $\Delta u'v'$ is often quoted as the value of the chromaticity shift, but this parameter only provides the magnitude of the shift, not the direction. To understand the direction of chromaticity shifts, it is essential to evaluate the change in the individual chromaticity coordinates such as u' and v' in the CIE 1976 chromaticity diagram. These changes are expressed as $\Delta u'$ and $\Delta v'$ in this report.

Chromaticity shifts in SSL devices are caused by changes in the chemical properties of the materials used in the device. As discussed in Section 1.1 and Section 1.2 of this report, these changes may occur in the LEDs themselves, their packages, or surrounding optical materials such as secondary lenses and reflectors. The chromaticity shifts occurring in SSL devices can often be deconvoluted into a fast-acting component that occurs during the initial operation of the device (e.g., often in the first 2,000 hrs or less) and one or more slow-acting components that take longer times to significantly impact chromaticity. In some cases (e.g., low operating temperatures and forward currents), it may take much longer before a fast-acting component reaches its maximum impact and for the slow-acting components to affect chromaticity.

During this work, the chromaticity change of the SSL devices is modeled by using a two-step process in which the fast-acting component is modeled with a bounded exponential function (see [Equation 1](#) and [Equation 2](#)), and one or more generalized logistic functions (see [Equation 3](#)) are used to model the slow-acting components.^{14, 16} The generalized form of the bounded exponential function is shown in [Figure 1-5](#), and the generalized form of the logistic function is shown in [Figure 1-6](#). To a first order, much of the middle part of the logistic function can be approximated by a line.¹⁷

Bounded exponent—Approach for a maximum value

$$A(1 - e^{-kt}) \quad (\text{Eq. 1})$$

Bounded exponent—Approach for a minimum value

$$L(1-e^{-kt}) \quad (\text{Eq. 2})$$

Generalized logistic—Approach for either a maximum or minimum value

$$L + \frac{A-L}{1+Ce^{-k(t-t_0)}} \quad (\text{Eq. 3})$$

Where:

- A = The maximum asymptotic value
- k = Rate of change in the function
- t = Time
- L = The minimum asymptotic value
- C = A fitting parameter
- t_0 = Starting time

Another feature of modeling chromaticity shifts using this approach is that multiple processes are often involved during the lifetime of an SSL device, and the impacts of each process on the chromaticity shift do not proceed indefinitely (i.e., there is an upper [A] and lower [L] bound to any process that causes a chromaticity shift). For a shift approaching an upper asymptote (A), the change in the relative chromaticity coordinate is positive, whereas for a shift approaching a lower asymptote (L), the change in the relative chromaticity coordinate will be in the negative direction. Sometimes, these limits are beyond those set for chromaticity shifts (e.g., $\Delta u'v' \geq 0.007$), and in this instance, the shift will ultimately produce a parametric failure; however, not every chromaticity shift produces a parametric failure.

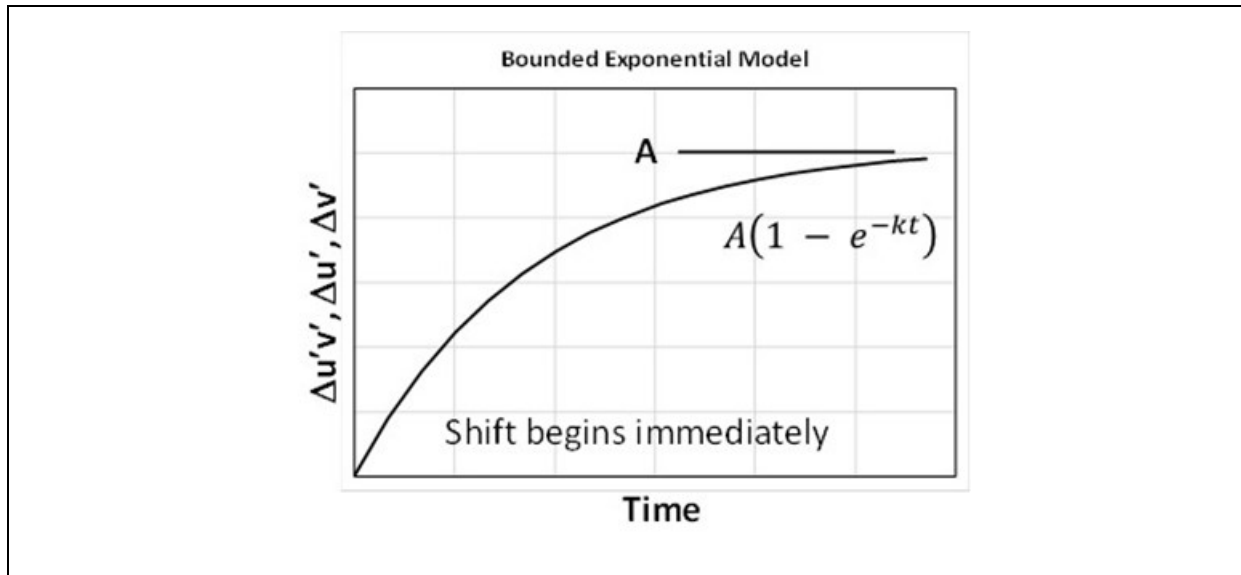


Figure 1-5. Generalized form of the bounded exponential function with a positive asymptote A .

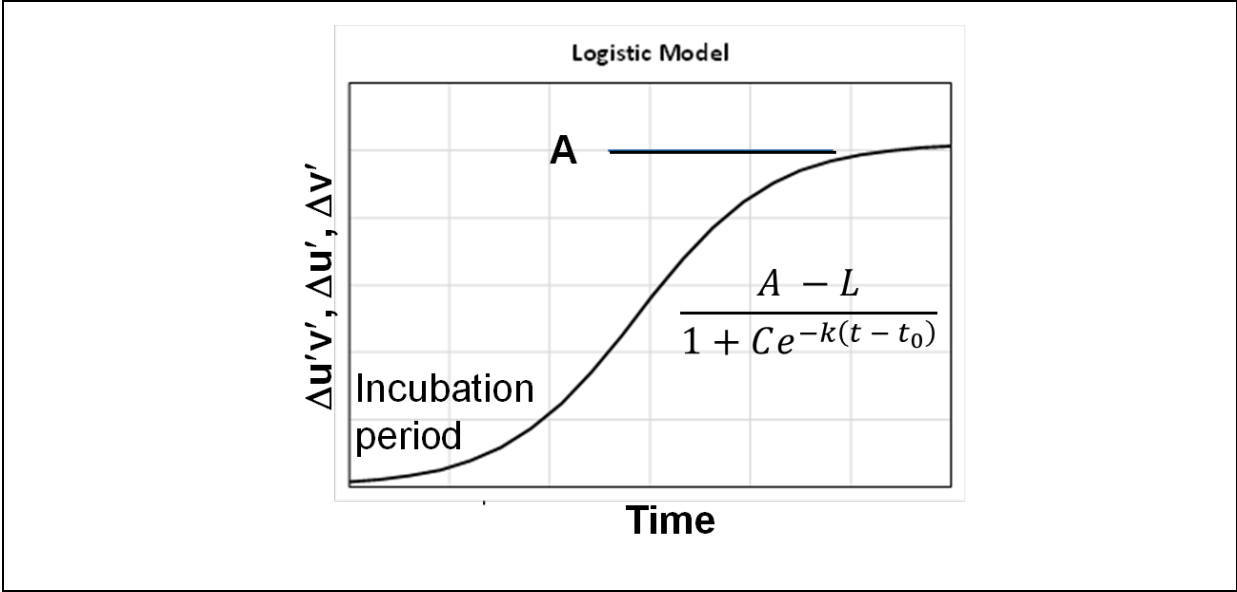


Figure 1-6. Generalized form of the logistic function, starting at the origin and proceeding to a positive asymptote A.

2 Multi-source LED Products: Horticulture Lamps

Horticulture lamps use similar LEDs, phosphors, lenses, and drivers as traditional white sources. The spectrum produced by the LEDs in a horticulture lamp does, however, differ from traditional white, tunable-white, and other multi-element LED systems. Namely, horticulture lamps contain no or a very little amount of green light, whereas traditional white sources contain a significant amount of green light. Chlorophyll, the pigment responsible for light absorption and conversion to energy in most plants, predominantly absorbs red and blue lights, and much less absorption typically occurs in the green light. Therefore, the amount of green light present in horticulture lamps can be reduced because horticultural lighting targets optimal plant growth. In contrast, green light is essential to human visual perception because the average human eye has a peak sensitivity at approximately 555 nanometers (nm; green light).

In addition, horticulture lamps are predominantly operated in elevated-stress conditions relative to the average indoor white light luminaire. Horticulture lamps will often experience high RH (90–100%), elevated temperature (35–40°C), and enclosed spaces. Previous stress testing studies (75°C and 75% RH) of LED luminaires have been shown to accelerate the rates of moisture ingress and mechanical stress on other LED luminaires, leading to LED emission losses, phosphor degradation, solder failures, and lens discoloration, which result in an overall decay in luminous flux and a shift in chromaticity of the device.¹⁴ However, these previous studies did not characterize horticulture lamps, and the devices under test (DUTs) were not housed in a structure that mimics enclosed luminaires such as typically used for parabolic aluminized reflector (PAR) lamps. Such enclosed luminaires have been shown to impact the luminous flux maintenance and overall reliability of A19 and PAR38 lamps.¹⁸

2.1 Experimental Methods

The current study focused on PAR horticulture lamps from two commercial sources: Lighting Science Group (LSG) and Newhouse Lighting. This report presents findings from stress testing these horticulture lamps in a temperature and humidity chamber maintained at 65°C and 90% RH (hereafter termed 65/90). This condition was chosen because of the high humidity and temperatures that are often found in horticulture facilities. During operation, the lamps were cycled on and off, and no dimming was applied.

2.1.1 Samples

Two horticulture lamp products (both PAR lamps) were investigated in the current study: a Vividgro PAR38 grow lamp by LSG and a PAR38 LED grow lamp by Newhouse Lighting. An overview of both lamps and their electrical properties is presented in **Table 2-1**.

Table 2-1. Comparison of Electrical Properties Between Horticulture Lamps

Manufacturer	Description	Output Voltage (Vdc)	Output Current (milliAmps [mA])	Efficiency (%)
LSG	Vividgro PAR38 grow lamp	41.6	323	87.5
Newhouse Lighting	PAR38 LED grow lamp	60.2	230	86.8

The LSG products were purchased for testing at two different times during the current work (i.e., July 2017 and August 2017); differences regarding the construction or the properties of the devices in these timeframes were not observed. As shown in **Figure 2-1**, the studied LED products consisted of 10 red LED packages and 6 pcLED packages mounted on a common PCB with a polycarbonate secondary lens. The LEDs used in this product are mid-power LEDs (MP-LED), and the LED packages are configured in series with each other. The spectrum of this LED module is fixed, and the lamps in this study had an average pre-operation CCT value of $3311\text{K} \pm 145\text{K}$. Six screws on the perimeter of the lens are used to attach the polycarbonate lens to the lamp housing. The screw holes are visible in Figure 2-1. An o-ring is placed in the circular groove between the

screw holes and the LED module to protect against moisture ingress. As previously demonstrated, an o-ring will decelerate chemical changes that occur to LEDs in a high humidity environment, but it will not stop moisture-related degradation processes because the seal is not hermetic.¹⁹

The Newhouse Lighting products were also purchased for testing at two different times during the current work (i.e., July 2017 and August 2017); differences regarding the construction or the properties of the devices in these timeframes were not observed. As shown in Figure 2-1, the studied LED module consists of 20 pcLEDs, which are mid-power devices. Although this lamp is not a multi-source LED product because there is only one type of LED package, the lamp does provide two distinct emissions. As a result, the behavior of the lamp provides insights regarding the characteristics of blue LEDs and red phosphors in mid-power packages. The spectrum of this LED module is fixed, and the lamps in this study had an average pre-operation CCT value of $1302\text{K} \pm 5\text{K}$. Above the LED module, there is a small optical mixing cavity that contains a plastic reflector made of polycarbonate. There is also a polycarbonate secondary lens (not shown in Figure 2-1) that is attached to the housing through six screws around the perimeter. A white o-ring in-line with the six screw holes is used to protect against moisture ingress.

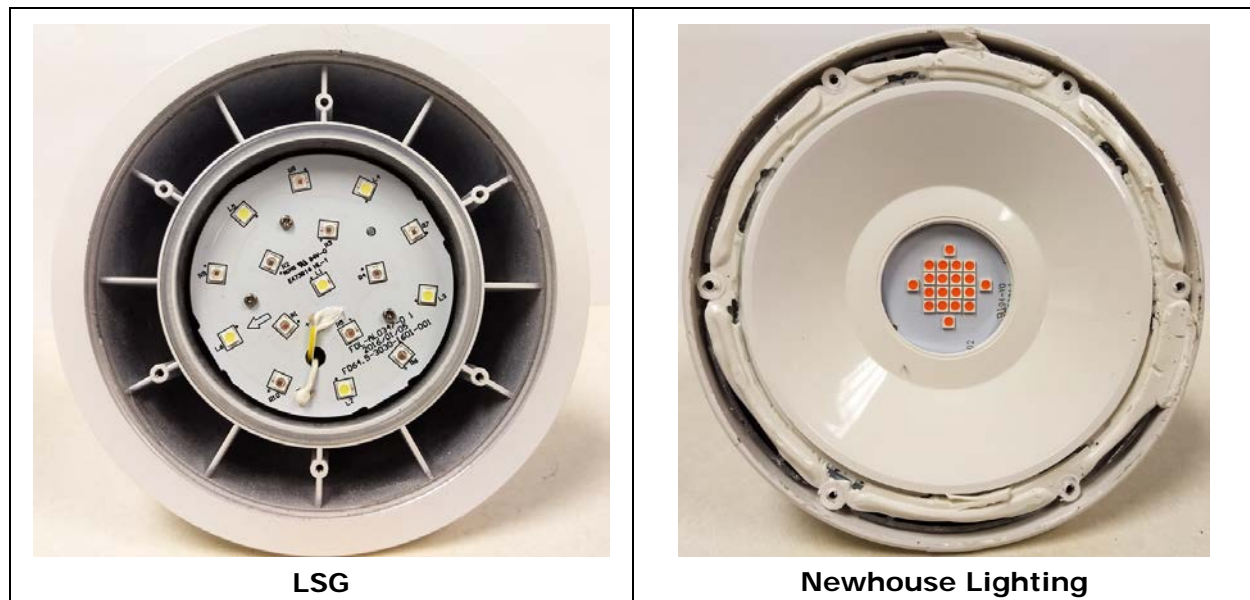


Figure 2-1. LED modules of the LSG and Newhouse Lighting PAR38 grow lamps.

2.1.2 Stress Testing Methods

This report presents findings from stress testing involving elevated temperature (65°C) and humidity (90% RH) on two horticulture lamps: a total of six LSG Vividgro PAR38 lamps and six Newhouse Lighting PAR38 GROW lamps were tested under these stress conditions. All DUTs underwent power cycling. For simplicity, the on and off cycle was set to 2 hrs on and 2 hrs off for the duration of the tests. This on and off cycle allowed the devices to reach their maximum and minimum operation temperatures, respectively. All DUTs were thermally monitored every 10 minutes by using chromel–alumel thermocouples multiplexed to a data acquisition module. In all cases, the temperature was monitored just below the lip of the heat sink. All DUTs were enclosed by an aluminum cylinder (6-inch outer diameter and 7.5-inch tall), as shown in **Figure 2-2**, to mimic real luminaire operation conditions in an enclosed fixture. An identical lamp from each manufacturer, which was not exposed to the stress testing environment, was kept aside to serve as a control lamp for the respective stressed lamps.

Upon completion of each stress test cycle during the current study, the photometric properties of each DUT were evaluated using a calibrated 65-inch integrating sphere following the Illuminating Engineering Society's

(IES's) LM-79-08 method employing 4π geometry.²⁰ Power was supplied to the DUTs within the integrating sphere by a porcelain keyless lampholder, which was mounted to the center post of the integrating sphere with a secured screw (white wiring was fed through the bottom of the integrating sphere to an external power source to provide the electrical connection). Electrical properties of the DUTs were measured using a Kill-A-Watt EZ power meter.



Figure 2-2. Horticulture luminaires enclosed by aluminum cylinders undergo stress testing at 65°C and 90% RH inside an environmental chamber at RTI International.

2.2 Spectral Changes

The MP-LED packages of the Newhouse Lighting lamp use a pcLED structure consisting of a direct-emitting blue LED and red phosphor to provide blue and red emissions from the device for plant growth. The lamp provides minimal light emissions between 510 nm and 550 nm. As a result, the lamp emissions displayed a magenta color as shown on the right side of Figure 2-2.

The red phosphor experienced a large drop in emission during the initial 500 hrs of testing in 6590, but subsequent phosphor emissions decreased at a slower rate than the loss of blue emissions, as shown in **Figure 2-3**. The steady decline in blue emissions through 3,000 hrs of testing led to a net increase in the red to blue radiant power ratio after the first 1,000 hrs of operation (see **Table 2-2**). Further analysis of the average spectral peak location of each emitter for the DUTs, represented herein as the centroid wavelength, reveals a minimal shift in peak location (<1.0 nm) for both emitters. As a result of the minimal change in the centroid wavelength of the LED and phosphor emissions, the chromaticity shift of this device was likely dominated by processes that impact the relative ratio of the blue and red emitters (see Figure 1-2).

Table 2-2. Average Centroid Wavelengths and Ratio of Red-to-Blue Radiant Power for Initial and After 3,000 Hrs of Ageing in 6590 for Newhouse Lighting PAR38 Grow Lamps

Hours	Blue LED Centroid Wavelength (nm)	Red Phosphor Centroid Wavelength (nm)	Red-to-Blue Radiant Power Ratio
0	453.9 ± 0.1	663.6 ± 0.4	4.26
3,000	454.1 ± 0.1	662.8 ± 0.1	4.70

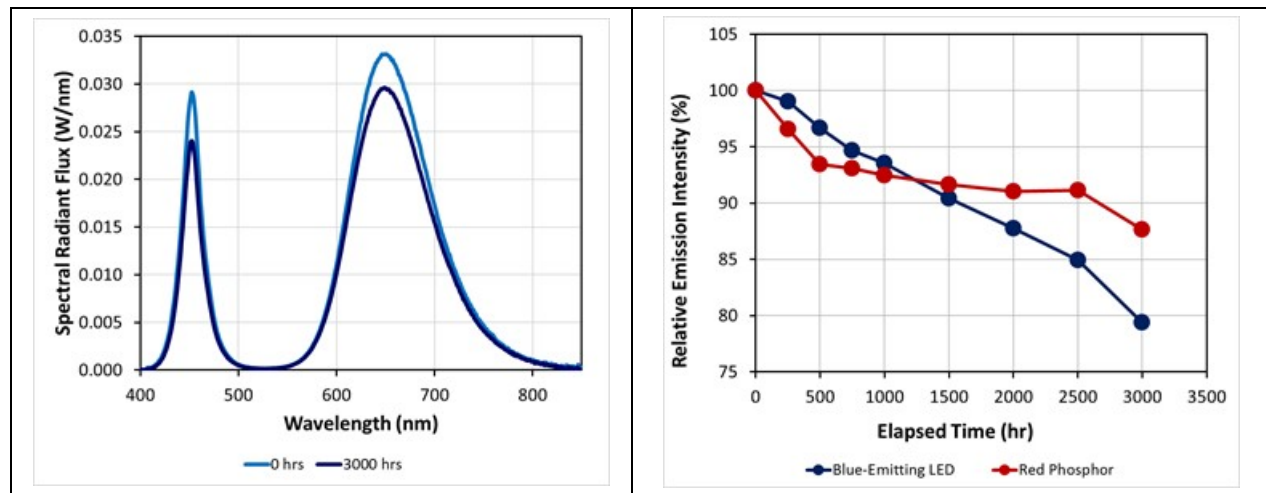


Figure 2-3. Spectral radiant flux of a Newhouse Lighting lamp (DUT 386) after ageing in 6590 (on left) and changes in the emission intensity of the blue direct-emitting LED and red phosphor relative to their respective initial values (on right).

The MP-LEDs of the LSG lamps use a combination of pcLED (direct blue emitter and broad green phosphor) and direct red emitter to provide a spectrum that optimizes plant growth. Relative to the direct red and blue emitters, the green phosphor experienced the largest drop in radiant power (see **Figure 2-4**). During the first 250 hrs of testing in 6590, the steepest emission loss in green was measured, and then a second wave of emission loss started at approximately 1,000 hours and continued through 3,000 hours. As of 3,000 hrs, the red LED has been shown to be the most stable with the smallest loss of emissions. Further analysis of the average spectral peak location for the direct blue, direct red, and phosphor green emitters reveals a minimal shift in peak location (≤ 0.4 nm) for all three emitters (**Table 2-3**). Because the centroid wavelength of the LED and phosphor emissions changed minimally, the chromaticity shift of this device is likely dominated by processes that impact the relative ratio of the blue, green, and red emitters.

Table 2-3. Average Centroid Wavelengths for Blue and Red LEDs and for the Green Phosphor for Initial and After 3,000 Hrs of Testing in 6590 for LSG PAR38 Grow Lamps

Hours	Blue LED Centroid Wavelength (nm)	Green Phosphor Centroid Wavelength (nm)	Red LED Centroid Wavelength (nm)
0	452.4 ± 0.7	553.4 ± 0.3	654.4 ± 1.1
3,000	452.7 ± 0.7	553.3 ± 0.3	654.0 ± 1.2

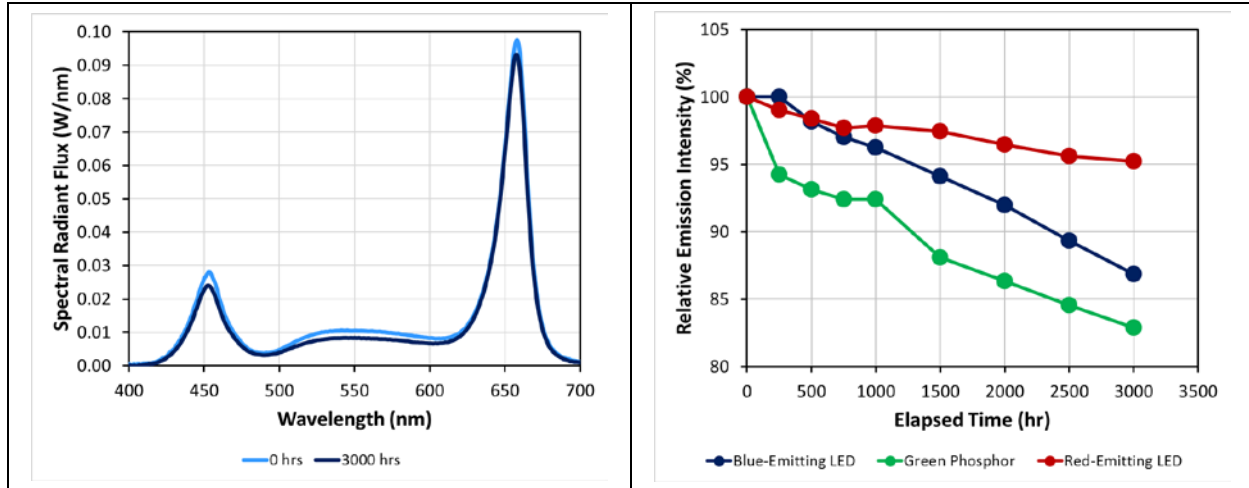


Figure 2-4. Spectral radiant flux of a LSG luminaire (DUT 401) after ageing in 6590 AST (on left) and changes in the emission intensity of the direct blue- and red-emitting LEDs and green phosphor relative to their respective initial values (on right).

2.3 Luminous Flux Changes

Through 3,000 hrs of exposure to 6590 AST, all Newhouse Lighting DUTs remained operational. Though still operational, the socket for one of the devices had oxidized in the humid environment, making electrical connection to alternating current (ac) mains difficult if it is not repolished between photometric testing as shown in **Figure 2-5**. The lenses of all the devices show signs of ageing (yellowing and cracking, more details are given later in this report). As of 3,000 hrs, the average luminous flux maintenance for these lamps was approximately 87%, as shown in **Figure 2-6**. Note that the luminous flux maintenance for the six Newhouse Lighting DUT lamps decreased from the onset of the stress test. Furthermore, the DUTs experienced a large drop in lumen output during the first 500 hrs, followed by slower, linear depreciation from 750 hrs onward. Using a line of best fit for the data between 750 hrs and 3,000 hrs (see **Figure 2-7**), it is estimated that the lumen maintenance may reach L70 by 10,000 hrs under these conditions, though additional data are still needed to create a projection by using standard methods such as IES's TM-21-11.²¹



Figure 2-5. The socket of an aged device (right) show signs of oxidation compared to the control device (left).

All LSG DUTs remain in good operational condition through 3,000 hrs in 6590 exposure. At 3,000 hrs, the average luminous flux maintenance for the six LSG DUTs is 85.7%, slightly lower than the Newhouse Lighting DUTs. Most of the LSG DUTs experienced an immediate—yet steady—decrease in luminous flux maintenance with time as shown in Figure 2-6. If their current lumen depreciation projection persists, these devices will likely reach L70 between 6,000–7,000 hrs (see Figure 2-7).

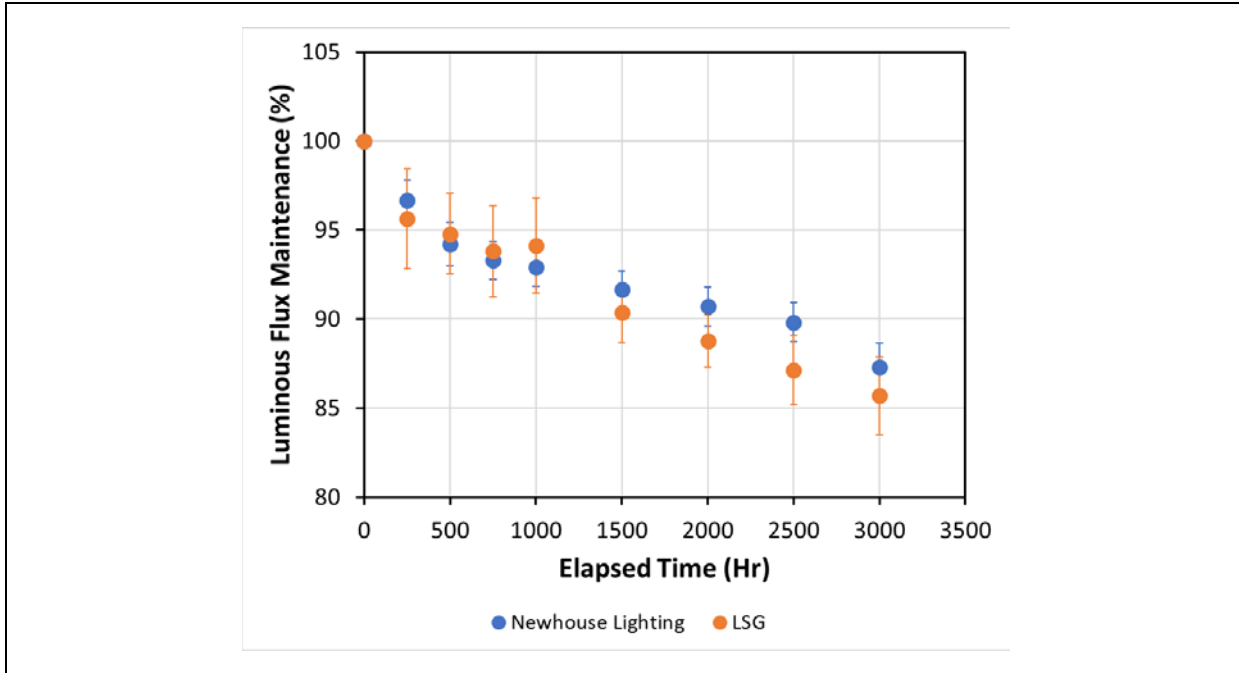


Figure 2-6. Average lumen maintenance of Newhouse Lighting and LSG PAR38 grow lamps after ageing in 6590. Note: Lumen maintenance was corrected for variation observed in the control lamp to account for spectrometer and experimental variations, and error bars represent one standard deviation.

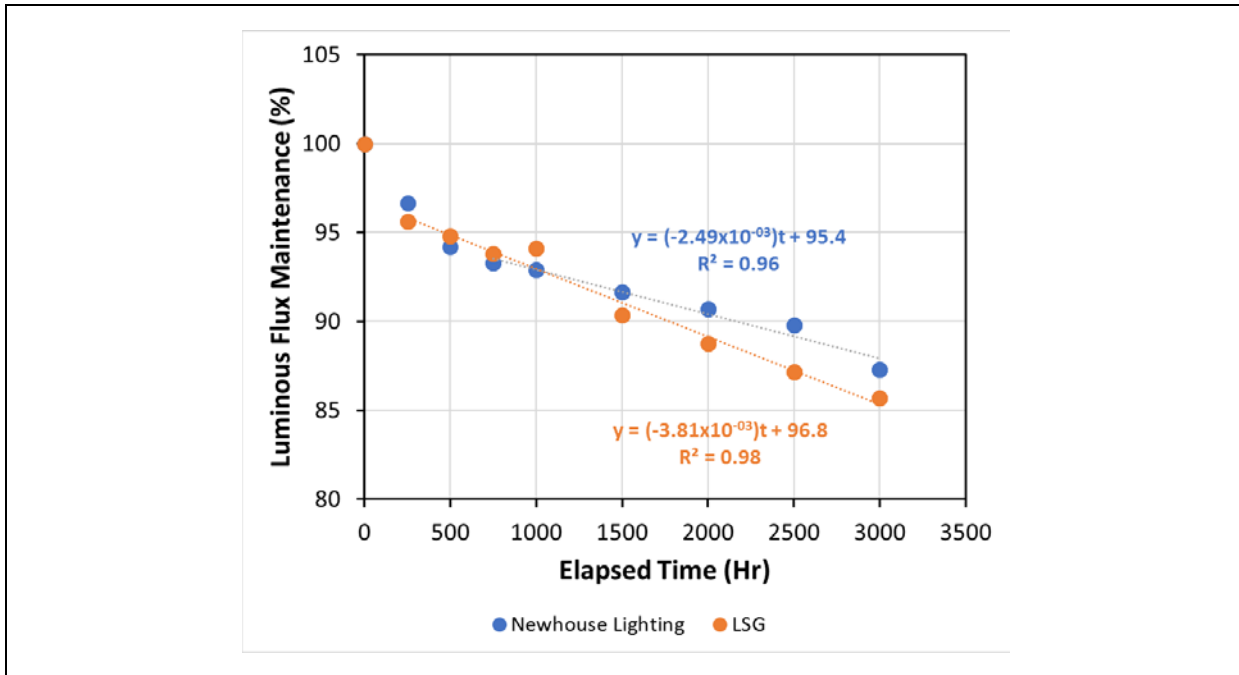


Figure 2-7. Lines of best fit used to project lumen maintenance for the Newhouse Lighting and LSG lamps.

2.4 Chromaticity Shift and Modeling

The average chromaticity shift for the six Newhouse Lighting DUTs initially proceeded toward negative u' and v' values during the first 250 hrs, as shown in **Figure 2-8**. This shift is followed by a second chromaticity shift that becomes dominant at approximately 750 hrs, wherein both u' and v' shift in the positive direction.

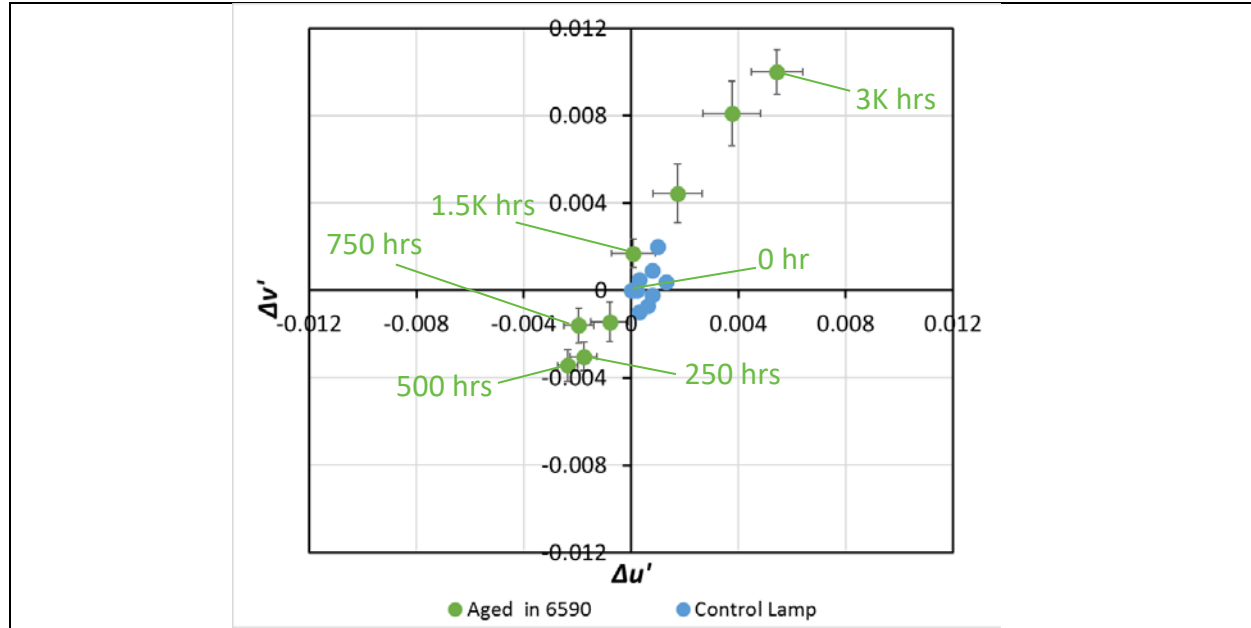


Figure 2-8. Average chromaticity diagram for Newhouse Lighting luminaires aged in 6590. Note: The control lamp is also graphed to show variation in spectrometer, and the variation in average $\Delta u'$ and $\Delta v'$ is represented with one standard deviation (black bars).

Further inspection of the temporal behavior of the $\Delta u'$ and $\Delta v'$ coordinates supports a two-shift process, as shown in **Figure 2-9** and **Figure 2-10**. Looking at the $\Delta u'$ component of chromaticity shift, a rapid initial shift was observed within the first 250 to 500 hrs; the $\Delta u'$ component of chromaticity shift dropped to its lowest value within this timeframe, as shown in Figure 2-9. The negative trajectory of the $\Delta u'$ component of chromaticity shift is short-lived, and at approximately 750 hrs, the $\Delta u'$ coordinate begins to shift toward positive values. The rapid process responsible for the initial negative trajectory can be fit with a bounded exponential model with high accuracy and was found to have a lower asymptote (L) of $\Delta u' = -0.00359$. The slower process responsible for the positive shift after 500 hrs was best fit with a logistic model. An exact termination point for the second chromaticity shift, modeled by the logistic function, has yet to be determined, though the model suggests $\Delta u' = 0.031$. Because the overall model is the sum of the two processes, the termination point $\Delta u' = 0.028$ is simply the sum of the lower asymptote derived from bounded exponential fit ($\Delta u' = -0.00359$) and the upper asymptote derived from the logistic model $\Delta u' = 0.031$.

The $\Delta v'$ component of chromaticity shift for the Newhouse Lighting DUTs followed a very similar trajectory as the $\Delta u'$ component of chromaticity shift, and the $\Delta v'$ also dropped quickly within the first 250 to 500 hrs of 6590 exposure before continuing in a positive trajectory through 3,000 hrs, as shown in Figure 2-10. The initial negative $\Delta v'$ component of chromaticity shift was fit with a bounded exponential model, and a lower asymptotic limit (L) $\Delta v' = -0.0038$ was found. The subsequent positive $\Delta v'$ component of chromaticity shift was fit with a logistic model, and the model suggests a termination point for the chromaticity shift to be $\Delta v' = 0.038$.

The chromaticity shift models of $\Delta u'$ and $\Delta v'$ were both optimized by summing one logistic function and one bounded exponential function, and the statistical parameters are presented in **Table 2-4**. The optimization was

performed with the sum of squared errors (SSE) and least squares methods. The correlation coefficient (R^2) was high for the fits, and Durbin-Watson (DW) statistic confirmed minimal autocorrelation of the residuals.

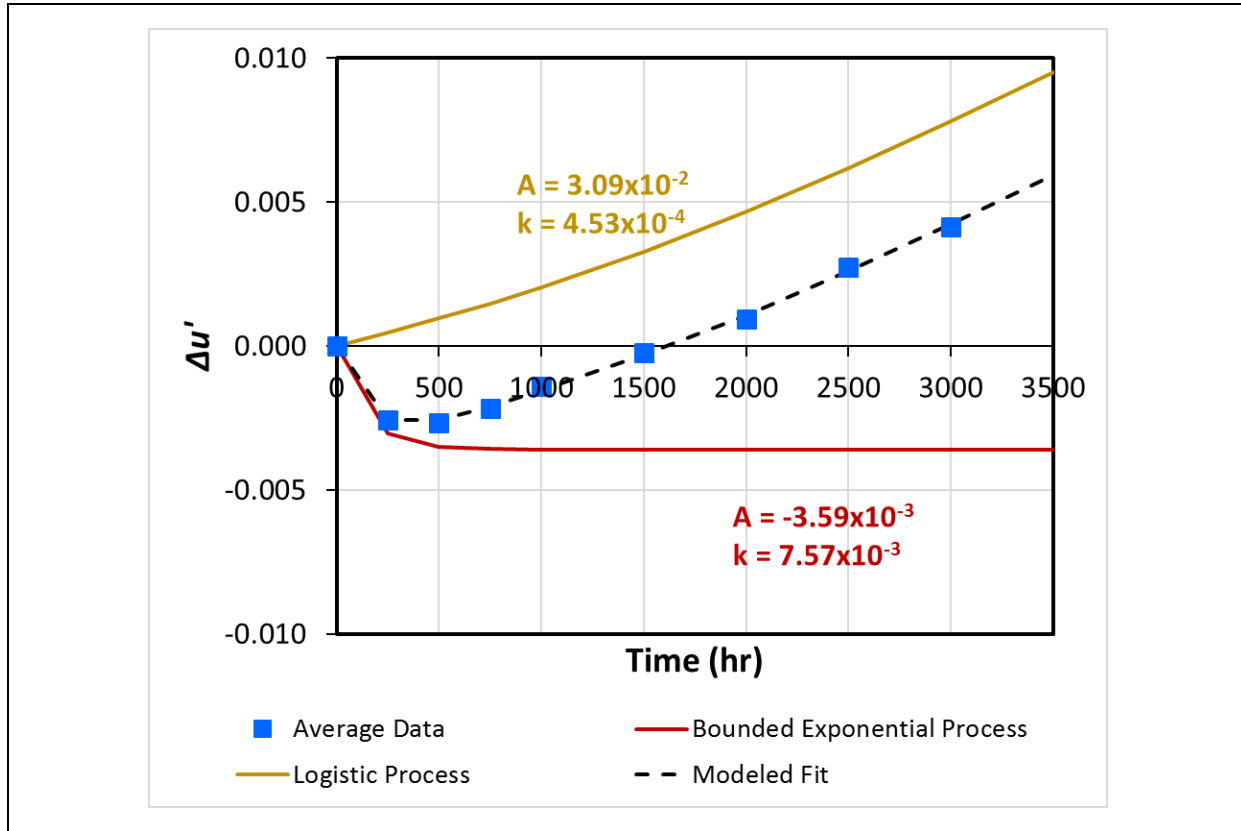


Figure 2-9. Chromaticity shift modeling for the average change in $\Delta u'$ for the Newhouse Lighting DUTs.

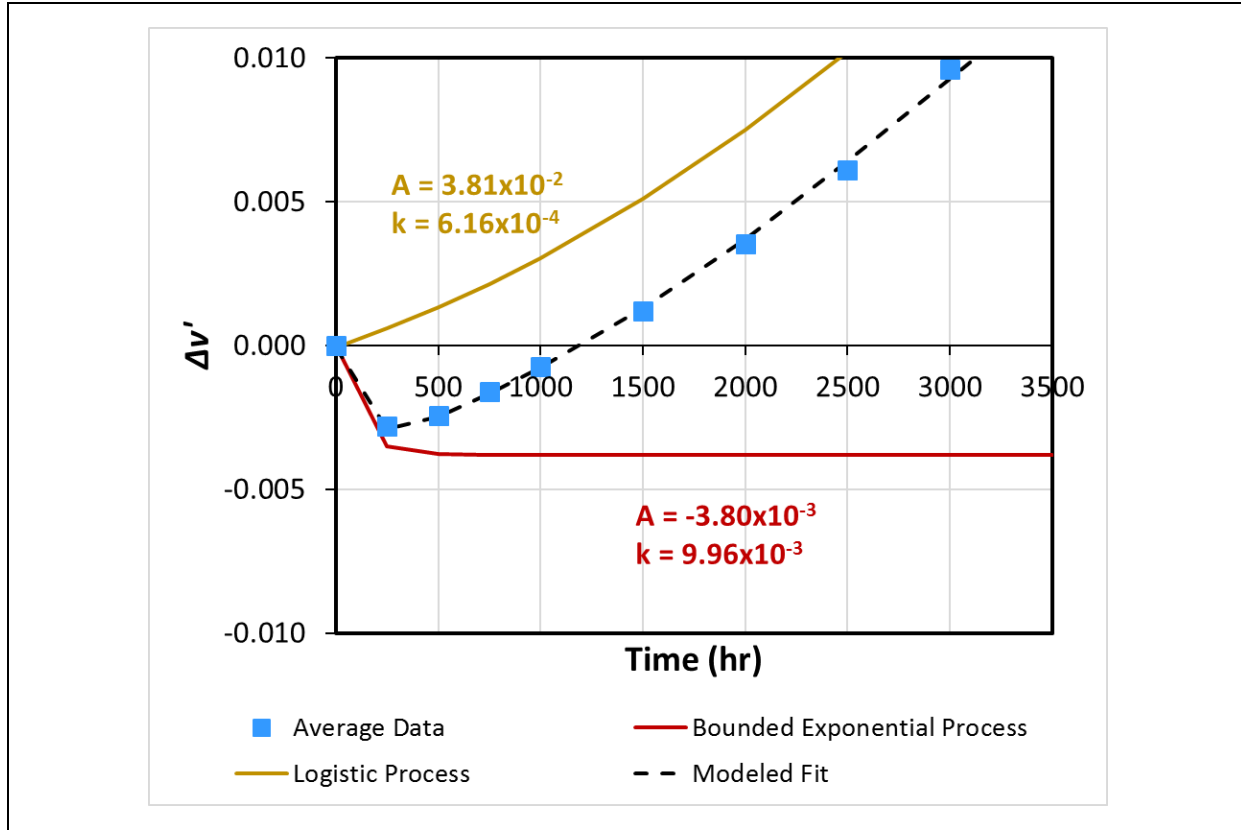


Figure 2-10. Chromaticity shift modeling for the average change in $\Delta v'$ for the Newhouse Lighting DUTs.

Table 2-4. Statistic Parameters of Models for $\Delta u'$ and $\Delta v'$ for the Newhouse Lighting DUTs

$\Delta u'$ Model	
Bounded exponential process	$\Delta u' = (-3.59 \times 10^{-3})(1 - e^{-(7.57 \times 10^{-3})t})$
Logistic process	$\Delta u' = -4.43 \times 10^{-3} + \frac{(3.09 \times 10^{-2})}{(1 + 5.30e^{-(4.53 \times 10^{-4})(t-258.16)})}$
SSE	9.99×10^{-8}
R ²	0.999
DW statistic	2.69
$\Delta v'$ Model	
Bounded exponential process	$\Delta v' = (-3.80 \times 10^{-3})(1 - e^{-(9.96 \times 10^{-3})t})$
Logistic process	$\Delta v' = -4.66 \times 10^{-3} + \frac{(3.81 \times 10^{-2})}{(1 + 6.19e^{-(6.16 \times 10^{-4})(t-268.51)})}$
SSE	2.61×10^{-7}
R ²	0.999
DW statistic	1.70

The six LSG samples experienced a large chromaticity shift within the first 250 hrs of operation, with $\Delta u'$ proceeding in the positive direction and $\Delta v'$ proceeding in the negative direction, as shown **Figure 2-11**. After

250 hrs, this initial shift is followed by a second chromaticity shift in which the main shift is a change in u' towards the positive direction.

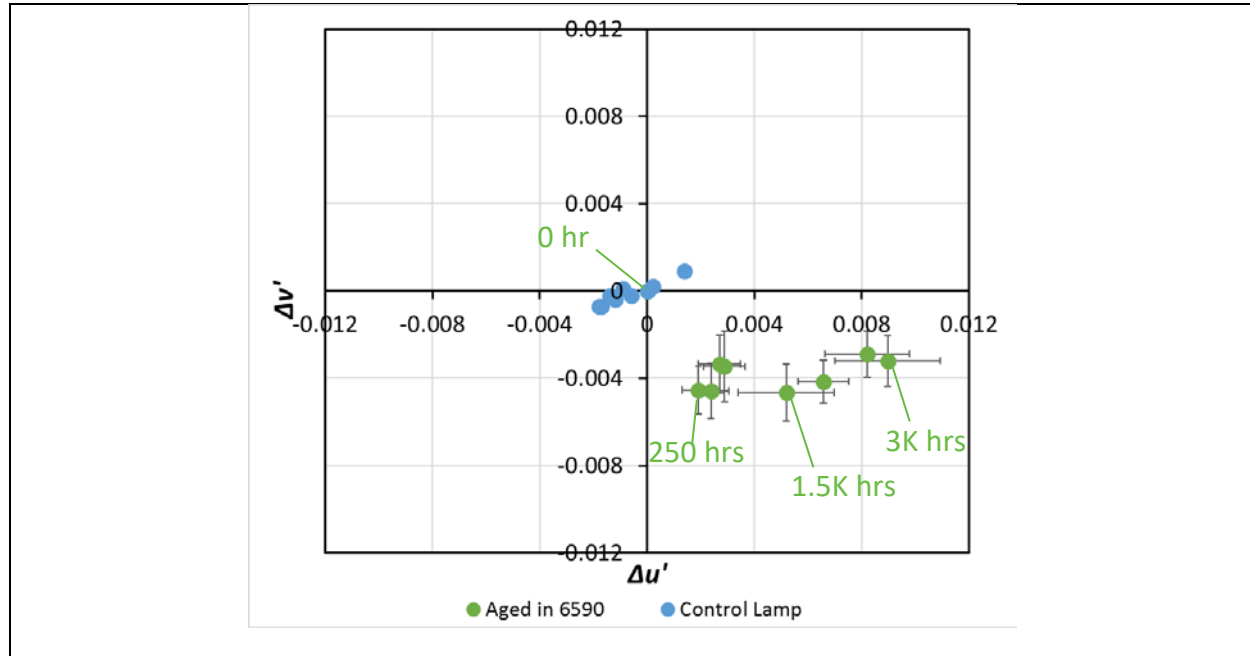


Figure 2-11. Average chromaticity diagram for LSG luminaires aged in 6590.

Note: The control lamp is graphed to show variation in the spectrometer, and the variation in average $\Delta u'$ and $\Delta v'$ is represented with one standard deviation (black bars).

The temporal behaviors of the $\Delta u'$ and $\Delta v'$ coordinates for the LSG DUTs are shown in **Figure 2-12** and **Figure 2-13**, respectively. The $\Delta u'$ component of chromaticity shift for the LSG DUTs rose rapidly in the positive direction within the first 250 hrs where an asymptotic limit was reached (Figure 2-12). After this initial chromaticity shift, the $\Delta u'$ component of chromaticity plateaued before continuing its rise from 1,000 hrs through 3,000 hrs of testing to date. The rapid process responsible for the large initial change in the $\Delta u'$ component of chromaticity shift can be fit with a bounded exponential model with high accuracy and was found to have an asymptote (A) of $\Delta u' = +0.0032$. The incubated process responsible for the positive shift after 1,000 hrs was best fit with a logistic model. An exact termination point for the second chromaticity shift modeled by the logistic function has yet to be determined, but the model suggests $\Delta u' = 0.055$. Therefore, the overall chromaticity shift, which is modeled as the sum of the bounded exponential process and logistic process, has an estimated terminal chromaticity shift of $\Delta u' = +0.058$.

The $\Delta v'$ component of chromaticity shift for the LSG DUTs also experienced a very large shift within the first 250 hrs of exposure: $\Delta v'$ dropped to a lower asymptote (L) of $\Delta v' = -0.0037$ within this timeframe. Although there appears to be slight, oscillate variation in the $\Delta v'$ component of chromaticity shift after 250 hrs of testing, there is no further evidence to support that other processes were occurring to change $\Delta v'$, and therefore the $\Delta v'$ component of chromaticity shift was fit with a single bounded exponential function that plateaus before 250 hrs.

The chromaticity shift model of $\Delta u'$ was optimized by summing one logistic function and one bounded exponential function. The chromaticity shift model of $\Delta v'$ was optimized with one bounded exponential function. The statistical parameters are presented in **Table 2-5**. The optimization was performed with the SSE and least squares methods.

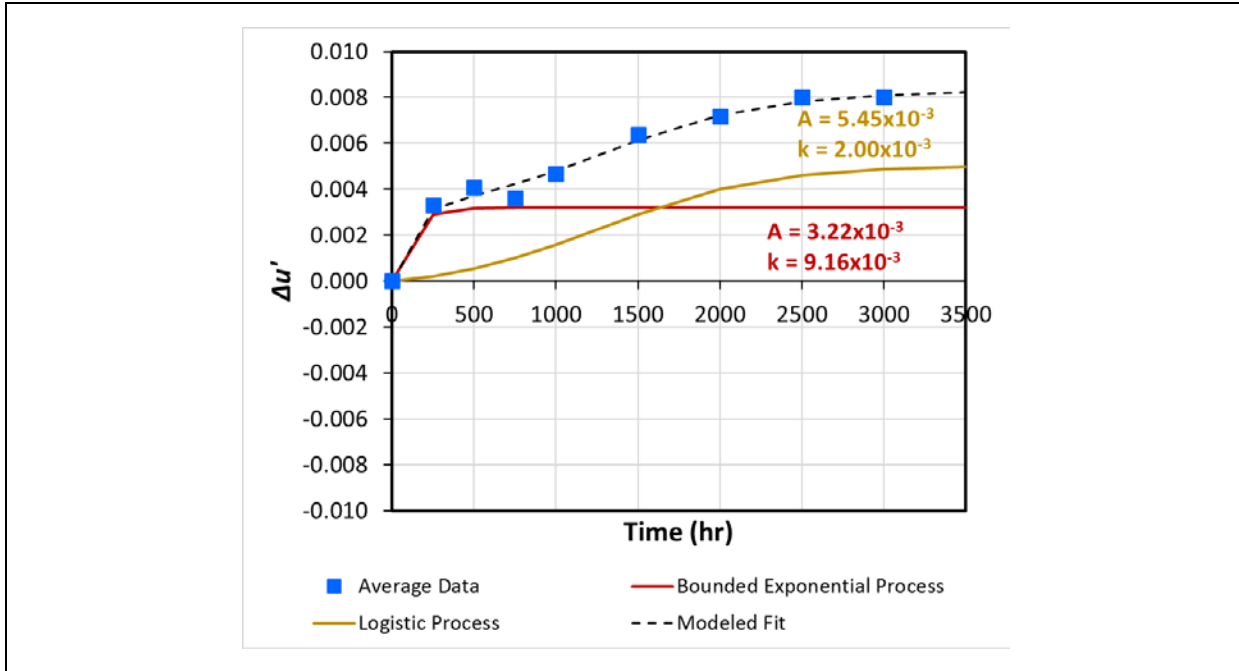


Figure 2-12. Chromaticity shift modeling for the average change in $\Delta u'$ for the LSG DUTs.

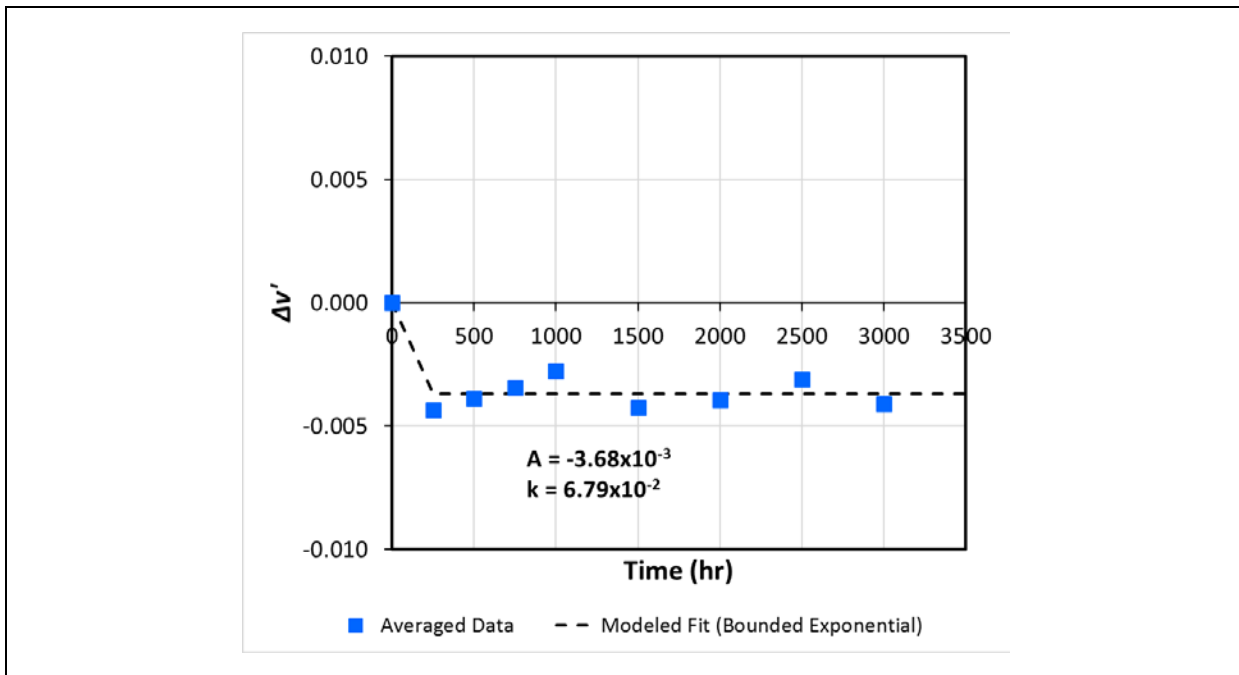


Figure 2-13. Chromaticity shift modeling for the average change in $\Delta v'$ for the LSG DUTs.

Table 2-5. Statistic Parameters of Models for $\Delta u'$ and $\Delta v'$ for the LSG DUTs

$\Delta u'$ Model	
Bounded exponential component	$\Delta u' = (3.22 \times 10^{-3})(1 - e^{-(9.16 \times 10^{-3})t})$
Logistic component	$\Delta u' = -3.92 \times 10^{-4} + \frac{(5.45 \times 10^{-3})}{(1 + 7.31e^{-(2.00 \times 10^{-3})(t-285.81)})}$
SSE	6.64×10^{-7}
R ²	0.994
DW statistic	2.41
$\Delta v'$ Model	
Bounded exponential component	$\Delta u' = (-3.68 \times 10^{-3})(1 - e^{-(6.79 \times 10^{-2})t})$
SSE	2.13×10^{-6}
R ²	0.919
DW statistic	2.49

2.5 Changes in Lenses

LED lenses have many functions, and various lens materials are used to manufacture a luminaire with a desired shape and aesthetic light source. Lenses are primarily used to control the beam angle over which light is distributed, the crispness of the beam-edge, and to contribute to light extraction from the LEDs. For an LED lamp to be reliable, its lenses must maintain high transparency and refractive index through operation, and they must be chemically and thermally stable. When lenses fail to maintain stability in any of these areas over the performance of the device, chromaticity and luminous flux maintenance parametric failures have occurred.^{14,15}

The two manufacturers, LSG and Newhouse Lighting, both use polycarbonate lenses in their respective products, though the shape of the lenses differ drastically. The Newhouse Lighting PAR38 grow lamp uses a large lens with a single dome-like structure in the center that diffuses the LED light from the center of the device. This dome spatially corresponds to the cluster of LED packages on the LED module for the Newhouse Lighting lamp. The LSG PAR38 grow lamp uses a smaller lens with 16 individual dome-like structures for light shaping above each LED. There are 16 LED packages on the LSG LED module, and they also spatially correspond to the 16 domes of the lens.

A comparison on new and lamps exposed to 6590 for 3,000 hrs is presented in **Figure 2-14** and **Figure 2-15** for the Newhouse Lighting and LSG products, respectively. The secondary lenses on the Newhouse Lighting DUTs began experiencing hairline cracks and yellowing early in exposure as shown in Figure 2-14. Hairline cracks in the secondary lens decrease light output due to increased internal reflection, which changes the refractive properties of the lens on a micro-scale, and light output decreases. Hairline cracks are an indication of thermomechanical stress caused by chemical degradation in the polymer due to the combined effects of temperature, humidity, and blue radiation, which is supported by the thermal data collected on these DUTs (**Figure 2-16**). The cause of the thermomechanical stresses that resulted in cracking is not known, but molded-in stress is a potential candidate. The lenses on the Newhouse Lighting DUTs also showed signs of yellowing with ageing. Polycarbonate lenses have been shown to photo-oxidize at moderate temperatures in high humidity environments and display increased light absorption in the region from 400 nm to 550 nm, which causes a yellow appearance.¹⁵

The lenses of the LSG DUTs have also yellowed with time, but show no signs of cracking. Because the LSG DUTs are also made of polycarbonate, the lack of hairline cracking must be attributed to the design and manufacturing processes used for the lens. Most likely, there is less molded-in stress in the lens used in the

LSG product. As shown in Figure 2-16, the temperature of the LSG DUTs was lower overall compared with the Newhouse Lighting DUTs, and this thermal management may be the reason for better lens stability.

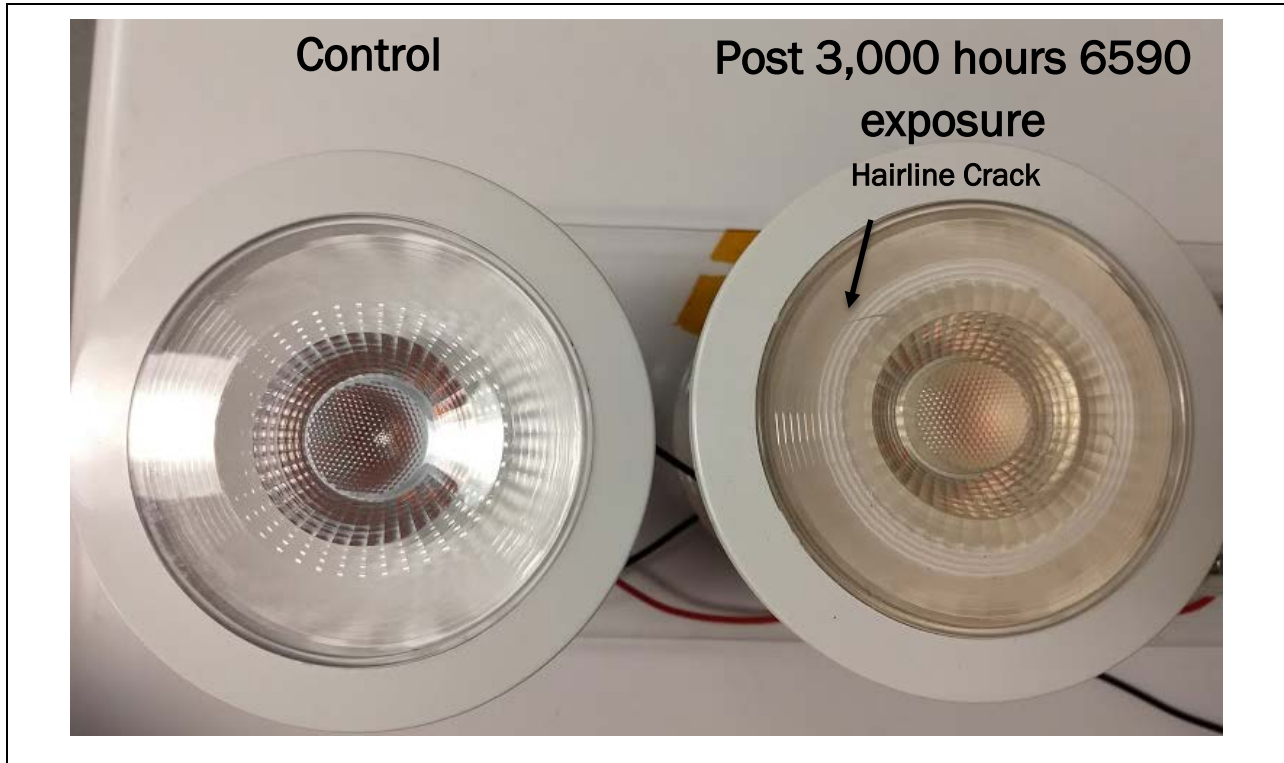


Figure 2-14. Aged lenses (right) of the Newhouse Lighting DUTs show cracking and yellowing compared with the control (left).

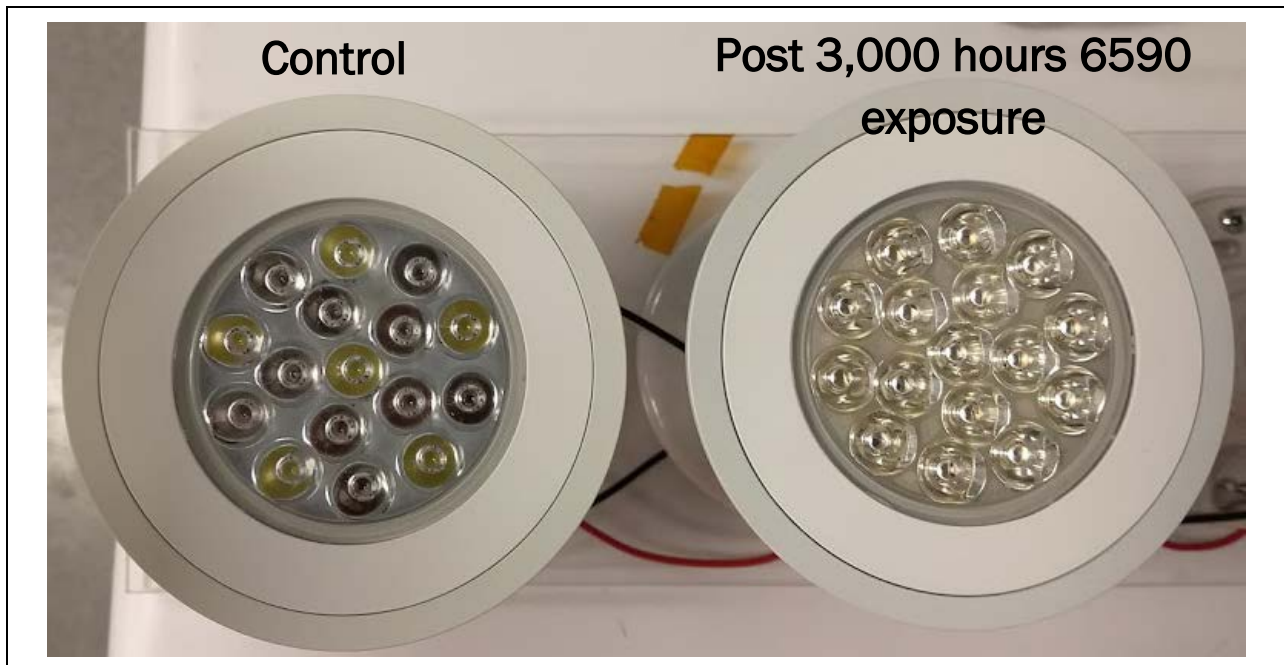


Figure 2-15. Aged lenses (right) of the LSG DUTs are yellowed compared with the control (left).

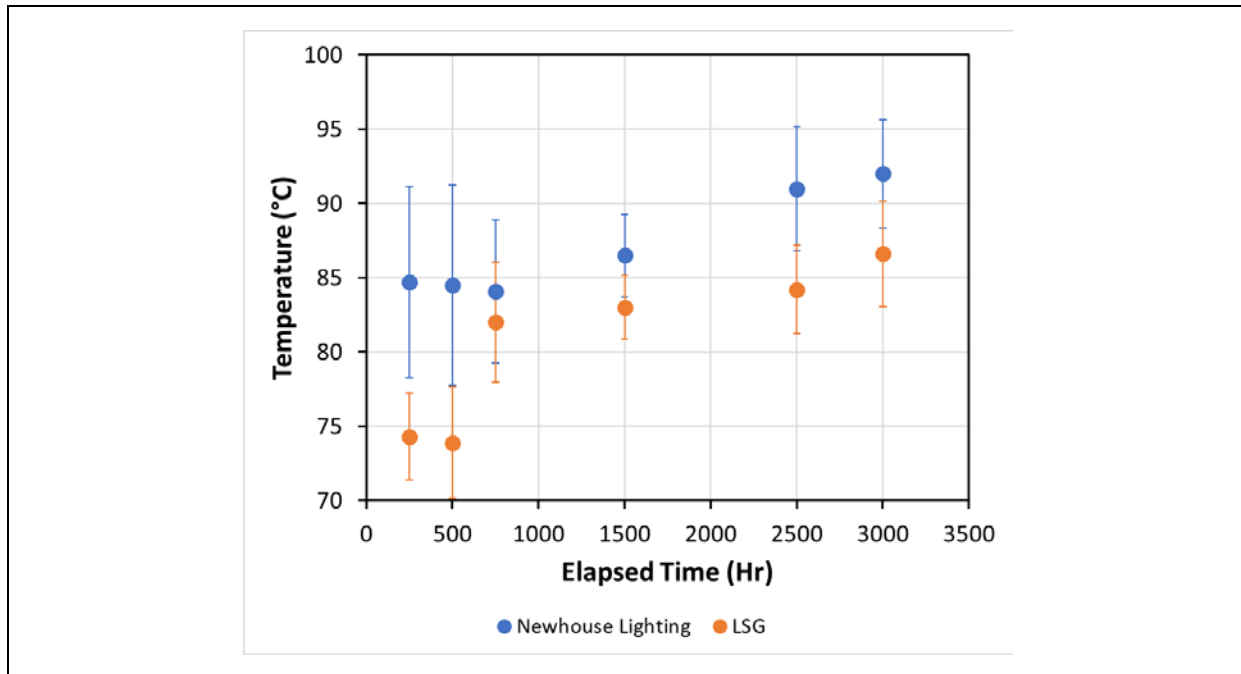


Figure 2-16. Average maximum temperature experienced by the Newhouse Lighting and LSG DUTs during each round of testing.

Note: Error bars represent one standard deviation.

Unfortunately, the impact of lens yellowing on the emission spectra cannot be evaluated directly at the current time because removing the lens for testing may change the o-ring seal. As a proxy, an experiment was performed to gauge the impact of lens yellowing on the emission spectra produced by the horticulture lamps. In this experiment, the lens of the control Newhouse Lighting and LSG lamps were covered by one of two films: a clear, light diffusing polycarbonate film or a yellowed, light diffusing polycarbonate film. The clear film was taken from a new downlight, whereas the yellowed film was taken from an equivalent downlight that had been subjected to elevated ambient temperatures during AST. The diffusing films were laid directly on top of the control lamps, and the spectral power distribution (SPD) was recorded with the 65-inch integrating sphere. The transmittance spectra of these two lenses clearly show that the transmittance of light in the blue spectral region was reduced with the yellowed lens, as shown in **Figure 2-17**. The measured SPDs for the Newhouse Lighting control lamp and LSG control lamp are presented in **Figure 2-18** and **Figure 2-19**, respectively. The yellowed diffusing film significantly reduced the emission of light in the blue spectral region for both control lamps due to the yellowed diffusing film's increased absorption at these wavelengths, as shown in Figure 2-17. In contrast, light emission at longer wavelengths (e.g., red), are essentially the same when either the clear or yellowed diffusing films were used, since the transmittance was similar at these wavelengths.

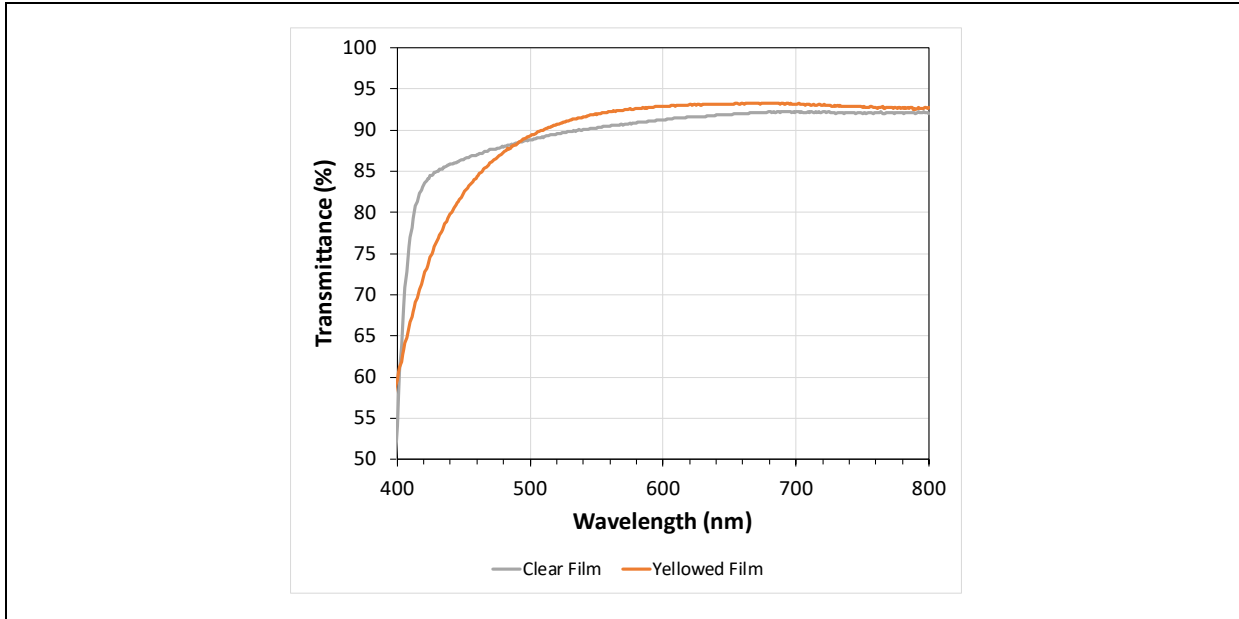


Figure 2-17. Transmittance spectra of the yellowed light diffusing film and the clear light diffusing film used to modify light emission from the controls.

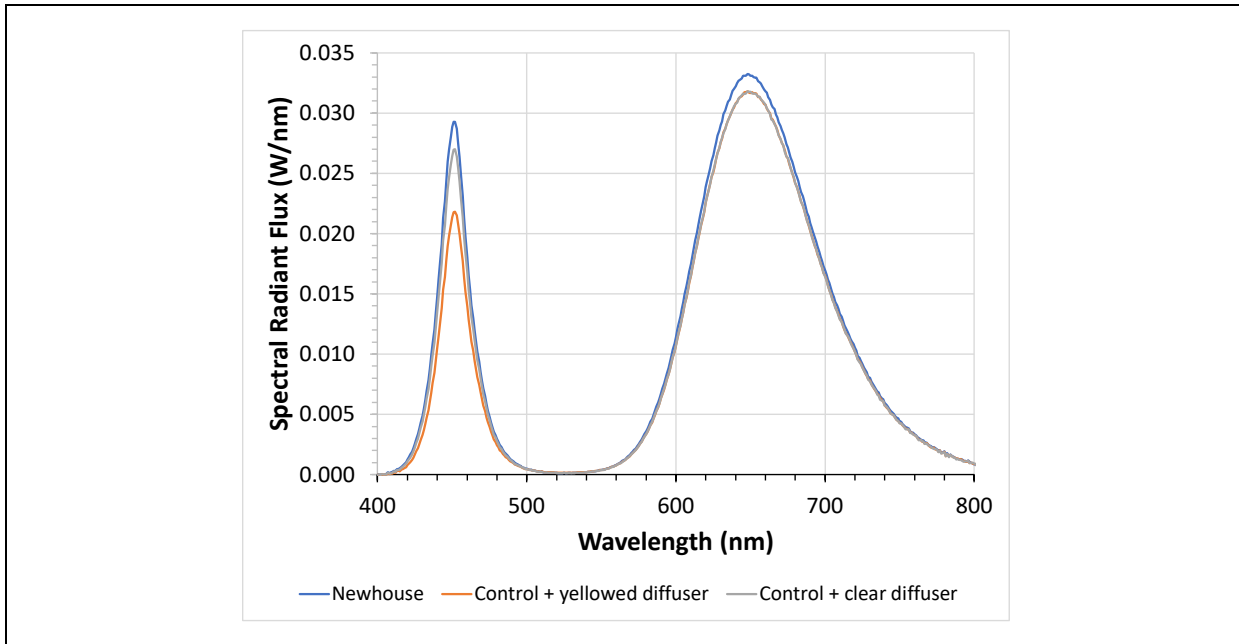


Figure 2-18. Measured SPDs of the Newhouse Lighting control lamp modified with the light diffusing films.

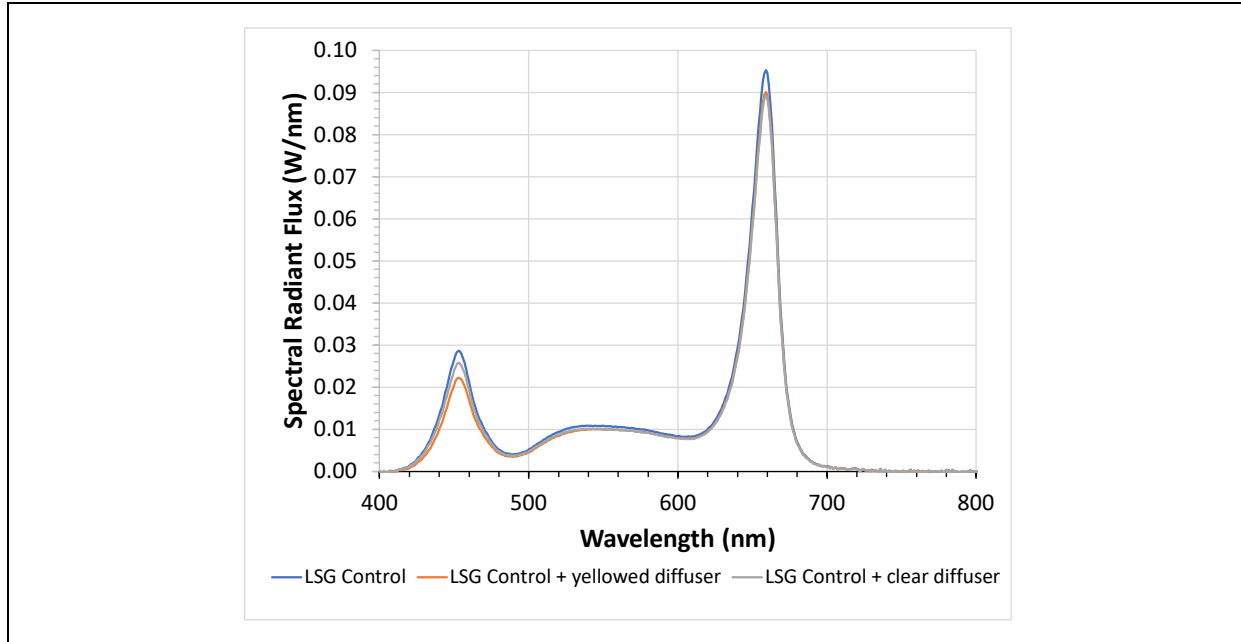


Figure 2-19. Measured SPDs of the LSG control lamp modified with the light diffusing films.

The impacts of these spectral changes on chromaticity of the device were significant. For the Newhouse Lighting lamp, the spectral changes were along a straight line as shown in **Figure 2-20**. For the LSG lamp, the initial chromaticity point was different because of the different emission profile. However, the chromaticity change in this instance also followed a straight line as shown in **Figure 2-21**. This straight line behavior for the Newhouse Lighting lamp was similar to those observed for the samples aged in 6590 (see Figure 2-10) and was consistent with the loss of blue emissions, either through filtering from yellowed lenses or changes in the LED package. In contrast, the chromaticity change found for the LSG control lamp did not match the measured changes for samples aged in 6590 (see Figure 2-10). This finding might have been a consequence of the fact that the LSG lamps have three sources of light emission (i.e., the blue LED, the green phosphor, and the red LED); therefore, the change in the balance of all three will impact chromaticity. Because this experiment effectively filters mainly blue light, it is not designed to compensate for changes in green emission through reduced blue down-conversion in the phosphor. As a result, the measured chromaticity shift for the LSG lamps aged in 6590 does not follow that of a simple blue filtering model.

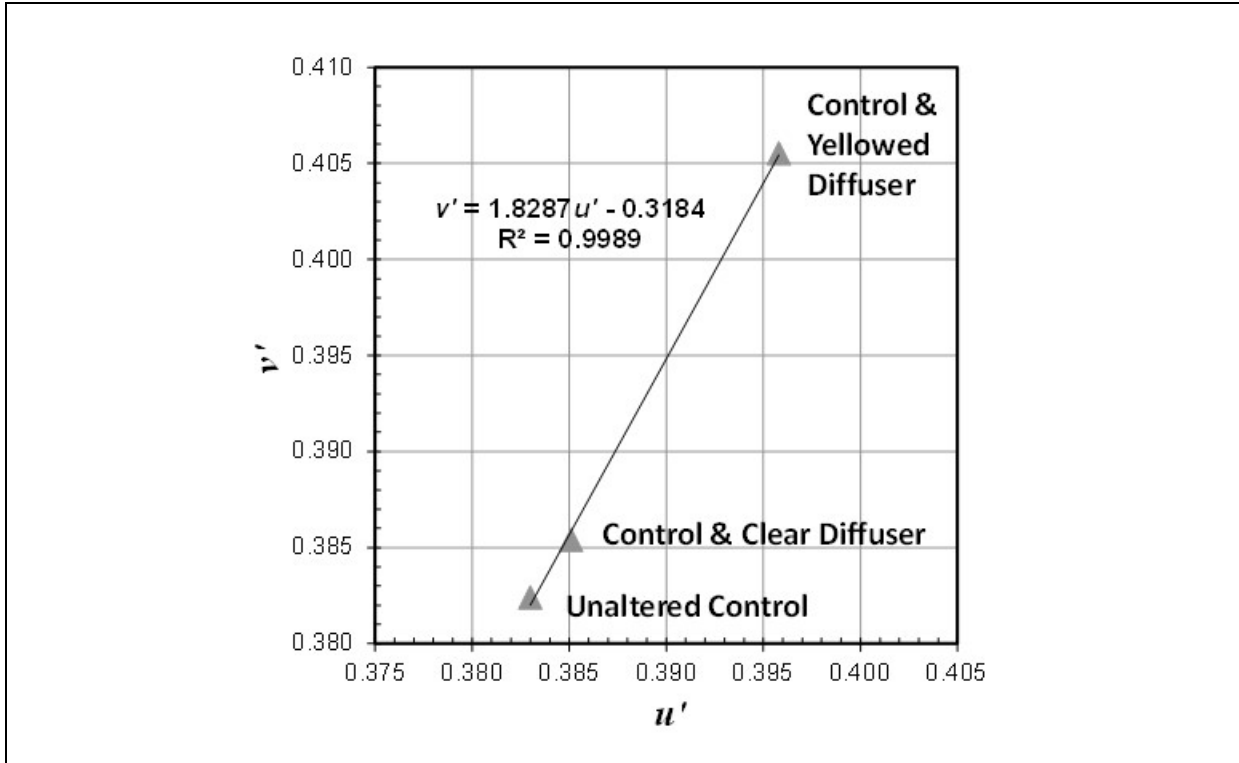


Figure 2-20. Chromaticity change of the Newhouse Lighting control lamp when modified by the light diffusing films.

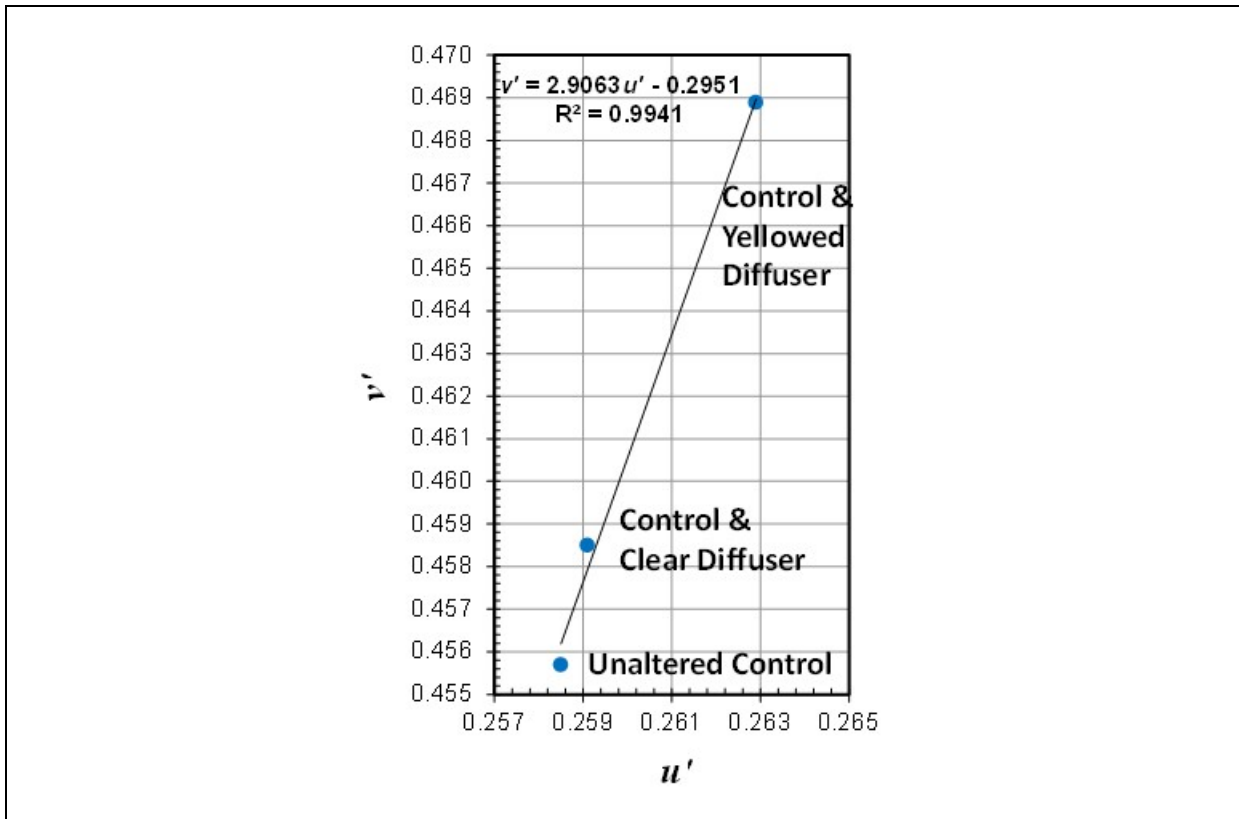


Figure 2-21. Chromaticity change of the LSG control lamp when modified by the light diffusing films.

3 Multi-source LED Products: Tunable-White Modules

The luminous flux and chromaticity maintenance of two-chip tunable-white LED modules was investigated to evaluate the behavior of the two LED primary sources and to compare the findings to those of horticulture lamps. As shown in **Figure 3-1**, the studied LED modules consisted of a warm white LED primary and a cool white LED primary mounted on the same FR-4 PCB. In these samples, each LED primary consisted of 40 MP-LEDs in the 5630 package. Both the warm white and cool white primaries are configured with 10 strings of LEDs in parallel with four LEDs in each string. The spectrum produced by these LED modules can be tuned in a linear manner between nominal CCT values of 2,700K and 6,500K with a user interface and a digital multiplex driver with separate output channels to operate the warm white and cool white primaries.⁵



Figure 3-1. Tunable-white LED module examined in this study.

The ASTs used in this portion of the study consisted of elevated ambient temperature bakes performed at either 75°C or 95°C. These conditions were chosen to be an acceleration of possible conditions in indoor settings. Within each elevated ambient temperature there were four separate test groups of LEDs, each operated at different currents as shown in **Table 3-1**. During testing, the DUTs were operated for 1 hour on and 1 hour off at the chosen forward current. The modules operated at 300 mA and 1,500 mA were switched on and off together, and the modules operated at 700 mA and 1,000 mA were switched on and off together. There were two identical samples per group, and an identical LED module, which was not exposed to the elevated ambient environment, was kept separate as a control. Both DUTs operated at the same current were powered with a dedicated single-channel driver set to the specific current, except for the samples operated at 1,500 mA, which were powered by a dual-channel laboratory power supply. Photometric testing of the samples and the control was performed in a 65-inch integrating sphere after each 500-hr increment of testing, up to 7,000 hrs of exposure. After 7,000 hours of testing, photometric testing was performed after every additional 1,000 hrs of exposure. All photometric testing was performed at room temperature, with the LED primaries operated at a forward current of 700 mA, regardless of the test currents used in elevated temperature exposure.

Table 3-1. Test Current, by Group, for the Tunable-White LED Modules

Test Group	LED Module Current (mA) per LED Primary	Current per LED Package (mA)
1	300	30
2	700	70
3	1,000	100
4	1,500	150

3.1 Spectral Changes

During testing, the warm white and cool white LED primaries exhibited different behaviors, and the magnitude of these changes varied depending upon the forward current and the elevated ambient temperature. The two primaries differed in the change of both luminous flux and chromaticity and such changes were accelerated in the higher temperature exposure environment. A comparison of the changes in SPDs from the initial reading to that after 13,000 hrs of exposure, are presented for the warm white LED primary (**Figure 3-2**) and the cool white LED primary (**Figure 3-3**), operated at a forward current of 1,000 mA and at a temperature of either 75°C or 95°C.

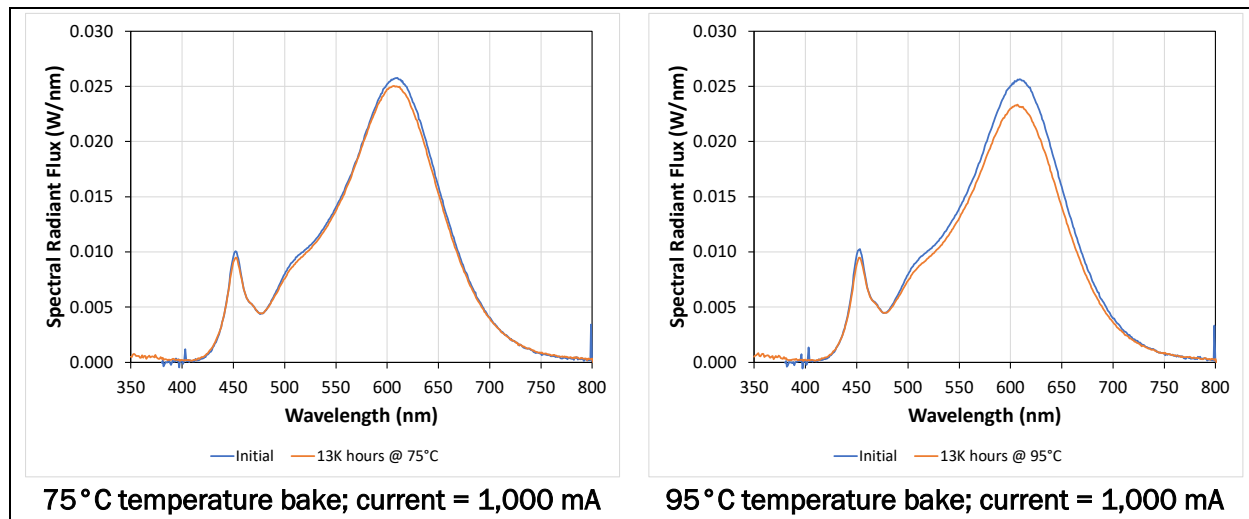


Figure 3-2. Comparisons of the changes in the SPDs of the warm white primary in 75°C (left) and 95°C (right) elevated ambient temperature testing. The forward current during testing was 1,000 mA for the warm white LEDs.

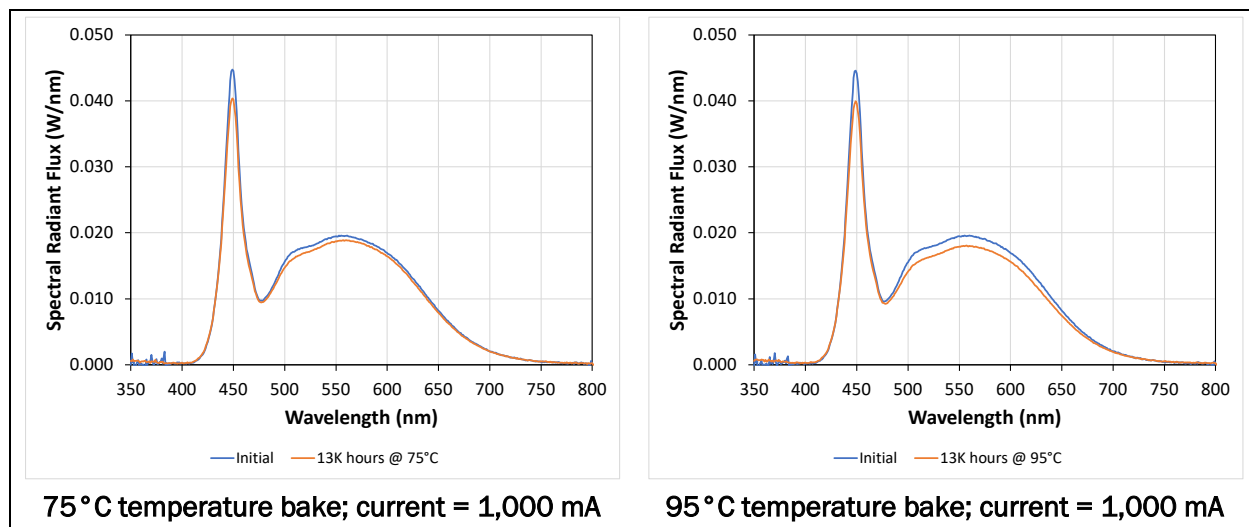


Figure 3-3. Comparisons of the changes in the SPDs of the cool white primary in 75°C (left) and 95°C (right) elevated ambient temperature testing. The forward current during testing was 1,000 mA for the cool white LEDs.

For the warm white primary samples, the luminous flux decreased after 13,000 hrs of testing, and the amount of luminous flux decrease was greater for the DUTs exposed to the 95°C environment than for those exposed to 75°C. Similar trends were observed for all forward currents examined in this study, which are discussed further in Section 3.2 of this report. In addition to the changes in luminous flux, there is a change in the

emission properties of the phosphor that resulted in a chromaticity shift for the warm white primaries. This chromaticity change was most clearly observed when the phosphor emission is normalized to its maximum value, as presented in **Figure 3-4**. After 13,000 hrs of testing, a shift in the phosphor emission peak toward shorter wavelengths by approximately 3 nm was found in the samples operated at 1,000 mA in the 95°C environments. Similar changes in the emission profiles were observed at other test conditions, which are discussed further in Section 3.3 of this report.

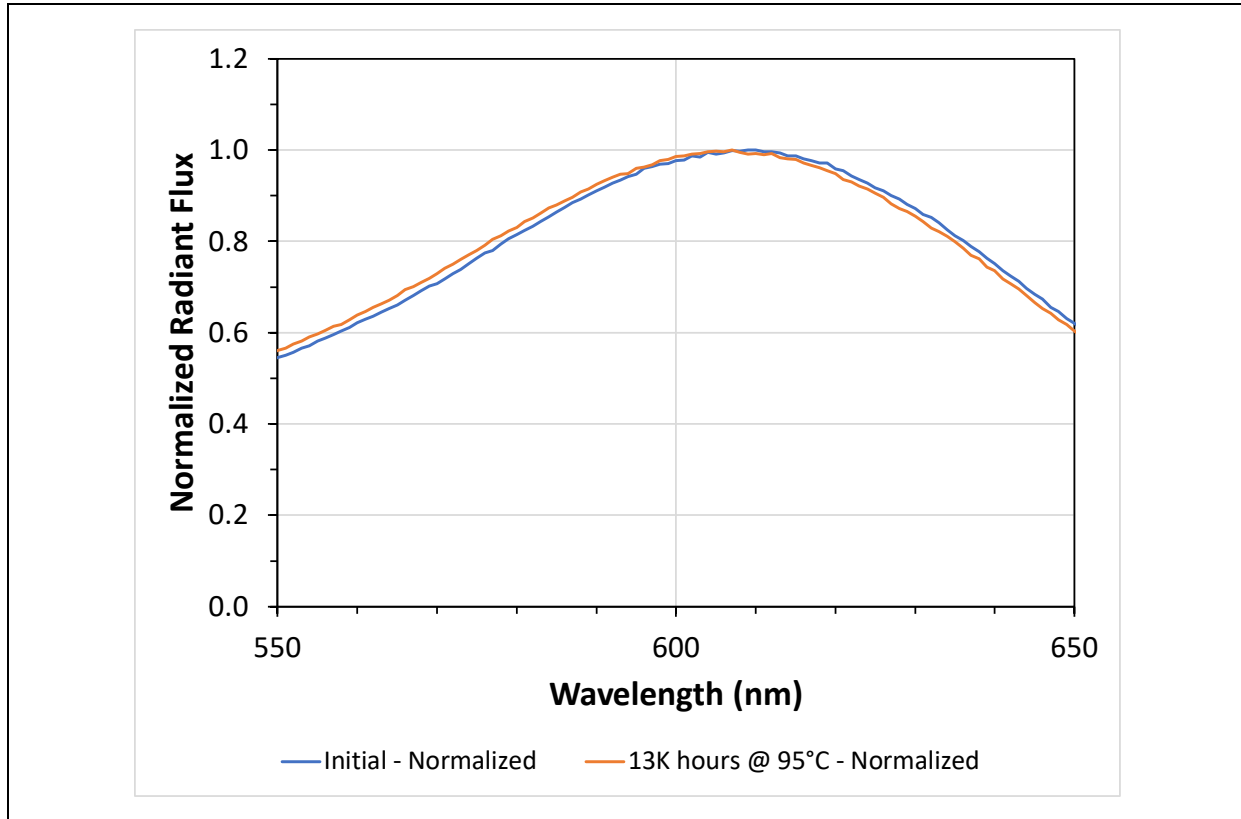


Figure 3-4. Normalized light emissions from warm white LED primaries, after 13,000 hrs of operation at 95°C and 1,000 mA (2-hr duty cycle).

For the cool white LED primaries, the luminous flux decreased with exposure to the elevated ambient temperatures, as shown in Figure 3-3, and the magnitude of this change was greater for the DUTs exposed to 95°C than for those exposure to 75°C. However, in contrast to the behavior for the warm white primaries, the cool white primaries did not exhibit a noticeable change in shape of the light emission peaks.

3.2 Luminous Flux Changes

The changes in luminous flux maintenance for the warm white and cool white LED primaries, at the different forward currents used in this test, are presented in **Figure 3-5** and **Figure 3-6** respectively. Several trends can be discerned by evaluating the data. First, the luminous flux maintenance of the DUTs operated at 1,500 mA was lower than that of the DUTs operated at lower currents. A second trend that deserves discussion is that there were three separate regions of luminous flux maintenance that are identified as follows:

- Region 1—The emission efficiency increases during the initial operation of the DUT, and the luminous flux maintenance exceeds 1.0.
- Region 2—The luminous flux maintenance begins to decrease from its maximum value.

- Region 3—The decrease in luminous flux maintenance changes to a slower rate than in Region 2.

The initial increase in efficiency that happened during Region 1 occurred rapidly and was completed by 500 hrs for all DUTs. A bounded exponential model was the best approach to account for this behavior.²² In the 75°C environment, the DUTs retained this improved efficiency until approximately 1,500 hrs, when they entered Region 2 and the luminous flux maintenance began to decrease. In the 95°C environment, the DUTs operated at the higher forward currents began to experience a drop in luminous flux maintenance at the 500-hr mark, but this same behavior did not occur until 1,500 hrs for the DUTs operated at 350 mA and 700 mA. Clearly, both temperature and forward current impact the timing of the transition between Regions 1 and 2. By 8,000 hrs, the rate of change in luminous flux maintenance for all DUTs was lower and the devices exhibited Region 3 behavior. It is anticipated that the decline in luminous flux will remain low beyond this point, even at these elevated exposure temperatures. Additional testing is underway to confirm this hypothesis.

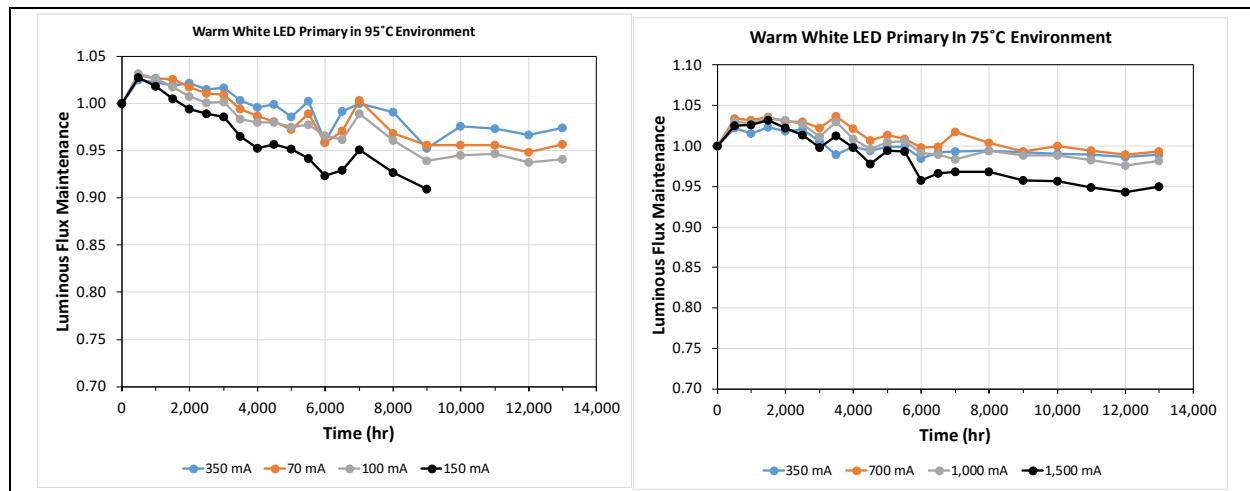


Figure 3-5. Luminous flux maintenance of the warm white LED primaries in the 75°C (left) and 95°C (right) elevated temperature environments.

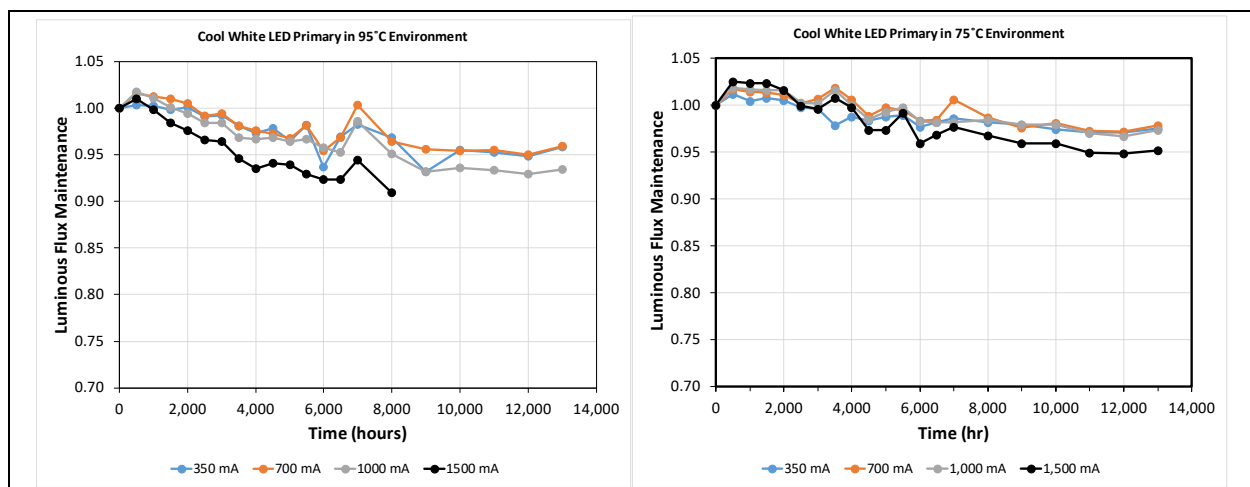


Figure 3-6. Luminous flux maintenance of the cool white LED primaries in the 75°C (left) and 95°C (right) elevated temperature environments.

During these tests, only the DUTs operated at 95°C and 1,500 mA began displaying intermittent shorts between 8,000 and 9,000 hours of testing. This behavior originated from only three or four LEDs in each DUT, but resulted in multiple cool white LEDs not working because of the way the LED packages are

interconnected. Applying pressure to the contacts on the LED package rendered the devices operational for a short period of time, but they eventually stopped working again. This phenomenon appears to be caused by the formation of excessive copper–tin (Cu-Sn) intermetallics in the solder, resulting in cracking of the solder joints connecting the LEDs to the PCB and produced an intermittent electrical open in the circuit. Because this effect was found in both DUTs tested at 95°C and 1,500 mA, testing of these samples was terminated at 9,000 hours. It is worth noting that none of the other samples have displayed this behavior so far. Specifically, through 13,000 hrs of testing, the phenomenon did not occur in any other DUTs in the 95°C test that were operated at lower currents. Likewise, the same phenomenon did not occur in the DUTs operated at 1,500 mA in the 75°C environment through 13,000 hrs of testing. Although it is highly probable that the other samples are producing Cu-Sn intermetallics during operation, the fact that no other solder failures have been observed to date suggests that a combination of temperature and forward current hastened the formation of the brittle Cu-Sn intermetallics and that the process is proceeding much slower in the other samples.

Finally, because there were 13,000 hrs of data, methods such as IES’s TM-21-11 can be used to project the long-term lumen maintenance of the devices.²¹ Although a full analysis using IES’s TM-21-11 method cannot be completed on these samples because there are only two LED modules for each test condition, applying that method does provide useful insights regarding the possible luminous flux maintenance of the devices. For tests that last longer than 10,000 hrs, the TM-21-11 method uses only the last half of the data. For most samples in this study, this requirement would be for data collected at 1,000-hr increments between 6,000 hrs and 13,000 hrs, which covers the end of Region 2 and all of Region 3 in the luminous flux maintenance curves. For the data collected at 95°C and 1,500 mA, the luminous flux maintenance values between 3,000 hrs and 8,000 hrs were used. Finally, IES’s TM-21-11 method only allows a projection of no more than 5.5 times the test period for test populations between 10 and 19 samples, which would be 71,500 hrs for a 13,000-hr test period. (Note: IES’s TM-21-11 method uses a maximum projection time of 5.5 times the test duration for sample sizes between 10 and 19. Although only two LED modules were tested per condition, this more conservative projection limit was used in this report.) The calculated decay rate constants (α) under these assumptions are presented in **Table 3-2**.

Table 3-2. Decay Rate Constant Values for Each Experimental Condition Determined with a Modified Method Based on IES’s TM-21-11

Operating Condition	Warm White LED Primaries		Cool White LED Primaries	
	75°C	95°C	75°C	95°C
Current to primary				
350 mA	1.93×10^{-7}	1.10×10^{-6}	1.46×10^{-6}	5.61×10^{-7}
700 mA	2.33×10^{-6}	3.92×10^{-6}	2.99×10^{-6}	3.19×10^{-6}
1,000 mA	1.65×10^{-6}	5.79×10^{-6}	2.21×10^{-6}	6.20×10^{-6}
1,500 mA	2.92×10^{-6}	9.88×10^{-6}	3.15×10^{-6}	7.99×10^{-6}

Note: The method used for determining these decay rate constants is a modification of the TM-21-11 method because of the low samples size (two units) per testing condition.

With the decay rate constant and the pre-exponential factor (i.e., B value in the TM-21-11 method) calculated as previously described, the projected lifetimes to 80% of the initial luminous flux values (L80) can be calculated and are presented in **Table 3-3**. An examination of Table 3-3 demonstrates that the projected lifetime of the LED primaries for most test settings exceeds the projection limit (i.e., 5.5 times the test duration). It should be noted that the projected lifetimes of the cool white LED primaries tended to be lower than that of the warm white LED primaries under equivalent conditions. The cause of this effect is not obvious from the luminous flux maintenance data, but it might be due to the chromaticity shift behavior as discussed in Section 3.3 of this report.

Table 3-3. Projected Lifetimes to L80 of the LED Primaries Under Different Operating Conditions

Operating Condition	Warm White LED Primaries		Cool White LED Primaries	
	75 °C	95 °C	75 °C	95 °C
Current to primary				
350 mA	>71,500 hrs	>71,500 hrs	>71,500 hrs	>71,500 hrs
700 mA	>71,500 hrs	56,669 hrs	>71,500 hrs	67,433 hrs
1,000 mA	>71,500 hrs	39,744 hrs	>71,500 hrs	36,313 hrs
1,500 mA	70,547 hrs	22,687 hrs	67,007 hrs	25,144 hrs

3.3 Chromaticity Shifts

Although the luminous flux maintenance behaviors of the warm white and cool white primaries are similar in these tests, the chromaticity shift behaviors of the two LED primaries were completely different. Representative examples of the different behaviors are shown in **Figure 3-7** for the warm white and cool white primaries operated at 1,000 mA and 95°C. The initial shift in the chromaticity of the warm white LED primaries produced a larger change in the v' chromaticity coordinate than in u' . This shift was generally in the yellow direction, and the change reached a maximum value ($\Delta u' = 0.0008$ and $\Delta v' = 0.0013$) after approximately 1,500 hrs, when the shift reversed. During the period from 8,000 hrs through the end of this test, the chromaticity shift in the warm white primaries involved mainly a change in u' with minimal change in v' , which indicates a shift toward green chromaticities. After 13,000 hrs of testing, the total chromaticity shift in u' was -0.0027 , and the shift in v' was only -0.0006 . The rate of change in the chromaticity appeared to be slowing down, suggesting that the shift in the green direction may be ending for these experimental conditions. Indeed, there was evidence from testing performed at 95°C and 1,500 mA that the chromaticity of the warm white components will stop shifting in the green direction and will begin to shift more along the $-\Delta v'$ axis, which is toward the blue direction. These data are presented in **Figure 3-8**. Although testing of the samples operated at 1,500 mA in the 95°C environment was terminated after 9,000 hrs, the observed chromaticity shift in the blue direction is consistent with expectations for MP-LEDs made with plastic molding resins.^{10, 12} This finding is also consistent with the cool white data discussed in the next paragraph below.

The chromaticity shift data for all experimental conditions of the warm white primaries examined in this study are provided in [Appendix 1](#). The same basic chromaticity shift behaviors were observed under all test conditions, although the timing of the shifts changed depending on the test conditions. In particular, milder conditions were found to delay some of the chromaticity shifts, whereas more harsh conditions accelerated their appearance.

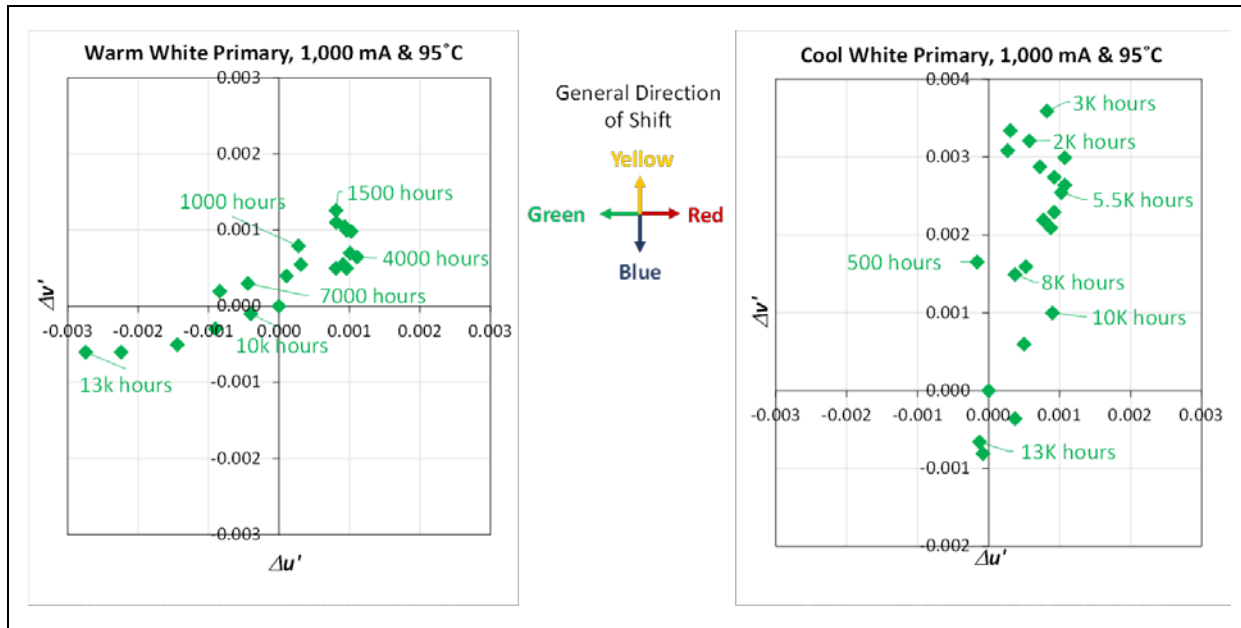


Figure 3-7. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 1,000 mA in the 95 °C temperature condition.

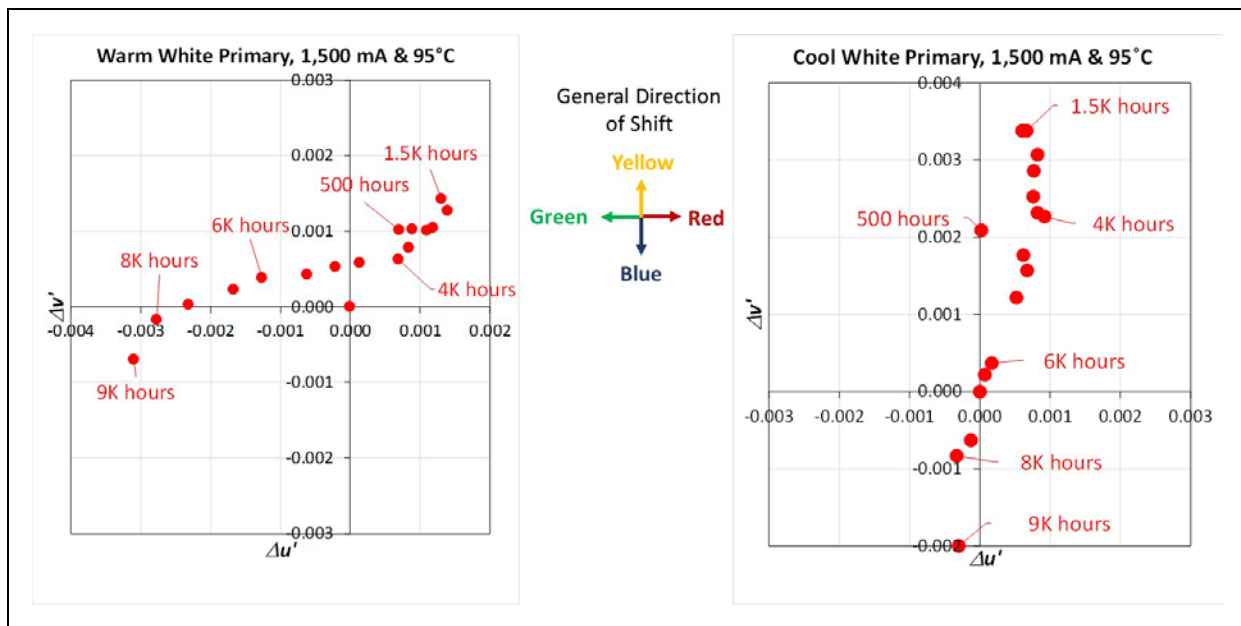


Figure 3-8. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 1,500 mA in the 95 °C temperature condition.

The chromaticity shift changes for the cool white primaries involved mainly a change in v' and minimal changes in u' as shown in Figure 3-7 and Figure 3-8. The initial shift of these cool white primaries produced an increase in v' (i.e., $\Delta v'$ is positive), which reached a maximum at 3,000 hrs for the 95 °C and 1,000 mA test setting and 1,500 hrs for 95 °C and 1,500 mA. Once the maximum was reached, the chromaticity shifts primarily in the $-\Delta v'$ direction and follows the yellow–blue line. In contrast to findings for the warm white LEDs, there was no evidence of a significant shift in the $\pm u'$ direction, indicating that no change in the phosphor emission peak was occurring.

The chromaticity shift data for the cool white primaries in all the experimental conditions examined in this study are presented in [Appendix 1](#). These DUTs followed the sample general pattern as observed at 95°C and 1,000 mA and 95°C and 1,500 mA testing. In addition to these chromaticity shifts, the DUTs experiencing the mildest stress conditions (i.e., 75°C and 350 mA and 75°C and 700 mA) had a short initial shift in the blue direction, followed by a shift in the yellow direction to the maximum point, and terminating with a second shift in the blue direction. This type of shift is characteristic of changes in the molding resin used in MP-LEDs and has been categorized as a chromaticity shift mode (CSM)-4 in MP-LEDs.^{10,12}

4 Discussion

LEDs provide the flexibility to produce light sources that incorporate packages that vary in size, luminous flux emissions, chromaticity, and other parameters. This capability enables enhanced functionality in the SSL devices that is difficult, if not impossible, to achieve with conventional lighting technologies. New lighting products that are better adapted to the needs of humans, plants, and animals have been built, leveraging this capability. For example, SSL products can provide a spectrum that is rich in blue and deep red, which are better tailored to the needs of specific plants, and indoor luminaires for schools and offices can provide a variety of light spectra that are better aligned with human physiology and the task being performed. Although these multi-element LEDs are creating new markets for SSL technologies, this study demonstrates that the ageing properties of all SSL devices is not the same and that careful consideration to potential ageing differences in the LED primaries needs to be given because SSL products may be deployed longer than their conventional counterparts.

This study compared the performance of two horticulture lamp products in the 6590 environment. The Newhouse Lighting product contained only pcLEDs emitting at blue (average peak centroid value of 453.9 nm) and deep red (average peak centroid value of 663.6 nm) wavelengths. The LSG products contained a mix of pcLEDs and direct-emitting red LEDs with major emissions at blue (average peak centroid value 452.4 nm), green (average peak centroid value of 553.4 nm), and deep red (average peak centroid value of 654.4 nm). The report provides findings from AST of these products in the 6590 environment. This test condition was chosen based on previous studies that showed high electronic failure rates in this test environment¹⁴ and feedback from those performing testing of horticulture lamps that high humidity stress testing is important in this application.

Although these products employed different LED architectures to provide lighting for horticulture applications, there are several significant similarities. Most notable among these was the finding that the LED emission peak centroid wavelengths changed little through 3,000 hours of 6590 exposure. Although this finding is not surprising for the direct emissions from the LED, it is surprising for the phosphor emissions, especially the red phosphor. Early studies on warm white LEDs have shown a tendency for the red phosphor to oxidize producing a shift to lower wavelengths in the phosphor emission peak.^{14, 24} This effect was even found in the testing of the tunable-white module reported here (see Figure 3-4). Based on the data, it can be concluded that the humidity stability of the deep red phosphor used in the pcLEDs in the Newhouse Lighting product may be better than that used in many warm white LEDs.

Although the Newhouse Lighting product produces red light through secondary emissions from a phosphor, whereas the LSG product produces red light from a direct-emitting LED, the stability of the two red sources was better than the blue emitter in either product. As a result, the light produced by both products became enriched in red with time in the 6590 test. In both cases, red emissions dropped sharply in the first 750 hours and then changed at a much slower rate, allowing red emissions to eventually overtake the blue emissions. In contrast, the blue emission from both products tended to decrease in a nearly linear manner during the first 3,000 hours of testing. The cause of this linear decrease in blue is unknown. Several factors could play a role in the decline of blue emissions, including optical filtering by the yellowing of the polycarbonate lenses¹³ or increased phosphor conversion of the blue pump.¹⁰ The latter cause seems less likely because phosphor emission decreased, relative to the initial emissions, for both products, and this decrease was especially large for the LSG product, which produced phosphor-converted white light. Additional studies will be conducted to try and isolate the root cause of the relative changes in red and blue emissions, but this analysis can only be performed when the test is complete because it is destructive to the sample.

Although there were several significant similarities in the behaviors of the Newhouse Lighting and LSG horticulture lamps, there was a significant difference in the chromaticity shift behaviors of the two products that can be directly traced to the LED module. The chromaticity of the Newhouse Lighting products initially shifted in a generally blue direction, and then changed course and began shifting in a direction that was

between red and yellow. This shift remained along a straight line that connects the blue LED and red phosphor emissions as shown in Figure 1-2. In some regards, the behavior observed for the Newhouse Lighting lamp is analogous to that of the cool white LED primary discussed in Section 3. Based on the 3,000 hours of test data reported here, the CSM that can be assigned to the Newhouse Lighting product is CSM-3; however, the testing is not complete and an additional blue shift may still occur, because MP-LEDs often exhibit CSM-4 behavior in long-term testing.^{10, 12}

The chromaticity shift behavior of the LSG horticulture lamp was completely different from the Newhouse Lighting product, and differences are directly tied to the device structure. The LSG device exhibited a CSM-5 behavior during the first 3,000 hours of testing in 6590.^{11, 17} This chromaticity shift was due in part to the rapid drop in green emissions during the first 1,000 hours of testing and the continued approximately linear drop in green emissions thereafter. The finding of the impact of green emission loss on chromaticity is consistent with earlier results that demonstrated that one of the causes of CSM-5 behavior was due to a drop in green emissions.¹⁷ The nearly linear drop in blue emissions from the LSG device likely also contributed to the CSM-5 behavior because the rate of blue emission losses was greater than that of red. It is worth noting that the radiant flux produced by the direct-emitting red LED remained relatively stable, and there was only a 5% drop in relative radiant flux (as shown in Figure 2-4) through 3,000 hours of testing. In contrast, the Newhouse Lighting product exhibited an approximately 12% decrease in red radiant flux during the first 3,000 hours of testing (see Figure 2-3). Despite these differences, it is still possible that the chromaticity of the LSG device will ultimately shift in the blue direction due to the impact of oxidation of the molding resin used in the MP-LED.¹⁰ A similar shift in the blue direction is not expected for the red direct-emitting LED because the molding resin photo-oxidation reaction likely requires blue photons in addition to heat. Further testing is being pursued to confirm this hypothesis; the results will be included in future reports.

Finally, the chromaticity shifts of the warm white and cool white LED primaries in the tunable-white module were different, and these differences were mainly derived from the relative stability of the phosphors used in each pcLED device. The cerium-doped yttrium aluminum garnet (Ce:YAG) phosphor often used in cool white LEDs is generally very stable chemically and will not undergo changes in the emission profile under normal operating conditions. Other factors, such as encapsulant degradation, phosphor-binder delamination, or molding resin oxidation, may produce changes in cool white LEDs.^{10, 11} In contrast, the nitride and oxynitride phosphors typically used to produce warm white colors have a tendency to undergo an oxidation reaction, especially in the presence of humidity,^{10, 11, 12, 14, 24} which reduces the emission wavelength of the device as shown in Figure 3-4.

Ultimately, the final chromaticity shift for both the cool white and warm white primaries is expected to be in the blue direction due to oxidation of the molding resin housing used in the MP-LED package.^{10, 12} This shift has already been observed for both the warm white and cool white primaries under the most severe conditions used in these tests (see Figure 3-8). There is also support for the CSM-4 behavior in the cool white primary from data taken under less severe conditions as shown in the [Appendix 1](#). It is hypothesized that the warm white LEDs are also likely to be affected by oxidation of the MP-LED molding resin and will ultimately shift in the blue direction, resulting in the CSM-4 behavior. However, because the conversion rate of blue photons to longer wavelength emissions is higher in warm white devices, it will likely take long for this reaction to have a significant impact. This hypothesis is supported by the data shown in the [Appendix 1](#).

5 Conclusions

The LEDs used in SSL products for horticulture lighting and tunable-white office lighting have provided enhanced capabilities to lighting products that are not possible with conventional technologies. The wide variety of form factors, luminous flux levels, and emission wavelengths allow the spectra produced by SSL devices to be tailored to application specific needs, whether the product is targeted for plants or humans. MP-LEDs are often used in these devices because of their ability to provide a low-cost diffuse light source, and the samples examined in this report all contained MP-LEDs. AST performed on these devices demonstrated the potential longevity of MP-LEDs in many lighting applications. These tests also showed that the chromaticity stability of MP-LEDs will vary depending on the LED design. Direct-emitting red LEDs were found to be stable both in chromaticity and emission wavelength peak through 3,000 hours of testing in 6590. In contrast, pcLEDs were limited by the characteristics of the phosphor and instances of phosphor emission quenching (LSG horticulture lamp), emission wavelength changes (warm white LED module), and decreases in luminous flux (Newhouse Lighting horticulture lamp) were traced back to the phosphor. Ultimately, many MP-LED packages may tend to exhibit chromaticity shifts in the blue direction (i.e., CSM-4) as a final chromaticity shift. Based on previous data, this terminal chromaticity shift is likely to proceed until a reasonable parametric threshold for chromaticity shift (e.g., $\Delta u'v' \geq 0.007$) is surpassed. This conclusion is based on findings from the tunable-white LED modules (consisting of cool white and warm white LED primaries) presented in this report. Based on this data and other similar data,^{10, 12} the timing at which this terminal chromaticity shift becomes dominant depends upon temperature, forward current, and the CCT of the device. Consequently, the best approach to minimize this potential failure mode in SSL products utilizing MP-LEDs (e.g., horticulture lamps, tunable-white troffers) is to minimize operational temperature and forward current.

6 References

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Appendix 1

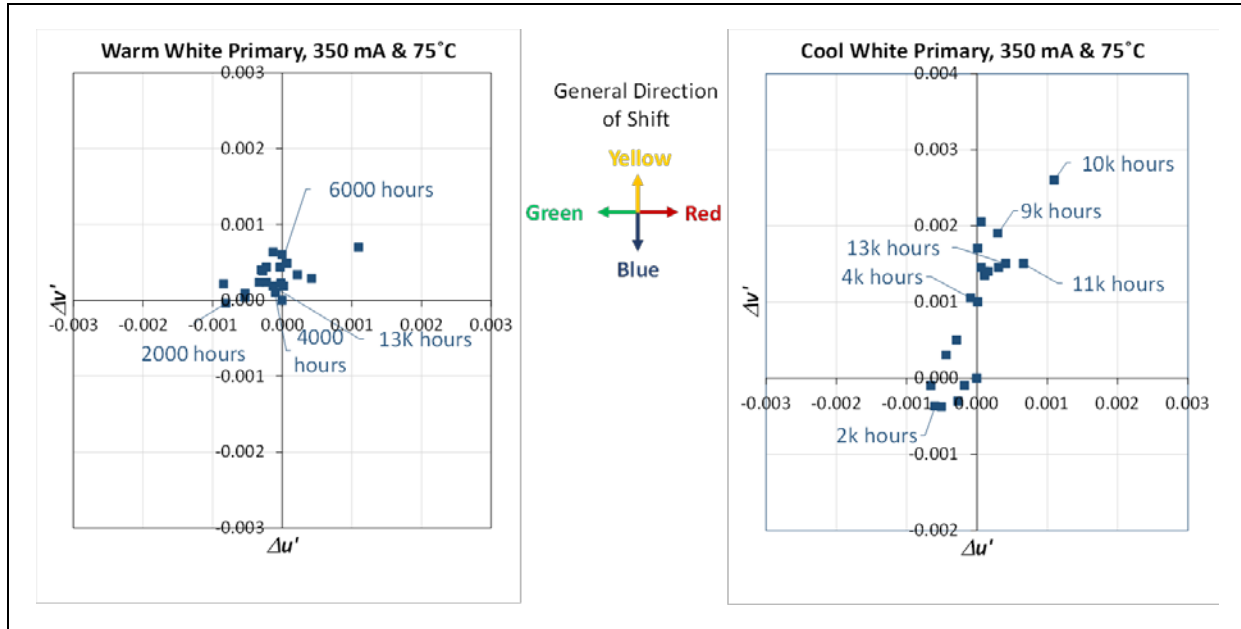


Figure A-1. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 350 mA in 75°C temperature conditions.

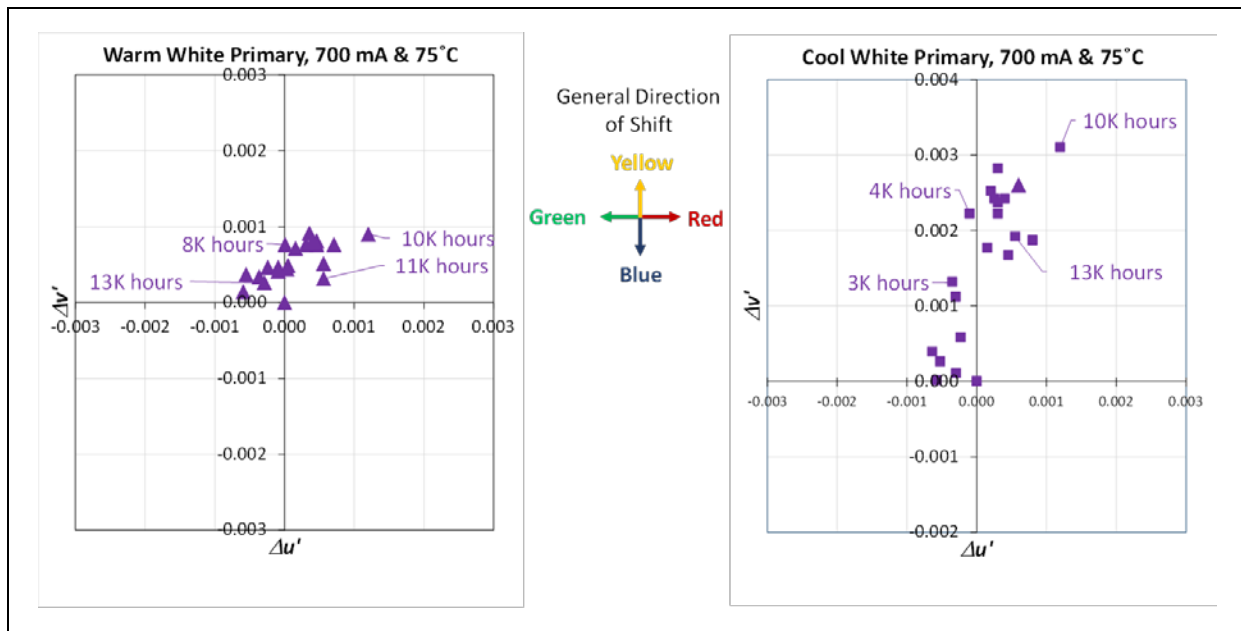


Figure A-2. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 700 mA in 75°C temperature conditions.

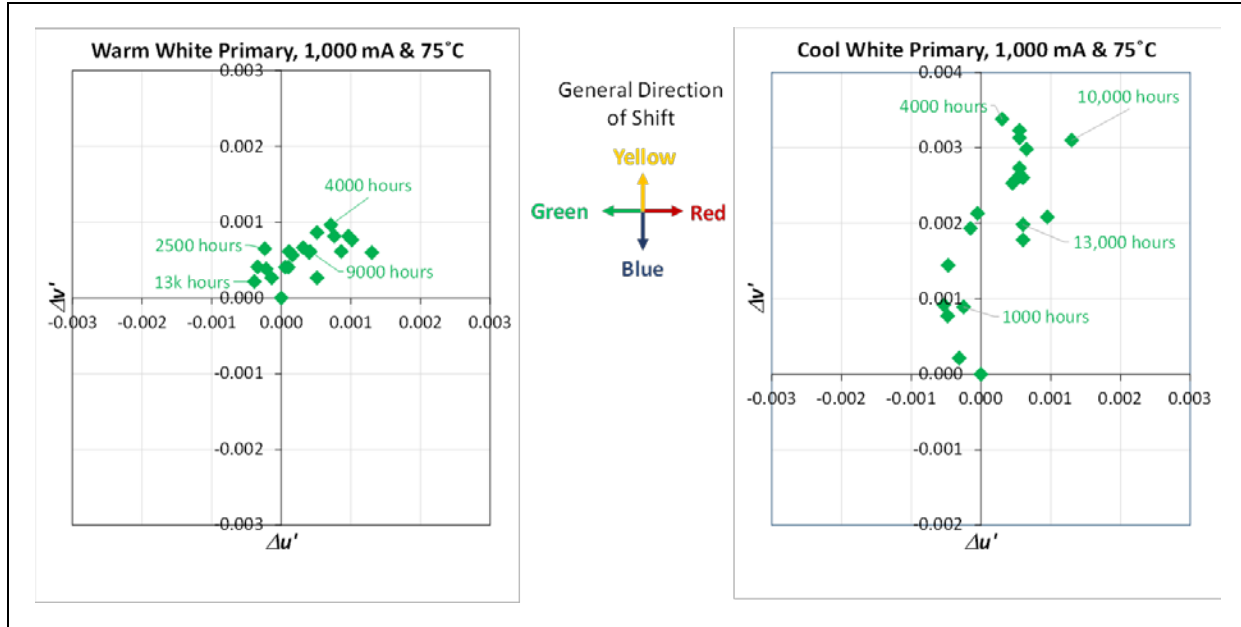


Figure A-3. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 1,000 mA in 75°C temperature conditions.

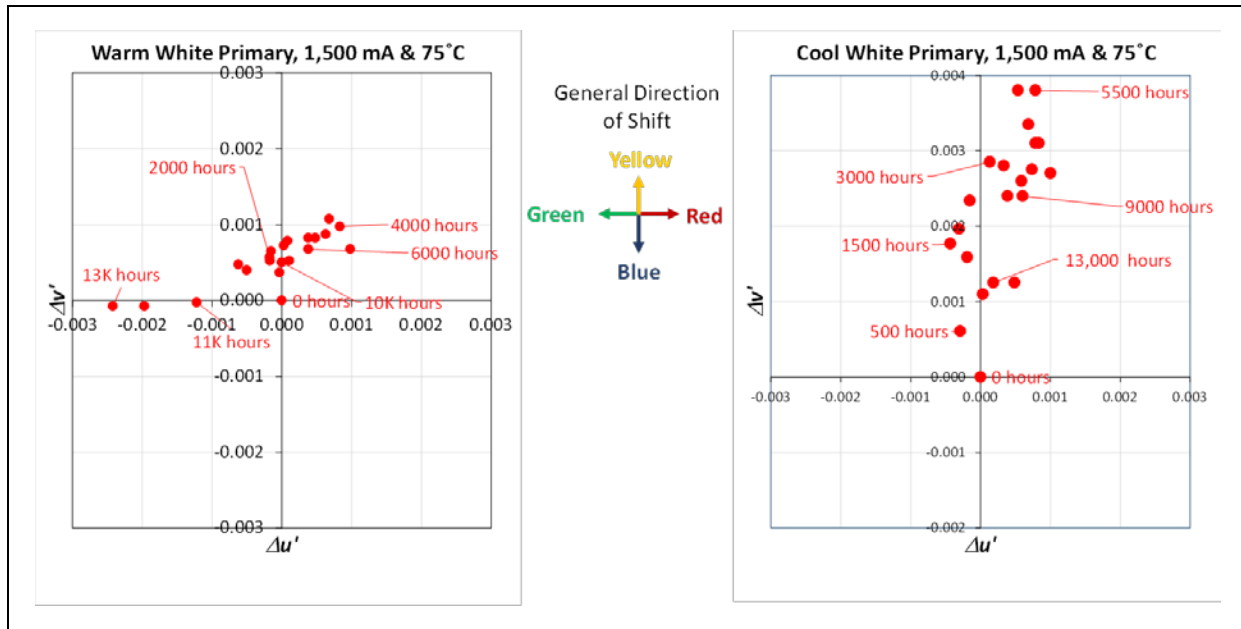


Figure A-4. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 1,500 mA in 75°C temperature conditions.

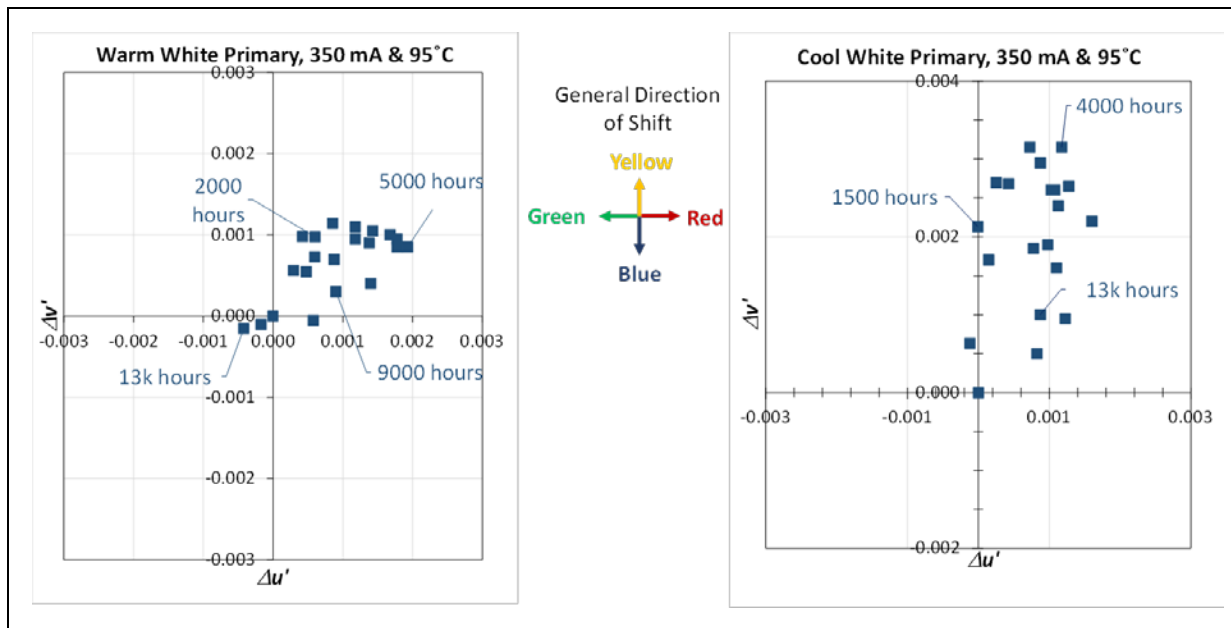


Figure A-5. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 350 mA in 95°C temperature conditions.

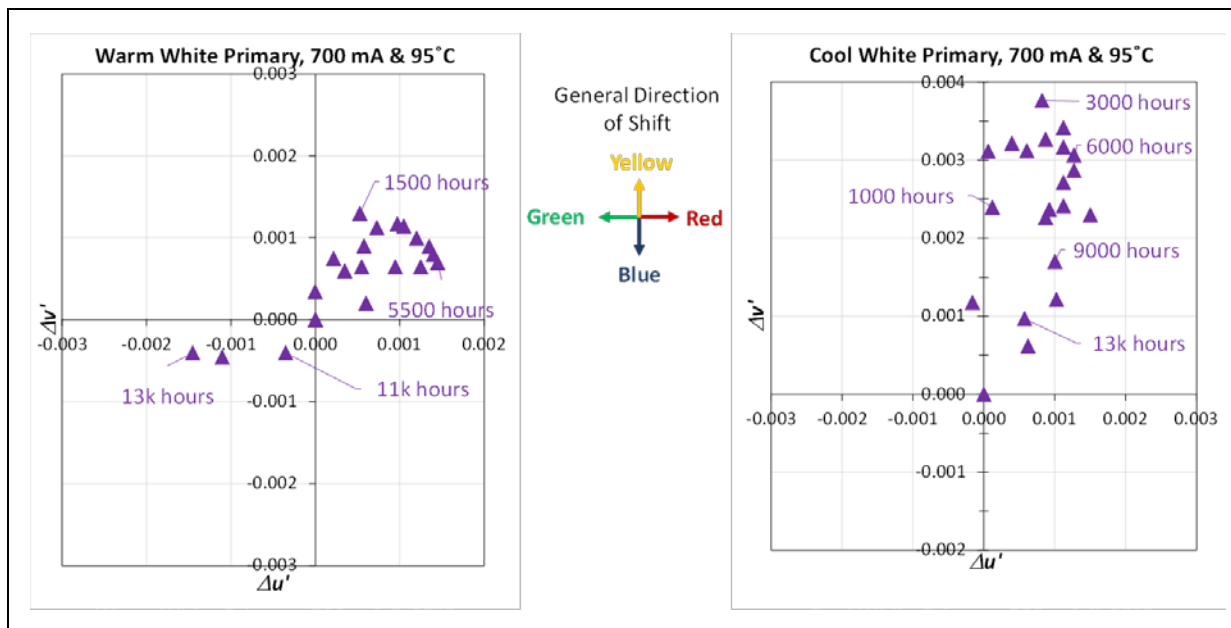


Figure A-6. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 700 mA in 95°C temperature conditions.

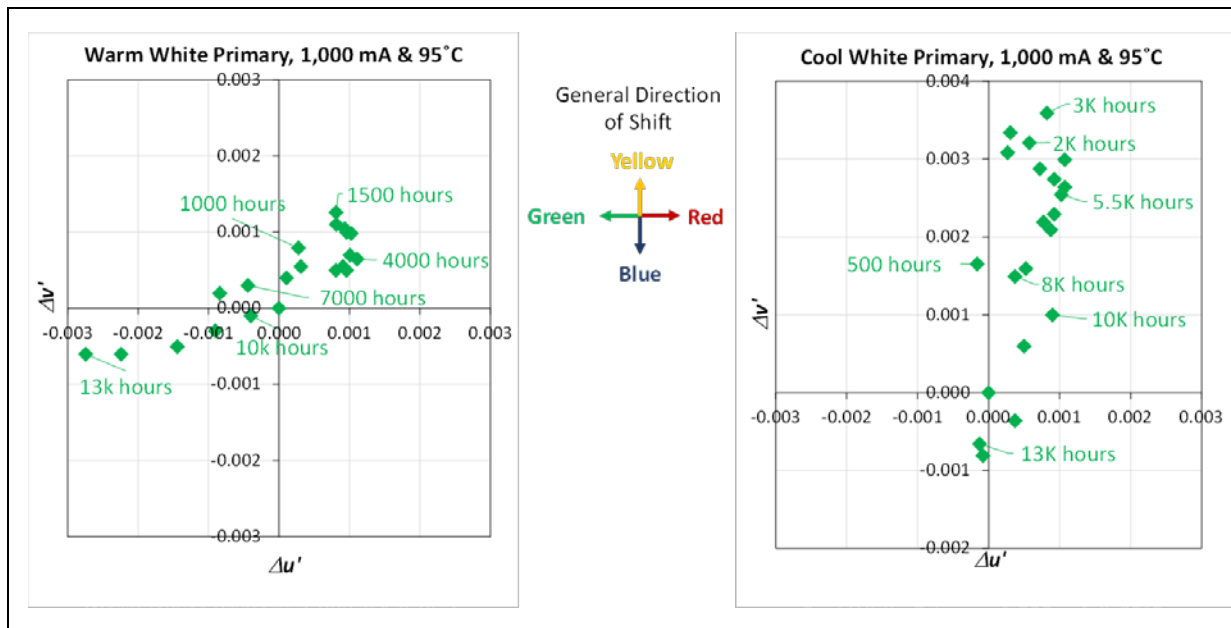


Figure A-7. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 1,000 mA in 95°C temperature conditions.

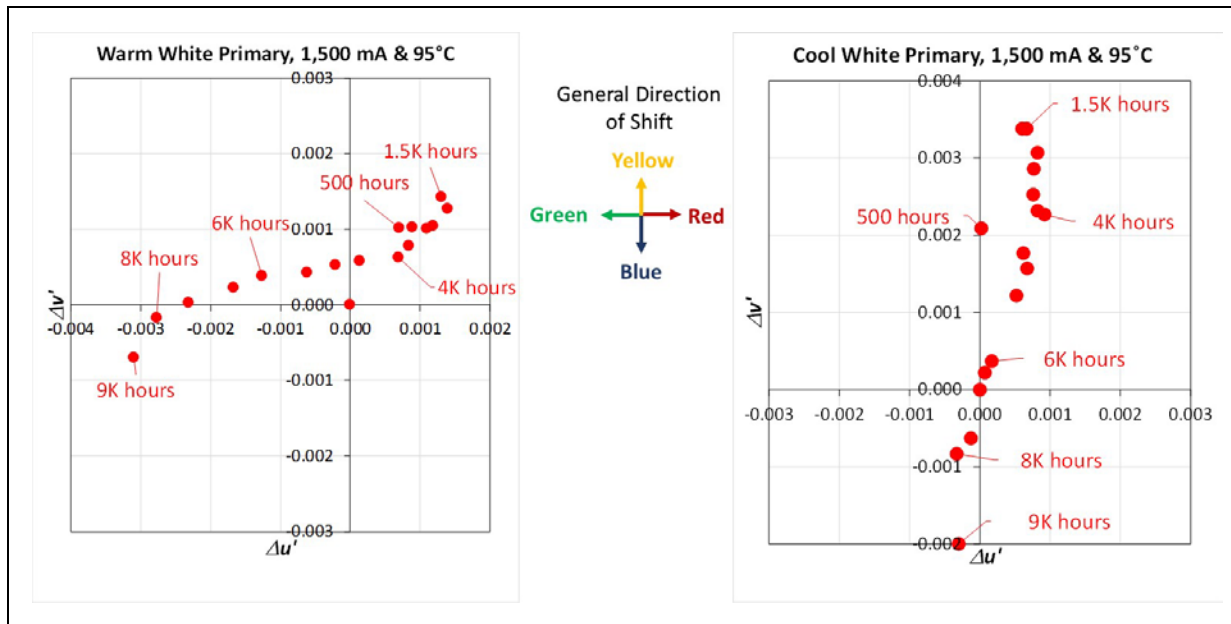


Figure A-8. Chromaticity shifts for warm white primaries (left) and cool white primaries (right) operated at 1,500 mA in 95°C temperature conditions.

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