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Lumen and Chromaticity Maintenance Behavior of Light-Emitting Diode (LED) Packages Based on LM-80 Data

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Disclaimer

List of Acronyms

$\delta u'(t_p)$ and $\delta v'(t_p)$	projected relative chromaticity changes from the initial values at time t_p
$\Delta u'$	change in u'
$\Delta v'$	change in v'
$\Delta u'v'$	chromaticity shift magnitude equal to $([\Delta u']^2 + [\Delta v']^2)^{1/2}$
$\Phi(t)$	averaged normalized luminous flux output at time (t)
°C	degree Celsius
α	exponential decay rate constant in TM-21-11 and TM-21-19
ANSI	American National Standards Institute
B	projected initial constant in TM-21-11 and TM-21-19
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	correlated color temperature
CIE	International Commission on Illumination (*Commission international de l'éclairage*)
COB	chip-on-board
CS4	chromaticity shift lifetime (in hours) to $\Delta u'v'$ = 0.004
CS7	chromaticity shift lifetime (in hours) to $\Delta u'v'$ = 0.007
CSM	chromaticity shift mode
CSP	chip-scale package
DCA	differential chromaticity analysis
DOE	U.S. Department of Energy
DUT	device under test
EERE	Office of Energy Efficiency and Renewable Energy
EMC	epoxy molding compound
HP-LED	high-power LED
hr, hrs	hour, hours
IES	Illuminating Engineering Society
I_f	forward current
InGaN	indium gallium nitride
L0, L1, L2	Level 0, Level 1, Level 2
L_{70}	the time for the luminous flux to decay to 70% of the initial value
L_{80}	the time for the luminous flux to decay to 80% of the initial value
L_{90}	the time for the luminous flux to decay to 90% of the initial value
LED	light-emitting diode
LES	light-emitting surface
lm/W	lumens per watt
L_p	rated flux maintenance life
L_x	the luminous flux maintenance value (e.g., L_{70}, L_{80}, L_{90})
mA	milliampere
MESA	Mission Execution and Strategic Analysis

mm	millimeter
MP-LED	mid-power LED
NETL	National Energy Technology Laboratory
PCB	printed circuit board
pc-LED	phosphor-converted LED
PCT	polycyclohexylenedimethylene terephthalate
PPA	polyphthalamide
SMC	silicone molding compound
SPD	spectral power distribution
SSL	solid-state lighting
t	time
T_j	LED junction temperature
t_p	projection time
u'	chromaticity coordinate in the CIE 1976 color space
v'	chromaticity coordinate in the CIE 1976 color space
V	volt
W	watt

Executive Summary

The four major light-emitting diode (LED) package platforms used in solid-state lighting (SSL) applications (i.e., ceramic-based, polymer-based, chip-on-board [COB] packages and chip-scale package [CSP]) were assessed for luminous flux and chromaticity maintenance by analyzing data sets from LM-80 testing of representative products from many Tier 1 LED manufacturers. A total of 223 separate data sets are included in this analysis, most of which (84%) are from testing completed in 2018–2019. Two-thirds of the LM-80 reports are in the LM-80-15 format.

The assessment of luminous flux maintenance was performed by using both LM-80-08 and LM-80-15 data sets to calculate the TM-21 decay rate constant (α) and normalization constant (B) at each test condition. Then, the performance by package type and operational conditions (e.g., temperature, forward current [I_f]) were plotted and compared. The results are shown in **Figure ES-1** for TM-21-11 α values.

This analysis, which is an update of an earlier study completed in 2015 that focused on only luminous flux maintenance, demonstrated that there has been continued improvement across all LED package types. In total, 96% of the α values in this study are less than 6×10^{-6} which corresponds to an L_{70} time of nearly 60,000 hours (hrs). Perhaps the largest gains have occurred in polymer-based packages where better materials have resulted in marked improvements in luminous flux maintenance to where the performance of polymer-based packages is nearly the same as that of ceramic-based packages for $I_f \leq 200$ milliamperes (mA). The current handling capabilities of COB and ceramic-based packages have also improved significantly, and these package platforms exhibit excellent luminous flux maintenance at operational currents of 1,500 mA and higher. The newly introduced CSP LEDs are shown to exhibit luminous flux maintenance values in line with the other package platforms, especially at operational temperatures of 120 degrees Celsius (°C) and lower and operational currents of 700 mA and lower.

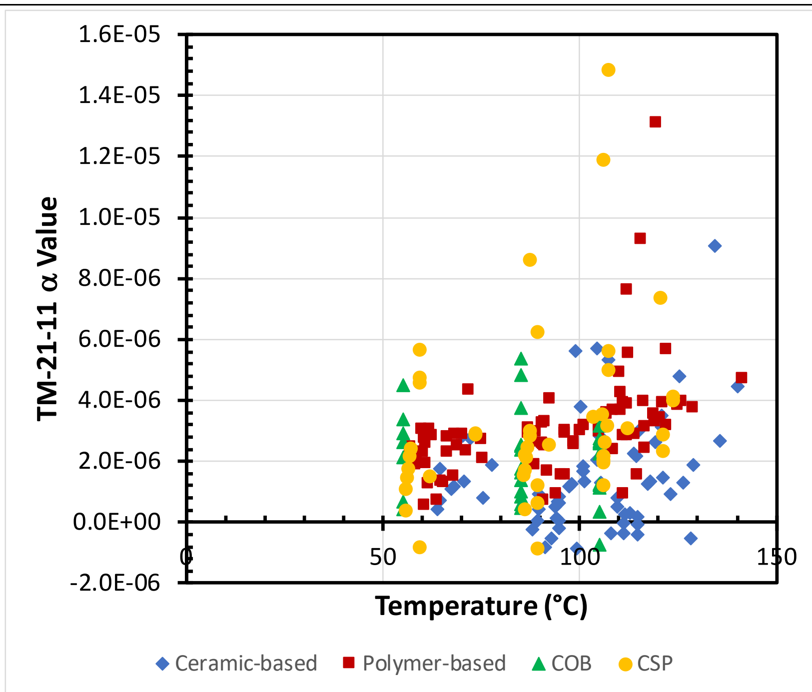

Figure ES-1: Calculated TM-21-11 α values as a function of temperature, sorted by LED package platform, for the data sets studied. The data sets are from 2015–2019, with 84% from 2018–2019.

For chromaticity maintenance, u' and v' data from LM-80-15 reports were used according to TM-35-19—the recently approved method for projecting long-term chromaticity coordinate shifts. The assessment of chromaticity shift is a new addition to this analysis, made possible by the requirement of LM-80-15 to report chromaticity coordinates (*u′*, *v′*). The first step in this analysis was to classify the chromaticity shift mode (CSM) behavior for the products as shown in **Figure ES-2**. Based on the results from this analysis, ceramic-based packages exhibited a high likelihood for CSM-3 behavior (i.e., yellow shift), polymer-based packages exhibited a strong preference for CSM-1 behavior (i.e., blue shift), and CSP LEDs were divided between CSM-1, CSM-2, CSM-3, and CSM-4 behaviors depending on the structure of the package. Determining the CSMs for COBs was more complicated since several different behaviors occurred in COB LED products. Consequently, more research is needed to understand the mechanisms responsible for chromaticity shifts in COB packages. These findings are consistent with earlier evaluations of CSMs in SSL products and demonstrate that the same chromaticity shift failure mechanisms are still active in the various LED packages, but the times for parametric failure to occur have increased.

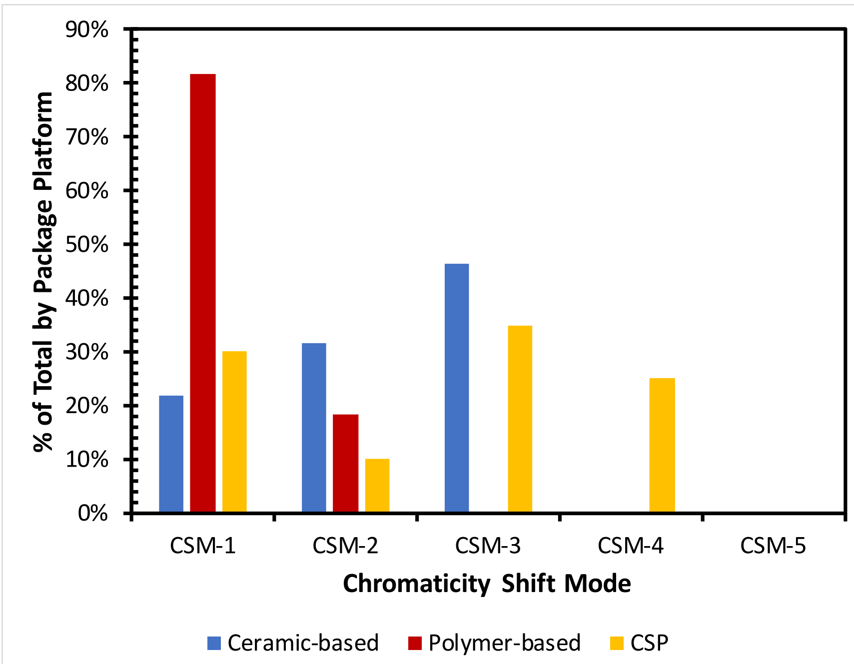

Figure ES-2: Breakout by percentage of the prevalence of different CSMs for the ceramic-based, polymer-based, and CSP LED packages. CSMs could not be assigned to the general COB population due to different behaviors that need additional study.

The second step in the assessment of chromaticity shift of these products was to perform projections of long-term chromaticity coordinate shifts by using the LM-80-15 data sets and the TM-35-19 method. To project future chromaticity, it is important to understand which phase of chromaticity shift the experimental data supports. TM-35-19 defines these phases as incubation, recovery, and emergence, and only the emergence phase involves shifts of sufficient magnitude to reach typical parametric failure thresholds (e.g., $\Delta u'v'$ = 0.004, $\Delta u'v'$ = 0.007). The ability of the TM-35-19 method to accurately predict chromaticity shifts was evaluated according to the following three criteria:

1. TM-35-19 should provide accurate projections of the chromaticity shift magnitude ($\Delta u'v'$) at future times using available experimental data. Alternatively, it is acceptable if the model is conservative in its projections of $\Delta u'v'$, meaning that projected CS4 and CS7 times are likely to be sooner than the true times needed for $\Delta u'v'$ to reach 0.004 or 0.007, respectively.

2. TM-35-19 should provide accurate estimates of the direction of the chromaticity shift (i.e., future *u′* and *v′* values) based on LM-80-15 data sets.

3. TM-35-19 should provide projected chromaticity shift patterns that are consistent across the data sets for a given product at similar test conditions; however, the time at which different chromaticity shifts occur may change depending on the stress level (e.g., temperature, I_f). For example, if an LED package was tested at 55°C, 85°C, and 105°C, then the projections would be expected to show a pattern of similar chromaticity behaviors at these temperatures, but future chromaticity shifts would be expected to happen sooner at the higher test temperatures.

Through a series of six case studies, this analysis demonstrated that Criterion 1 is often, but not always, met. TM-35-19 models are usually conservative in their estimates and, in many cases, they likely over-estimate the future values of u' and v', resulting in larger projected chromaticity shift magnitude values ($\Delta u'v'$) than the expected actual values. The instances in which TM-35-19 underestimates the likely true value of the chromaticity shift magnitude, and predicts much longer CS4 and CS7 times than expected, are cases in which TM-35-19 projects a sudden change in chromaticity that is not supported by experimental data. Such instances can be identified by the lack of consistent chromaticity shift pattern among the data sets (Criterion 3). Graphs of $\Delta u'$ versus time and $\Delta v'$ versus time are often helpful in examining data set consistency. Finally, an additional consequence of the conservative nature of the model is a general low success rate in projecting future chromaticity shift directions (Criterion 2). For example, many TM-35-19 calculations result in projections of the chromaticity shifting toward the magenta direction, a shift that has not been observed for white phosphor-converted LEDs (pc-LEDs).

This analysis found that TM-35-19 provides reasonable and often conservative estimates of chromaticity shift magnitude ($\Delta u'v'$) and generally meets the conditions of Criterion 1. In particular, the model works best when the emergence phase is known and there is at least some data to indicate that emergence has occurred. The method is much less likely to produce a reliable estimate of chromaticity shift direction and does not consistently meet Criterion 2. Finally, the instances in which Criterion 1 is not met can often be identified by a sudden change in chromaticity shift behavior that is not supported by available experimental data when examining performance across different LM-80-15 test conditions for the same LED product.

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1 Introduction

1.1 Background

Solid-state lighting (SSL) technologies are becoming the dominant lighting solution across many applications, as evidenced by the rapid sales growth of SSL devices over the past decade. The basic building block of SSL products is the white light-emitting diode (LED), which is made from indium gallium nitride (InGaN) epitaxial materials that emit blue radiation in proximity to a phosphor. Emissions from the InGaN blue LED die excite (or optically pump) the broadly emitting phosphor, and the combination of unabsorbed blue light (from the LED) and emissions from the yellow-green phosphor provide the resulting white light that can be used in general illumination. Because of the numerous technology breakthroughs, the luminous efficacy of white phosphor-converted LEDs (pc-LEDs), as measured in lumens per Watt (lm/W), continues to advance toward a practical limit of 255 lm/W. As a result, the transition from less efficient incandescent and fluorescent white lighting sources to LED-based SSL technologies reduced the annual energy consumption attributed to lighting by 1.1 quads in 2017, and the energy savings is expected to increase to 4.8 quads annually in 2035, if the current research path is followed. The aggressive research goals of the U.S. Department of Energy's (DOE) Lighting Research and Development Program has the potential to provide even larger energy savings and reduce annual energy consumption attributed to lighting by a total of 6.1 quads in 2035 [1].

To function properly over their expected lifetimes, LED die are housed in packages that provide easy optical and electrical coupling, as well as protection from operational and environmental stressors. There is a general hierarchy of LED packaging, shown in **Figure 1-1**, proceeding from the LED die (Level 0 [L0]), to a packaged LED die (Level 1 [L1]), to LED modules (Level 2 [L2]) and beyond [1,2]. This report will focus on the fundamental building block of SSL systems, the L1 LED package. The LED package serves many functions during operation, including the following:

- Containing the phosphor for converting the blue emissions of the LED into white light
- Providing a robust structure that can be rapidly assembled into modules, printed circuit boards (PCBs), and lighting arrays with reduced risk of mechanical damage
- Protecting the LED die from environmental contamination
- Electrically and thermally connecting the LED die to higher levels of packaging to provide electrical power and heat dissipation.

Because the LED package interacts with light emitted by the LED, the choice of package platform impacts the overall performance of the lighting system.

Figure 1-1: Hierarchy of LED packages for lighting applications (adapted from [1]).

As the LED lighting industry has evolved, a variety of L1 packages have emerged that differ by packaging materials, photopic properties, power levels, and physical dimensions. From this diversity of choices, the LED package platforms most widely used in general lighting applications can be sorted into one of four main groups [1]: ceramic-based packages, polymer-based packages, chip-on-board (COB) packages, and chip-scale package (CSP) LEDs. Some representative examples of these LED package platforms are shown in **Figure 1-2** [1]. The characteristics of these four primary LED package platforms are summarized as follows:

- **Ceramic-based packages.** In this type of package, a single LED die sits on top of a ceramic substrate. A phosphor-silicone composite on top of the die places the phosphor in proximity to the LED die, and a separate silicone lens is molded over the entire assembly. Ceramic-based packages are most used in high-power LED (HP-LED) products (1 to 5 watts [W]), but can also be found in a few mid-power LED (MP-LED) products. LEDs in ceramic-based packages are typically used in products requiring small optical source size (e.g., directional lamps) or high reliability (e.g., street lights).

- **Polymer-based packages.** This platform is termed the polymer-based package platform because it is derived from the plastic leaded chip carrier used in general electronics packaging. In this type of package, one or more LED die are housed in a cavity formed from a molded polymer (e.g., thermoset resin, thermoplastic). After placing the die on a lead frame in the molded polymer package, the optical cavity is filled with a phosphor-silicone mixture to place the phosphor near the LED die, resulting in the production of white light. Polymer-based packages are the most common LED package platform, and they are found mainly with MP-LEDs (0.3 to 1 W), although in the case of polymer-based packages with multiple LED die, the operational power levels may rise into the HP-LED realm. Polymer-based LED packages are typically used in products requiring omnidirectional emission (e.g., troffers, A-type lamps).

- **COB packages.** This type of package consists of multiple LED die arrayed on a thermally conductive substrate such as a metal-core PCB or a thermally conductive ceramic such as aluminum nitride. The die are dispersed on the substrate, connected by either wire bonds or solder bumps, and are covered by a phosphor-silicone composite, which creates a “fried egg” appearance (**Figure 1-2**) [1]. The power levels of these package range from 5 W to more than 80 W, and these packages are used in products that require high luminous flux from small optical sources or extremely high lumen density (e.g., high-bay lighting).

- **CSP LEDs.** In this type of package, which is also referred to as package-free LEDs or white chips, the package has a similar footprint to the LED die, and a phosphor-silicone mix is then molded over the die to complete the package. CSP LEDs have gain attention as a compact, low-cost alternative to the ceramic- and polymer-based package platforms.

Figure 1-2: Representative examples of L1 LED packages, including (from left) ceramic-based packages, (B) polymer-based packages, (C) COB packages, and (D) CSP LEDs.

1.2 Previous Studies of Luminous Flux Behavior by Package

Previous work funded by the DOE showed that there was a significant difference in the luminous flux maintenance behavior of LEDs related to the LED package platform [3,4,5]. This conclusion was reached by analyzing more than 250 data sets of luminous flux maintenance. The data sets were collected by using the approved industry standard method, the LM-80* method, which was developed by the Illuminating Engineering Society (IES) [6,7]. LM-80 data sets were then fit with an exponential decay model by using the methodology established in IES TM-21-11 [8] and American National Standards Institute (ANSI)/IES TM-21-19 [9], resulting in a model of the form of Equation 1, which is presented as follows:

$$\Phi(t) = Be^{-\alpha t} \qquad \text{(Equation 1)}$$

Where

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

B = The projected initial constant which is approximately 1.0 when $\Phi(t)$ is normalized

α = The exponential decay rate constant.

The decay rate constant, α, and the initial constant, B, can be used to project the luminous flux maintenance at future times. To avoid projections that exceed the statistical significance of the data, both TM-21-11 and TM-

* References to IES standards that do not include a date (e.g., the LM-80 method) are referring to the standard in general, whereas references to an IES standard with a specific date (e.g., LM-80-08, LM-80-15) are referring to the specific standard document approved that year.

21-19 mandate that *rated flux maintenance life (L_p) times cannot be greater than 6 times the actual LM-80 test duration*, and only when specific test conditions, such as the number of samples, have been met. This requirement is often termed the "6X rule." For example, if L_{70} is the time required to reach 70% luminous flux maintenance and an LM-80 test was conducted for a total of 10,000 hours, then the *maximum* value of L_{70} is 60,000 hours, although the L_{70} time could be less. Together, LM-80 and TM-21 have become the accepted methods for reporting the luminous flux maintenance performance of LEDs used in lighting applications, especially for white LEDs.

The early DOE-funded work examined LM-80-08 data sets from 2011 to 2015. This analysis showed that the exponential decay rate constants (α), a measure of luminous flux maintenance, are distributed by LED package type and junction temperature (T_j) as shown in **Figure 1-3** [3,5]. For clarity, 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 $\alpha = 3.56 \times 10^{-6}$, assuming $B = 1$ and the 6X rule allows a projection to these times.

Although there is a significant amount of overlap between the α values of a given LED package platform in **Figure 1-3**, it is also clear that the structure of the LED package has an impact on α. The ceramic-based and COB packages tend to have the lowest α values at a given T_j, and polymer-based packages often have higher α values. Because α and L_{70} are inversely related, a lower α value results in a longer L_{70} time; therefore, in most instances, the lifetime of ceramic-based packages are expected to exceed that of polymer-based packages. The results from the early analysis also showed that the performance of early polymer-based package LEDs, which extensively used polyphthalamide (PPA) in early products, could be improved by using new molding resins such as polycyclohexylenedimethylene terephthalate (PCT), epoxy molding compound (EMC), and silicone molding compound (SMC) as shown in **Figure 1-4** [3,4,5].

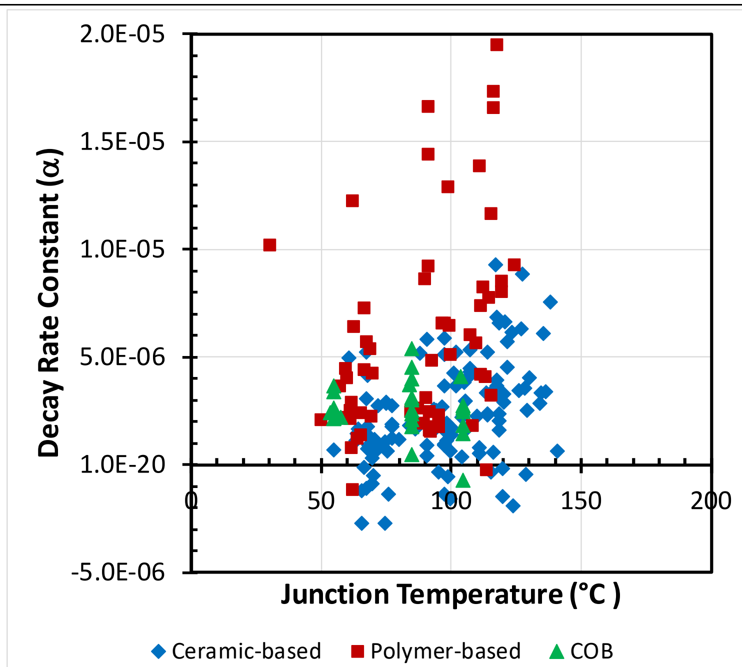


Figure 1-3: Calculated decay rate constants (α) of TM-21-11 projections from LM-80-08 data sets for commercial white LEDs available in the 2011–2015 time frame [3–5].

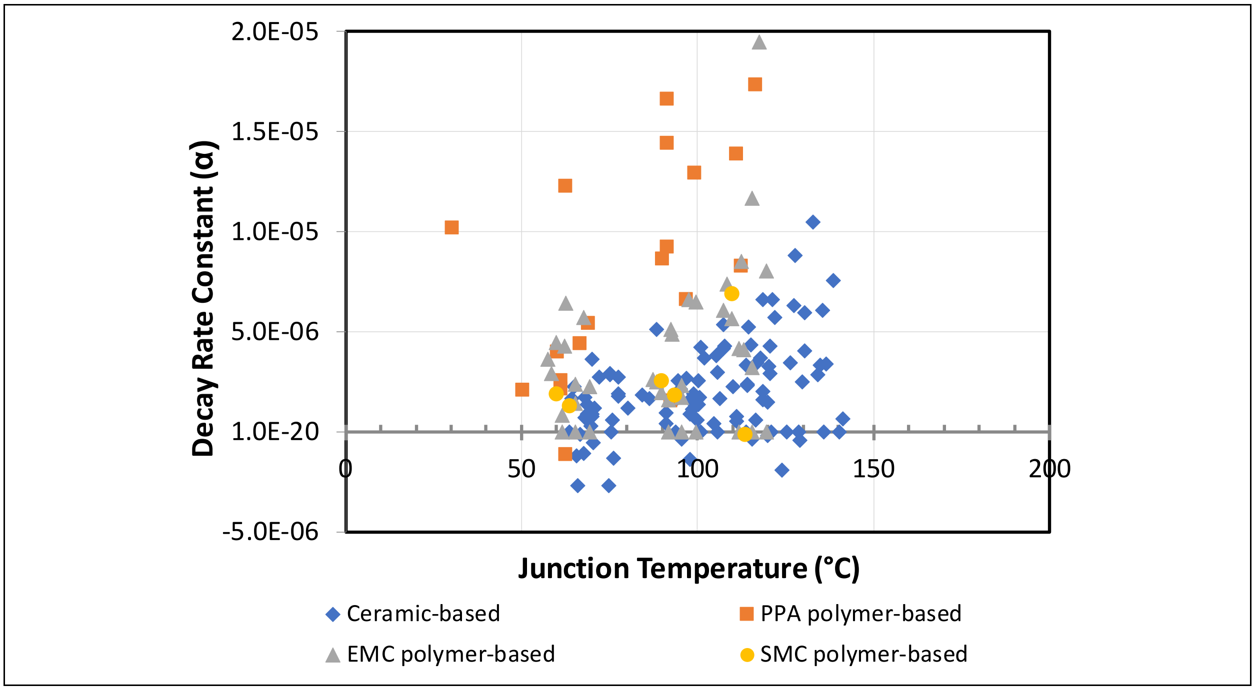


Figure 1-4: Decay rate constants (α) of TM-21-11 projections from LM-80-08 data sets for commercial white LEDs in polymer packages broken out by polymer type. Data for ceramic-based packages are also included for comparison. These LM-80-08 data are from the 2011–2015 timeframe [3-5].

Corresponding data sets for CSP LEDs have only recently become available because of the increased use of this new LED package platform in SSL products. Likewise, growth in the use of the COB LED package platform has resulted in additional data sets becoming available for analysis. As a result, luminous flux maintenance data can be analyzed from these platforms to provide an updated picture of the impacts of the L1 package on LED performance.

1.3 Differences Between IES LM-80-08 and ANSI/IES LM-80-15

The lighting industry has used two different versions of the LM-80 method to measure luminous flux maintenance. Published in 2008, the LM-80-08 method provides procedures for collecting luminous flux maintenance data and the magnitude of chromaticity shifts as measured by $\Delta u'v'$ [6]. LM-80-08 requires that measurements be taken at three different LED case temperatures: 55°C, 85°C, and a third temperature selected by the manufacturer [6]. Although the LM-80-08 method has some limitations [10], it became the de facto standard for reporting luminous flux maintenance data for LED packages.

However, as the industry grew, the reporting of chromaticity shift, as measured by $\Delta u'v'$, was deemed to be inadequate [5,11,12]. Therefore, when LM-80 was updated in 2015 (i.e., LM-80-15), additional reporting requirements were added to provide greater insights into chromaticity maintenance behavior. The six reporting requirements in LM-80-15 for each working device under test (DUT) at each test interval are as follows:

- Initial and subsequent flux values (e.g., luminous flux, radiant flux, photon flux).
- Initial and subsequent chromaticity coordinates, dominant wavelength, peak wavelength, or centroid wavelength. Chromaticity is required to be expressed in International Commission on Illumination (*Commission international de l'éclairage* [CIE]) *u'* and *v'* chromaticity coordinates.
- Statistical information for all of the DUTs at each measurement interval.
- Electrical drive level for photometric and electrical measurements.

- Measurement point temperature and location for photometric and electrical measurements.
- Description of the photometric measurement method.

In moving from LM-80-08 to LM-80-15, the lighting industry decided that data regarding chromaticity shift magnitude (i.e., $\Delta u'v'$) needed to be augmented by reporting chromaticity shifts in standard chromaticity coordinates (i.e., u' and v') or other measures of the change in the spectral power distribution (SPD) at each measurement interval. It is important to note that $\Delta u'v'$ provides the chromaticity shift magnitude but not the direction, whereas the new chromaticity measures required by LM-80-15 provide additional information about the chromaticity shift direction.

1.4 Chromaticity Shift in LED Devices

DOE supported the study of chromaticity shift modes (CSMs) in PAR38 lamps that had been subjected to nearly 14,000 hours of constant use in an elevated ambient environment of 45°C [13]. The results from this analysis showed that the CSMs for LED products can be divided into five different types [11–13]. From the white point on the Planckian locus, a chromaticity change in a generally blue direction can be seen to produce a negative change in v' (i.e., $\Delta v' < 0$, where $\Delta v'(t) = v'(t) - v'_0$) and a smaller change in u' (i.e., $\Delta u'$ is small, where $\Delta u'(t) = u'(t) - u'_0$), as shown in **Figure 1-5**. Likewise, a chromaticity shift in the generally yellow direction involves a positive change in v' ($\Delta v' > 0$) and a smaller change in u' ($\Delta u'$ is small). Similarly, a shift in the generally green direction produces a negative change in u' ($\Delta u' < 0$) and a smaller change in v' ($\Delta v'$ is small), whereas as shift in the generally red direction produces a positive change in u' ($\Delta u' > 0$) and a smaller change in v' ($\Delta v'$ is small). The characteristic changes in u' and v' are caused by different mechanisms, which are summarized in **Table 1-1**.

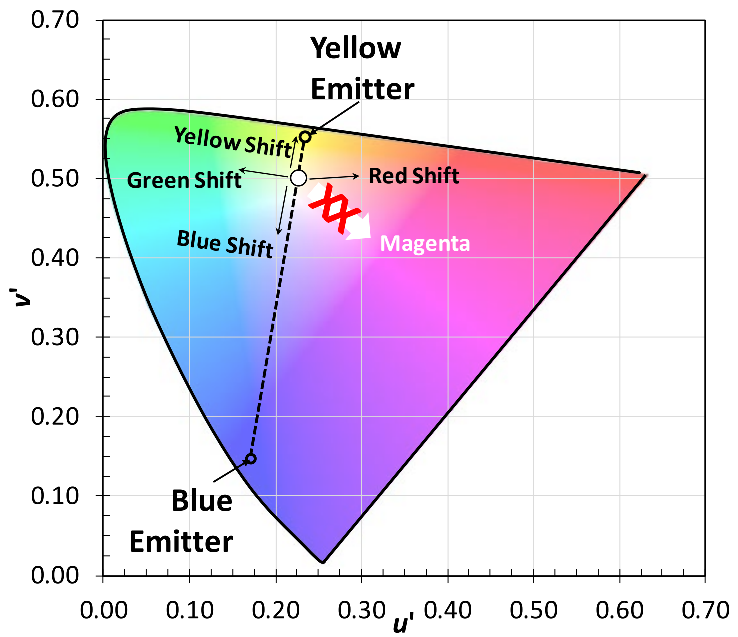


Figure 1-5: CIE 1976 diagram showing the general change of chromaticity shifts observed for white pc-LEDs. For white pc-LEDs, chromaticity generally changes toward the blue, yellow, green, or red directions. Shifts in the magenta direction have not been observed for white pc-LEDs.

Table 1-1: Characteristics of different CSMs.

CSM	Direction of Final Chromaticity Shift	Changes in u' and v'	Link to LED Package Platform
1	Blue	v' typically decreases much faster than u'	Can occur in any package and is often caused by cracking of the encapsulant
2	Green	u' decreases while there is minimal change in v'	Tends to occur in some warm white LED devices due to changes in the phosphors
3	Yellow	v' typically increases much faster than u'	Dominant CSM mode for some ceramic-based packages and is often caused by delamination or absorption of blue
4	Blue, then yellow, then blue	v' increases much faster than u' in yellow shift, and then v' decreases much faster than u' in blue shift	Dominant CSM mode for some polymer-based packages and is often due to polymer photo-oxidation
5	Red	u' increases while there is minimal change in v'	Tends to occur in some warm white LED devices due to changes in the phosphors

Virtually all chromaticity shifts in white pc-LEDs generally fall into one of these five CSMs, which cover most of the major colors in the color space. However, chromaticity shifts toward the magenta region (see **Figure 1-5**) have not been reported for white pc-LEDs. Such a shift would be characterized by an increase in $\Delta u'$ and a decrease in $\Delta v'$. Because there are typically no magenta emitters in white pc-LEDs, such a shift could only occur in white pc-LEDs by simultaneous changes in two colors (e.g., blue and red). For example, such a shift could occur if the relative red emissions increase (which increases $\Delta u'$) while the blue emissions are also increasing (which decreases $\Delta v'$). These two trends are mutually exclusive and unlikely to happen simultaneously in white pc-LEDs because an increase in blue emissions means that more photons are bypassing the phosphor layer and are not being converted by the phosphor while an increase in red emissions in a pc-LED device means that more photons are being converted by the red phosphor (and less by the green phosphor). Consequently, this type of chromaticity shift is not likely to occur in white pc-LEDs.

By examining the CSM behavior of different SSL devices and identifying the root cause of the chromaticity shift, significant progress has been made in understanding the causes of chromaticity shifts and the linkages to specific LED package platforms [3–5,12,14], as indicated in **Table 1-1**. For example, ceramic-based LED packages often exhibit a yellow chromaticity shift (i.e., CSM-3) during prolonged use because of delamination of the phosphor layer from the die [3–5,12,14]. As another example, photo-oxidation of the polymer molding resin used in some polymer-based LED packages has also been shown to produce a brief yellow chromaticity shift followed by a prolonged blue chromaticity shift (i.e., CSM-4) with continued use [12,15]. However, some CSMs are due to changes in materials commonly used in LED packages and may affect any LED package platform. For example, cracks in the silicone encapsulants in LED packages will often produce shifts in the generally blue direction (CSM-1). Likewise, changes in the phosphor material will often produce changes in the generally green direction (CSM-2) or generally red direction (CSM-5), depending on the chemical nature of the phosphor [5,16].

Of course, the direction of chromaticity shift may change several times during the operational lifetime of an LED device as shown for two different LED modules consisting of MP-LEDs in **Figure 1-6** [17]. In LM-80-08, the nature of such chromaticity shifts were only reported as $\Delta u'v'$ (see **Figure 1-7**), which provided information about the magnitude, but not the direction, of the shift. The warm white LED module in this example was observed to initially shift in a generally red direction, and then reversed direction after 2,500 hours (hrs) of operation and shifted in a generally green direction (i.e., CSM-2) for the remainder of the test period (20,000 hrs). In contrast, the cool white LED module initially shifted in the generally yellow direction, and then reversed course after 2,500 hrs of testing to shift in the generally blue direction (i.e., CSM-4). If the test conditions are changed (e.g., higher ambient temperature or operational current), then the timing of these chromaticity shifts changed (see **Figure 1-7**), but the long-term behavior was remarkably consistent as long as the underlying chemical processes remained the same and the test conditions did not create new failure modes [17]. In short, LEDs generally follow the same chromaticity shift behavior under most operational conditions, but the rate of the shift may change because of the impacts of temperature and forward current (I_f).

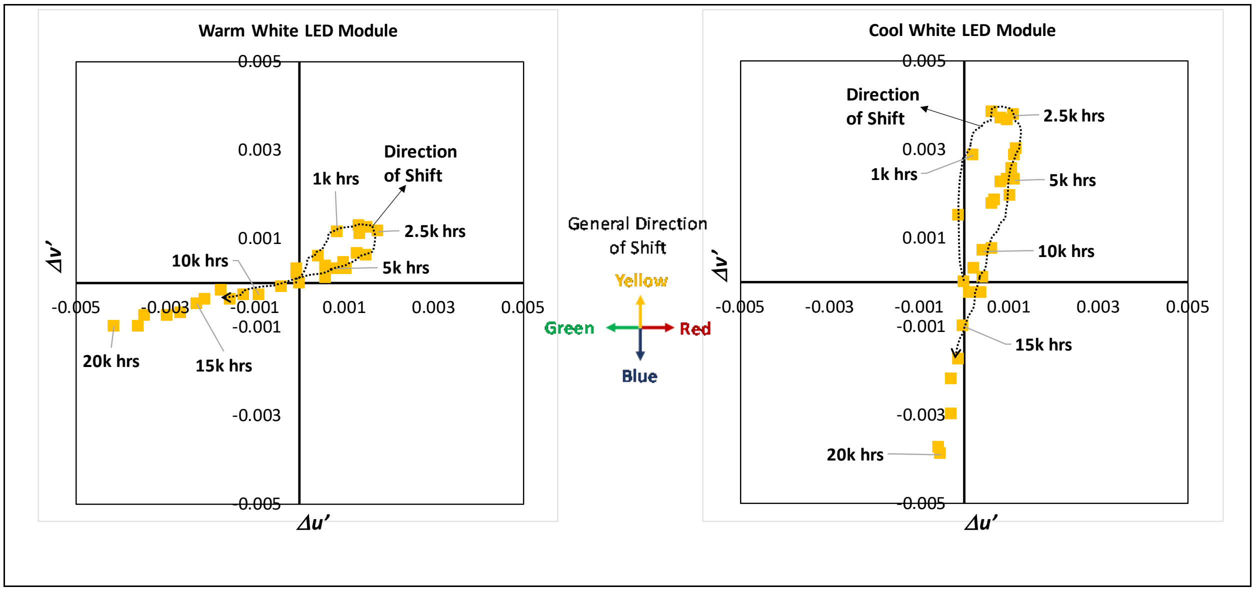


Figure 1-6: Chromaticity shifts for warm white and cool white LED modules comprised of MP-LEDs in similar packages. Both LED modules were operated at 95°C and 1,000 milliamperes (mA) [17].

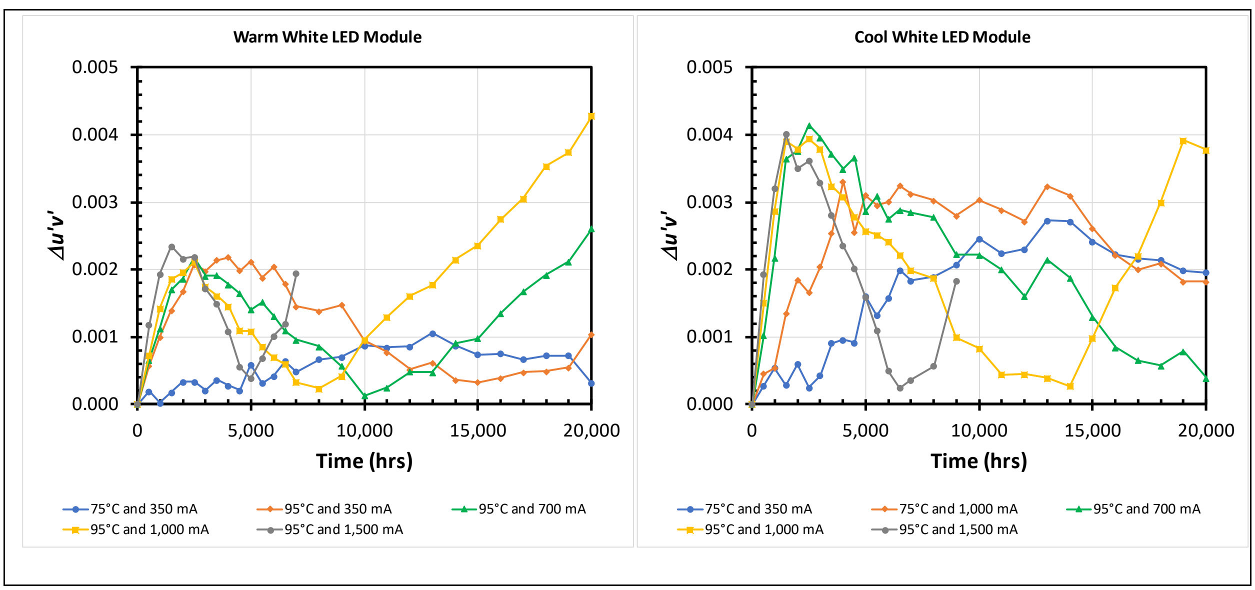


Figure 1-7: Temporal graph of chromaticity shift magnitude ($\Delta u'v'$) for the warm white and cool white LED modules operated during different test conditions [17]. The LED modules were comprised of MP-LEDs in similar polymer-based packages.

The details of such chromaticity shifts are difficult to elucidate solely from *Δu′v′* values (see **Figure 1-7**). However, during TM-35-19, temporal graphs of *Δu′v′* can be helpful in identifying three major phases of chromaticity shift (i.e., incubation, recovery, and emergence) [18]. ANSI/IES TM-35-19 defines the incubation phase as when *Δu′v′* is approximately constant; the recovery phase, if present, as the phase that follows the incubation phase and shows a decrease in *Δu′v′* with time; and the emergence phase as the final phase of the color shift. These three phases are labeled in **Figure 1-8**, and estimations of the approximate duration of each phase are provided in **Table 1-2** for the data in **Figure 1-7**. Of these phases, the emergence phase has the greatest impact on long-term chromaticity shifts (in terms of direction and magnitude) because it is the final phase of chromaticity shift, during which *Δu′v′* increases as an approximately linear function of time until a chromaticity shift failure threshold is reached. The elapsed operating time when an LED light source exhibited a chromaticity shift greater than common thresholds are denoted as CS4 (for the time when *Δu′v′* = 0.004) and CS7 (for the time when *Δu′v′* = 0.007). Consequently, knowing when the emergence phase occurs is important to understanding the long-term chromaticity maintenance of any LED device. It is also important to understand which phase of chromaticity shift the available data represents because this information will improve the accuracy of chromaticity shift projection.

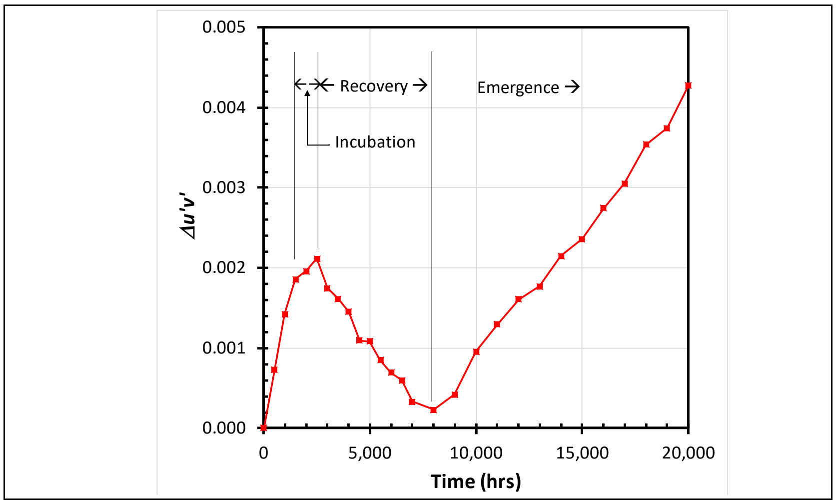


Figure 1-8: The three phases of chromaticity shift for a warm white LED module operated at 95 °C and 1,000 mA.

Table 1-2: Approximate breakout of the different phases of chromaticity shift for the examples in Figure 1-7.

LED Module	Test Condition	Incubation	Recovery	Emergence
Warm white	75°C and 350 mA	9,000–19,000 Hrs	19,000–20,000+ Hrs	Not determined
	95°C and 350 mA	3,000–6,000 Hrs	6,000–19,000 Hrs	20,000+ Hrs
	95°C and 700 mA	2,000–3,500 Hrs	3,500–10,000 Hrs	10,000 Hrs onward
	95°C and 1,000 mA	1,500–2,500 Hrs	2,500–8,000 Hrs	8,000 Hrs onward
	95°C and 1,500 mA	1,500–2,500 Hrs	2,500–5,000 Hrs	5,000 Hrs onward
Cool white	75°C and 350 mA	10,000–20,000+ Hrs	Not determined	Not determined
	75°C and 1,000 mA	4,000–14,000 Hrs	14,000–20,000+ Hrs	Not determined
	95°C and 700 mA	1,500–4,500 Hrs	4,500–20,000+ Hrs	Not determined
	95°C and 1,000 mA	1,500–3,000 Hrs	3,000–14,000 Hrs	14,000 Hrs onward
	95°C and 1,500 mA	1,000 Hrs	1,000–6,500 Hrs	6,500 Hrs onward

2 Analysis Methods for LM-80 Data Sets

2.1 Data Sets Used in This Analysis

During this analysis, the leading LED manufacturers were contacted and were requested to provide LM-80-15 data sets for commercial LEDs in the different package platforms from their white LED product lines. The request was not intended to cover all LEDs in the different package formats but rather to provide a sampling of the performance of available products in each package platform. During the initial canvas of LED manufacturers, several findings were realized. First, many, but not all, LED manufacturers use external test houses to perform LM-80 testing. Second, many manufacturers are providing LM-80-08 reports (often from the original tests conducted before 2015) for long-running product lines that are still sold, whereas LM-80-15 reports are provided for the newer product lines. As a result, the number of LM-80-15 reports that the authors of this report received was lower than expected, but the number of LM-80-08 reports was higher. The luminous flux maintenance analysis reported here includes data sets from both LM-80-08 and LM-80-15 reports, but a chromaticity analysis was not conducted on LM-80-08 data sets because only $\Delta u'v'$ data were available. Chromaticity analyses were only performed on data sets adhering to the LM-80-15 standard.

A total of 223 different LM-80 data sets were collected across all package types. The dates of the LM-80 reports ranged from 2014 to 2019 (see **Figure 2-1**), with most of the data sets (84%) coming from reports that were completed between 2018 and 2019. Out of the 223 data sets, 146 (66%) included u' and v' chromaticity coordinates either directly through the LM-80-15 reports or through supplemental materials provided by the manufacturers and can be considered as meeting the reporting requirements of LM-80-15. In addition, many of the LM-80-15 data sets provide measurements at approximately 500-hr increments, which helps to improve the resolution of chromaticity shift analyses. In many instances, manufacturers will often provide a minimal amount of data in official LM-80-15 reports, with data rarely surpassing 10,000 hrs of testing; 1,000-hr test increments are the most common. <u>Consequently, the data used in this analysis greatly exceed the current industry norms</u>.

In this analysis, all data sets that did not meet the reporting requirements of LM-80-15 were classified as LM-80-08 data sets; as a result, some data sets were classified differently than as stated by the manufacturers. Out of the 77 data sets classified as LM-80-08 data sets during this analysis, 62 (81%) were properly labeled as LM-80-08 reports, but the remaining 15 were erroneously classified by the manufacturer as LM-80-15 data sets, despite only reporting $\Delta u'v'$ values at each measurement time instead of the required u' and v'. There were also 41 data sets that provided correlated color temperature (CCT) data for each test LED at every measurement time, but not u' and v'. Most of these data sets were correctly labeled as LM-80-08 reports, but several were mislabeled as LM-80-15 reports. Although the CCT data for each test LED at every measurement time does provide some insights regarding chromaticity changes, there is still some ambiguity in the chromaticity shift direction. Consequently, reporting CCT values is not an adequate substitute for u' and v' values, and the data sets do not conform with LM-80-15. In some instances, the LM-80-15 designation that was assigned to non-compliant data sets by the test house was changed to the more accurate LM-80-08 designation by the LED manufacturer. However, in other cases, the erroneous LM-80-15 designation given by the test house was passed along by the LED manufacturer. <u>It is important that both the test houses and the LED manufacturer understand the reporting requirements of standards such as LM-80-15 and that report data are identified with the appropriate standard test method</u>.

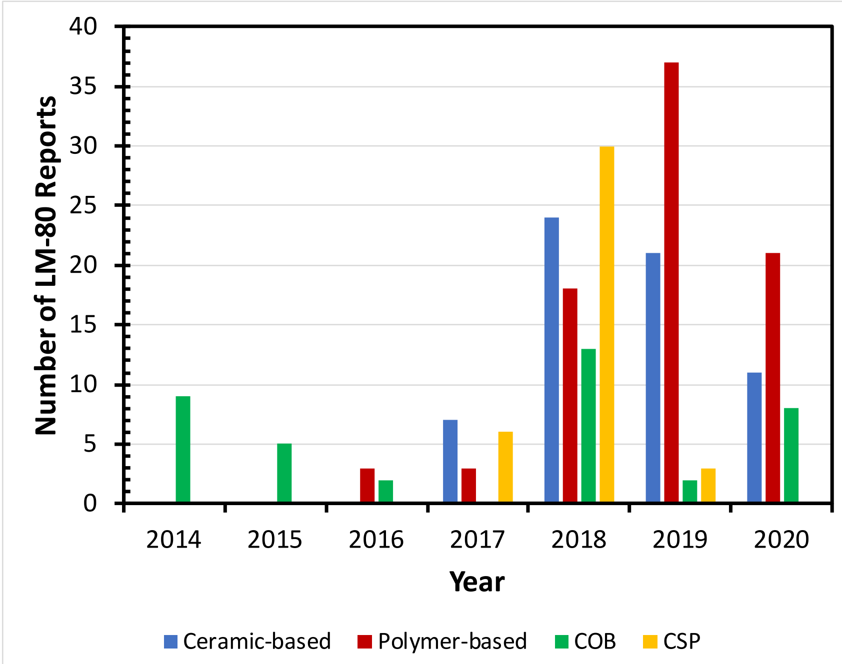


Figure 2-1: Distribution of LM-80 data sets collected during this analysis by year of testing completion and LED package type.

2.2 Luminous Flux Data Analysis

All luminous flux data analysis performed during this work used the α and B values reported by the manufacturer when these values were available. When these values were not available, the average luminous flux maintenance was calculated for each reading of $\Phi(t)$ at every experimental condition, and α and B were derived by using the ENERGY STAR TM-21 calculator [19].

2.3 Chromaticity Maintenance Data Analysis

Recently, a method for projecting long-term chromaticity coordinate shifts was published jointly by ANSI and IES as TM-35-19 [18]. The differential chromaticity analysis (DCA) procedure that is the basis for TM-35-19 is a single-parameter method for projecting future chromaticity coordinates based on LM-80-15 data sets taken after 2,000 hours of testing [18,20,21]. A minimum of 7,000 hrs of u' and v' data is required to project the magnitude and direction of future chromaticity shifts. Although results from the DCA/TM-35-19 projections can vary, the method does offer the benefits of a single parameter and a functional form that is relatively straightforward to apply. Other methods may offer improved accuracy, but at the expense of additional parameters or need data from longer test times [22,23].

TM-35-19 projections can only be performed on LM-80-15 data sets that report the chromaticity coordinates (u', v') at regular measurement intervals. Measurement intervals of less than 600 hrs are preferred, and measurement intervals greater than 1,000 hrs are not allowed. Furthermore, TM-35-19 can only be used when DUT chromaticity data are reported to at least five significant figures (after computing the average of all LEDs in a data set) to ensure accuracy of the future chromaticity coordinates [18]. In this analysis, 146 data sets meet the requirements of LM-80-15 and are used in the following analysis.

The five main steps to the TM-35-19/DCA projection method are presented as follows:

1. Convert the LM-80-15 chromaticity data to relative chromaticity $\delta u'$ and $\delta v'$ at each measurement point [i.e., $\delta u'(t) = u'(t) - u'(t=0)$ and $v'(t) = v'(t) - v'(t=0)$ where t is time and is less than or equal to the test duration]

2. Calculate the differential chromaticities (i.e., time derivative of chromaticity) $\delta u'^*$ and $\delta v'^*$ [i.e., $\delta u'^*(t) = \{u'(t) - u'(t - \delta t)\}/\delta t$ and $v'^*(t) = \{v'(t) - v'(t - \delta t)\}/\delta t]^\dagger$

3. Calculate the linear least squares fit coefficients of the differential chromaticities (e.g., $\delta u'^*$, $\delta v'^*$)

4. Use the linear fit data to project the change rate of chromaticity coordinates $\delta u'(t_p)$ and $\delta v'(t_p)$ where t_p is a projected time beyond the test duration and $\delta u'(t_p)$ and $\delta v'(t_p)$ are the projected relative chromaticity changes from the initial values at time t_p

5. Calculate future relative chromaticity coordinates $u'(t_p)$ and $v'(t_p)$ by adding $\delta u'(t_p)$ and $\delta v'(t_p)$ to the starting chromaticity values $u'(t = 0)$ and $v'(t = 0)$

The maximum value of the projected time (t_p) in TM-35-19 varies from 4.5 times to 6.0 times the test duration depending on the number of samples tested and the measurement interval. The maximum projection time requires a minimum of 30 samples and a measurement interval of no more than 600 hrs.

3 Luminous Flux Maintenance Trends by Package

For the data sets examined during this study, the α values as a function of temperature that were calculated using TM-21-11 are shown in **Figure 3-1**, and those calculated with TM-21-19 are shown in **Figure 3-2**. The same data replotted as TM-21-11 α values versus forward current are shown in **Figure 3-3**, and the TM-21-19 α values plotted versus forward current are presented in **Figure 3-4**. The data are plotted in these formats to facilitate comparisons with data from the previous study of luminous flux maintenance in LEDs (see **Figure 1-3**). In **Figure 3-1** and **Figure 3-2**, the x-axis is T_j for the ceramic-based, CSP, and polymer-based package platforms. However, ambient temperature is used for the COB package platform because there is likely a distribution of temperatures within the package, making it difficult to assign a single T_j value. One of the main differences between TM-21-11 and TM-21-19 is that the latter method establishes a minimum α value of 2×10^{-6}. Because this α value corresponds to an L_{70} value in excess of 175,000 hrs (assuming B = 1), α values below this number are assumed to be equivalent as shown in **Figure 3-2**.

In total, 96% of the α values in this study are less than 6×10^{-6} which corresponds to a L_{70} time of nearly 60,000 hrs. The only α values in excess of 1×10^{-5} occur at high currents levels for a particular package type as shown in **Figure 3-3** and **Figure 3-4** In contrast to the findings from the 2015 survey, very few outliers can be assigned to one package format (see **Figure 1-3**).

† Note: In the DCA method, the differential chromaticities are linear with time (i.e., the first derivative of the relative chromaticities is assumed to be linear with time), and this makes the integral (i.e., the future chromaticity coordinates) a second-order function with time.

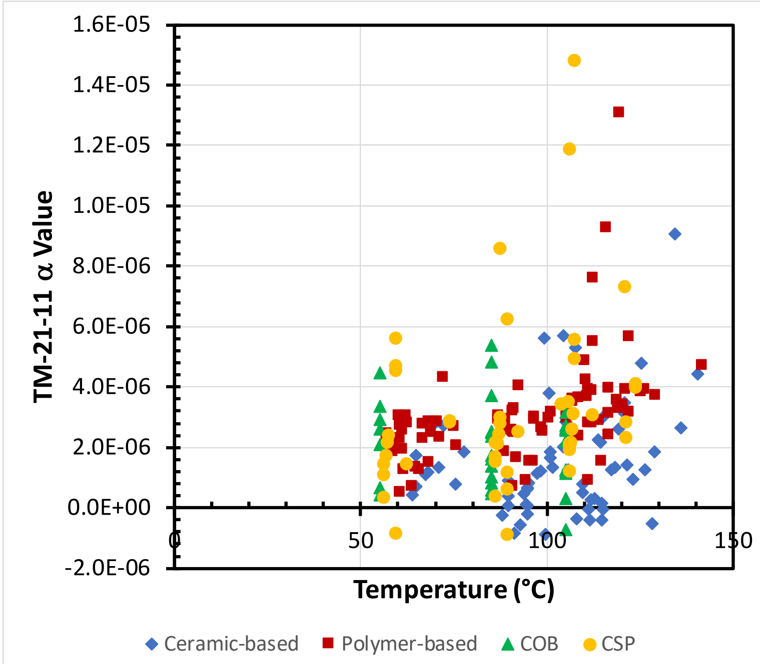


Figure 3-1: Calculated TM-21-11 *α* values as a function of temperature, sorted by LED package platform, for the data sets examined during this study. The *x*-axis corresponds to T_j for ceramic-based, polymer-based, and CSP LED packages but ambient temperature for COB packages.

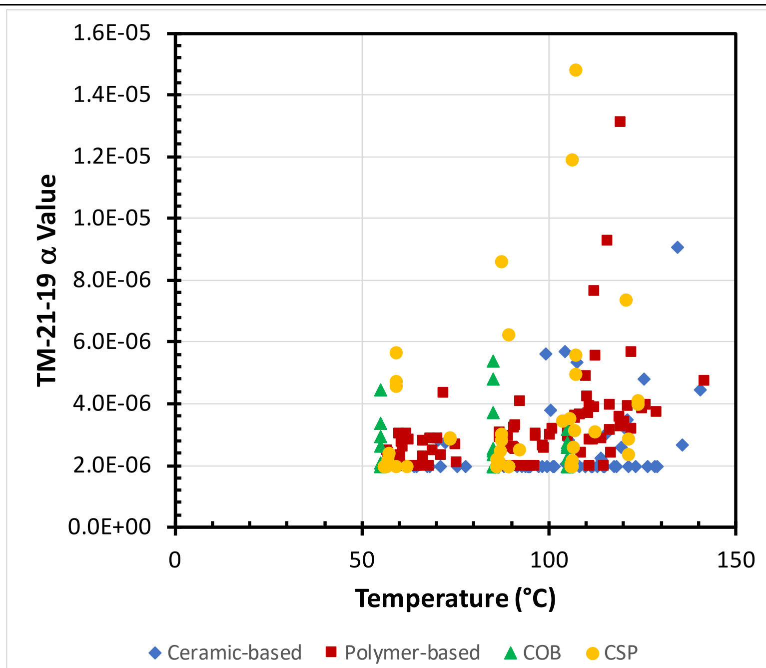


Figure 3-2: Calculated TM-21-19 *α* values as a function of temperature, sorted by LED package platform, for the data sets examined during this study. The *x*-axis corresponds to ceramic-based, polymer-based, and CSP LED packages but ambient temperature for COB packages. TM-21-19 has a minimum α value of 2×10^{-6}, and all calculated values smaller than this are set to 2×10^{-6}.

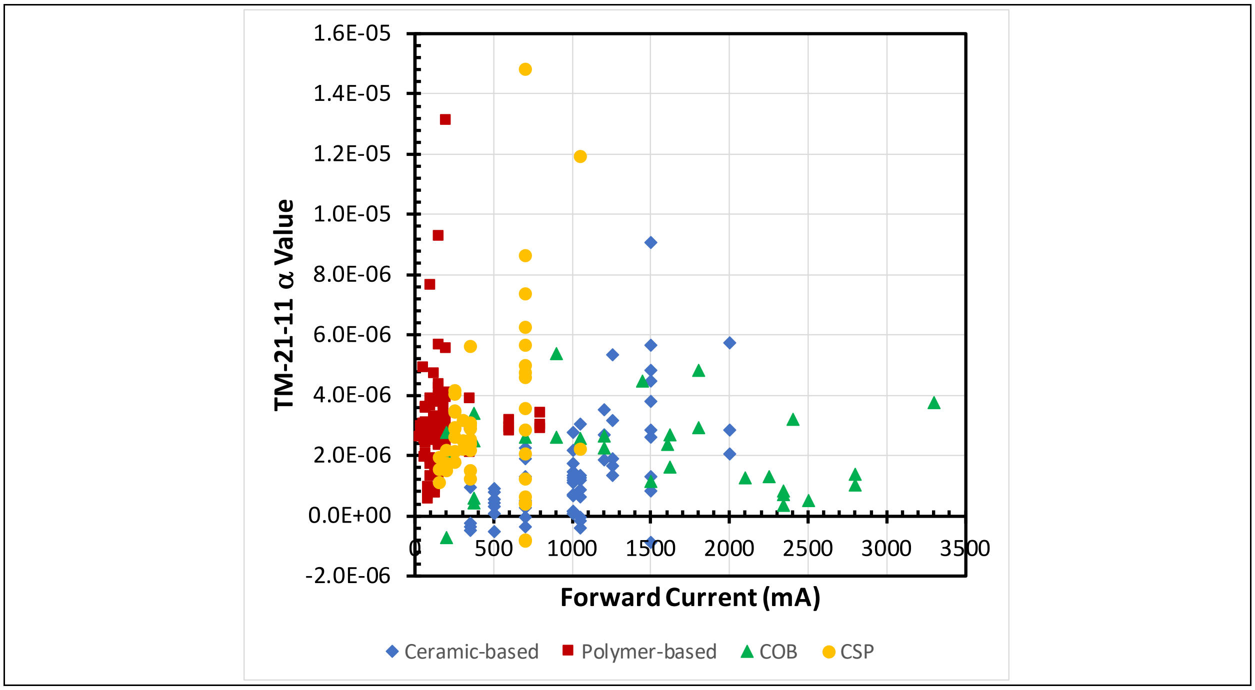


Figure 3-3: Calculated TM-21-11 α values as a function of forward current, sorted by LED package platform, for the data sets examined during this study.

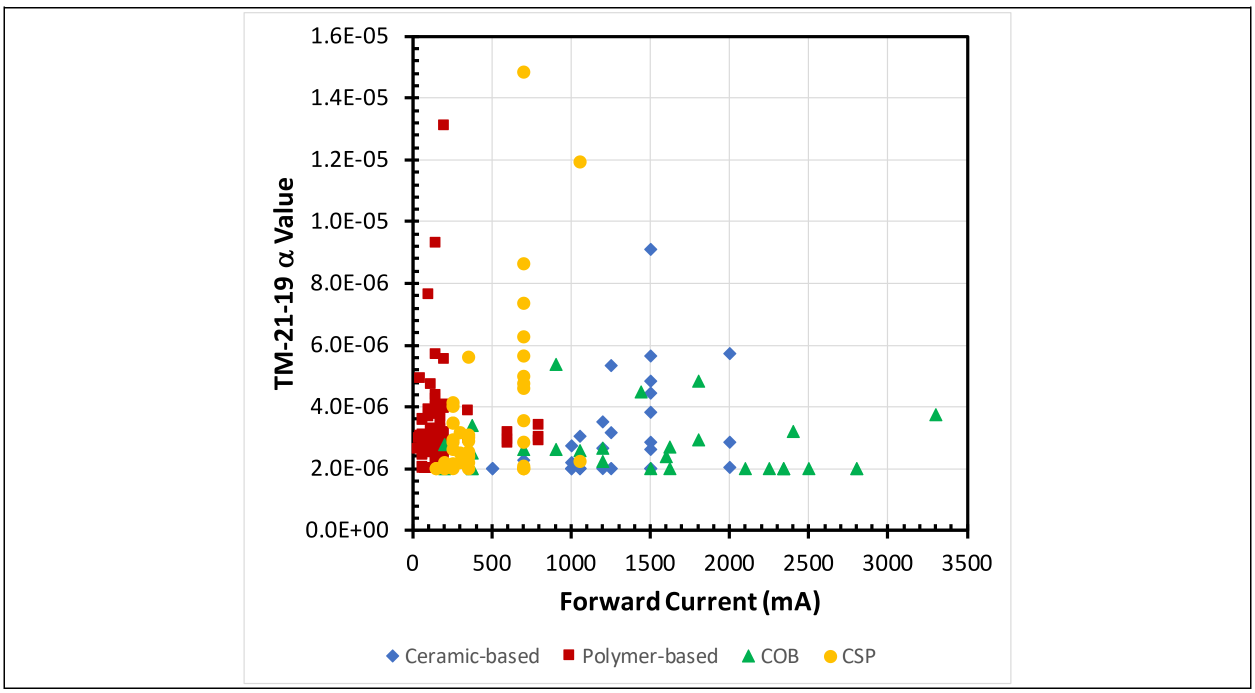


Figure 3-4: Calculated TM-21-19 α values as a function of forward current, sorted by LED package platform, for the data sets examined during this study. TM-21-19 has a minimum α value of 2 x 10^{-6}, and all calculated values smaller than this are set to 2 x 10^{-6}.

A review of **Figure 3-1** and **Figure 3-2** shows significant overlap between the α values for all packaging formats. This finding suggests that under some conditions, it is possible for the different package platforms to yield comparable performance. This finding is in contrast to earlier results (**Figure 1-3**) in which there was a clear performance difference between the packages [3–5]. The newer CSP platform also follows the same general temperature trends as the other platforms. Together, these results indicate a convergence in the temperature sensitivity of the different package platforms, especially at low currents, likely due to improved materials and construction methods.

However, there are differences in the current handling capabilities of the different package platforms as shown in **Figure 3-3** and **Figure 3-4**. As can be deduced by examining the manufacturers' specifications, polymer-based packages are typically limited to currents of 200 milliamperes (mA) and lower, although there are exceptions for some multi-die polymer packages. The CSP platform appears to have a higher current limit of 700 mA to 1,000 mA. Both ceramic-based and COB packages have much higher maximum current limits, which reinforce their use in applications requiring high luminous flux output from small source sizes and high reliability.

The following items are the most important takeaways from **Figure 3-1** through **Figure 3-4**:

1. The new LED package formats (e.g., COB, CSP) have luminous flux maintenance performance comparable to the other LED packages.

2. During the past 5 years, the performance of polymer-based package LEDs has improved significantly, which is likely due to the increased use of new polymer molding resins such as EMC and SMC.

3. The current handling capabilities of ceramic-based and COB packages are better than polymer-based and CSP LEDs. However, polymer-based and CSP LEDs are generally cheaper to purchase, thereby allowing high luminous flux levels (e.g., encountered in troffers) to be spread among many LEDs for the same or lower cost.

Another way to view these data sets is to project the luminous flux maintenance value at a future time based on the experimental data in the LM-80 report, and then compare the projected luminous flux maintenance at that time across the different package types. This analysis requires knowledge of both the α and B values from the TM-21-19 analysis. The luminous flux maintenance value of an LED package usually scales inversely with the environmental and operational stresses that it experiences. Low stress conditions (e.g., lower temperature and I_f settings) will generally produce higher luminous flux maintenance values at a given time, while higher stress conditions (e.g., higher temperatures and I_f setting) will generally show lower luminous flux maintenance values.

The time chosen for the luminous flux projection in this analysis was arbitrarily set to 36,000 hours because some of the LM-80 data sets in this analysis only have experimental measurements to 6,000 hrs, which limit projection times to 36,000 hrs by the 6X-rule [8]. Consequently, all data sets available for this analysis can provide a projected luminous flux maintenance value at 36,000 hrs, but some will not be able to project beyond that time.[‡] For an LED package to have a L_x[§] number less than 36,000 hrs (i.e., the chosen projection limit), the α values must be greater than 1×10^{-5} for L_{70}, 6.2×10^{-6} for L_{80}, and 3×10^{-6} for L_{90} (assuming $B = 1$).

As shown in **Figure 3-2**, only three DUTs exhibited an α value high enough for L_{70} to be less than 36,000 hrs; therefore, the projected luminous flux value at 36,000 hours would be greater than 0.70 for nearly all samples in this analysis. For L_{80}, very few samples exhibited an α value high enough for L_{80} to be less than the chosen

[‡] Note: Some COB data sets contained 10 to 19 DUTs, and their projection times were limited to 5.5-times the test duration by both TM-21-11 and TM-21-19.

[§] L_x is the luminous flux maintenance value (e.g., L_{70}, L_{80}, L_{90})

projection limit (i.e., 36,000 hrs). However, there were 56 separate data sets (25% of the total) that had α values greater than the L_{90} limit of 3×10^{-6}. Because these experimental conditions produced the lowest luminous flux maintenance, they can be used to determine whether there is a prevalence for lower luminous flux maintenance in specific package platforms. Therefore, determining whether the time to reach L_{90} is less than 36,000 hrs is being used during this analysis as a method for analyzing the data sets and identifying any potential package-related tendencies. This analysis approach is not being used as a failure requirement or as a comparison of reliability because other factors, such as temperature, I_f, and environmental influences, will also impact the luminous flux maintenance.

Using the available α values from the 223 data sets, the L_{90} values were calculated for all experimental conditions in the available data. Then, the luminous flux maintenance at 36,000 hrs was determined. All data sets with a projected luminous flux maintenance at 36,000 hrs of less than 0.90 were identified and sorted by LED package platform. The number of data sets, by LED package platform, meeting this criterion is provided in **Table 3-1**. Based on this analysis, there was clearly a large set of operational conditions in which all four LED package platforms are projected to have an L_{90} time greater than 36,000 hrs. However, the ceramic-based and COB LED package platforms exhibited a much wider operational space in which to achieve an L_{90} time greater than 36,000 hrs than either the CSP or polymer-based LED package platform. This behavior is in line with the current handling capabilities of the different platforms.

Table 3-1: Break out by package of data sets with L_x less than 36,000 hrs.

LED Package Platform	Total Number in Data Set	Number with L_{70} < 36,000 hrs[a]	Number with L_{80} < 36,000 hrs[a]	Number with L_{90} < 36,000 hrs[a]
Ceramic-based LED package	63	1 (2%)	3 (5%)	15 (24%)
Polymer-based LED package	81	1 (1%)	4 (5%)	40 (49%)
COB	31	1 (3%)	2 (6%)	10 (32%)
CSP	47	2 (4%)	4 (9%)	21 (45%)

[a] The percentage of data sets, relative to the total for a given LED package platform, appears in parentheses.

4 Chromaticity Maintenance and Chromaticity Stability

4.1 Chromaticity Shift Trends in the Data Set

In total, there were 146 different data sets with u' and v' values at all measurement intervals. Out of these data sets, 31 (21%) had test durations of more than 6,000 hrs but less than 10,000 hrs, 75 (51%) had test durations between 10,000 hrs and 15,000 hrs, and 40 (27%) had test durations of 15,001 hrs or longer, with the longest test duration being 24,152 hrs. Using procedures described in Commercially Available LED Product Evaluation and Reporting (CALiPER) Program Report 20.5 [13], the chromaticity behavior in each data set was matched to a CSM, if possible.

In general, it is better to assign CSMs after the emergence phase has occurred in at least one test condition for a product because the long-term performance of the LED would be known. CSM assignment was fairly easy to accomplish for ceramic-based, polymer-based, and CSP LED packages; however, it was not clear that most of the COB samples had reached the emergence phase. As a result, assignment of CSMs for some of the COB LED packages cannot be determined based on the available test data.

The results, broken out by ceramic-based, polymer-based, and CSP LED packages, are presented in **Figure 4-1A** (the total number of each LED package platform displaying the different CSMs) and **Figure 4-1B** (the percentage of the cumulative number for each LED package platform displaying the different CSMs).

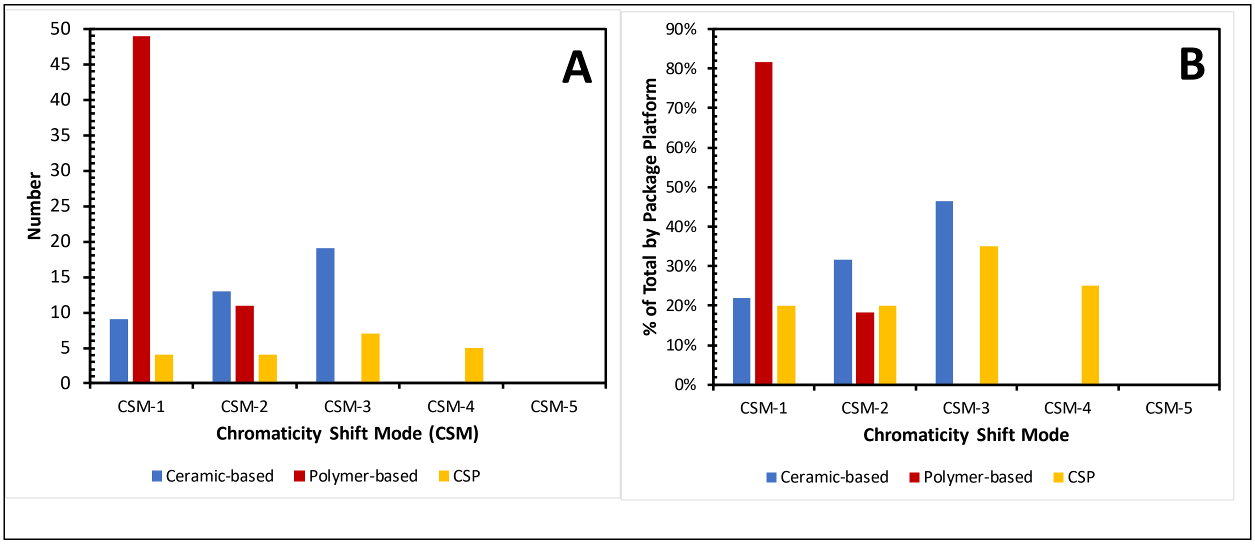


Figure 4-1: Breakout of the prevalence of different CSMs by package types: (A) gives the total number by LED package platform and (B) gives the percentage within each package platform.

These CSMs are determined by the prevailing chromaticity shift at the time when the LM-80-15 measurement was terminated. In some instances, the observed CSM is likely the emergence phase chromaticity shift that could ultimately exceed a preset limit such as $\Delta u'v' = 0.007$. However, it is also possible that the LM-80-15 measurements terminated before the emergence phase occurred, which would impact the determination of the final CSM. For example, some CSM-1 and CSM-2 shifts are precursors to more complicated shifts such as CSM-3 and CSM-4 [5]. The best way to avoid this situation is to examine the behavior of a particular product under the most stressful conditions (i.e., highest temperature and I_f), and then examine how this behavior changes as the test duration and operational parameters change. If there is no evidence that an emergence phase occurred at the most stressful condition, then most likely the test conditions been insufficient to produce the emergence phase. The fact that 79% of the data sets in this analysis contain data from 10,000 hrs or more of testing will be beneficial; however, this number of hours does not guarantee that at least one test condition will produce an emergence phase for a specific product. This topic will be explored when discussing projection of future chromaticity shifts by using TM-35-19.

The emergence shift for the ceramic package platform is most likely to be CSM-3 (46% of available data sets displayed this behavior), although CSM-2 (32%) and CSM-1 (22%) are also possible depending on the package design and operational parameters. In CALiPER 20.5, which used PAR38 lamps purchased in 2012, the CSM breakout for the ceramic-based packages was CSM-1 (6%), CSM-2 (22%), and CSM-3 (67%) [11,13]. Because the failure mechanism responsible for CSM-3 is known to be delamination of the phosphor–silicone mix from the top surface of the die [12], the reduction in CSM-3 behavior in newer LED packages is likely a sign of improved adhesion between the phosphor–silicone layer and the surface of the die.

In this data set, the polymer-based LED package platform exhibited a strong preference to shift in the blue direction through CSM-1 behavior (84%), and this shift is likely indicative of the emergence phase in this package. There was a weak preference for a CSM-2 shift (18%) that generally occurred at low stress conditions such as 55°C and 100 mA, but it is possible that this behavior could change to a blue shift with prolonged testing. As demonstrated in **Figure 4-2**, at least some of the observed CSM-2 behavior can be attributed to low stress test conditions that take longer than the experimental duration to enter the emergence phase. After 17,000 hrs of testing at 55°C and 80 mA, the LEDs in this low stress condition shown in **Figure**

4-2 had not reached the emergence phase. As a result, the chromaticity shifted along the -*Δu'* axis (i.e., CSM-2). In contrast, the emergence phase occurred after 5,500 hrs of testing at 105°C and 180 mA, and chromaticity abruptly began to shift in the blue direction. At the intermediate setting of 85°C and 150 mA, the emergence phase still occurred but was delayed until 13,500 hrs. As a result, it can be expected that the emergence phase of this device will be characterized by a strong CSM-1 (i.e., blue) shift that may be due to photo-oxidation of the polymer used in the polymer housing, cracking of the encapsulant, or both [12]. Finally, it is important to note that a shift in the generally yellow direction followed by a prolong blue shift (i.e., CSM-4 behavior) was not observed for the polymer-based packages in these recent data sets. The yellow shift is likely an indicator of delamination of the phosphor-silicone component from the polymer package, whereas the prolonged blue shift has been shown to arise from polymer photo-oxidation and encapsulant cracking [12,15]. The absence of the yellow shift—even at high stress conditions—suggests that the adhesion between the phosphor-silicone component and the package polymer has improved.

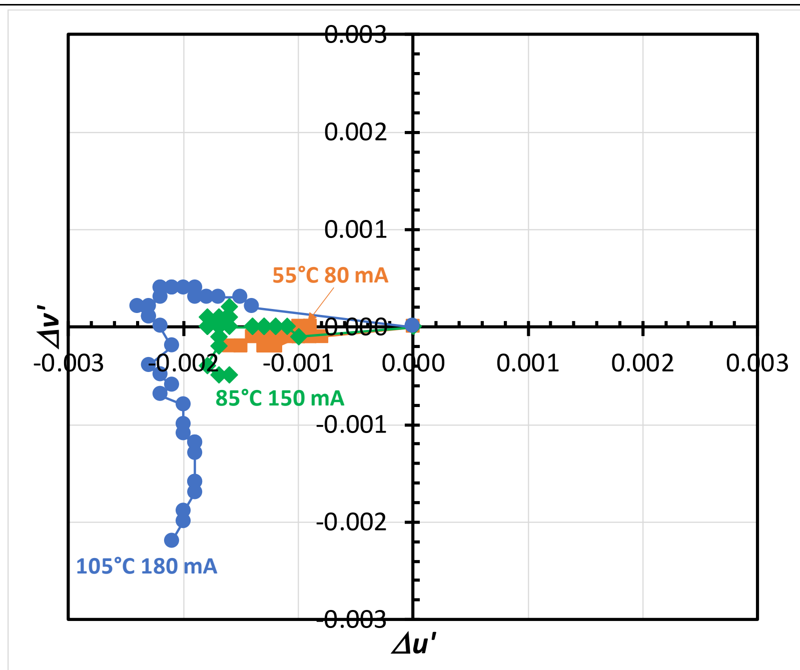


Figure 4-2: A chart of 17,000 hrs of chromaticity shift data for identical populations of LEDs in the polymer-based package platform operated at three different conditions.

Previous examinations of the chromaticity shifts in the CSP package platform did not have sufficient data to assign CSMs to this LED package platform [4]. However, as shown in **Figure 4-1**, the CSP LED platform exhibited the widest variety of chromaticity shift mechanisms with CSM-1 (30%), CSM-2 (10%), CSM-3 (35%), and CSM-4 (25%) occurring. The preference for one CSM over another appears to be tied to package architecture and operational conditions (e.g., temperature, I_f). The CSPs examined in this study can be approximately divided into those with sidewalls made of white polymer resin and those without white sidewalls. The purpose of the sidewalls is to reduce light emissions from the package sidewalls and produce more of a Lambertian profile from a CSP LED. CSP LEDs with polymer sidewalls tended to shift with CSM-3 behavior at low environmental stresses and short test durations, whereas higher environmental stresses and long test durations tended to produce CSM-4 behavior. The likely causes of these shifts are phosphor-silicone composition delamination (for CSM-3 behavior) and photo-oxidation of the polymer sidewalls and possibly the appearance of cracks in the encapsulant for the blue shift in CSM-4.

For CSP LED packages without sidewalls, a shift in the generally green direction (i.e., CSM-2 behavior) occurred under low stress, but the packages ultimately shifted in the blue direction under prolonged operation at high temperatures and currents (CSM-1). This behavior is similar to that reported in **Figure 4-3** for a CSP LED package, with the green shift likely caused by oxidation of the red phosphors [16] and the blue shift caused by cracking in the encapsulant [12]. Ultimately, the emergence phase of CSP LEDs appears to cause a shift in the blue direction, although these data demonstrate that such a shift can occur in different ways depending upon the specifics of the CSP structure.

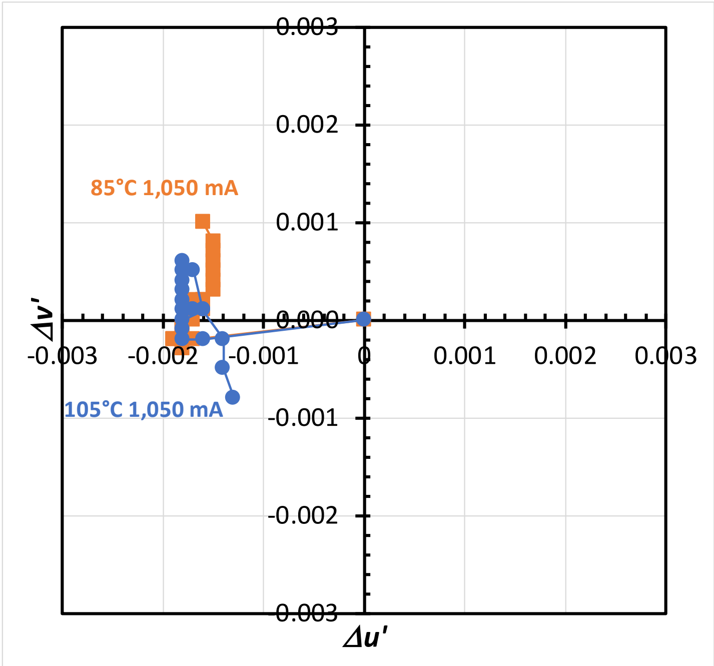


Figure 4-3: A chart of 17,000 hrs of chromaticity shift data for identical populations of LEDs in the CSP LED platform operated at low stress (85°C and 1,050 mA) and high stress (105°C and 1,050 mA) conditions.

Assigning CSMs to the COB packages was more difficult because multiple types of behavior were found in this data set. **Figure 4-4** shows the temporal change in chromaticity shift magnitude (*Δu'v'*) for three different COB products, each tested at different conditions, and **Figure 4-5** shows the corresponding changes for *Δu'* versus time and *Δv'* versus time. For completeness, the chromaticity shift directions plotted as *Δv'* versus *Δu'* are given in **Figure 4-6**. The chromaticity shift magnitude of COB1 changed slowly but steadily over time, and the change, which was largely toward the blue emitter chromaticity point, was assumed to occur during the emergence phase for these types of COBs. For COB2, there was a rapid change in chromaticity magnitude (*Δu'v'* changes by approximately 0.002) in the first 1,000 hrs of testing, but then the chromaticity stabilized and minimal further change occurred thereafter. The initial shift was in the green direction, but a clear emergence phase has not occurred in these types of COBs, even after prolonged testing. COB3 is a combination of these two behaviors—there is a rapid initial shift early in testing (similar to COB2) followed by a continuous change in chromaticity shift magnitude for the remainder of the test period (similar to COB1). For COB3, both the rapid initial chromaticity change and the prolonged shift were toward a direction between the blue and green points, suggesting a combination of CSM-1 and CSM-2 behaviors. Based on these findings, CSMs were not assigned to the COBs because of the difficulty with identifying a clear emergence phase in some samples (e.g., COB2) even after more than 18,000 hrs of testing. This finding highlights the need for additional accelerated testing on COB packages to understand their failure mechanisms.

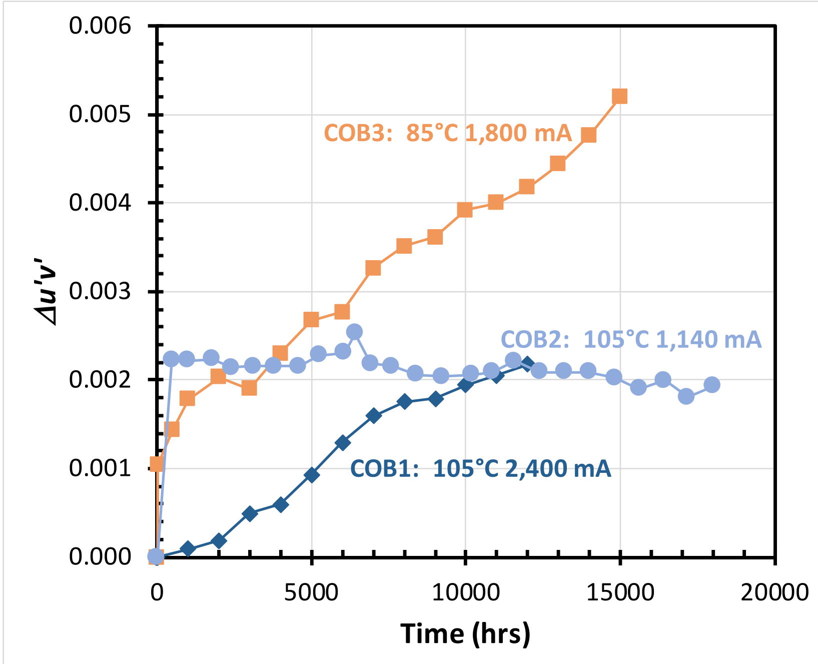


Figure 4-4: Chromaticity shift magnitude ($\Delta u'v'$) for three different COB products in LM-80-15 testing. The absence of a clear emergence phase in some COB products (e.g., COB2) made it difficult to assign CSMs to this general class of LED packages.

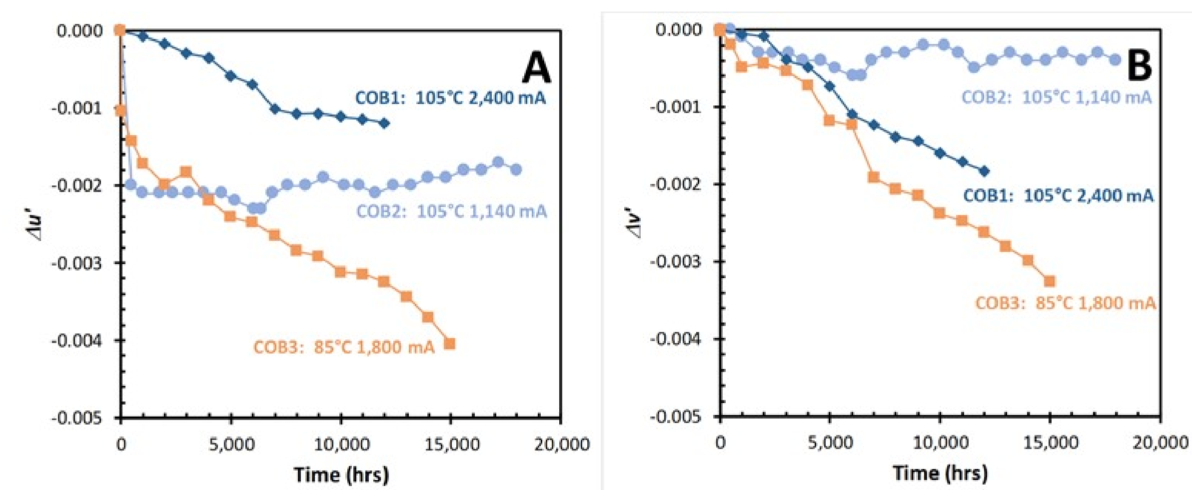


Figure 4-5: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for three difference COB products in LM-80-15 testing. The absence of a clear emergence phase in some COB products (e.g., COB2) made it difficult to assign CSMs to this general class of LED packages.

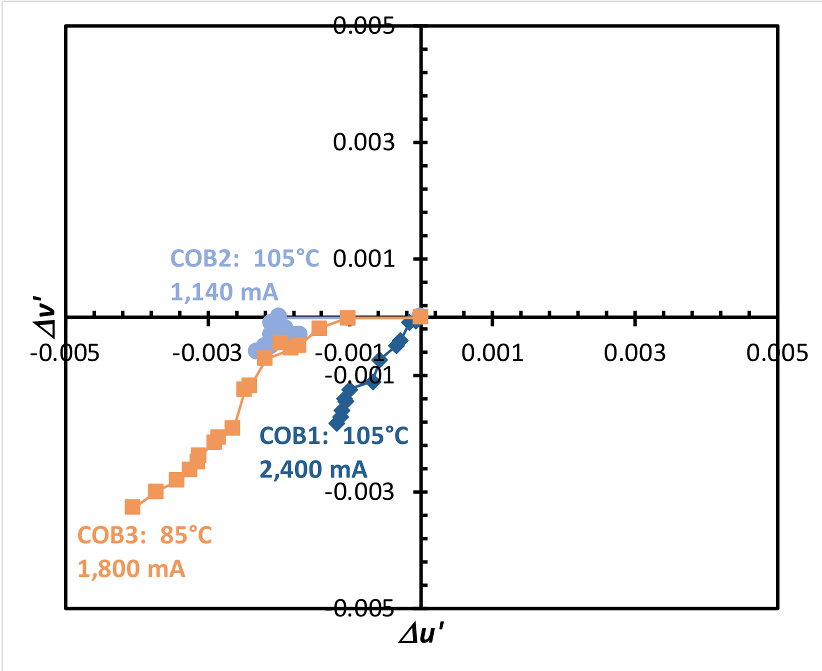


Figure 4-6: Chromaticity shift direction measured for three different COB products in LM-80-15 testing. The absence of a clear emergence phase in some COB products (e.g., COB2) made it difficult to assign CSMs to this general class of LED packages.

4.2 Projecting Future Chromaticity with TM-35-19

4.2.1 Motivation for TM-35-19

The lighting industry realized the importance of chromaticity shift in determining the long-term performance of LED products [12]. Consequently, when LM-80 was updated in 2015, a requirement to report experimental values of *u'* and *v'* at each measurement interval was added to the standard. This information has helped to accelerate research into the mechanisms responsible for chromaticity shifts and the development of models for projecting future chromaticity shifts. A variety of approaches have been used to create these models. Some approaches include projections from the emergence phase [18,22] or analytical models of the chemical processes responsible for the chromaticity shift [23]. Although these methods hold some attraction for predicting the final magnitude and direction of chromaticity shifts, they have limitations, including potentially longer test times and the complexity of optimizing multiple fitting parameters across the data sets [18,23].

TM-35-19 was developed with a goal of having a single parameter model that would be simple to implement and simple to standardize across multiple LED package platforms [18]. One of the goals of the present study was to examine the ability of TM-35-19 to provide accurate projections of chromaticity shifts based on available LM-80-15 experimental data. Accurate projections of chromaticity shifts require that the model meet the following three criteria:

1. The model should provide accurate estimates of the chromaticity shift magnitude ($\Delta u'v'$) at future times based on experimental data. Alternatively, it may be acceptable if the model is conservative in its projections of $\Delta u'v'$, meaning that projected CS4 and CS7 times are likely to sooner than the true times needed for chromaticity shift magnitude ($\Delta u'v'$) to reach 0.004 and 0.007, respectively.

2. The model should provide accurate estimates of the direction of the chromaticity shift (i.e., future *u'* and *v'* values) based on experimental data.

3. The model should provide projected chromaticity shifts that show consistent patterns across the data sets for a given product at test conditions that produce the same phase (i.e., incubation, recovery, and emergence) of chromaticity shift; however, the time at which different phases and the corresponding chromaticity shifts occur may change depending on the stress level (e.g., temperature, I_f).

These criteria are not mutually encompassing. For example, a model could accurately predict future values of *Δu'v'*, but could do a poor job with predicting the direction of the chromaticity shift or vice versa. However, even with such shortcomings, such a model could be beneficial to the lighting industry provided that its limitations are recognized.

To understand the ability of TM-35-19 to predict future chromaticity, its performance, relative to these criteria, was examined for all of the LM-80-15 data in this data set. The remainder of this subsection of the report discusses representative case studies from each of the four major LED package platforms.

4.2.2 Case Study 1: TM-35-19 Examples for a Ceramic-Based LED Package

This case study is from an HP-LED in a ceramic-based package that is operated at relatively high stress conditions during LM-80-15 (120°C and 700 mA) to produce emergence. The experimentally measured values (through 12,096 hrs) and projected values (through 24,192 hrs) of the chromaticity shift magnitude (i.e., *Δu'v'* versus time) and chromaticity direction (i.e., *Δv'* versus *Δu'*) are shown in **Figure 4-7**. Graphs of the temporal nature of *Δu'* and *Δv'* are presented in **Figure A-1** of **Appendix A**. This DUT is exhibiting CSM-2 behavior (*u'* is decreasing, while there is much less change in *v'* [see **Table 1-1**]) and remains on that trajectory through 24,192 hrs when the projection was stopped because *Δu'v'* exceeded 0.010. TM-35-19 projects that *Δu'v'* = 0.007 for this HP-LED device at approximately 20,000 hours. Also, as shown in **Figure A-1**, the projected changes in *u'* and *v'* are a continuous extension of the experimental data, so these projections appear to meet the model effectiveness criteria.

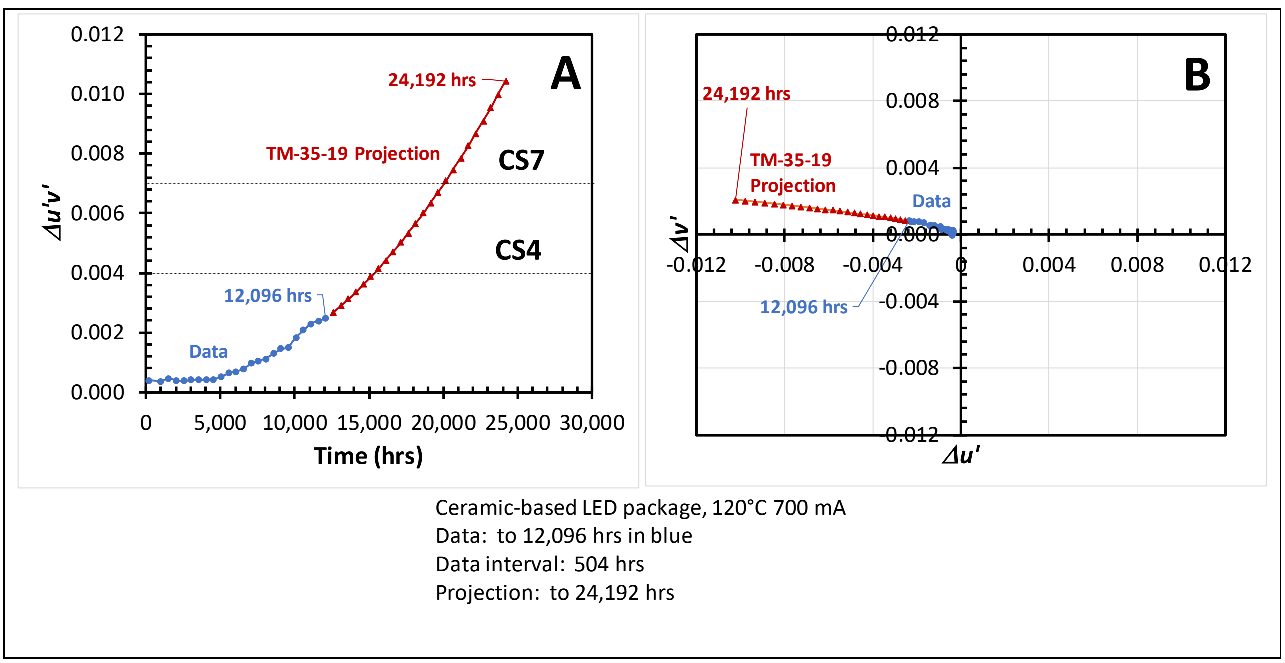


Figure 4-7: TM-35-19 projections for a population of HP-LEDs in ceramic-based packages for Case Study 1, with (A) showing the magnitude of the chromaticity shift, and (B) showing the projected direction of the chromaticity shift. The blue circles are the experimental data, and the red triangles show the TM-35-19 projections. The LEDs were operated at 120°C and 700 mA.

4.2.3 Case Study 2: Comparing TM-35-19 Projections with Extended Data for a Ceramic-Based LED Package

To assess the impacts of test duration on the projected chromaticity magnitude and chromaticity shift direction, a TM-35-19 analysis was performed on a data set for HP-LEDs in ceramic-based packages with 24,192 hrs of experimental data. However, only 12,096 hrs of experimental data were used to build the projection. These data are from the same product as shown in **Figure 4-7** and used the same measurement interval of 504 hrs, thereby allowing a direction comparison of the results, but the operational temperature was lower.

During this case study, the DUTs were HP-LEDs in ceramic-based packages operated at 85°C and 700 mA. The experimentally measured values (through 12,096 hrs) and projected values (through 50,400 hrs) of the chromaticity shift magnitude (i.e., *Δu'v'* versus time) and chromaticity shift direction (i.e., *Δv'* versus *Δu'*) are shown in **Figure 4-8**.** In addition, the experimental data from 12,600 hrs to 24,192 hrs that are not used in the projection are shown in gray in **Figure 4-8**. Graphs of the temporal nature of *Δu'* and *Δv'* are presented in **Figure A-2**. During a review of the data sets, the projected chromaticity shift magnitude can be seen to deviate from the actual data, resulting in a CS4 time that is likely sooner than the true value. The actual chromaticity data appear to be changing much slower than the projections, and it is unclear whether this stage is an incubation phase for a pending shift or something else. This deviation is driven mainly by the projection for *Δu'* because the extra data show that the initial green shift stops after a few thousand hours of testing, but the projection continues on a similar trajectory as the early experimental data (see **Figure A-2**). The projection for *Δv'* is slowly increasing in agreement with the experimental data. Consequently, the future chromaticity shift direction is unclear from the experimental data, and, at a minimum, the chromaticity shift magnitude is likely to change much slower than predicted by the TM-35-19 projection.

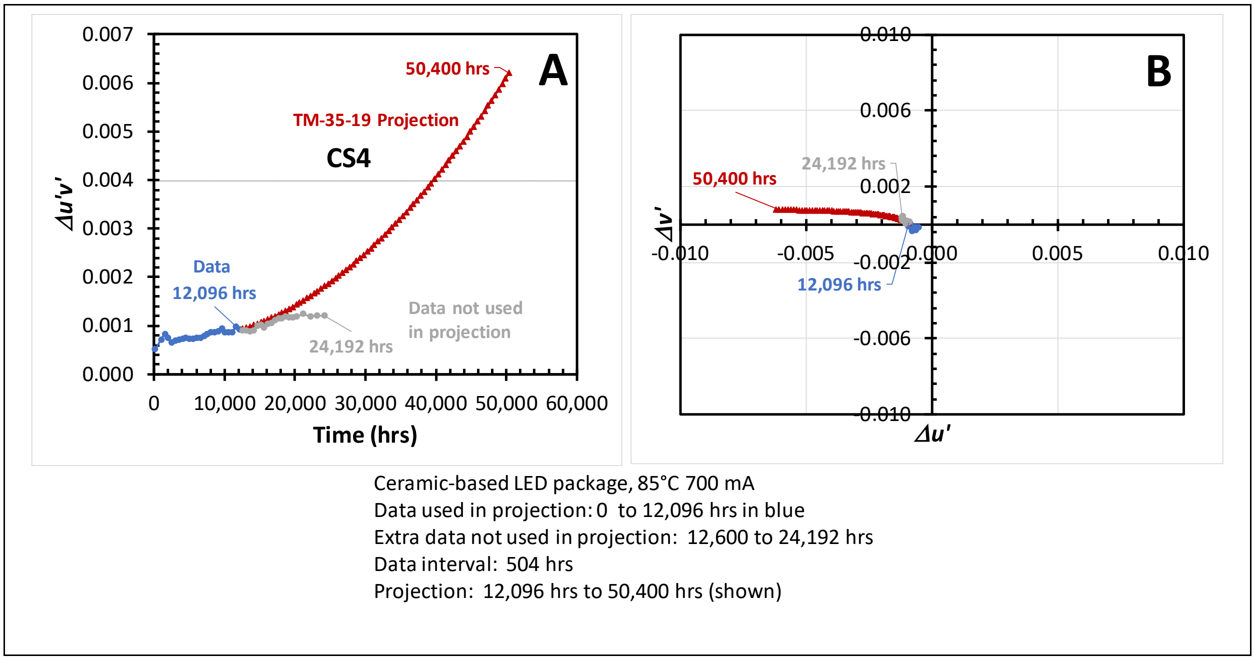


Figure 4-8: TM-35-19 projections for the population of HP-LEDs in ceramic-based packages in Case Study 2, with (A) showing the magnitude of the chromaticity shift, and (B) showing the projected direction of the chromaticity shift. The blue circles are the experimental data, the red triangles show the TM-35-19 projections, and the gray circles show extra data not used in the projections. The LEDs were operated at 85 °C and 700 mA.

** Note: The TM-35-19 projection for this case study actually exceeds 60,000 hrs, but only 50,400 hrs are shown in the graphs to allow better viewing of the test data.

4.2.4 Case Study 3: Comparing TM-35-19 Projections for Different Measurement Intervals

As set forth in TM-35-19, the preferred measurement interval is 600 hrs or less and the method shall not be used if the measurement interval exceeds 1,000 hrs.†† A shorter extrapolation period is applied for larger measurement intervals. The entire data set shown in **Figure 4-8** is used in this case study, and TM-35-19 projections are first developed by using measurement intervals of 504 hrs (see **Figure 4-9**), and then using measurement intervals of 1,008 hrs (see **Figure 4-10**) with very different results. The corresponding $\Delta u'$ versus time data and $\Delta v'$ versus time data are shown in **Figure A-3** (504-hr increments) and **Figure A-4** (1,008-hr increments).

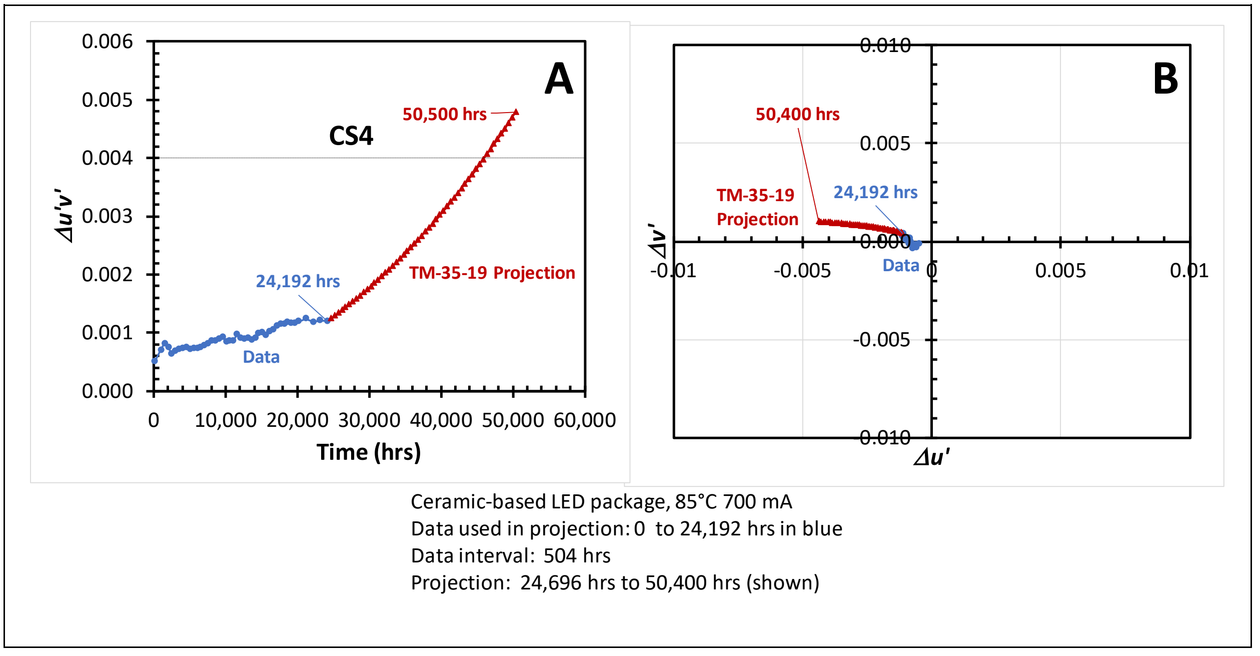


Figure 4-9: TM-35-19 projections for a population of HP-LEDs in ceramic-based packages for Case Study 3, with (A) showing the magnitude of the chromaticity shift, and (B) showing the projected direction of the chromaticity shift. The blue circles are the experimental data at measurement intervals of 504 hrs, and the red triangles show the TM-35-19 projections. The LEDs were operated at 85°C and 700 mA.

†† NOTE: There is a 48-hour buffer allowed for test duration end times and measurement intervals in TM-35-19.

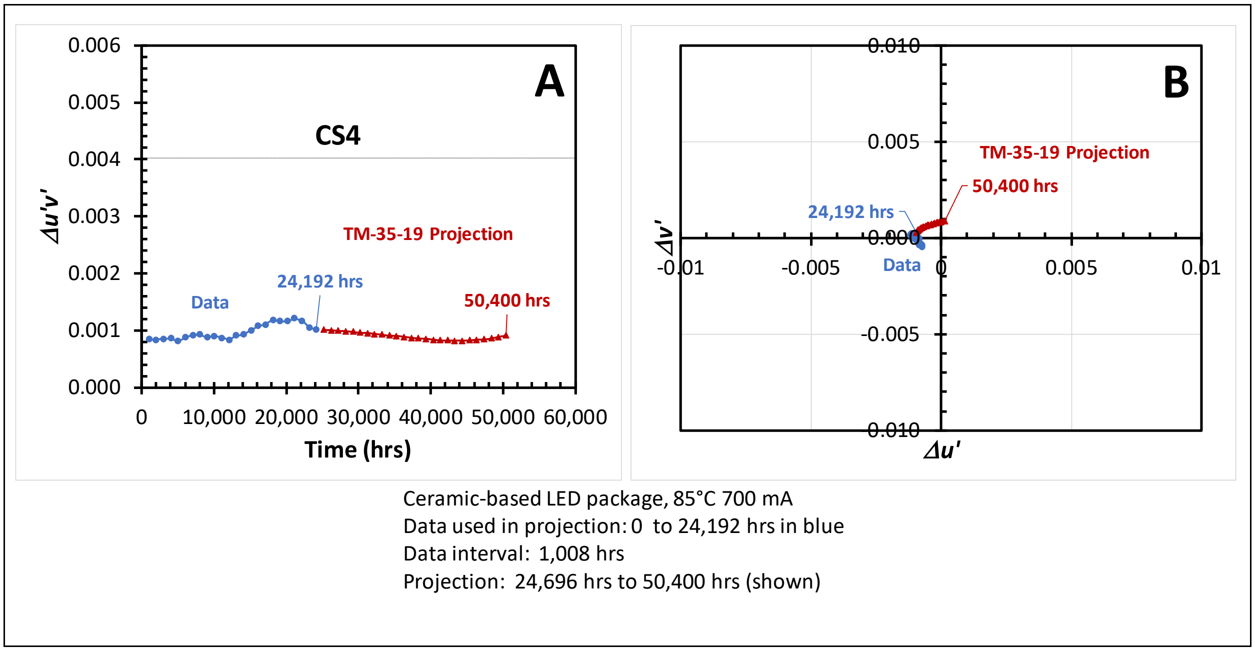


Figure 4-10: TM-35-19 projections for a population of HP-LEDs in ceramic-based packages for Case Study 3, with (A) showing the magnitude of the chromaticity shift, and (B) showing the projected direction of the chromaticity shift. The blue circles are the experimental data at measurement intervals of 1,008 hrs, and the red triangles show the TM-35-19 projections. The LEDs were operated at 85°C and 700 mA.

When using data taken at 504-hr intervals, the projection for chromaticity shift magnitude (*Δu'v'*) follows the same general trend as observed for Case Studies 1 and 2. The most important difference between Case Studies 1, 2, and 3 is that the chromaticity shift process is occurring at a slower rate in Case Study 3, resulting in longer CS4 and CS7 times; however, the chromaticity trend is proceeding according to CSM-2 (i.e., green chromaticity shift), as in the previous case studies. This finding suggests that the three criteria for a good model are achieved in this instance. An examination of **Figure A-3** shows that the projected rate of chromaticity change is being driven by the *Δu'* component. However, when the same experimental data duration (0 hrs to 24,192 hrs) is used, but at 1,008-hr increments, a totally different chromaticity projection is calculated by using TM-35-19 as shown in **Figure 4-10**. The chromaticity is now projected to shift in the red direction and with minimal change in chromaticity through 50,400 hrs. An examination of **Figure A-4** illustrates that the difference between the two examples in this case study is driven by the *Δu'* component. Over the same test period (0 hrs to 24,192 hrs), *Δu'* steadily decreases with time when measurement intervals of 504 hrs are used, whereas *Δu'* begins to slowly increase after 25,000 hrs when measurement intervals of 1,008 hrs are used. As a result, the projected CS4 and CS7 times are increased significantly, and the projected direction of chromaticity shift is different from the other conditions in this data set. Consequently, this example shows a failure to meet any of the three evaluation criteria.

A comparison of the CS4 and CS7 times for the four examples in Case Studies 1 through 3 is provided in **Table 4-1**. The CS4 and CS7 times follow the expected trend in the first three examples, with more severe conditions reducing the CS4 and CS7 times. However, the large increase in CS4 and CS7 times that occurred with a change in the measurement interval indicates a high degree of sensitivity to that parameter, as mentioned in TM-35-19. This is potentially an issue for the industry because a manufacturer can significantly impact the chromaticity projections for its product simply by choosing what information to report. It should be noted that most TM-80 reports only provide data up to 10,000 hrs and in 1,000-hr increments. Case Studies 1 through 3 suggest that such data would be highly suspectable to inaccuracies when using the TM-35-19 method.

Table 4-1: Comparison of the TM-35-19 results for Case Studies 1 through 3.

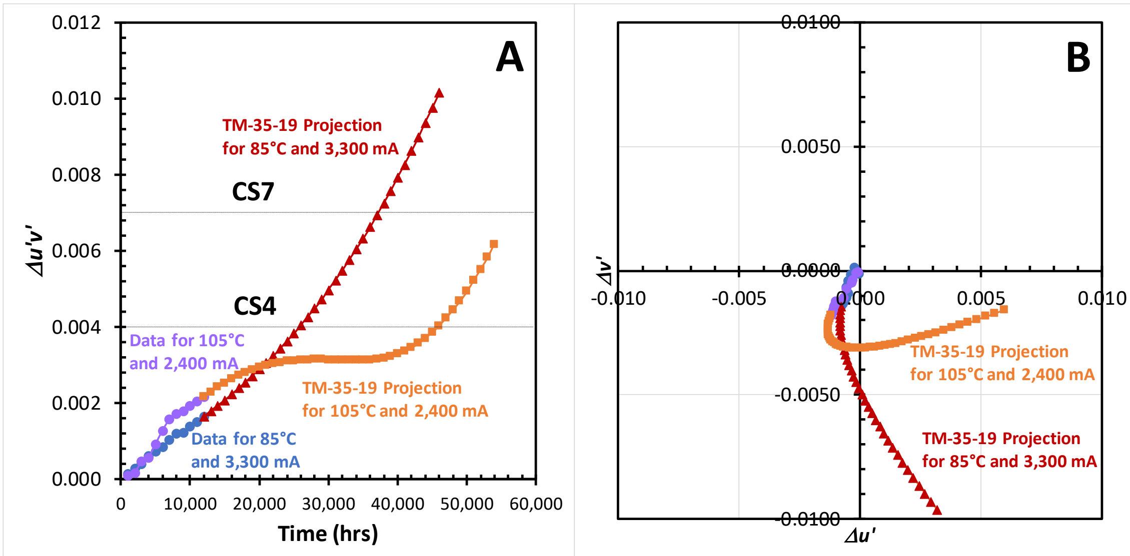
Test Conditions	Test Duration (hrs)	Measurement Interval (hrs)	CS4 (hrs)	CS7 (hrs)	Evaluation Criteria Met
120°C and 700 mA	12,096	504	15,400	20,100	Yes
85°C and 700 mA	12,096	504	39,700	53,700	Yes
85°C and 700 mA	24,192	504	46,000	61,000	Unclear
85°C and 700 mA	24,192	1,008	83,900	102,500	No

4.2.5 Case Study 4: TM-35-19 Examples for COB Packages at 1,000-Hr Measurement Intervals

Case Study 4 consists of two populations of the same 48 volt (V) COB LED operated at different test conditions. One population was tested at 85°C and 3,300 mA, and the other population was tested at 105°C and 2,400 mA, and data from both populations are showing signs of emergence. The COB package consisted of a light-emitting surface (LES) that is approximately 22.4 millimeters (mm) in diameter, and the individual LED die are wire bonded to a metal substrate. The chromaticity shift magnitude ($\Delta u'v'$) and chromaticity shift direction ($\Delta v'$ versus $\Delta u'$) for both test conditions are presented in **Figure 4-11** and the CS4 and CS7 times are given in **Table 4-2**. The corresponding graphs of $\Delta u'$ vs time and $\Delta v'$ vs time are shown in **Figure A-5** for both test conditions. Significant differences in the TM-35-19 projections for two test conditions are apparent in **Figure 4-11**.

For Test Condition 1 (85°C and 3,300 mA), the chromaticity shift magnitude is projected to increase steadily until $\Delta u'v'$ reaches the allowed projection limit (0.010). According to the TM-35-19 projection, this increase in chromaticity shift magnitude is driven by the simultaneous increase in u' and a decrease in v' (see **Figure A-5**). However, the chromaticity shift direction is projected to proceed toward a magenta direction, which is highly unlikely for the reasons discussed in **Section 1.4** of this report. This outcome is likely the result of over protecting the change in u', which will result in a conservative estimate of time for CS4 and CS7 times but an unrealistic projection for chromaticity shift direction; therefore, the projected CS4 and CS7 times in **Table 4-2** are likely earlier than the true times to reach these levels of chromaticity shift magnitude. Consequently, this projection meets Criterion 1 (because the CS4 and CS7 values are conservative), but it does not meet Criterion 2 (because the projected chromaticity shift direction is highly unlikely).

For Test Condition 2 (105°C and 2,400 mA), the TM-35-19 projection is showing a clear incubation period between 20,000 hrs and 38,000 hrs. Then, there is a clear emergence phase with the chromaticity shift displaying CSM-5 characteristics (i.e., shifting in the generally red direction). Because the projected behavior of $\Delta u'$ versus time is the same for both test conditions, the difference in projected chromaticity shift is driven by a significant difference in the projected values of $\Delta v'$ versus time (see **Figure A-5B**). The net result is a significant increase in CS4 and CS7 times (see **Table 4-2)**, which violates Criterion 1. In addition, the disparity in projected chromaticity shifts for these two samples violate Criterion 3 (consistency).



COB LED package
Data used in projection: 0 to 12,000 hrs
Data interval: 1,000 hrs

Figure 4-11: TM-35-19 projections for a population of LEDs in the COB package platform with a metal-core substrate used for Case Study 4, with (A) showing the magnitude of the chromaticity shift and (B) showing the projected direction of the chromaticity shift.

Table 4-2: Comparison of the TM-35-19 results for the 48 V COB LEDs in Case Study 4.

Test Conditions	Test Duration (hrs)	Measurement Interval (hrs)	CS4 (hrs)	CS7 (hrs)	Evaluation Criteria Met
85°C and 3,300 mA	12,000	1,000	25,800	37,200	No
105°C and 2,400 mA	12,000	1,000	45,800	> 54,000	No

4.2.6 Case Study 5: TM-35-19 Example for Polymer-Based Packages

Projecting chromaticity shifts in polymer-based packages can be difficult for any modeling approach because of the directional changes that typically occur in these packages with sustained operation. As shown in **Figure 4-2**, the chromaticity of polymer-based packages can initially shift in one direction (e.g., the green direction in the case of **Figure 4-2**), and then abruptly change as other failure modes arise [5,11,12]. The timing of this abrupt change depends upon the temperature and I_f. The question arises whether TM-35-19 could predict the shift both in instances in which the experimental data show the change in chromaticity shift direction from the emergence phase (e.g., 105°C and 180 mA test condition in **Figure 4-2**) and in instances in which the experimental data was not acquired for a long enough time to reach the emergence phase.

Figure 4-12 provides the temporal change in chromaticity shift magnitude (i.e., $\Delta u'v'$ versus time) and chromaticity shift direction ($\Delta u'$ versus $\Delta v'$) for an LED housed in a polymer-based package tested at 85°C and 150 mA. This test condition is believed to produce an emergence phase beginning at 13,500 hours as discussed in **Section 4.1** of this report. To calculate the TM-35-19 projection, only 10,000 hrs of experimental data (shown as blue circles in **Figure 4-12**) were used, with the remaining 7,000 hrs (shown as gray circles) serving as a check. The corresponding temporal changes in *Δu'* and *Δv'* are shown in **Figure A-6**. When using 10,000 hrs of data, the TM-35-19 projection for chromaticity shift magnitude (*Δu'v'*) deviates from the experimental data at 10,000 hrs. These differences are driven mainly by an over-estimation of the change in *u'* (see **Figure A-6**). The concept of the three phases of chromaticity shift (i.e., incubation, recovery, and emergence) can also be applied to the individual components. **Figure A-6** clearly shows that the *Δu'* is in incubation phase between 7,000 hrs and 17,000 hrs, whereas the *Δv'* enters the emergence phase at approximately 13,500 hrs. It has been previously shown that changes in chromaticity shift direction will occur first in one component, and then later in another [23], consistent with the findings presented in **Figure A-6**. TM-35-19 also predicted that chromaticity will shift in the generally green direction (i.e., CSM-2) as shown in **Figure 4-12**; however, the unused experimental data showed that the chromaticity actually shifted in the blue direction (i.e., CSM-1) because of the *v'* component entering the emergence phase of chromaticity shift.

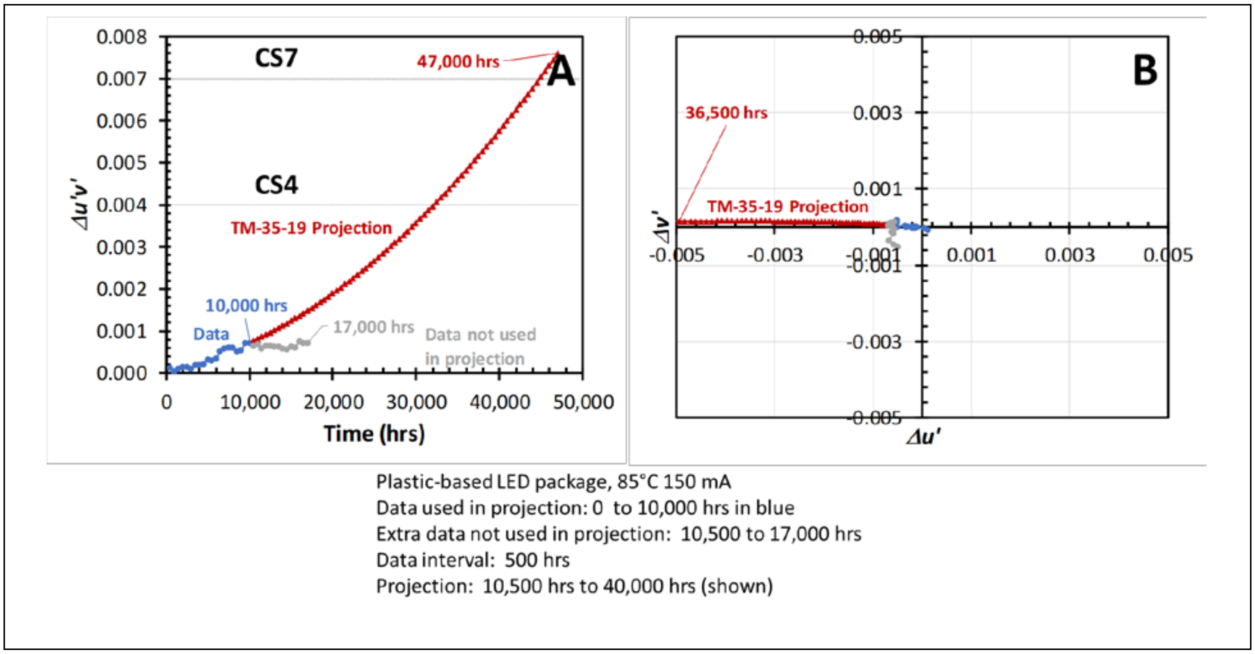


Figure 4-12: Experimental data and TM-35-19 projections for LEDs housed in a polymer-based package operated at 85 °C and 150 mA, with (A) showing the chromaticity shift and (B) showing the chromaticity shift direction. The first 10,000 hrs of data (shown as blue circles) were used in the TM-35-19 projections (shown as red triangles), with the additional data shown in gray.

Repeating the TM-35-19 calculation by using the entire 17,000 hrs of experimental data for TM-35-19 produces an entirely different result as shown in **Figure 4-13**. The corresponding temporal changes in *Δu'* and *Δv'* are shown in **Figure A-7**. With all of the experimental data used in the TM-35-19 projection, the change in chromaticity shift magnitude (*Δu'v'*) proceeds at a slower rate than when only 10,000 hrs of data are used. In addition, the chromaticity is predicted to shift in the magenta direction, which is highly unlikely as discussed in **Section 1.4** of this report. The estimate for a slower change in chromaticity shift magnitude is driven by a complete flip in the temporal nature of *Δu'* versus time and *Δv'* versus time. When using 10,000 hours of data, the *Δu'* component changes the most, but when using 17,000 hours of data, the rate of change in the *Δu'* component slows and the rate of change in the *Δv'* component increases. Consequently, the chromaticity shift magnitudes are conservative, but the projection for chromaticity shift direction is incorrect both when using 10,000 hrs and 17,000 hrs of data. This case study demonstrates again that TM-35-19 provides conservative estimates of chromaticity shift magnitude (*Δu'v'*) and that these estimates improve with additional data. However, one consequence of the conservative model is an over-estimation of the change in some chromaticity coordinates, resulting in a projected chromaticity shift direction that is highly unlikely (e.g., shift in the magenta direction). Consequently, for this case study, TM-35-19 is meeting Criterion 1 but not Criterion 2.

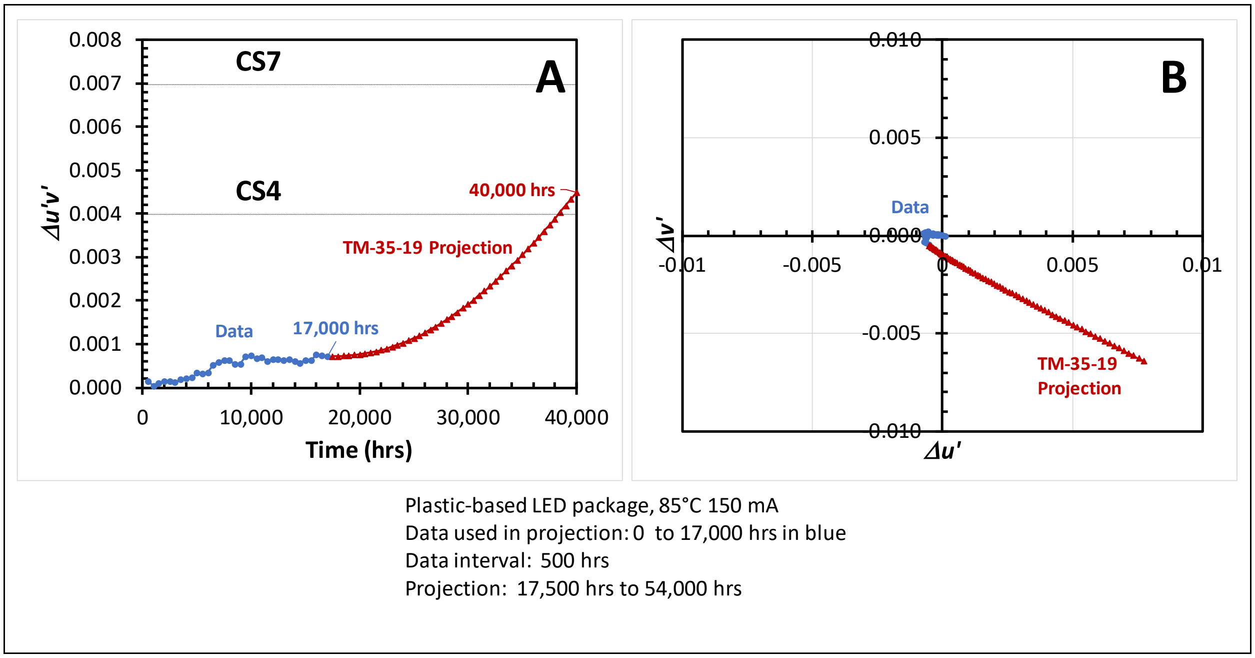


Figure 4-13: Experimental data and TM-35-19 projections for LEDs housed in a polymer-based package operated at 85 °C and 150 mA, with (A) showing the chromaticity shift magnitude and (B) showing the chromaticity shift direction. The entire 17,000 hrs of data (shown as blue circles) were used in the TM-35-19 projections (shown as red triangles).

4.2.7 Case Study 6: TM-35-19 Example for CSP LEDs

LEDs in the CSP LED platform exhibited the widest variety of chromaticity shifts as shown in **Figure 4-1**; however, the most interesting shift examples for the CSP LED platform are those that exhibited CSM-4 behavior. As previously noted, CSM-4 behavior is characterized by an initial shift in the blue direction, followed by a shift in the yellow direction, and terminating with another shift in the blue direction [12]. As shown in **Figure 4-3**, some CSP LEDs can demonstrate this type of chromaticity shift during 17,000 hrs of testing under high stress conditions (e.g., 105°C and 1,050 mA). In contrast, 17,000 hrs of testing under lower stress conditions (e.g., 85°C and 1,050 mA) produced only the first two parts of this shift (i.e., blue shift followed by yellow shift) and were judged to exhibit CSM-3 behavior.

Figure 4-14 shows 17,000 hrs of experimental data for chromaticity shift magnitude ($\Delta u'v'$) and chromaticity shift direction ($\Delta v'$ versus $\Delta u'$) for two separate populations of identical LED products in the CSP LED platform operated at different conditions. In one case (i.e., 85°C and 1,050 mA), 17,000 hours of testing were not sufficient to produce the likely true emergence phase, whereas in the second case (i.e., 105°C and 1,050 mA), it did produce an emergence phase. **Figure 4-14** also shows the projected values for chromaticity shift magnitude versus time. Plots of $\Delta u'$ versus time and $\Delta v'$ versus time are presented in **Figure A-8**. In both cases, TM-35-19 predicted a continuation of the chromaticity shift observed during the experimental period with the change in $\Delta v'$ dominating the chromaticity shift.

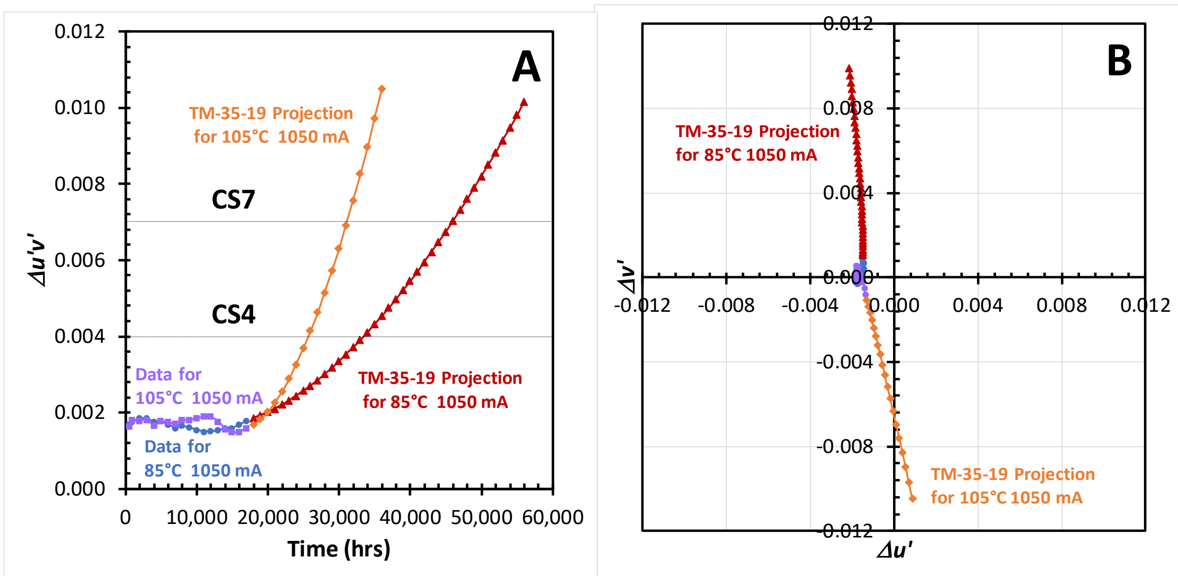


Figure 4-14: Experimental data and TM-35-19 projections for identical populations of the same LED product in CSP LEDs operated at two different conditions, with (A) showing the magnitude of the chromaticity shift and (B) showing the projected direction of the chromaticity shift.

For the 105°C and 1,050 mA test condition, the chromaticity was projected to continue proceeding in the generally blue direction (i.e., CSM-1 behavior) in agreement with the experimental data. This finding indicates that a blue shift is the emergence phase for this test condition. However, it is worth noting that TM-35-19 projected a color shift slightly toward magenta, which is unlikely as previously discussed. It is probable that the model over-estimated the change in the *Δu'* component (see **Figure A-8**), resulting in added weight to this component, which pulls the chromaticity shift towards magenta instead of the more likely shift toward the blue emitter point. Therefore, the projected *Δu'v'* value would also be conservative, and the CS4 and CS7 times are near the likely minima satisfying Criterion 1.

The population operated at 85°C and 1,050 mA in LM-80-15 testing was also projected to continue shifting in the direction indicated by available data. However, in this instance, the shift occurred before emergence and was in the generally yellow direction (i.e., CSM-3 behavior). Based on the *Δu'* versus time and *Δv'* versus time data (see **Figure A-8**), the chromaticity changes in these conditions were projected to proceed in a continuous manner, in contrast to the behavior at 105°C and 1,050 mA. However, the experimental data at 105°C and 1,050 mA clearly demonstrated that the chromaticity shift will reverse and proceed in the blue direction (see **Figure 4-3**), and a similar reversal in chromaticity shift can be speculated to occur for the 85°C and 1,050 mA test condition, but cannot be confirmed with available experimental data. If such a reversal were to occur, the time to reach CS4 or CS7 would increase (because of the time required to reverse direction and achieve a similar chromaticity shift magnitude in the blue direction). Consequently, the *Δu'v'* projection for these test conditions is likely to be conservative, satisfying Criterion 1, but there is some uncertainty about the projected chromaticity shift direction (Criterion 2).

5 Conclusions

The four major Level 1 LED package platforms used in SSL applications (i.e., ceramic-based, polymer-based, COB, and CSP) were assessed in terms of luminous flux and chromaticity maintenance by analyzing data sets from LM-80 testing of representative products from many of the Tier 1 LED suppliers. For luminous flux maintenance, the assessment was performed by using LM-80 data sets to calculate the TM-21 α and B, and then the performance by package type and operational conditions (e.g., temperature, I_f) was compared. For chromaticity maintenance, the assessment involved using LM-80-15 data sets as inputs to TM-21. For chromaticity maintenance, u' and v' data from LM-80-15 data sets were used for inputs into TM-35-19—the recently approved method for projecting long-term chromaticity coordinate shifts. A total of 223 separate data sets are included in this analysis, most of which (84%) are from the 2018–2019 time period. Two-thirds of the reports met the reporting requirements of LM-80-15.

This analysis, which is an update of an earlier study completed in 2015 that focused on only luminous flux maintenance, demonstrated that there has been continued improvement across all LED package types. In total, 96% of the α values in this study are less than 6×10^{-6} which corresponds to an L_{70} time of nearly 60,000 hrs. Perhaps the largest gains have occurred in polymer-based packages where better materials have resulted in marked improvements in luminous flux maintenance to where the performance of polymer-based packages is nearly the same as that of ceramic-based packages for $I_f \leq 200$ mA. The current handling capabilities of COB and ceramic-based packages have also improved significantly, and these package platforms exhibit excellent luminous flux maintenance at operational currents of 1,500 mA and higher. The newly introduced CSP package types are shown to exhibit luminous flux maintenance values in line with the other package platforms, especially at temperatures of 120°C and lower and operational currents of 700 mA and lower.

The assessment of chromaticity shift is a new addition to this analysis made possible by the requirement to report chromaticity coordinates (u', v') that is part of the LM-80-15 standard. The first step in this analysis was to classify the CSM behavior for the products. Based on the results from this analysis, ceramic-based packages exhibited a likelihood for CSM-3 behavior (i.e., yellow shift), polymer packages exhibited a strong preference for CSM-1 behavior (i.e., blue shift), and CSP LEDs were either divided between CSM-1 and CSM-2 for CSP LEDs without polymer sidewalls or divided between CSM-3 and CSM-4 behaviors for CSP LED packages with polymer sidewalls. Assignment of CSMs for COB packages was complicated by significantly different behaviors found in this package that made identification of the emergence phase difficult. This outcome suggests that additional work is needed to understand the mechanisms of chromaticity shift in COB LEDs. Overall, these findings indicate that improvements in package die and materials by LED manufacturers have reduced or delayed the impact of some known failure modes (e.g., delamination behavior in ceramic-based packages), thereby allowing other chromaticity failure modes (e.g., warm white phosphor stability) to rise in importance.

The second step in the assessment of chromaticity shift of these products was to perform projections of long-term chromaticity coordinate shifts by using the LM-80-15 data sets and TM-35-19. The ability of the TM-35-19 method to predict chromaticity shifts was evaluated according to the following three criteria:

1. TM-35-19 should provide accurate projections of the chromaticity shift magnitude ($\Delta u'v'$) at future times using available experimental data. Alternatively, it is acceptable if the model is conservative in its projections of $\Delta u'v'$, meaning that projected CS4 and CS7 times are likely to be less than the true values.

2. TM-35-19 should provide accurate estimates of the direction of the chromaticity shift (i.e., future u' and v' values) based on experimental data.

3. The model should provide projected chromaticity shifts that show a consistent pattern across the data sets for a given product at test conditions that produce the same phase of chromaticity shift; however, the time at which different phases and the corresponding chromaticity shifts occur may change depending on the stress level (e.g., temperature, I_f).

Through a series of six case studies, this analysis demonstrated that Criterion 1 is often, but not always, met. The TM-35-19 model is usually conservative in its estimates and, in many cases, it predicts future CS4 and

CS7 times that are conservative and occur sooner than the likely actual times. The instances in which TM-35-19 underestimates the likely true value of the chromaticity shift magnitude ($\Delta u'v'$) and consequently predicts longer CS4 and CS7 times than are likely are cases in which a sudden change in chromaticity is projected by TM-35-19 but not supported by experimental data. An additional consequence of the conservative nature of the model is a generally low success rate in projecting future chromaticity shift directions. For example, many TM-35-19 calculations result in projections of the chromaticity shifting toward the magenta direction, a shift that has not been observed for white pc-LEDs. In summary, TM-35-19 often provides conservative estimates of chromaticity shift magnitude ($\Delta u'v'$), but it is much less likely to produce a reliable estimate of chromaticity shift direction. The method appears to be more reliable when used with data sets that show at least the beginning of an emergence phase.

References

1. Walker, B. (ed). (2020). *2019 Lighting R&D opportunities*. DOE Building Technologies Office SSL Program. Available at https://www.energy.gov/sites/prod/files/2020/01/f70/ssl-rd-opportunities2-jan2020.pdf

2. Mehr, M. Y., Bahrami, A., van Driel W. D., Fan, X. J., Davis, J. L., & Zhang, G. Q. (2019). Degradation of optical materials in solid-state lighting systems. *International Materials Review, 65*(2), 102–108. https://doi.org/10.1080/09506608.2019.1565716

3. Hansen, M. (2015). *The true value of LED packages.* Presented at the 2015 Strategies in Light Conference, Las Vegas, NV.

4. Hansen, M. (2016). *Package impact on color shift in LEDs*. Presented at the 2016 Strategies in Light Conference, Santa Clara, CA.

5. 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. Available at https://www.osti.gov/servlets/purl/1360770

6. IES (Illuminating Engineering Society). (2008). *IES LM-80-08 Approved Method: Measuring Lumen Maintenance of LED Light Sources.* New York.

7. ANSI (American National Standards Institute) and 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.

8. IES (Illuminating Engineering Society). (2011). IES TM-21-11, *Projecting Long Term Lumen Maintenance of LED Light Sources.* New York.

9. ANSI (American National Standards Institute) and IES (Illuminating Engineering Society). (2019). IES TM-21-19, *Technical Memorandum: Projecting Long-Term Lumen, Photon, and Radiant Flux Maintenance of LED Light Sources.* New York.

10. Van Driel, W. D., Schuld, M., Jacobs, B., Commissaris, F., van der Eyden, J., & Hamon, B. (2015). *Lumen maintenance predictions for LED packages using LM80 data*. Presented at the 2015 16th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE). Budapest, Hungary. Available at 10.1109/EuroSimE.2015.7103165

11. 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.

12. Next Generation Lighting Industry Alliance and LED Systems Reliability Consortium. (2017, April). *LED luminaire reliability: Impact of color shift*. Available at https://www.energy.gov/sites/prod/files/2019/10/f67/lsrc_colorshift_apr2017.pdf

13. Davis, J. L., Young. J., & Royer M. (2016, February). *CALiPER Report 20.5: Chromaticity shift modes of LED PAR38 lamps operated in steady-state conditions.* Available at https://www.energy.gov/sites/prod/files/2016/03/f30/caliper_20-5_par38.pdf

14. Hansen, M. (2020). *Color shift behavior in LED package platforms.* Presented at the 2020 Strategies in Light Conference, San Diego, CA.

15. Tuttle, R., & McClear, M. (2014, February). Understand the true cost of LED choices in SSL systems. *LEDs Magazine.* Available at https://www.ledsmagazine.com/leds-ssl-design/packaged-leds/article/16695263/understand-the-true-cost-of-led-choices-in-ssl-systems-magazine

16. Yeh, C.-W. S., Chen, W.-T., Liu, R.-S., Hu, S.-F., Sheu, H.-S., Chen, J.-M., & Hintzen, H. T. (2012). Origin of thermal degradation of $Sr_{2-x}Si_5N_8$: Eu_x phosphors in air for light emitting diodes. *Journal of the American Chemical Society, 134*(34), 14108–14117.

17. Davis, J. L., Rountree, K. J., McCombs, M., & Mills, K. (2019, July). *Accelerated stress testing of multi-source LED products: Round 2*. Available at https://www.energy.gov/sites/prod/files/2019/09/f66/ssl_rnd2-multi-source-led-products_jul2019.pdf

18. ANSI (American National Standards Institute) and IES (Illuminating Engineering Society). (2019). *ANSI/IES TM-35-19: Technical Memorandum: Projecting Long-Term Chromaticity Coordinate Shift of LED Packages, Arrays, and Modules.* New York.

19. 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

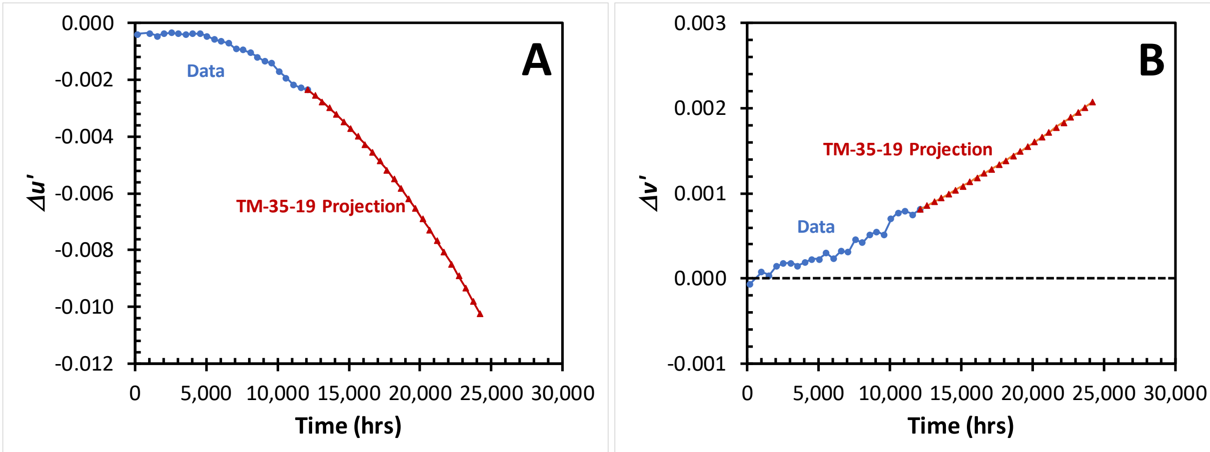
20. Bretschneider, E. (2017, February 28–March 2). *Models for color point stability of LEDs: An introduction to differential chromaticity analysis*. Presented at the Strategies in Light (SIL) 2017 Conference, Anaheim, CA.

21. Bretschneider, E. (2018). *Models for predicting color point stability*. Council for Optical Radiation Measurements (CORN). Available at http://cormusa.org/wp-content/uploads/2018/11/02-01_EBretschneider.pdf

22. Davis, J. L., Mills, K. C., Lamvik, M., Perkins, C., Bobashev, G., Young, J., Yaga, R., & Johnson, C. (2017). *Understanding and controlling chromaticity shift in LED devices*. Presented at the 2017 18th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE). Dresden, Germany. Available at https://ieeexplore.ieee.org/document/7926223

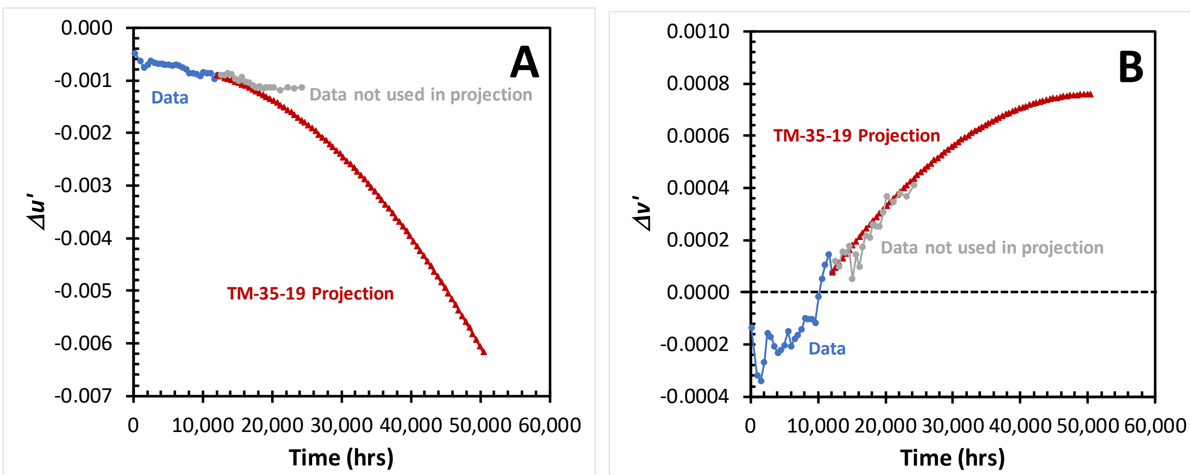
23. Davis, J. L., Mills, K. C., Bobashev, G., Rountree, K. J., Lamvik, M., Yaga, R., & Johnson, C. (2018). Understanding chromaticity shifts in LED devices through analytical models. *Microelectronics Reliability, 84*, 149–156. https://doi.org/10.1016/j.microrel.2018.03.023

Appendix A



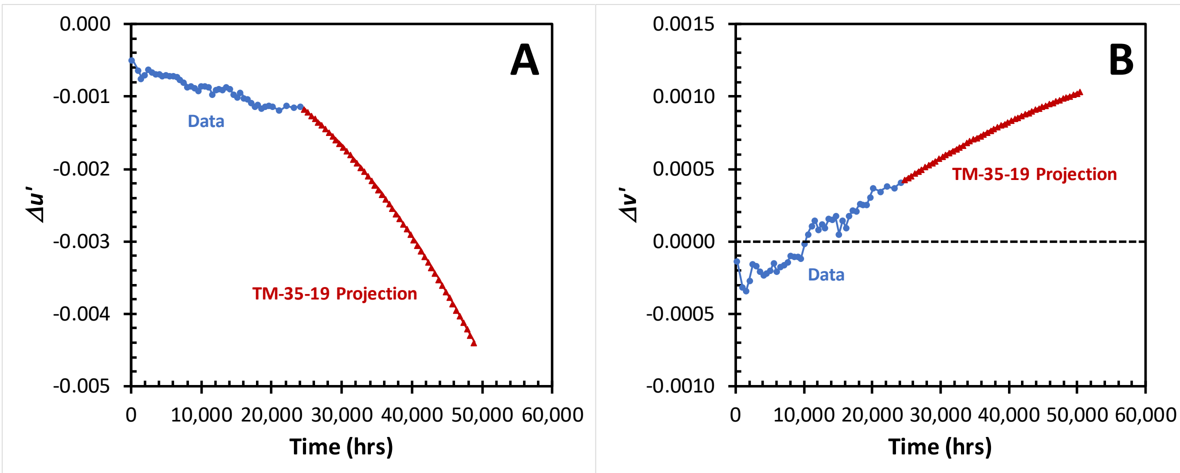
Ceramic-based LED package, 120°C 700 mA
Data: to 12,096 hrs in blue
Data interval: 504 hrs
Projection: to 24,192 hrs

Figure A-1: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for Case Study 1 with HP-LEDs in a ceramic-based package operated at 120°C and 700 mA. The experimental data used in the projections are shown as blue circles, and the TM-35-19 projections are shown as red triangles.



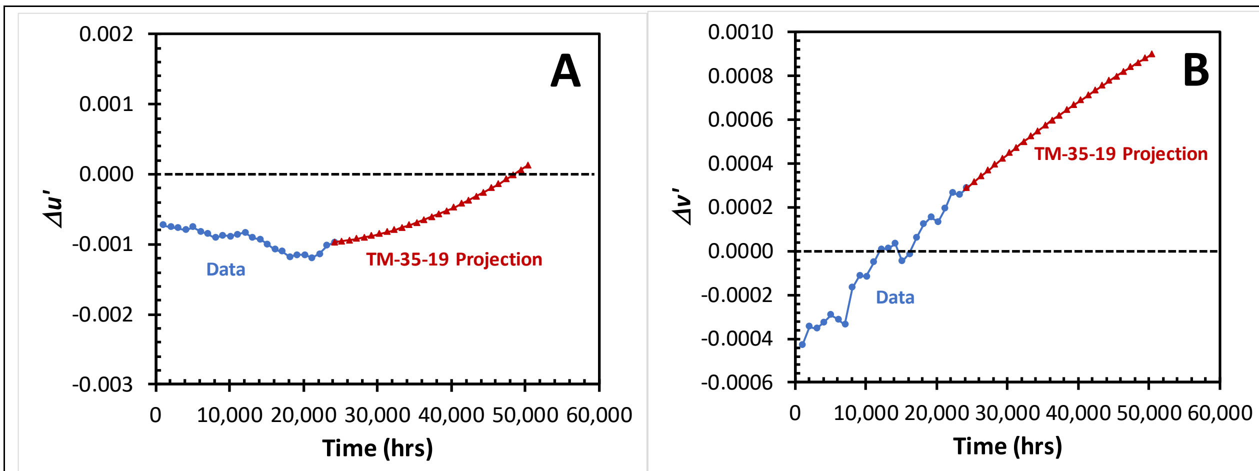
Ceramic-based LED package, 85°C 700 mA
Data used in projection: 0 to 12,096 hrs in blue
Extra data not used in projection: 12,600 to 24,192 hrs
Data interval: 504 hrs
Projection: 12,096 hrs to 50,400 hrs (shown)

Figure A-2: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for Case Study 2 with HP-LEDs in a ceramic-based package operated at 85°C and 700 mA. The experimental data used in the projections are shown as blue circles, and the TM-35-19 projections are shown as red triangles. The experimental data not used in the projections are shown in gray.



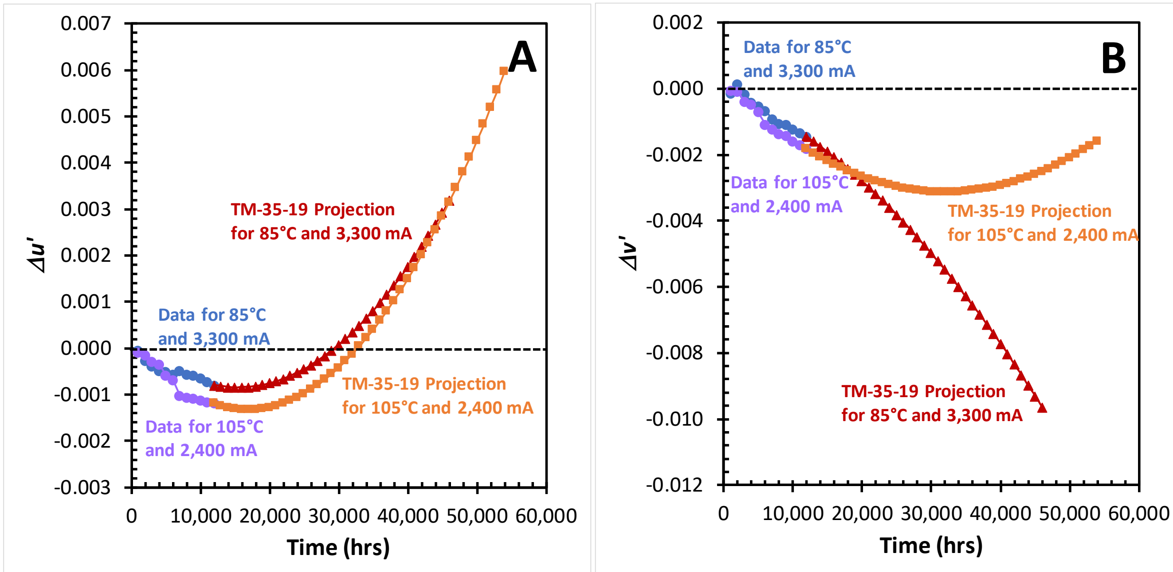
Ceramic-based LED package, 85°C 700 mA
Data used in projection: 0 to 24,192 hrs in blue
Data interval: 504 hrs
Projection: 24,696 hrs to 50,400 hrs (shown)

Figure A-3: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for Case Study 3 with HP-LEDs in a ceramic-based package operated at 85°C and 700 mA with the measurement interval chosen to be 504 hrs. The experimental data used in the projections are shown as blue circles, and the TM-35-19 projections are shown as red triangles.



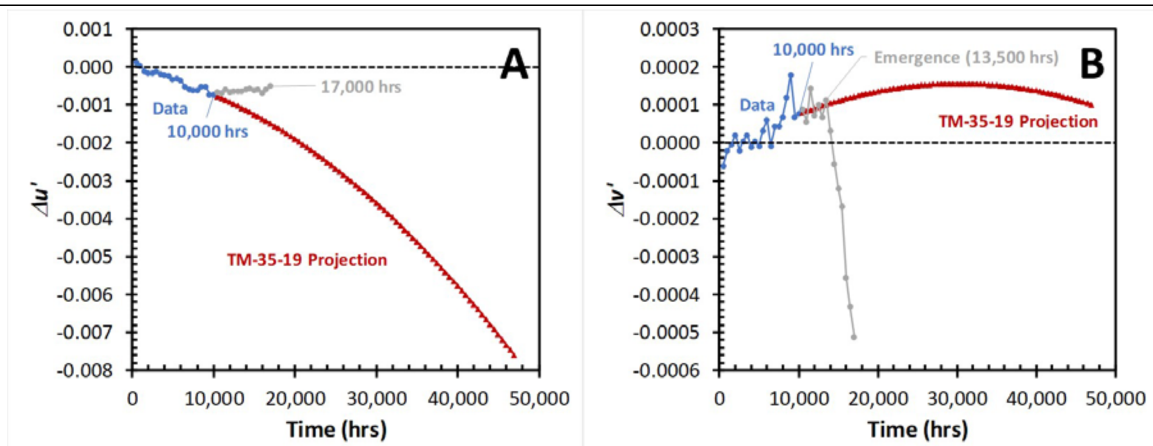
Ceramic-based LED package, 85°C 700 mA
Data used in projection: 0 to 24,192 hrs in blue
Data interval: 1,008 hrs
Projection: 24,696 hrs to 50,400 hrs (shown)

Figure A-4: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for Case Study 3 with HP-LEDs in a ceramic-based package operated at 85°C and 700 mA with the measurement interval chosen to be 1,008 hrs. The experimental data used in the projections are shown as blue circles, and the TM-35-19 projections are shown as red triangles.



COB LED package
Data used in projection: 0 to 12,000 hrs
Data interval: 1,000 hrs

Figure A-5: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for Case Study 4 with LEDs in the COB package platform. Operational conditions are show on the graphs, and the measurement interval was chosen to be 1,000 hrs.



Plastic-based LED package, 85°C 150 mA
Data used in projection: 0 to 10,000 hrs in blue
Extra data not used in projection: 10,500 to 17,000 hrs
Data interval: 500 hrs
Projection: 10,500 hrs to 40,000 hrs (shown)

Figure A-6: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for Case Study 5 with LEDs in a polymer-based package operated at 85 °C and 180 mA. The experimental data used in the projections are shown as blue circles, and the TM-35-19 projections are shown as red triangles. Experimental data not used in the projections are shown in gray.

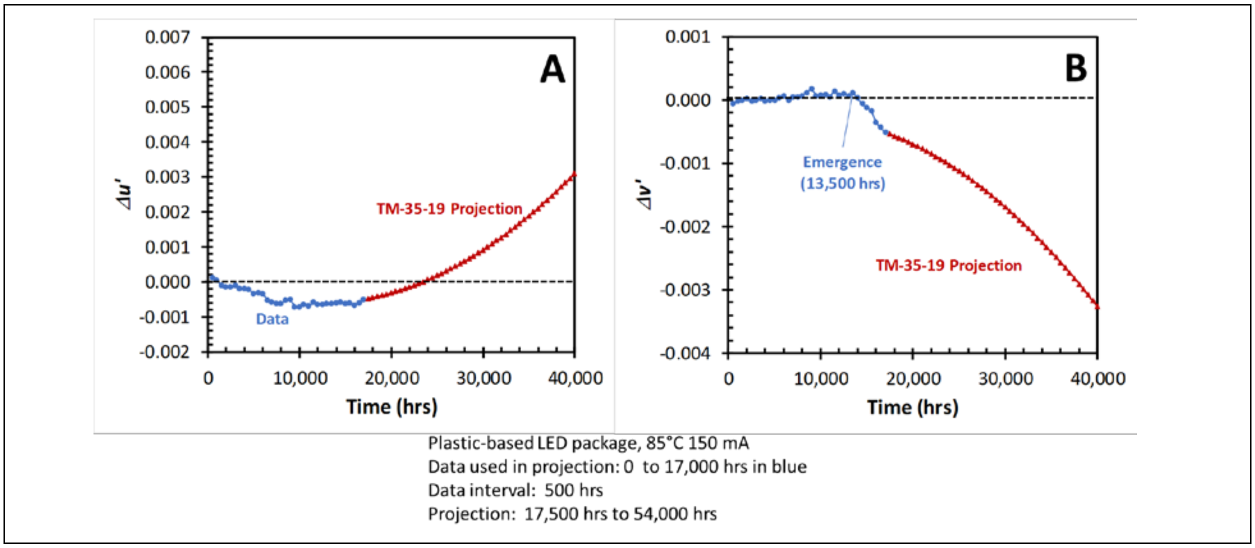


Figure A-7: Plots of (A) $\Delta u'$ versus time and (B) $\Delta v'$ versus time for Case Study 5 with LEDs in a polymer-based package operated at 85°C and 180 mA. All experimental data (17,000 hrs) were used in the projections and are shown as blue circles. The TM-35-19 projections are shown as red triangles.

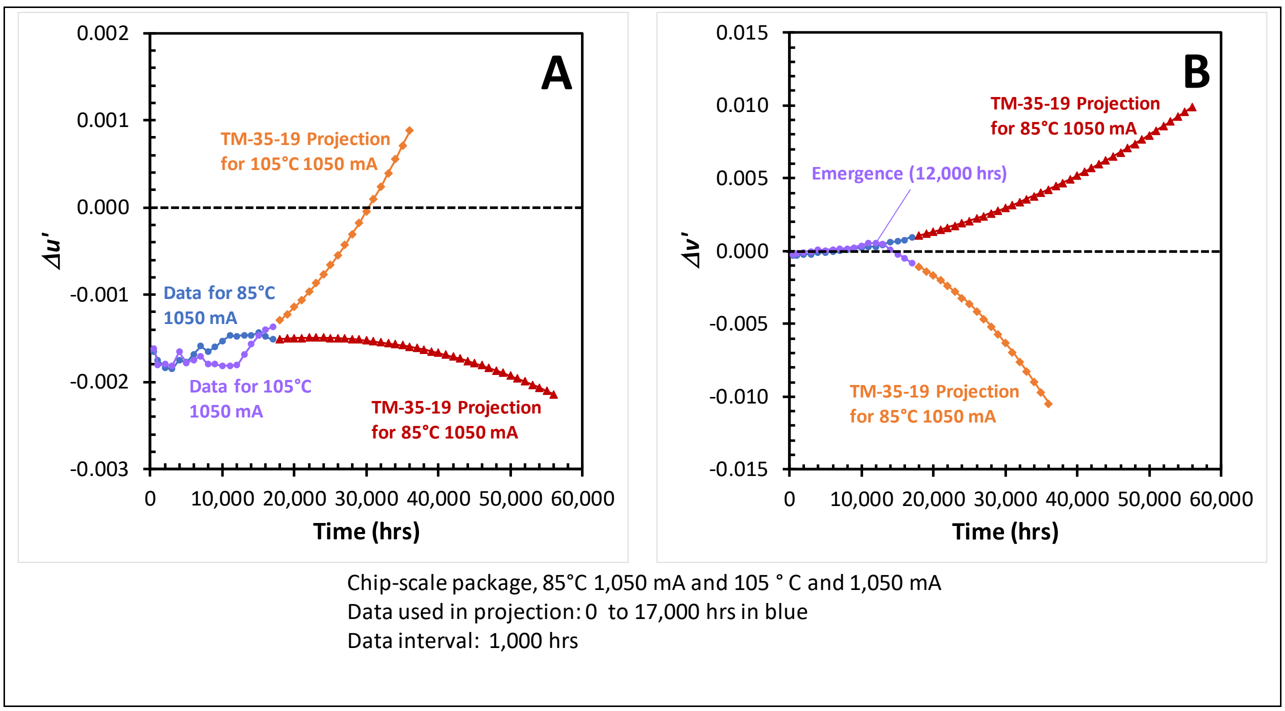


Figure A-8: Plots of $\Delta u'$ versus time and $\Delta v'$ versus time for LEDs in a representative polymer-based package operated at three different conditions.

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