

Luminous Flux and Chromaticity Maintenance for Select High-Power Color Light-Emitting Diodes

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List of Acronyms

°C	degree Celsius
α	exponential decay rate constant in TM-21-11
$\Phi(t)$	averaged normalized luminous flux output at time (t)
AlGaInP	aluminum gallium indium phosphide
B	projected initial constant in TM-21-11
CIE	International Commission on Illumination (Commission Internationale d'Éclairage)
COB	chip-on-board
CSM-2	chromaticity shift mode-2
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FWHM	full-width at half maximum
GaN	gallium nitride
HP-LED	high-power LED
IES	Illuminating Engineering Society
InGaN	indium gallium nitride
K	Kelvin
L_{70}	the time for the luminous flux to decay to 70% of the initial value
LED	light-emitting diode
LER	luminous efficacy of radiation
mA	milliamperere
MP-LED	mid-power LED
nm	nanometer
PC	phosphor converted
pcLED	phosphor-converted LED
SSL	solid-state lighting
TCL	tunable-color lighting
T_j	LED junction temperature
TWL	tunable-white lighting
u'	chromaticity coordinate in the CIE 1976 color space
v'	chromaticity coordinate in the CIE 1976 color space
$\Delta u'$	change in u'
$\Delta v'$	change in v'
$\Delta u'v'$	magnitude of the total chromaticity shift equal to $([\Delta u']^2 + [\Delta v']^2)^{1/2}$

Executive Summary

Although white light-emitting diodes (LEDs) have been the mainstay of the solid-state lighting (SSL) industry for the past decade, color LEDs are gaining in prominence in some areas of general illumination. Today, color LEDs are used in a wide variety of products, ranging from horticultural lighting to tunable-color luminaires for human-centric lighting. The use of color LEDs in these applications is attractive because of the potential for higher luminous efficacy of radiation (LER) values, better color rendering, and greater lighting spectrum flexibility compared with conventional lighting sources and white LEDs. The increased use of color LEDs in general lighting has raised the need for more information about the capabilities and limitations of these light sources. Lighting products incorporating color LEDs are likely to behave differently than those using fixed-spectrum white LEDs. These differences are likely to be compounded when multiple LED colors, each with distinctive characteristics, are used in lighting devices. Consequently, information about the short- and long-term performance of color LEDs is needed.

To provide additional insights regarding the current state of color LEDs, this report describes findings from a review of LM-80-15 data of color LEDs in high-power LED (HP-LED) packages. Products in HP-LED packages were chosen for this analysis because this package is known to be more stable than polymer-based packages such as mid-power LEDs. This review focuses on changes in luminous flux maintenance, as well as chromaticity changes caused by long-term aging (i.e., chromaticity maintenance) and those caused by changes in operational settings (i.e., chromaticity stability). Future luminous flux performance is projected by applying the TM-21-11 procedure to the LM-80-15 data. Due to the lack of an accepted standard for projecting chromaticity maintenance by using LM-80-15 data, chromaticity maintenance behavior in this report was analyzed by comparing with the chromaticity behavior that was characterized in white LEDs.

Color LEDs used in general lighting have two basic constructions: direct-emitting LEDs and phosphor-converted LEDs (pcLEDs). Direct-emitting LEDs produce light directly through electron-hole recombination in the active region of the LED. Indium gallium nitride (InGaN) materials are used to make direct-emitting LEDs that produce light in the spectral region from purple to green. Aluminum gallium indium phosphide (AlGaInP) materials are used in direct-emitting LEDs that provide light emissions in the yellow to red spectral regions. The light emission region between these two material systems is the “green gap,” where the efficiency of direct-emitting sources drops precipitously. In this region, pcLEDs, made by combining royal blue InGaN emitters with broadband phosphors, are often used to make LEDs with colors ranging from mint green to amber. Because white LEDs also employ a similar phosphor-converted (PC) structure, there is a direct linkage between white LEDs and some color LEDs.

During this study, these LED architectural choices were found to have significant impacts on the performance of color LEDs. PC amber LEDs are often used instead of direct-emitting amber LEDs to maintain overall system efficiency. However, the PC amber LEDs generally had lower luminous flux maintenance than the LEDs of other colors. Furthermore, the PC amber LEDs also exhibited the poorest performance in chromaticity maintenance tests performed as part of the LM-80-15 procedure. In contrast, white pcLEDs in HP-LED packages are usually not as susceptible to such significant changes in luminous flux and chromaticity. This fact suggests that the issues with luminous flux and chromaticity maintenance in PC amber LEDs may lie with the phosphor and not with the LED light source or the package.

In general, the luminous flux maintenance of the InGaN devices examined during this study was similar to that of white LEDs, as might be expected from the use of InGaN as the optical pump in white LEDs. Consequently, one outcome of this study is that the luminous flux maintenance of direct-emitting InGaN LEDs was found to be very similar to that of white LEDs, for the HP-LED package, regardless of InGaN doping levels. This finding was true for the doped InGaN emitters ranging in color from royal blue to green. To the limit of the accuracy of LM-80-15 data, this behavior was true for a wide range of LED junction temperatures (T_j) and forward currents. Other LED packages may behave differently because of photo-oxidative degradation of materials in the package that is more prevalent at shorter wavelengths.

InGaN doping levels played a role in the chromaticity maintenance and the chromaticity stability of color LEDs made with this material. For the more efficient InGaN materials, such as royal blue LEDs, the chromaticity shift was minimal during LM-80-15 tests, and the chromaticity maintenance was excellent. However, for less efficient and more highly doped InGaN materials, such as green and cyan LEDs, the chromaticity tended to change by a measurable amount during the LM-80-15 chromaticity maintenance tests. These chromaticity shifts occurred mainly along the $\Delta u'$ axis for most color; however, the shift was in the $+\Delta u'$ direction for some LEDs and in the $-\Delta u'$ direction for others, even for the same color. In addition, the chromaticity stability to changes in T_j and forward current for doped InGaN LEDs tended to be poorer for the more highly doped and less efficient colors (e.g., cyan, green) than for royal blue LEDs.

Orange and red LEDs made with AlGaInP materials tended to exhibit excellent luminous flux maintenance levels, comparable with that measured for the InGaN materials within the limits of LM-80-15 measurements. Likewise, the performance of red-orange and red AlGaInP LEDs in chromaticity maintenance tests were excellent. The chromaticity stability of LEDs made from AlGaInP was affected more by changes in T_j than forward current. Increasing the T_j tended to shift the chromaticity in the $-\Delta u'$ direction by a small, but significant, amount (i.e., $\Delta u' > -0.0005$).

These findings indicate the importance of understanding both the short- and long-term performance of the color LEDs used in a lighting system. Although both InGaN and AlGaInP direct-emitting material systems examined during this study exhibited excellent luminous flux maintenance, the PC amber materials demonstrated the lowest luminous flux maintenance. The lighting control performance difference will have to compensate for this difference for any lighting product that combines PC amber LEDs with direct-emitting LEDs. The chromaticity maintenance of direct-emitting LEDs also varied by doping level, and the direction of chromaticity shift changed within the same nominal color depending on manufacturer. Consequently, direct-emitting LEDs from one manufacturer may not be a drop-in replacement for those from another because of differences in chromaticity behavior. This finding underscores the importance of knowing the changes in color LED performance as a function of temperature, current, and age. Such information can only be obtained through a combination of long-term and accelerated stress testing.

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1 Introduction

White light-emitting diodes (LEDs), the mainstay of the solid-state lighting (SSL) industry, are used in a variety of products, including lamps, modules, and luminaires. The basic construction of white LEDs uses a blue LED that is made from indium gallium nitride (InGaN) epitaxial materials in proximity to a phosphor. The InGaN blue LED excites (or optically pumps) the broadly emitting phosphor, and the combination of unabsorbed blue light (from the LED) and emissions from the phosphor produce white light. Such phosphor-converted LEDs (pcLEDs) are used in a variety of lighting products ranging from LED lamps to luminaires. Recently, tunable-white lighting (TWL) products, using white LEDs of two different chromaticities, have appeared on the commercial market. These products provide the ability to tune the lighting spectrum in a linear manner between the white LED end points. The capability to tune the lighting spectrum in TWL devices is an enhancement to the first generation of SSL products, which produce light with a fixed spectrum.

An alternative SSL technology for general illumination is to mix the light from color LEDs (e.g., blue, green, amber, red) to provide white illumination instead of using white LEDs. Color LEDs appeared on the market long before white LEDs and have found uses in a variety of applications, including calculators, watches, indicator lamps, automobile tail lights, and traffic signals. The use of color LEDs in general illumination is relatively new, and color LEDs are beginning to be used in a variety of lighting products, including lamps, downlights, and tunable-color lighting (TCL) products. TCL products provide white lighting and color illumination that are useful in a variety of lighting applications. Among the potential advantages of using color LEDs in lighting applications are the possibility of higher luminous efficacy of radiation (LER), better color rendering, and greater flexibility in the lighting spectrum.¹

Although both TWL and TCL products allow the lighting spectrum to be tuned, there are several significant differences between them. For instance, TWL products often use only two white LED primaries (e.g., warm white, cool white), whereas TCL products employ three or more color LEDs (e.g., red, green, blue). In addition, the color of white light produced by TWL luminaires can only be varied in a linear manner between the parameters of the two LED primaries. In contrast, the color of light produced by TCL luminaires can be varied in a non-linear manner over a much larger color gamut and is only limited by the color of the chosen LED colors. Consequently, TCL luminaires can provide both white and color lighting depending on the operational setting.²

Perhaps the biggest difference between TCL and TWL products is the level of system control that is needed because the increased flexibility provided by TCL luminaires requires tighter control over lighting settings than TWL systems. The most basic TWL systems typically use only two control channels: one for warm white LEDs and one for cool white LEDs. However, TCL luminaires need separate control channels for each LED color (e.g., red, green, amber, blue). Although increasing the number of different LED colors in a TCL device improves usage flexibility and provides a wider gamut of colors, it also increases the complexity of the control system needed to provide consistent luminous flux levels at a chosen lighting spectrum. This requirement holds for TCL luminaires used for human-centric lighting and for tunable luminaires used in horticultural applications.

There are at least two additional complications for any tunable lighting control systems: (1) the long-term performance of the LEDs (e.g., both luminous flux and chromaticity) can change over time, and (2) changes in LED junction temperature (T_j) and forward current will alter the illuminance and chromaticity of light emissions. Long-term changes in the luminous flux and chromaticity of LEDs produce a potentially visible change in lighting properties (e.g., illumination, chromaticity) as the device ages. The ability to provide a consistent luminous flux at the same chromaticity is referred to as luminous flux maintenance* and

* In earlier documents, luminous flux maintenance is sometimes referred to as "lumen maintenance."

chromaticity maintenance, and any control system will seek to compensate for changes in the LED light sources with age. However, short-term effects, such as changing the operational settings on the color LEDs, can also have an impact. The chromaticity stability of all LEDs will change depending on T_j and forward current, and this effect seems to be especially pronounced in color LEDs. Consequently, changing the current supplied to a group of LEDs of one color not only changes the amount of light produced, but it also changes the chromaticity of that group of LEDs, which must be compensated for by the other LED colors to maintain a consistent chromaticity. All of these factors (e.g., luminous flux maintenance, chromaticity maintenance, chromaticity stability) must be incorporated into any lighting control system to achieve consistent long-term performance. This issue is especially critical for TCL systems with three or more LED primaries because the larger the number of LED colors that must be optimized to achieve a desired lighting setting, the more complex the system control. Therefore, it is important to understand the changes that occur in luminous flux and chromaticity during the operational lifetime of LED light sources.

The Illuminating Engineering Society (IES) developed a standard method, termed LM-80[†], for measuring the luminous flux and color maintenance of LED packages, arrays, and modules.^{3,4} LM-80-08, which was released in 2008, required that luminous flux measurements be made at three different case temperatures: 55 degrees Celsius (°C), 85°C, and a third temperature selected by the manufacturer.³ In 2015, the IES released LM-80-2015, which simplified the LED case temperature requirements to a minimum of two temperatures: one that must be either 55°C or 85°C.⁴ LM-80-15 also improved reporting of LED chromaticity information by requiring that chromaticity coordinates, dominant wavelength, peak wavelength, or centroid wavelength be provided for each sample at every measurement interval. This additional requirement added the capability to track chromaticity changes from the LM-80-15 data, in addition to luminous flux maintenance, over time.

The IES released TM-21-11 as a technical memorandum to describe a standard method to project the long-term lumen maintenance of LED light sources by using data from LM-80 tests that lasted for 6,000 hours or longer.⁵ TM-21-11 treats the luminous flux change in LED packages, array, and modules as having an exponential decay of the form of Equation 1, which is presented as follows:

$$\Phi(t) = B e^{-\alpha t} \quad (\text{Equation 1})$$

Where

$\Phi(t)$ = The averaged normalized luminous flux output at time (t)

B = The projected initial constant

α = The exponential decay rate constant.

When $\Phi(t)$ is normalized, the constant B is approximately 1. The decay constant α determines the time required for the luminous flux to drop to a pre-determined level, such as 70% of the initial value (i.e., L_{70}). Assuming $B = 1$, an L_{70} value of 50,000 hours corresponds to $\alpha = 7.13 \times 10^{-6}$, and an L_{70} value of 100,000 hours corresponds to $\alpha = 3.56 \times 10^{-6}$. To avoid projections of luminous flux maintenance that exceed the statistical significance of the data, TM-21-11 mandates that the projected L_{70} time can be no greater than six times the actual LM-80 test time. For example, if an LM-80 test was conducted for a total of 10,000 hours, then the maximum projected L_{70} time for the tested LEDs is 60,000 hours, although the value could be lower if the lumen maintenance performance is poor. This requirement is often termed the “6X rule.” Together, LM-80

[†] LM-80-08 and LM-80-15 have slightly different requirements for maintenance tests and slightly different reporting requirements. The term “LM-80” will be used when either method is applicable. The specific method (i.e., LM-80-08 or LM-80-15) will be used when referring only to that specific approved method.

and TM-21-11 have become the accepted methods for reporting the luminous flux maintenance performance of LEDs used in lighting applications, especially for white LEDs.

From 2011 through 2015, the U.S. Department of Energy (DOE) funded research that studied trends in the LM-80-08 data and the corresponding TM-21-11 projections obtained from white LEDs produced by major LED manufacturers.⁶ More than 250 LM-80-08 data sets were collected during that timeframe. In all instances, the data were acquired by using the procedures of LM-80-08, meaning that information was limited to the changes in luminous flux, and there was no information about the changes in the individual chromaticity coordinates (i.e., u' and v') only the aggregated chromaticity shift parameter $\Delta u'v'$. The data were sorted by LED package types, and a compilation of the calculated α values for the 250 data sets is shown in **Figure 1–1**. It is important to note that although the values provided in Figure 1–1 are the calculated α values for white LEDs, the L_{70} times reported by the manufacturers of these LEDs will be less than those determined from these α value if the LM-80 test time limits the projected L_{70} value through the 6X rule.

Although there is a significant amount of overlap between the α values, it is also clear that the structure of the LED package has an impact on α .⁷ The high-power LED (HP-LED) and chip-on-board (COB) packages tend to have lower α values, while mid-power LED (MP-LED) packages often have higher α values.[‡] Since α and L_{70} are inversely related, a lower α value results in a longer L_{70} time, so the lifetime of HP-LED packages can be expected to exceed that of MP-LED packages in some instances. Another observation is that in some test conditions (typically lower LED T_j and drive currents), α can assume a negative value which is an unrealistic condition.⁸

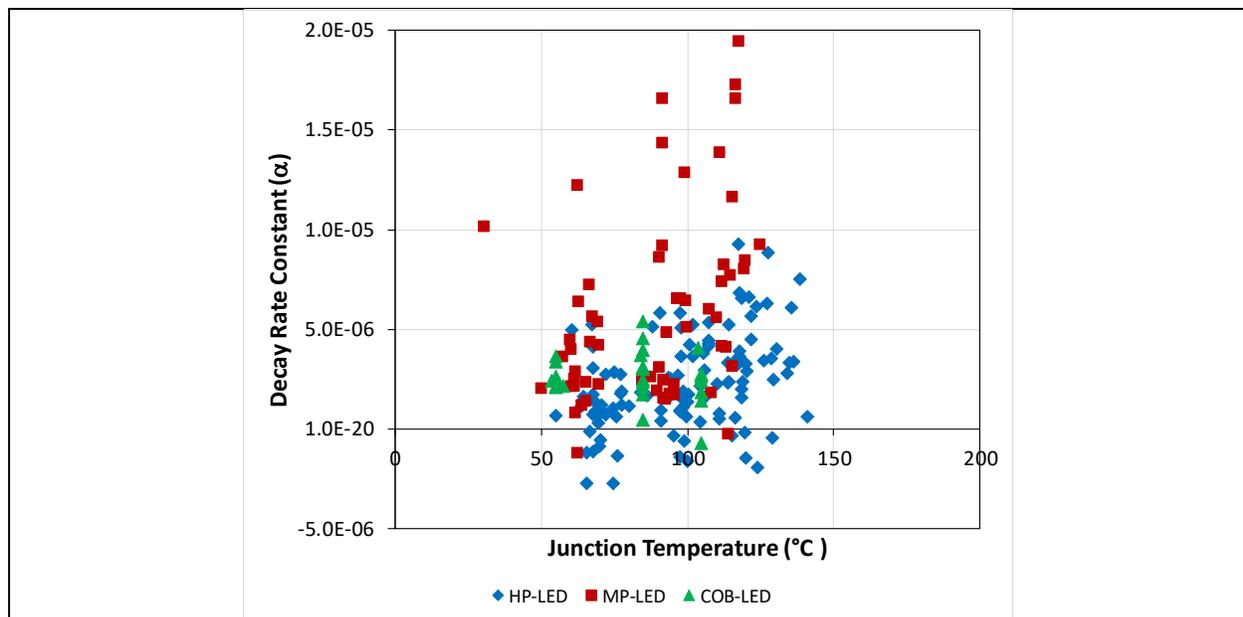


Figure 1–1. Calculated decay rate constants (α) of TM-21-11 projections for commercial white LEDs.^{6,7}

‡ HP-LED packages have a ceramic base and silicone encapsulants and lenses. Light emitted from LED dies in HP-LED packages are more likely to directly exit the package and would be affected less by the degradation of the packaging materials. HP-LEDs typically have an operational forward current ranging from zero (0) to more than 1,000 milliamperes (mA). In contrast, MP-LEDs are made by using a polymeric molding compound that forms the sidewalls of the package. Some light emitted from the LED die strikes the polymeric molding compound before it exits the package. Aging and discoloration of the polymeric sidewall will change the properties of light emitted from the package. MP-LEDs are typically operated between zero (0) mA and 200 mA.

With the increased use of color LEDs for TCL and horticultural applications, the DOE wanted to conduct a similar analysis of the LM-80 data for commercially available color LEDs. There are two main material systems that are used to make color LEDs for SSL applications: InGaN and aluminum gallium indium phosphide (AlGaInP). Known as the workhorse semiconductor for many SSL products, InGaN produces the direct emission of light spanning the color gamut from violet to green, with the color of light emission being tuned by changing the doping level of indium in the gallium nitride (GaN) matrix. The AlGaInP chemistry provides direct emission of light spanning the color gamut between yellow and red. The color of light emissions from an AlGaInP LED are tuned by small changes in the composition. However, for both InGaN and AlGaInP materials, there is a limit to the doping levels that can be used with each materials system without causing a significant drop in device efficiency. This efficacy drop occurs in the green to yellow spectral regions and is often called the “green gap.”¹ Mint green, amber, and yellow emissions typically fall within this gap. LEDs tuned to these colors are often made in the pcLED structure, in which a blue InGaN emitter and a broadband phosphor are combined to produce light at the desired chromaticity. These devices are made by using a process similar to that of white LEDs. For LEDs producing colors in the green gap, the efficiency of color LEDs with the pcLED architecture is better than that of directing-emitting LEDs of that color, prompting the use of the pcLED structure for many devices requiring mint green, yellow, and amber emissions. The materials systems often found in color LEDs can be summarized as follows:

- Doped GaN materials for direct emission of violet, royal blue, blue, cyan, and green colors
- AlGaInP materials for direct emission of yellow, orange, red, and deep red colors
- pcLED materials (usually with a blue LED pump) for emissions of mint green, amber, and yellow colors.

Within a given semiconductor material system used in LEDs for SSL applications, performance may change because of differences in doping levels. For example, more highly doped colors (e.g., cyan, green) are not likely to exhibit the same performance of less doped InGaN colors such as royal blue. The differences arise partly from the changes in the semiconductor lattice with doping.¹ In addition, the core InGaN and AlGaInP materials systems have distinct characteristics, including significant differences in some physical properties. In particular, the thermal efficiency droop of the two material systems is known to be different.¹ Insights regarding these materials-related performance issues can be gained through testing, including accelerated stress testing and long-term studies such as LM-80. This information is critical to developing control systems for tunable lighting devices that provide proper compensation for changes in the LED illuminance and chromaticity at different operational settings and those resulting from the different aging characteristics of the color LEDs when in use.

This report provides an initial benchmark of LM-80-15 data and TM-21-11 projections for luminous flux and chromaticity maintenance for high-power color LEDs sold by commercial LED manufacturers. These benchmarks enable a comparison between different colors of LEDs and between color LEDs and white LEDs but are not intended to compare performance between manufacturers. Future studies may evaluate other packaging formats such as MP-LEDs and chip-scale packages.

2 Collection of LM-80-15 Data Sets for Color LEDs

Although the LM-80 method is most often associated with white LEDs, it can be applied to any LED that emits light (i.e., produces optical radiation with wavelengths between 380 and 720 nanometers [nm]). In addition, the TM-21-11 procedure can be applied to provide projections of long-term lumen maintenance, provided that the data are acquired according to the guidelines established in LM-80 and that a minimum of 6,000 hours of testing has been completed. Unfortunately, an approved method for projecting chromaticity maintenance by using LM-80-15 data does not currently exist, but inferences can be made by analyzing the chromaticity shift of color LEDs and comparing it to the behavior of white LEDs.^{9,10}

When gathering LM-80 data about color LEDs from the manufacturers that participated in the earlier study of white LEDs, the decision was made to focus on products in the HP-LED package format. This choice was based on previous findings that HP-LED packages generally showed less package-induced changes in luminous flux maintenance (see Figure 1–1) than MP-LED packages.^{6,7} The major package-induced chromaticity change occurring in white HP-LEDs is caused by delamination of the phosphor in the pcLED structure, an issue that is not relevant with direct-emitting LEDs.^{9,10} Although some packages may contain color LEDs (e.g., red) that are unlikely to induce photo-oxidative changes in the package materials during use, the lower wavelength versions (e.g., royal blue, blue) of the same LED package could experience photo-oxidation of the packaging material that could complicate data analysis. For example, MP-LED packages have been shown to undergo photo-induced yellowing of the package molding resin, and this change significantly impacts both luminous flux and chromaticity maintenance.⁹ Based on this information, data from HP-LEDs are viewed to be less likely to suffer changes caused by the LED package than MP-LED packages, and this capability is likely to provide for a better comparison of the behavior of different LED colors.

The LED manufacturers that were contacted for data about color LED products as part of this study are classified into three main groups. The three groups are companies that manufacture

- Both white and color LEDs and have LM-80 data on their products
- Only white LEDs and do not currently have color LED products
- White and color LEDs in two separate portions of the business (e.g., lighting and automotive) and only have LM-80 data for white LED products intended for use in general illumination.

Consequently, the available pool of color LED manufacturers for general lighting applications was smaller than that of the earlier white LED study. However, the LM-80 data that were collected spanned a variety of colors, and the initial chromaticity values of the color LEDs discussed in this study are shown in **Figure 2–1**.

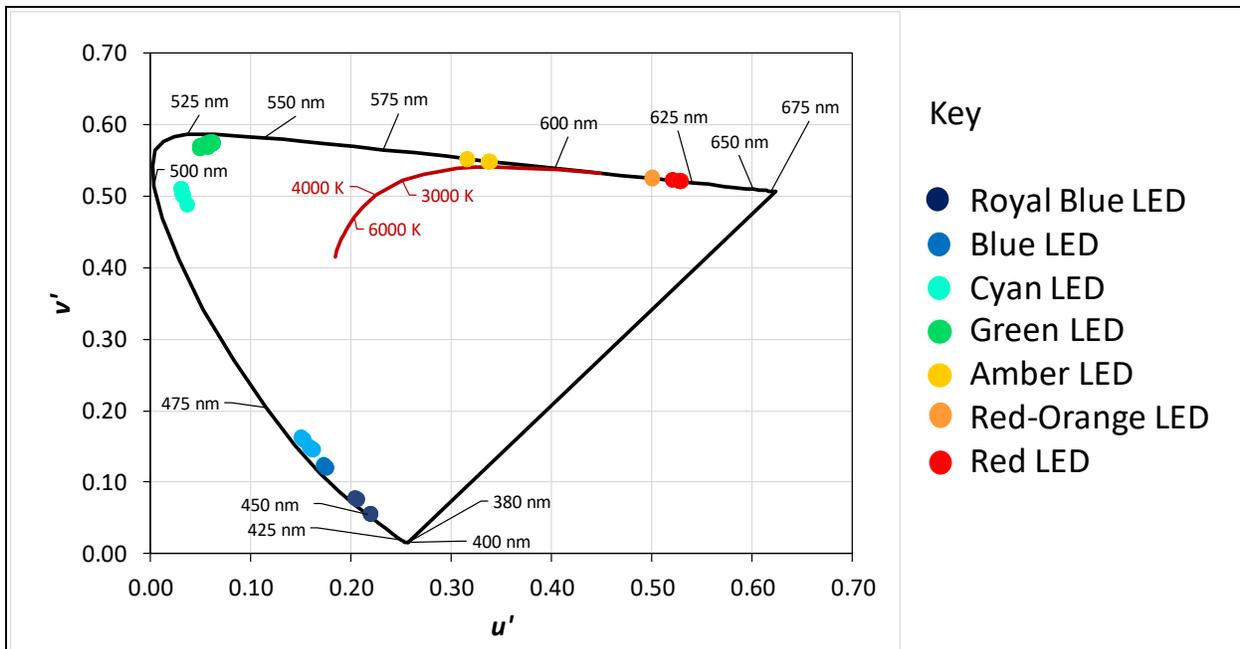


Figure 2–1. The International Commission on Illumination (CIE, Commission Internationale d’Éclairage) 1976 chromaticity diagram showing the initial chromaticity values of the color LEDs examined during this work. The solid red line shows the Planckian Locus and the associated correlated color temperature values in Kelvin (K). The solid black line is the spectrum locus of monochromatic emitters.

The spectrum locus of the International Commission on Illumination (CIE, Commission Internationale d'Éclairage) 1976 chromaticity diagram consists of the chromaticity coordinates of perfectly monochromatic radiation at each visible wavelength between 380 nm and 720 nm. The chromaticity coordinates of the blue and red LEDs examined during this study are near the spectrum locus, indicating that the color purity of these products is high even though the light emission is not monochromatic. For the GaN semiconductor material systems, the spectrum full-width at half maximum (FWHM) progressively increased from a low of 18 nm (for royal blue LEDs) to a high of 35 nm (for green LEDs) according to the manufacturer's specifications for these products. In addition, Figure 2–1 demonstrates that the color purity of cyan and green LEDs is less than that of blue InGaN emitters. For the PC amber LEDs, the FWHM was 85 nm, and a weak blue peak is produced from these sources (in addition to the dominant amber peak).

Data for the color HP-LEDs examined during this analysis were collected during LM-80-15 testing at a variety of temperatures and currents for each type of color LED. The data contains at least one test population that was measured at a high temperature (at least 105°C) and a high forward current (700 mA or higher). This effort collected and then analyzed 68 different data sets spanning the color range from royal blue to red, the most common colors in general illumination products. RTI International staff were unable to find sufficient data at the extremes of the visible spectrum (i.e., violet and deep red) for inclusion in this study. All data sets that were provided by the LED manufacturers for this study were acquired by using LM-80-15 protocols, meaning that both luminous flux and chromaticity data are included in the LM-80-15 report. Typically, each data set contained 20 to 25 LEDs, so the cumulative number of individual LEDs included in the data sets examined during this study exceeded 1,400.

In the analysis reported here, the luminous flux and luminous flux maintenance of every LED in each data set were plotted versus time to assess the variability of the data set and to ensure the quality of the data. The average luminous flux maintenance was calculated by averaging the normalized luminous flux for all LEDs tested at a given condition in the data set at each reported time interval. In addition to the average value, the standard deviation and coefficient of variation were also calculated at each time interval. This procedure was repeated for every combination of manufacturer, LED color, forward current, and case temperature covered by the available data. The average luminous flux maintenance values at each forward current and case temperature were inserted into the U.S. Environmental Protection Agency's (EPA's) ENERGY STAR TM-21 calculator¹¹ to determine the values of α and B by using the TM-21-11 procedure.

The analysis of the chromaticity shift data proceeded in a similar manner with an examination of the temporal behavior of u' , v' , $\Delta u'$, and $\Delta v'$ data for individual LEDs to assess data quality. The average values of these variables and associated statistics were calculated. When analyzing the chromaticity data and drawing inferences about the behavior, the analysis was conducted by using $\Delta u'$ and $\Delta v'$ data (i.e., the change in u' and the change in v' from the starting value) to have a common starting point for all measurements.[§] The direct-emitting LEDs were also analyzed by base semiconductor material, whereas the amber pcLED devices were treated separately from the direct-emitting LEDs.

3 Luminous Flux Maintenance

An examination of the TM-21-11 curve fitting parameters (i.e., α and B) for each LED population provides insights regarding the luminous flux maintenance behavior of each specific type of color LED and allows for comparisons between different colors. The α value provides information about the change in luminous flux over time, whereas the B value provides an indication of whether the change occurs quickly or gradually. This information is important for both TCL and horticulture luminaires. TCL fixtures typically operate by varying

[§] $\Delta u'$ and $\Delta v'$ are more accurately represented as a function of time t (i.e., $\Delta u'(t)$ and $\Delta v'(t)$). Note: $\Delta u'(t) = u'(t) - u'(t=0)$ and $\Delta v'(t) = v'(t) - v'(t=0)$, where $u'(t=0)$ and $v'(t=0)$ are the starting chromaticity values.

the forward current levels supplied to each LED color; therefore, the LEDs will likely encounter different current settings and T_j during normal operation. If the color LEDs in a TCL device change in different ways during use, then it may be more difficult to achieve reproducible system performance over the lifetime of the product, and greater system control may be necessary. For horticulture applications, large unexpected changes in emission flux with device aging can impact growth rates and crop yields. Consequently, this information impacts system maintenance and relamping schedules for indoor farms.

3.1 TM-31-11 Decay Rate Constant

Figure 3–1 provides the calculated α values, as a function of T_j , for all of the color LED data sets examined during this study. The same data, plotted as a function of forward current, appear in Figure 3–2. The data shown in these figures are the calculated α values determined with the EPA ENERGY STAR TM-21 Calculator¹¹ and have not been adjusted for the 6X rule.

An examination of Figure 3–1 and Figure 3–2 reveals that the α values for many LEDs range from -2.5×10^{-6} to 2.5×10^{-6} . This trend generally holds for both high T_j (Figure 3–1) and high forward currents (Figure 3–2). It is worth noting that the α values of the white LEDs in the HP-LED package also tended to fall in this range (see Figure 1–1). This observation suggests that the luminous flux maintenance of many of the direct-emitting color HP-LEDs examined during this study is comparable to that of white HP-LEDs under the LM-80-15 test conditions. This finding is not surprising because white LEDs employ an InGaN emitter to provide the blue pump for phosphor excitation. For reference, an α value of 2.5×10^{-6} corresponds to an L_{70} time of approximately 140,000 hours, which is longer than the lifetime of most luminaires; therefore, the other luminaire components (e.g., driver, controls, secondary optics) may fail before this time. According to the rules established as part of TM-21-11, a L_{70} value of 140,000 hours would require at least 23,333 hours^{**} of testing. As a result, the reported L_{70} values for most of the direct-emitting LEDs examined here will be limited by the 6X rule.

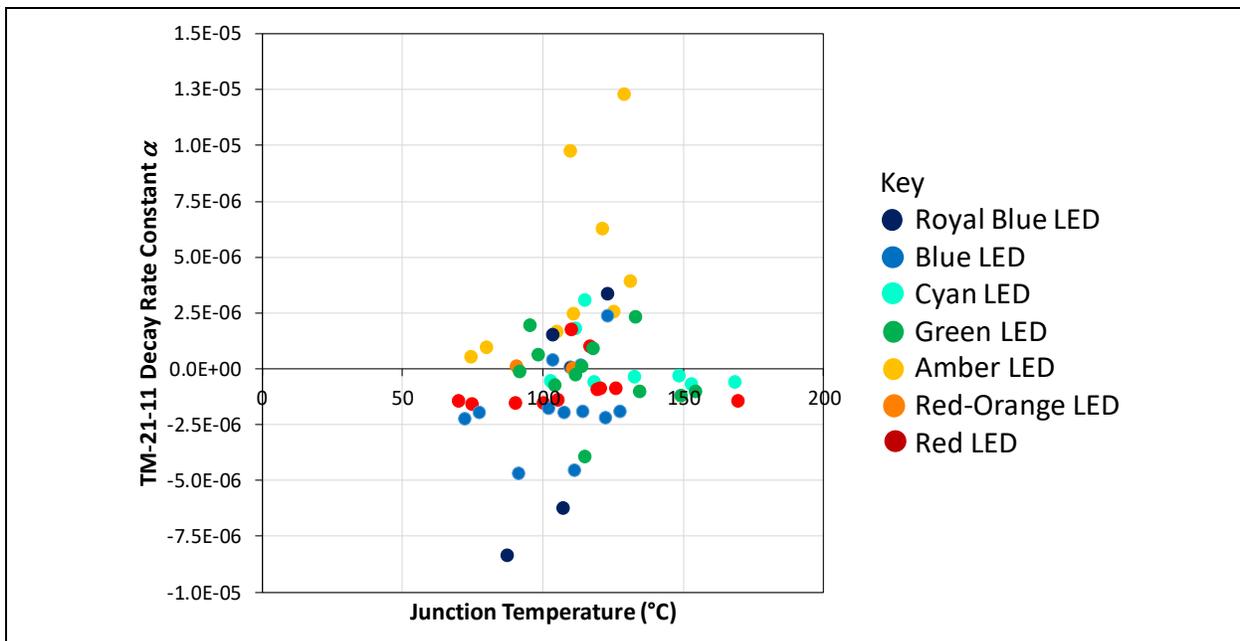


Figure 3–1. Calculated TM-21-11 α values for the color LEDs evaluated in this study as a function of T_j .

** One year corresponds to 8,766 hours; therefore, 23,333 hours of testing would take 2.7 years to complete, not including measurement time.

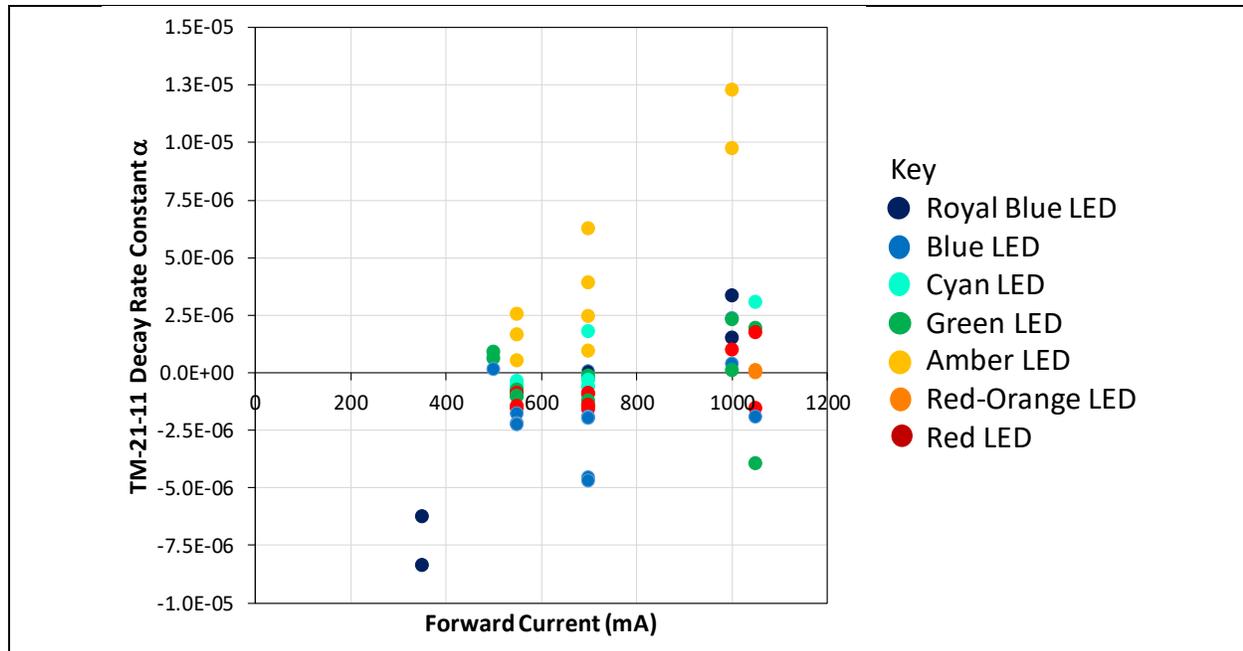


Figure 3–2. Calculated TM-21-11 α values for the color LEDs evaluated in this study as a function of LED forward current.

However, the PC amber HP-LEDs deviated from this behavior and exhibited α values exceeding 1.0×10^{-5} at high current and temperatures. For reference, an α value of 1.0×10^{-5} corresponds to an L_{70} value of 35,700 hours. This finding indicates that the luminous flux maintenance of amber pcLEDs may be significantly lower than the direct-emitting LEDs of blue, green, and red colors. Consequently, a TCL system employing amber pcLED devices along with direct-emitting LEDs may experience a significant difference in luminous flux maintenance between the LED colors. The control system will have to compensate for these differences either by decreasing the power (and illumination levels) of the other LEDs to hold a constant chromaticity or maintaining the illumination level but allowing the chromaticity coordinates to drift, possibly away from the Planckian Locus. In all cases examined here, the PC amber LEDs were pumped by a blue InGaN LED; therefore, the poor luminous flux maintenance may be an issue with the phosphor (as discussed in **Section 4.1** of this report).

3.2 TM-21-11 B Value

Figure 3–3 provides the calculated TM-21-11 B values from all of the color LED data sets examined during this study. The primary finding revealed in Figure is that each population of red and red-orange LEDs (i.e., AlGaInP materials) had B values greater than 1.0, whereas many green and amber LEDs tended to produce B values less than 1.0 under the LM-80-15 test conditions. The B value in Equation 1 is the y-axis intercept of the TM-21-11 fit; however, due to the rules applied during the TM-21-11 procedure, the intercept is determined after at least 1,000 hours of operation.⁵ Consequently, the value of B will change depending on the behavior of the LED during the first 1,000 hours of operation, as shown in Figure ^{††} A B value greater than 1.0 may indicate that a rapid increase in luminous flux occurred during the first 1,000 hours of testing. Such an increase could result from an improvement in device emission efficiency or a shift in emission wavelength to a higher flux value wavelength.^{6,8} Likewise, a B value less than 1.0 could indicate a decrease in luminous flux during

^{††} Note: According to the guidance in TM-21-11, for tests with durations ranging between 6,000 hours and 10,000 hours, only the data from the last 5,000 hours of testing are used for the curve fit. For tests with durations longer than 10,000 hours, only the last 50% of the total test data is used in the curve fit. As a result, the time from which the TM-21-11 curve fit starts (and the time used as the starting point to project the value of B to the y-axis) becomes increasingly longer as the test duration increases.

the first 1,000 hours of testing. Such a decrease may be due to a rapid change in light emission that stabilizes after several hundred hours of use.

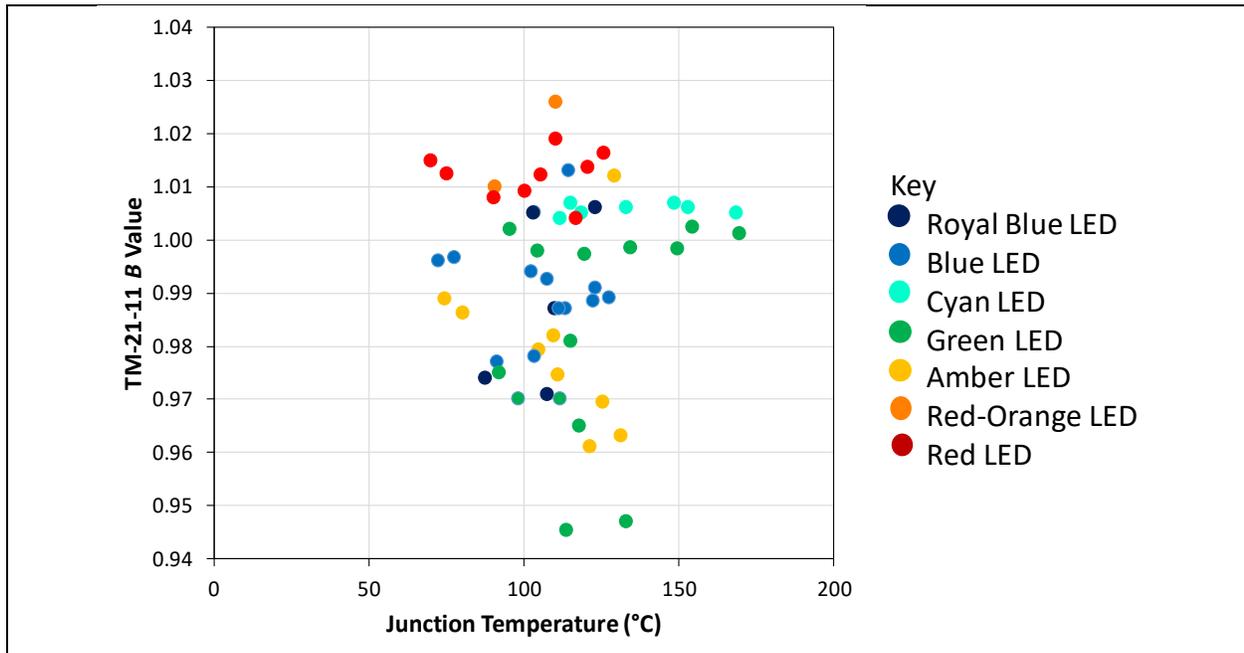


Figure 3-3. The TM-21-11 B values for the color LEDs examined during this study.

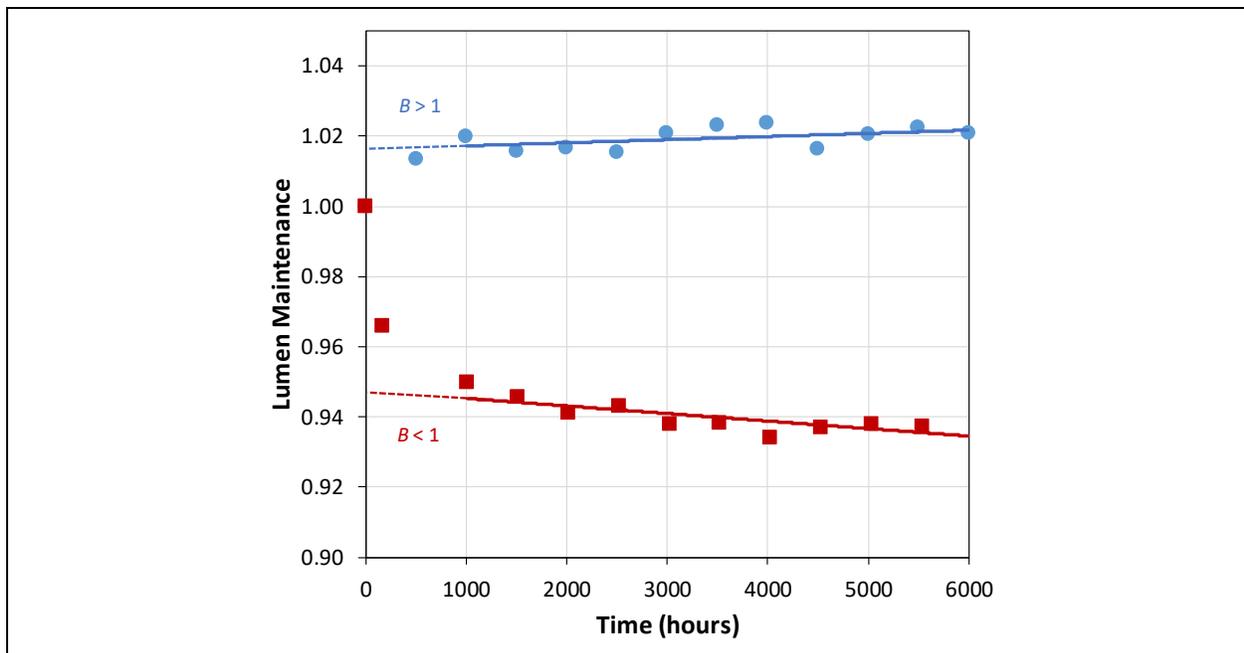


Figure 3-4. Examples of applying TM-21-11 to a device with a B value > 1 (blue) and another device with B < 1 (red).

A combined examination of the α and B values of the TM-21-11 curve fits for color LEDs provides significant insight regarding the long-term luminous flux behavior and the behavior during the first 1,000 hours of operation. In the example of red and green LEDs, the differences in the B values indicate that the luminous flux level of the two can change in significantly different ways (relative to their respective initial values) during the first 1,000 hours of operation. The red LEDs increased in luminous flux (indicated by $B > 1$), whereas the green LEDs decreased in luminous flux (indicated by $B < 1$). However, after 1,000 hours of operation, the decay rates of red and green LEDs (as measured by the TM-21-11 α value) are comparable. Consequently, there is a temporal element to the luminous flux maintenance of these LEDs that must be accommodated in a control system, especially early in the product life. Blue and royal blue LEDs are not as likely to show a substantial change in early operation because B is approximately 1; therefore, their luminous flux maintenance will be affected mainly by T_j and forward current during operation.

4 Chromaticity Maintenance and Chromaticity Stability

Chromaticity changes in LED devices are dependent upon many factors, including T_j , forward current, and the operational time of the device. When analyzing any chromaticity changes of the color LEDs in this study, consideration must be given to the minimal detected changes in u' and v' that can be accurately measured by a testing laboratory. These thresholds are determined by the inherent uncertainty in the measurement, experimental drift, and the uncertainty of the calibration source. For this study, the threshold for a minimum significant change in either u' or v' over the lifetime of testing was chosen to be ± 0.0005 . Consequently, changes in either parameter of less than ± 0.0005 over the duration of the test are viewed as inconsequential. This uncertainty value was chosen based on conversations with industry professionals who indicated that a certified testing laboratory should be able to achieve this level of measurement uncertainty and that some laboratories may be able to yield more accurate results, thereby lowering the measurement uncertainty.

During this study, the largest chromaticity shifts were observed for the PC amber LEDs, which will be discussed in **Section 4.1** of this report. The chromaticity shifts of the direct-emitting LEDs were generally much smaller than those of the PC amber LEDs. The chromaticity shifts of InGaN color LEDs are discussed in **Section 4.2**, and the chromaticity shifts for AlGaInP color LEDs are discussed in **Section 4.3**.

The initial chromaticity coordinates and the coordinates after 6,000 hours of operation under LM-80-15 test conditions are provided in Figure 4–1 for all LEDs examined during this study. In Figure 4–1, each graduation on the x- and y-axes corresponds to a change of 0.1 in u' and v' , which is equivalent to a 100-step MacAdam ellipse.†† At the scale used in Figure 4–1, it is difficult to discern the chromaticity shifts of individual LEDs; therefore, expanded scale figures are provided in **Appendix A** for each LED color. During this analysis, the term “chromaticity maintenance” is used when referring to the long-term change in the chromaticity of a color LED operated at a constant T_j and forward current. The term “chromaticity stability” is used when referring to changes in u' and v' caused by altering either the T_j or forward current. Accounting for both chromaticity maintenance and chromaticity stability is important to achieving a consistent lighting environment in both human-centric lighting (by using TCL luminaires) and horticultural lighting (with color LED lamps and luminaires).

†† For reference, a person with normal vision can distinguish between two different chromaticity values if they are separated by a one-step MacAdam ellipse or a change in $\Delta u'v'$ of 0.001; therefore, a 100-step MacAdam ellipse corresponds to a very large difference in color.

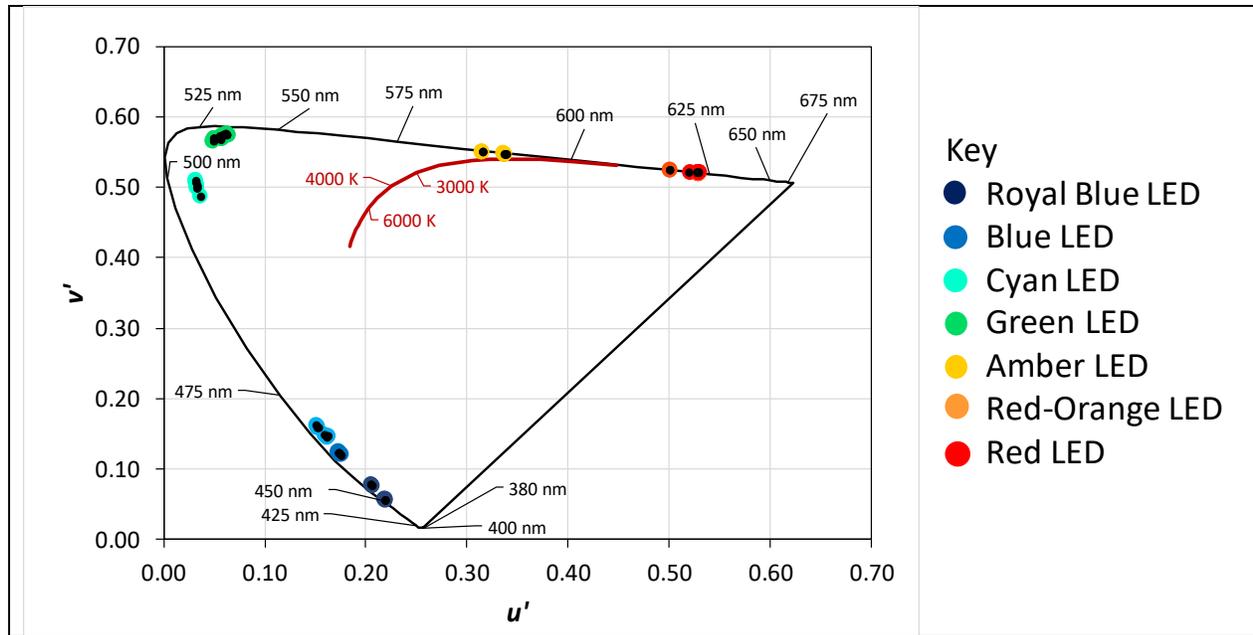


Figure 4-1. The CIE 1976 chromaticity diagram of the color LEDs examined during this study. The initial chromaticity coordinates are shown as small black circles, and the chromaticity after 6,000 hours of use are shown as larger color circles. Expanded scale views of each color are presented in Appendix A.

4.1 PC Amber

The PC amber LEDs exhibited the largest chromaticity shifts ($\Delta u'v' > 0.001$ in all cases) of all of the color LEDs examined during this study. The PC amber LEDs also demonstrated the poorest luminous flux maintenance (see Figure 3-1), suggesting that these two effects may be related. Details of the chromaticity shifts for the PC amber LEDs under the different experimental conditions examined during this study are provided in Figure A-5 in **Appendix A**.

During the first 1,000 hours of operation during LM-80-15 tests, the chromaticity of the PC amber LEDs shifted predominantly in the $-\Delta u'$ direction by -0.001 to -0.002 (i.e., one-step to two-step MacAdam ellipse) depending upon the forward current and case temperature. This type of shift was labeled as chromaticity shift mode-2 (CSM-2) behavior during previous work involving white LEDs. Regarding white LEDs, CSM-2 shifts have been associated with changes in the phosphor emissions wavelengths.^{10,12,13} Unfortunately, the spectral power distributions of the PC amber LEDs examined during this study were not included in the LM-80-15 data sets; therefore, it could not be confirmed whether the centroid wavelength of the phosphor emissions shifted to lower values.

The PC amber LEDs also exhibited a rapid loss of luminous flux (as evidenced by the large α values provided in Figure 3-1 and Figure 3-2). Although the exact cause of this change cannot be determined from the LM-80-15 data, one possibility is that a change in the external quantum efficiency of the phosphor occurred during use. If such a change in external quantum efficiency also produced a change in the phosphor emission spectrum, then a chromaticity shift would be observed. This explanation is consistent with the experimental evidence provided in the LM-80-15 reports and with data regarding green phosphors.¹³

The chromaticity stability of PC amber LEDs showed a dependence on temperature and current with the forward current having a larger impact than T_j . Increasing the forward current had the effect of shifting the chromaticity in the $-\Delta u'$ direction by as much as -0.0014 ; however, the change in the $\pm \Delta v'$ direction was below the significance threshold (± 0.0005). Changes in T_j did not have a significant effect for a 30°C -temperature increase, but exceeded the ± 0.0005 threshold for significance when the change in T_j was 50°C .

PC amber LEDs could potentially be used in TCL luminaires for human-centric lighting. Based on the data provided in the LM-80-15 reports examined during this study, the luminous flux and chromaticity maintenance of these LEDs deserve special consideration when developing a control system for TCL lighting because of the large changes that occurred relative to direct-emitting LEDs. Chromaticity stability is less of a concern but could become important when switching from low to high drive currents for the PC amber LEDs.

4.2 InGaN Materials

The chromaticity maintenance of the doped InGaN materials exhibited a dependence on doping, with values of $\Delta u'v'$ ranging from < 0.0005 to 0.0011 . For the more efficient InGaN devices such as royal blue LEDs, the chromaticity shift tended to be minimal after 6,000 hours of operation under LM-80-15 conditions (see Figure A-1 in **Appendix A**). For blue LEDs, the chromaticity shift tended to be equally in the $-\Delta u'$ and $+\Delta v'$ directions, although there were exceptions, as shown in Figure A-2 in **Appendix A**. For less efficient and more highly doped GaN materials such as green LEDs, significant chromaticity shifts were observed during LM-80-15 testing (see Figure A-4 in **Appendix A**). A similar trend was also observed in the LM-80-15 data for cyan LEDs (see Figure A-3 in **Appendix A**), although the magnitude of the shifts was less. Although the chromaticity changes for green LEDs were mainly along the $\Delta u'$ axis, the shift during chromaticity maintenance experiments was primarily in the $+\Delta u'$ direction for most LEDs and in the $-\Delta u'$ direction for others. This observation suggests that detailed knowledge of the chromaticity shift of each color LED is necessary to design a control system for TCL luminaires. Simply changing the source of the color LEDs without adjusting the control system may produce chromaticity shifts over time in the opposite direction from expectations.

For all GaN LEDs examined during this study, the chromaticity stability to changes in forward current or T_j had an equal—and in some case greater—impact on the overall chromaticity than any aging effects. Chromaticity stability can be judged by looking at the change in chromaticity when temperature or current is varied. Chromaticity stability changes can be small in some instances and when chromaticities at different temperatures or currents are similar (see Figure A-1). However, changing the temperature or current can also produce a large change in chromaticity for some LED colors, resulting in lower chromatic stability (see Figure A-3). This finding is especially important for TCL luminaires in which a variety of current settings may be used with different LED primaries. If changing the current supplied to a color LED has a greater impact on the chromaticity of that LED than it does on a different color LED, then the control system must compensate for these differences. In addition, the direction of this change varied between different LED products, with some shifting in one direction and others shifting in the opposite direction. Therefore, it is critical that both the chromaticity maintenance and chromaticity stability of each LED color be understood and designed into the TCL control system.

4.3 AlGaInP Materials

The chromaticity maintenance of the AlGaInP color LEDs examined during this study was excellent, with $\Delta u'v' < 0.001$ during the test period. For both the red-orange and red LEDs examined during this study, the change in chromaticity was largely confined to the $\Delta u'$ axis, with minimal changes in the $\pm \Delta v'$ directions. This behavior may be because of the proximity of the spectrum locus to the initial chromaticity values for red-orange and red LEDs. The initial chromaticity and that after 6,000 hours of LM-80-15 testing is shown in Figure A-6 for the red-orange and red LEDs examined during this study. There was no consensus regarding the direction of change along the $\Delta u'$ axis among all AlGaInP LEDs in the data set. The chromaticity of most products changed in the $+\Delta u'$ direction during LM-80-15 test, but there were some products that changed in the $-\Delta u'$ direction.

For the AlGaInP materials (e.g., red-orange and red LEDs), the chromaticity stability was affected more by a change in temperature than by forward current. For the LEDs examined during this study, increasing the T_j tended to shift the chromaticity in the $-\Delta u'$ direction by a small but significant amount (i.e., $\Delta u' > -0.0005$). Smaller changes in chromaticity were observed for the different forward current settings in this study.

5 Conclusions

Color LEDs can be classified into two broad groups: direct-emitting LEDs (made with InGaN or AlGaInP semiconductors) and pcLEDs (made from blue-emitting InGaN LEDs and a phosphor to provide secondary emission of visible wavelengths). Color LEDs are rising in importance in SSL applications and are finding uses in TCL lamps and luminaires and horticulture lighting. A critical element of the long-term performance of these SSL products is the luminous flux and chromaticity behavior of the color LEDs that are used as the light source. This report provides the results of an analysis of the LM-80-15 data for select commercial color LED products. This analysis was performed only on color LEDs in high-power packages. Because the HP-LED package in general exhibits minimal package-related changes in luminous flux and chromaticity, the performance benchmarked during this analysis likely proves to be a good snapshot of the performance of color LEDs. Other packaging formats, such as polymer-based MP-LED packages, may exhibit lower performance, especially for violet and deep blue colors operated at high forward currents and T_j , because of photo-oxidation of the polymer resin used in these packages.

An analysis of the TM-21-11 projections of luminous flux maintenance data for the direct-emitting LEDs acquired by using LM-80-15 demonstrated that the performance of these products is similar to that of white LEDs in HP-LED packages. However, it is worth noting that the green direct-emitting LEDs typically demonstrated a noticeable drop in luminous flux during the first 1,000 hours of operation, whereas the red LEDs typically demonstrated a noticeable increase during the same period. After this time, the direct-emitting LEDs examined during this study, including both red and green LEDs, displayed a prolonged period with a low rate of luminous flux decline. This finding indicates that control systems for TCL luminous and other devices employing different colors of LEDs must account for the potentially rapid changes in luminous flux during the first 1,000 hours of operation and the slower, steady decline in luminous flux afterwards.

The behavior of PC color LEDs appears to be quite different from that of the direct-emitting color LEDs. This study demonstrated that PC amber LEDs exhibited lower luminous flux maintenance than the direct-emitting LEDs and that the L_{70} value of PC amber LEDs examined during this study was below 50,000 hours for most operational conditions. This reduced level of performance, compared with direct-emitting color LEDs, may be related to the phosphor used for PC amber LEDs and could be ameliorated with improved materials.

For chromaticity maintenance, the direct-emitting LEDs exhibited variable performance depending upon the level of doping necessary to produce the various colors. For the more efficient colors made from InGaN and AlGaInP LEDs (e.g., royal blue, red), the chromaticity maintenance was high, and the overall chromaticity shift was minimal. For less efficient and more highly doped InGaN materials, such as those used in cyan and green LEDs, the chromaticity maintenance was lower, and measurable chromaticity shifts ($\Delta u'v' \geq 0.001$) were found during 6,000 hours of LM-80-15 testing. Although the chromaticity changes for royal blue, cyan, green and red LEDs were mainly along the u' axis, the shift during chromaticity maintenance experiments was primarily in the $+\Delta u'$ direction for some LEDs and in the $-\Delta u'$ direction for others, even for the same nominal color.

The PC amber LEDs exhibited the largest chromaticity shifts ($\Delta u'v' > 0.001$ in all operational conditions examined here) of all of the color LEDs examined during this study. During the first 1,000 hours of operation during the LM-80-15 tests, the chromaticity of the PC amber LEDs shifted predominantly in the $-\Delta u'$ direction by -0.001 to -0.002 (i.e., one-step to two-step MacAdam ellipse) depending upon the forward current and case temperature. After this time, the rate of chromaticity shift slowed for PC amber LEDs, but the shift continued in the $\Delta u'$ direction for the duration of the test.

The findings from this analysis of color LED LM-80-15 data suggest that a detailed knowledge of the luminous flux and chromaticity maintenance of each color LED used in TCL luminaires is necessary to design a control system that delivers consistent luminaire performance. In addition, the control system must compensate for changes in chromaticity and luminous flux that occur as forward current and T_j change. There

are also differences in chromaticity shift behavior between LEDs of the same nominal colors but made by different manufacturers. Consequently, some color LEDs may not be interchangeable in tunable designs without proper accommodations in the control system. The changes in chromaticity and luminous flux of color LEDs found during this review of LM-80-15 data demonstrate the increased complexity of the control system needed for lighting devices providing tunable color illumination. The increased market interest in these products, despite the complexity of system control, underscores the potential impact of TCL, including their capability to provide higher LER and greater lighting spectrum flexibility than other lighting technologies.

References

1. Pattison, M., Bardsley, N., Hansen, M., Pattison, L., Schober, S., Stober, K., et al. (2017, September). *Solid state lighting—2017 suggested research topics: Technology and market context*. Brodrick, J. (Ed.) Report prepared for the U.S. Department of Energy. Available at https://energy.gov/sites/prod/files/2017/09/f37/ssl_supplement_suggested-topics_sep2017_0.pdf
2. Paolini, S., & Weaver, M. (2018). *Technical panel: R&D directions of color-tunable lighting and Advanced LED product concepts*. Presented at the 2018 U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Research and Development Workshop, Nashville, TN. Available at <https://www.energy.gov/eere/ssl/2018-solid-state-lighting-rd-workshop-presentations-and-materials>
3. IES (Illuminating Engineering Society). (2008). *IES LM-80-08 Approved Method: Measuring Lumen Maintenance of LED Light Sources*. New York.
4. IES (Illuminating Engineering Society). (2015). *ANSI/IES LM-80-15 Approved Method: Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays and Modules*. New York.
5. IES (Illuminating Engineering Society). (2011). *IES TM21-11, Projecting Long Term Lumen Maintenance of LED Light Sources*. New York.
6. Davis, J. L., & Mills, K. (2017). *Final Report: System Reliability Model for Solid-State Lighting (SSL) Luminaires*. U.S. Department of Energy (DOE) project DE-EE0005124. Washington, DC: DOE. doi: [10.2172/1360770](https://doi.org/10.2172/1360770)
7. Hansen, M. (2015). *The true value of LED packages*. Presented at the 2015 Strategies in Light Conference, Las Vegas, NV.; and Hansen, M. (2016). *Package impact on color shift in LEDs*. Presented at the 2016 Strategies in Light Conference, Santa Clara, CA.
8. Bobashev, G., Baldasaro, N. G., Mills, K. C., & Davis, J. L. (2016). An efficiency-decay model for lumen maintenance. *IEEE Transactions on Device and Materials Reliability*, 16(3), 277–281. doi: [10.1109/TDMR.2016.2584926](https://doi.org/10.1109/TDMR.2016.2584926)
9. Next Generation Lighting Industry Alliance and the LED Systems Reliability Consortium. (2017, April). *LED luminaire reliability: The impact of color shift*. Available at https://energy.gov/sites/prod/files/2017/04/f34/lsrc_colorshift_apr2017.pdf
10. Davis, J. L., Young, J., & Royer M. A. (2016, February). *CALiPER report 20.5: Chromaticity shift modes of LED PAR38 lamps operated in steady-state conditions*. Report prepared for the U.S. Department of Energy. Available at https://www.energy.gov/sites/prod/files/2016/03/f30/caliper_20-5_par38.pdf
11. ENERGY STAR. (2018). EPA ENERGY STAR Calculator. Updated March 14, 2018. Available at <https://cmadmin.energystar.gov/sites/default/files/asset/document/ENERGY%20STAR%20TM-21%20Calculator%20rev%2003-14-2018.xlsx>
12. Davis, J. L., Mills, K., Yaga, R., Johnson, C., Hansen, M., & Royer, M. (2017). Chromaticity maintenance in LED devices. In *Solid State Lighting Reliability: Components to Systems*. van Driel, W. D., Fan, X., & Zhang, G. Q. (Eds). New York, NY: Springer.
13. Davis, J. L., Mills, K. C., Bobashev, G., Rountree, K. J., Lamvik, M., Yaga, R., et al. (2018, May). Understanding chromaticity shifts in LED devices through analytical models. *Microelectronics Reliability*, 84, 149–156. doi: [10.1016/j.microrel.2018.03.023](https://doi.org/10.1016/j.microrel.2018.03.023)

6 Appendix A

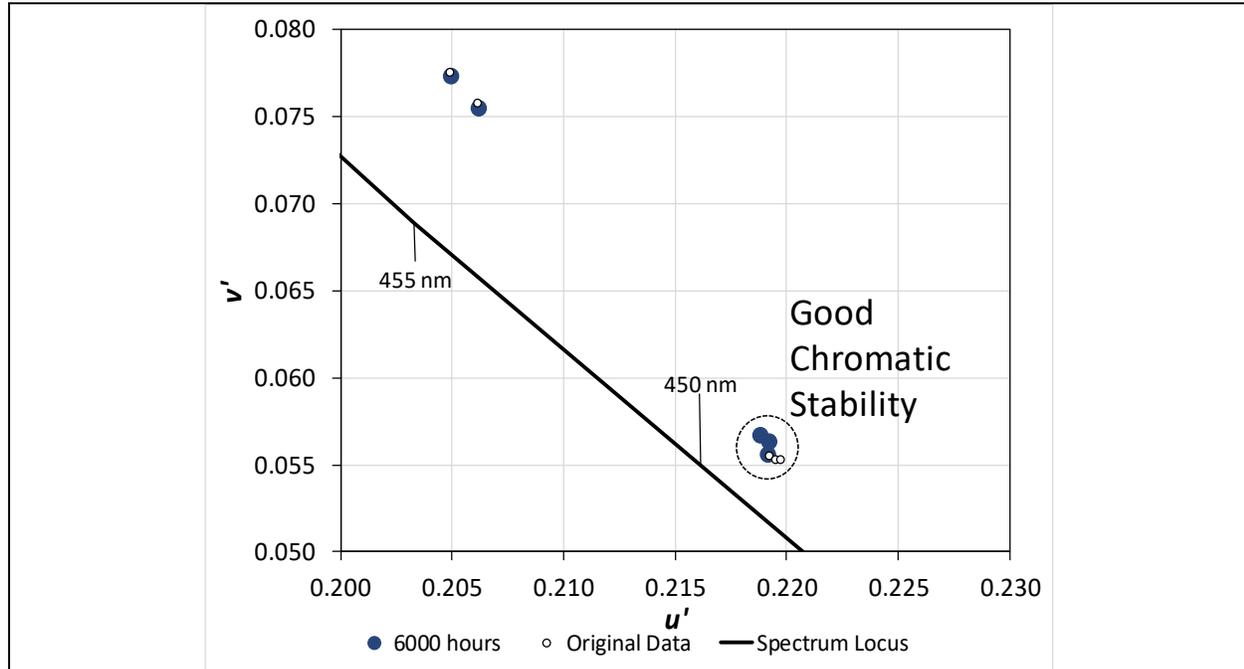


Figure A-1. Expanded view of the royal blue light-emitting diode (LED) section of the International Commission on Illumination (CIE, Commission Internationale d'Éclairage) 1976 chromaticity diagram for the LEDs examined during this study. Small white circles represent the initial chromaticity coordinates; larger, dark blue circles represent the chromaticity coordinates after 6,000 hours of LM-80 testing.

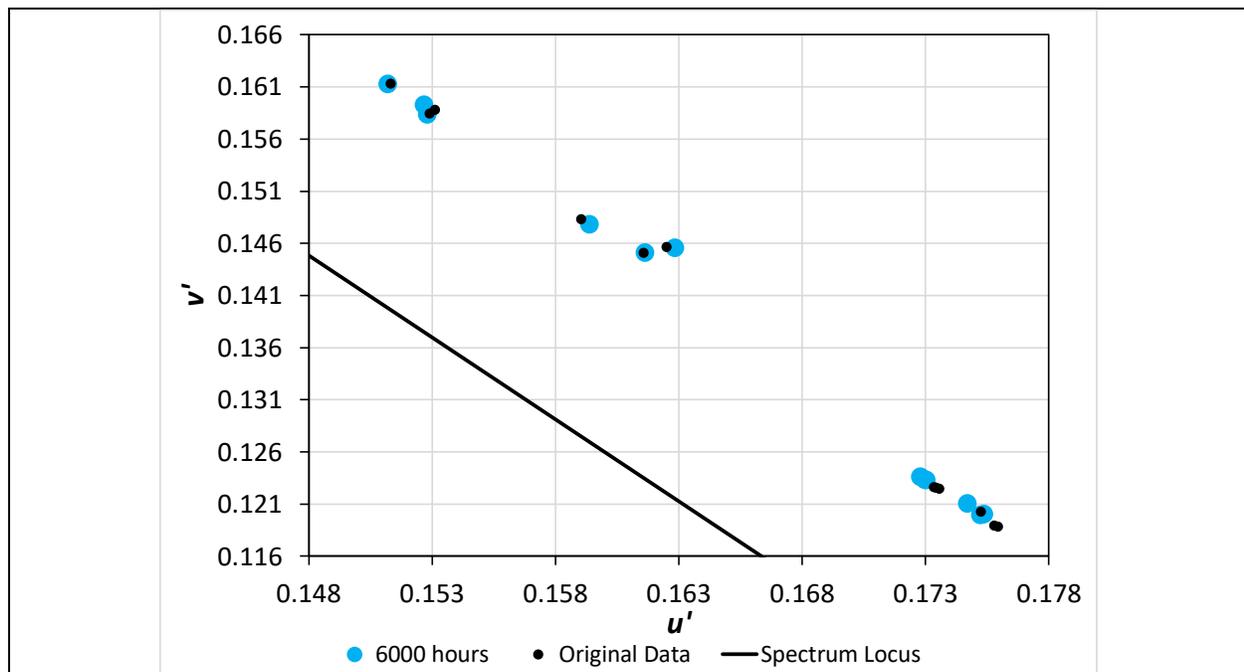


Figure A-2. An expanded view of the blue LED section of the CIE 1976 chromaticity diagram for the LEDs examined during this study. Small black circles represent the initial chromaticity coordinates; larger blue circles represent the chromaticity coordinates after 6,000 hours of LM-80 testing.

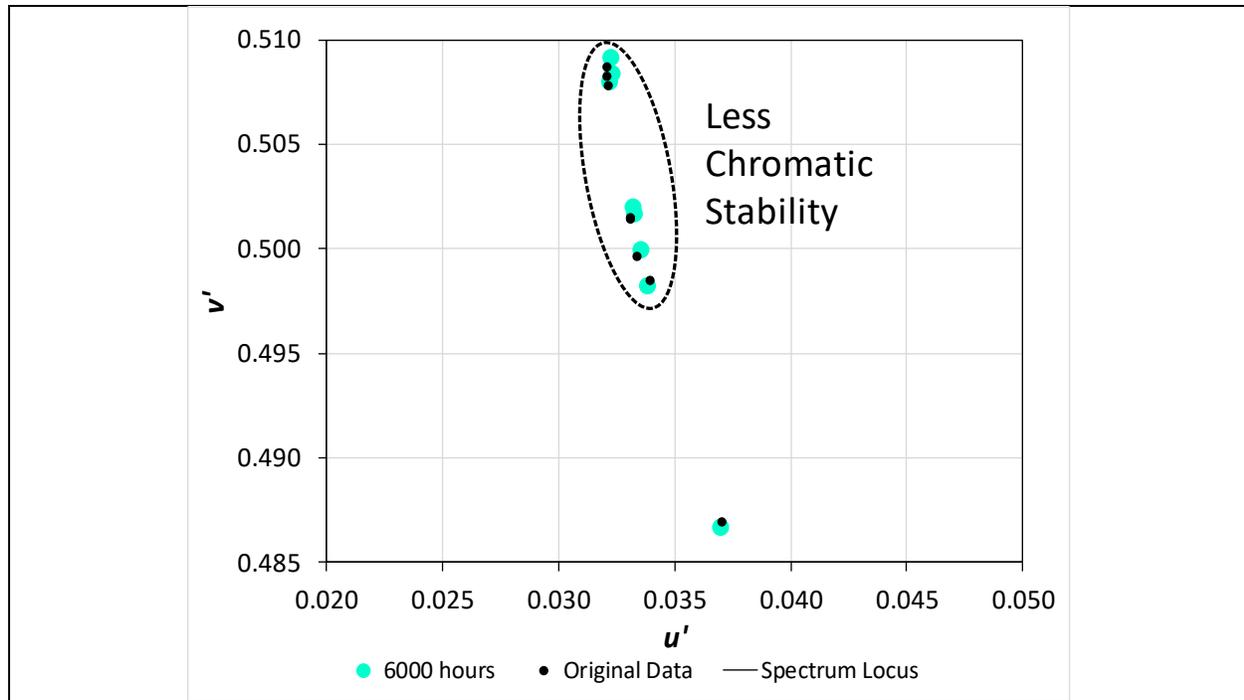


Figure A-3. Expanded view of the cyan LED section of the CIE 1976 chromaticity diagram for the LEDs examined during this study. Small black circles represent the initial chromaticity coordinates; larger cyan circles represent the chromaticity coordinates after 6,000 hours of LM-80 testing.

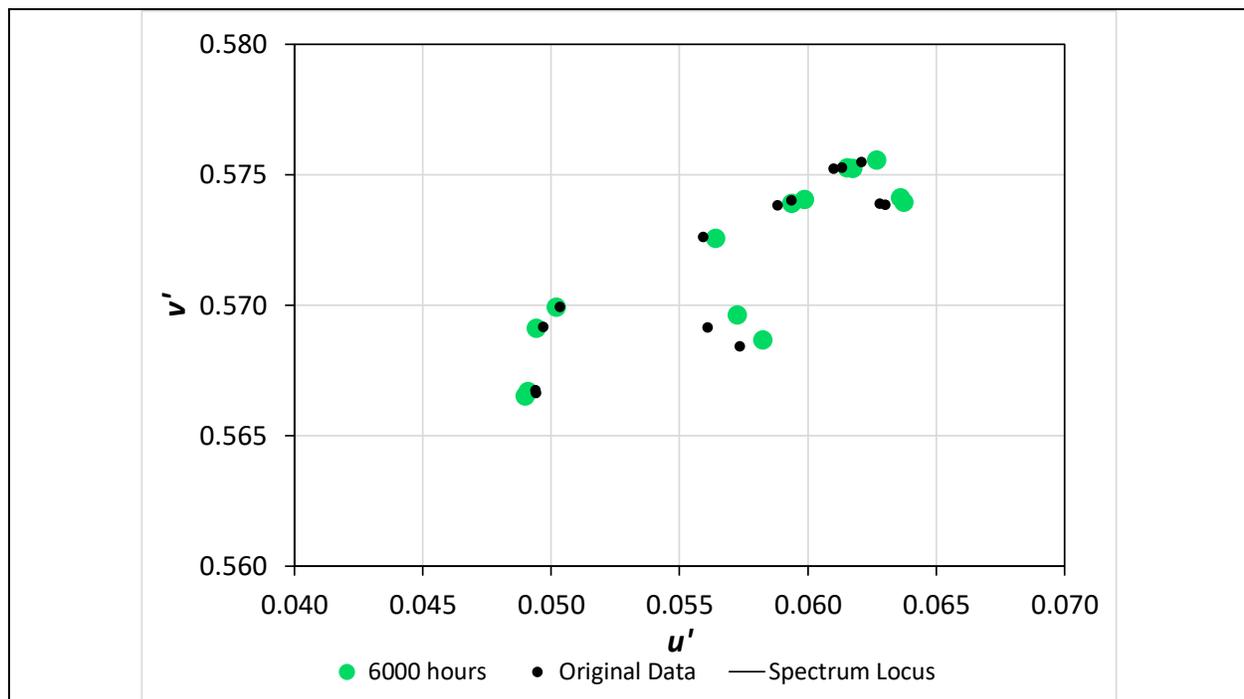


Figure A-4. An expanded view of the green LED section of the CIE 1976 chromaticity diagram for the LEDs examined during this study. Small black circles represent the initial chromaticity coordinates; larger green circles represent the chromaticity coordinates after 6,000 hours of LM-80 testing.

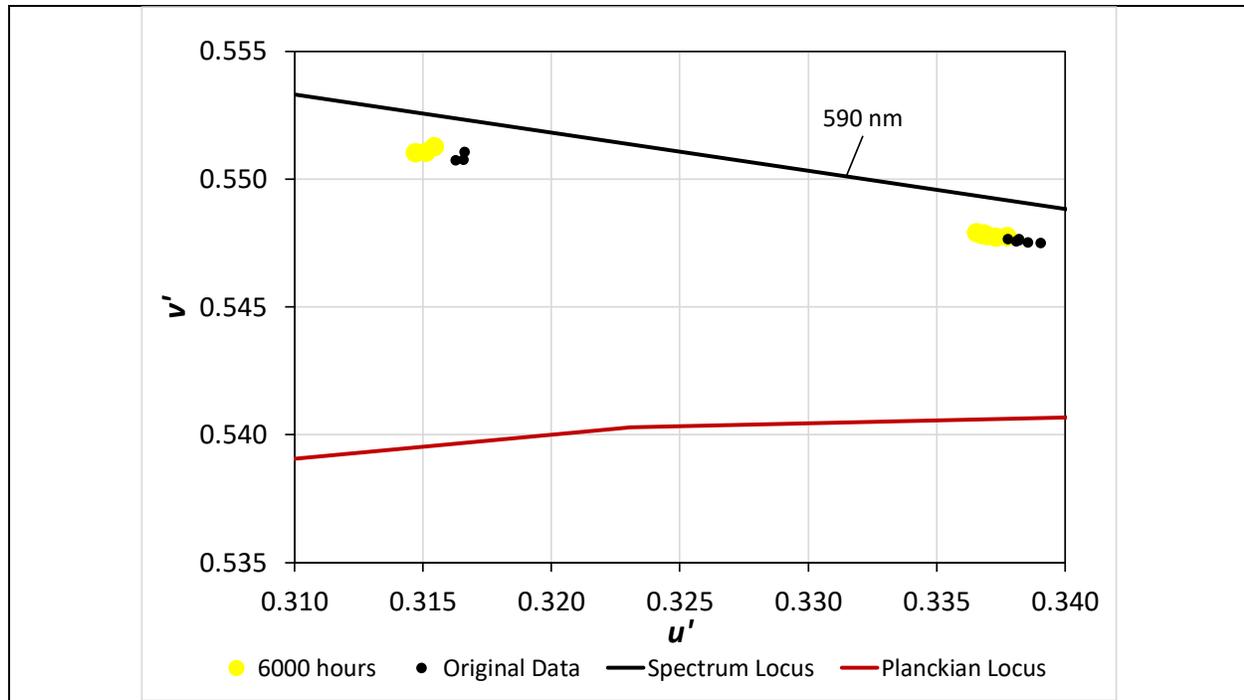


Figure A-5. An expanded view of the amber LED section of the CIE 1976 chromaticity diagram for the LEDs examined during this study. Small black circles represent the initial chromaticity coordinates; larger amber circles represent the chromaticity coordinates after 6,000 hours of LM-80 testing.

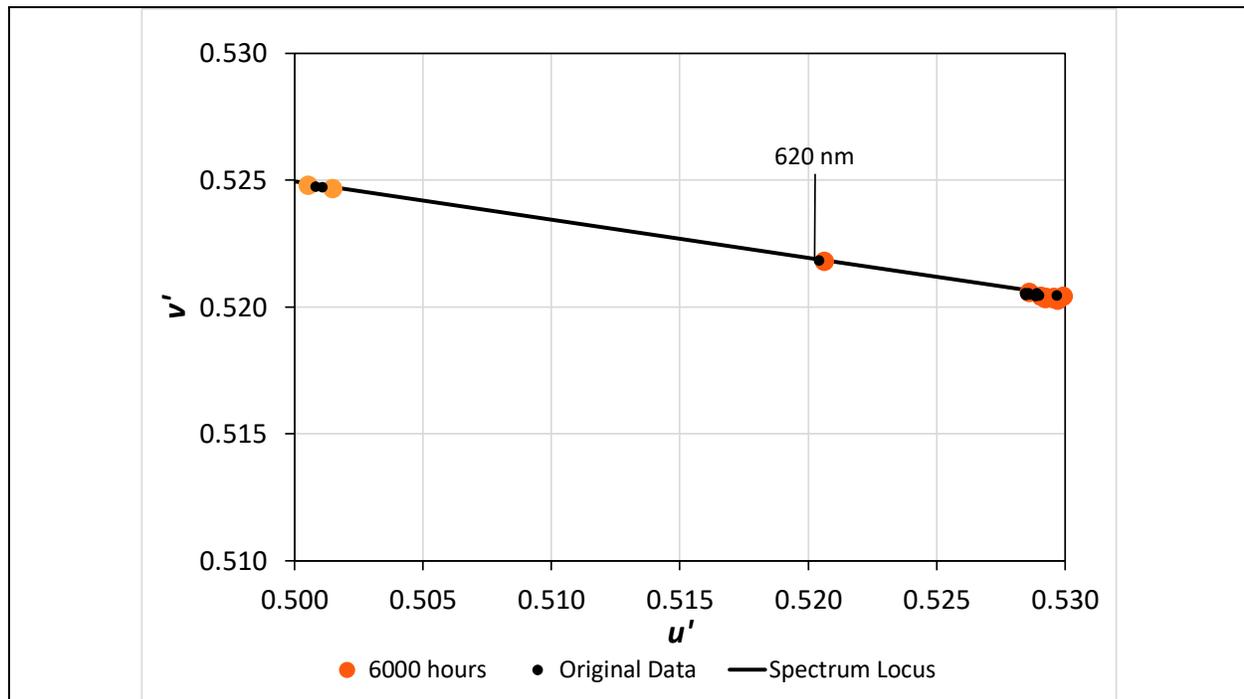


Figure A-6. An expanded view of the red-orange and red LED sections of the CIE 1976 chromaticity diagram for the LEDs examined during this study. Small black circles represent the initial chromaticity coordinates; larger orange and red circles represent the chromaticity after 6,000 hours of LM-80 testing.

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