LED Luminaire Reliability: Impact of Color Shift

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Next Generation Lighting Industry Alliance
LED Systems Reliability Consortium

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Introduction

The emergence of solid state lighting (SSL) with its high efficiencies and long lifetimes has led to the potential for significant energy and cost savings to our nation once wide-scale adoption occurs. Light emitting diodes (LEDs) are the heart of SSL lighting products and can provide long lifetimes that last well beyond 50,000 hours of operation, much longer than most conventional light sources. The end of life for all lighting technologies is signaled by the loss of light, but this may be less evident for LED luminaires, where the light output may continuously fade or the color may slowly shift to the point where low light output or an unacceptably large color change constitutes practical failure.

As integrated lamps and luminaires appeared on the market, it was at first assumed that one could estimate the lumen depreciation of the LED packages to describe the degradation characteristics of the integrated lighting product. While the lifetime of an LED source is one important indicator of LED luminaire life, it would be misleading to rate the entire LED luminaire based solely on the LED source. Now, after further research, it is understood that electronics failures in the driver or degradation of optical components can often occur long before LED lumen depreciation causes failures. Lifetime claims should take into account the whole luminaire system, not just the LEDs. A system reliability model that integrates the failure mechanisms in the various luminaire subsystems would create a much more accurate lifetime claim from LED luminaire manufacturers.

To address the challenge of developing accurate lifetime claims, the SSL Program of the U. S. Department of Energy (DOE) together with the Next Generation Lighting Industry Alliance (NGLIA) formed the creation of an industry consortium, the LED Systems Reliability Consortium (LSRC), to coordinate activities and foster improved understanding. The LSRC has published three editions of the document *LED Luminaire Lifetime: Recommendations for Testing and Reporting,*[1] in which they reviewed studies intended to identify potential failure modes and provide additional understanding of product life. The resulting conclusions were that numerous other subsystems and components in a luminaire introduce other potential failure modes which will affect, and may actually dominate, the determination of system lifetime. Work by the LSRC and other funded R&D by the DOE SSL program is focused on understanding the various degradation mechanisms to enable the development of new models so that system reliability can be confidently understood, modeled, predicted, and communicated.

LED Lifetime and Lumen Maintenance

LED packages rarely fail abruptly (i.e., instantaneously stop emitting light), but rather experience parametric failures such as degradation or shifts in luminous flux, color point (chromaticity coordinates), color rendering index (CRI), or efficacy. Of these parametric shifts, lumen depreciation has received the most attention because it was previously thought that the degradation of lumen output of the LED source itself would be the prime determinant of lifetime for the completed product. While it is now understood that this is not the case, lumen maintenance is still used as a proxy for LED lamp or

[1] LED Systems Reliability Consortium, *LED Luminaire Lifetime: Recommendations for Testing and Reporting, Third Edition*, September 2014. Available: http://energy.gov/sites/prod/files/2015/01/f19/led_luminaire_lifetime_guide_sept2014.pdf.

luminaire lifetime ratings, largely due to the availability of standardized methods for measuring and projecting LED package lumen depreciation.

The useful life of an LED package is often cited as the point in time where the luminous flux output has declined to 70% of its starting value or L_{70}. For products with lifetimes of many years or even decades, failures may be very slow to appear under normal operation. In 2008, the Illuminating Engineering Society (IES) published IES LM-80, which is an approved method for measuring the lumen maintenance of solid-state (LED) light sources, arrays, and modules.[2] The LM-80 test method has been recently updated to reflect the experience and knowledge gained by the LED industry. The LM-80-08 procedure required measurements of lumen output and chromaticity for a representative sample of products to be taken at least every 1,000 hours, for a minimum of 6,000 hours. Luminous flux and chromaticity shifts are to be measured for three different LED case temperatures: 55°C, 85°C and a third temperature to be selected by the manufacturer. A newer version, LM-80-15, has undergone changes to the testing method, which now requires only two different case temperature, one of which should be 55°C or 85°C (commonly used case temperatures for industry testing to support direct product comparisons of testing results).

Many researchers have put a great deal of effort into devising a way to project the time at which L_{70} will be reached for an LED package in a luminaire, and IES has documented a forecasting procedure, IES TM-21,[3] which uses the LM-80 test data for the lumen maintenance projections (a minimum of 6,000 hours of test data is required). The LM-80 data (luminous flux vs. test hours) for the LEDs tested is averaged and an exponential curve fit is applied to the data; the results of the curve fit are used to calculate a lumen maintenance lifetime projection. This technical memorandum stipulates that any projection may not exceed a set multiple (depending on sample size statistics) of the actual hours of LM-80 testing data taken, which helps avoid exaggerated claims.

With the development of IES TM-21 for projecting lumen maintenance, experts agreed the projecting method should use the trend (over a sufficient period of time) of single case temperature testing data. There is a separate projection method in TM-21 based on using two tested case temperatures and interpolating data between the tested case temperatures. Thus, the requirement of testing three case temperatures is not completely necessary and leads to an unnecessary testing burden on LED manufacturers. (LM-80-15 reduced the number of test temperatures.)

It should be noted that LM-80 measurements are taken with the LED packages operating continuously in a temperature-controlled environment, where the solder point and ambient air temperature are at equilibrium. This does not necessarily reflect real-world operating conditions, so there may not be a perfect match between predictions based on laboratory test results and practical experiences with lamps and luminaires in the field. Nevertheless, lumen maintenance projections can help sophisticated users compare products, as long as their limitations are properly understood.

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[2] Illuminating Engineering Society, *LM-80-08: Measuring Lumen Maintenance of LED Light Sources*, 2008.
[3] Illuminating Engineering Society, *TM-21-11: Projecting Long Term Maintenance of LED Light Sources*, 2011.

When LEDs are installed in a luminaire or system, there are many additional factors that can affect the rate of lumen depreciation or the likelihood of catastrophic failure. These include temperature extremes, humidity, chemical incursion, voltage or current fluctuations, failure of the driver or other electrical components, damage or degradation of the encapsulant material covering the LEDs, damage to the interconnections between the LEDs and the fixture, degradation of the phosphors, and yellowing of the optics. In addition, abrupt semi-random short-term failures may be observed due to assembly, material, or design defects. More information on system level lifetime can be found in LSRC's *LED Luminaire Lifetime: Recommendations for Testing and Reporting*.[1]

Chromaticity Stability

While lumen maintenance has dominated discussions about LED lifetime, the color stability (also known as chromaticity stability) is another important performance attribute that can be a barrier to purchase or lead to unmet expectations of LED lighting. Shifts in color and appearance are a regular part of our lives, whether it is fading paint, fabric colors, or lighting. Color shift in lighting has always occurred in traditional lighting technology, but has gained more prominence with LED lighting due to its long operating life of 10 years or more in many applications. Traditional lighting technology, such as halogen, fluorescent, or metal halide technology, experiences color shifts. Frequent relamping every few years is required due to catastrophic failures or lumen depreciation and this mitigates the impact of the color shift of these lighting technologies.

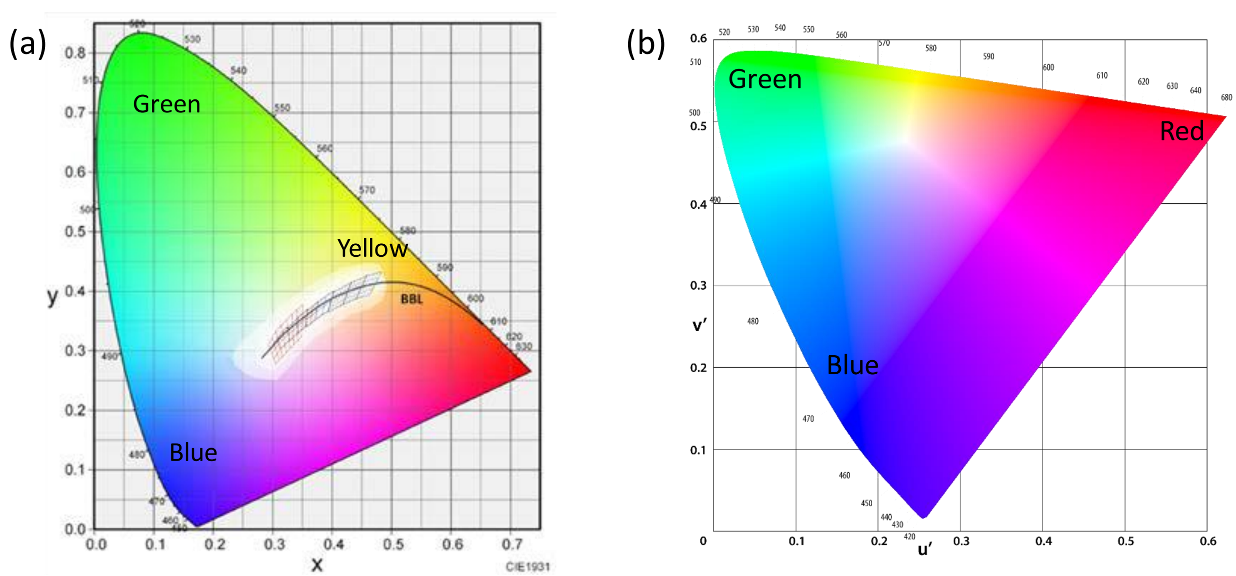

Figure 1. CIE 1931 chromaticity diagram (a) and CIE 1976 chromaticity diagram (b).

The color of light can be represented using chromaticity coordinates to describe its hue and saturation. A pair of chromaticity coordinates corresponds to a unique color of light; two sources with the same chromaticity coordinates should theoretically appear the same. Chromaticity diagrams to represent the different color space have been developed and standardized by the Commission Internationale de l'Eclairage (CIE). The most commonly used chromaticity diagrams are the CIE 1931 chromaticity diagram using (x, y) coordinates to specify chromaticity and the CIE 1976 chromaticity diagram using (u', v') coordinates. Examples of the chromaticity diagrams are shown in Figure 1. The 1976 CIE diagram has been used more extensively by the LED industry in recent years to describe chromaticity changes with its advantage of describing a linear color space, which allows for a more intuitive determination of chromaticity differences or shifts (Δu'v'). Note: Δu'v' describes the magnitude of a chromaticity change, but not the direction of shift; this is the value provided in the LM-80-08 reports. The newer LM-80-15 reports do require reporting of the individual chromaticity coordinates (u' and v') instead of the total shift (Δu'v'). LED package manufacturers have been shifting to this new LM-80-15 reporting requirement with newer LED product lines.

The importance of chromaticity stability varies by application. For example, a high degree of chromaticity stability is crucial for light sources in a museum or retail store, but less important for street lighting. Chromaticity stability of the lamp and luminaires is important where multiple lamps or luminaires are being used to wash a wall, or where objects are being evaluated based on color, such as in a hospital or factory. The chromaticity maintenance of LED lamps and luminaires varies among different products, and potentially for the same product used in different applications. Like many other metrics, there are no official standards limiting the amount of acceptable chromaticity shift.

Traditional Lighting Technologies

Many types of light sources have some chromaticity instability over time. The most pronounced is metal halide, but fluorescent and halogen lamps can also shift. The problem with this chromaticity instability is illustrated in Figure 2, where the lamps are creating a different visual appearance for the wall wash.

A DOE study on the chromaticity maintenance of LED PAR38 lamps was performed to understand the current performance of LED products on the market. As part of this broader study on the chromaticity

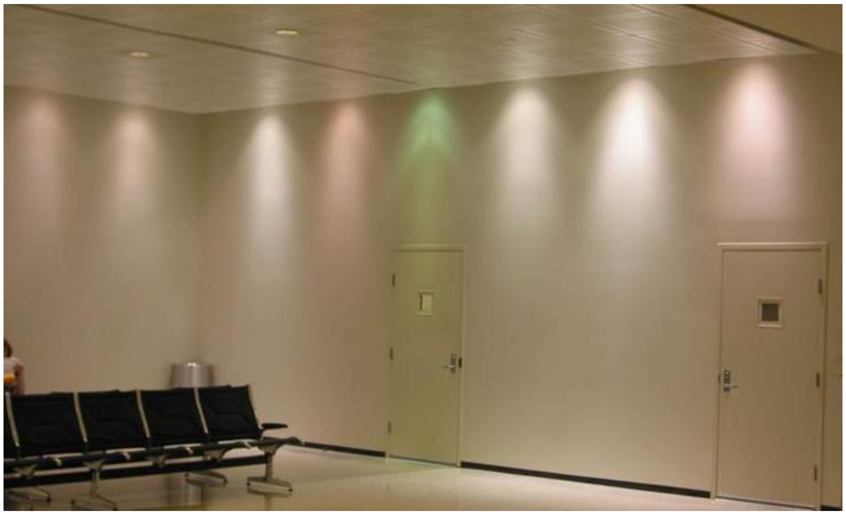

Figure 2. A room lit with ceramic metal halide lamps shows the impact of poor chromaticity stability on the appearance of the wall wash. The varying color appearance of neighboring lamps would necessitate relamping.

shift in LED lamps, the chromaticity shift of various conventional lamp technologies has been measured.[4] The average change in chromaticity for PAR38 lamp samples with different lighting source technology was measured and the results are shown in Figure 3. A high-level analysis shows that on average, the LED PAR38 lamps had better chromaticity stability than any of the comparable conventional lighting benchmarks. Of the traditional lighting technologies, ceramic metal halide had the poorest chromaticity stability compared to halogen and compact fluorescent lamps, whereas the latter two are generally considered to have acceptably small levels of color stability.

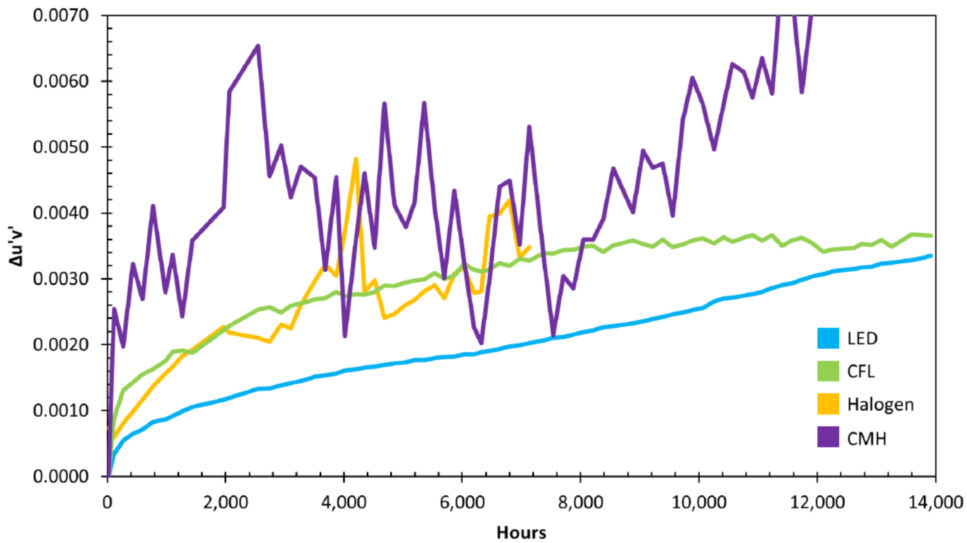

Figure 3. Average change in chromaticity for PAR38 lamp samples with different lighting source technology.[4] Traditional lighting technology can exhibit as much or more color shift compared to LED lighting products.

LED Lighting

Chromaticity stability can vary based on LED lamp or luminaire product design with several factors affecting the resulting performance. Ambient air temperature, drive current, and the design of the lamp or luminaire's thermal management system can influence the junction temperature of the LED, which in turn, can affect its output characteristics. Of greater concern for long-term chromaticity stability is the effect that high operating temperatures can have on certain package and optical materials. Depending on the design of the LED package, the phosphor layers may settle, curl, delaminate, or otherwise change the number of photons that are converted to white. This behavior can occur even in the absence of high ambient temperatures. Likewise, other materials in the optical path, such as silicones or plastics may discolor over time. In addition, materials such as glues or chemicals may diffuse into the LED package and affect chromaticity stability. Temperature fluctuations during operation may also intensify degradation mechanisms for some LED products.

[4] DOE SSL Program, CALiPER Report 20.4: *Lumen and Chromaticity Maintenance of LED PAR38 Lamps Operated in Steady-State Conditions*, December 2014. Available: http://energy.gov/sites/prod/files/2015/02/f19/caliper_20-4_par38_0.pdf.

There are no official standards limiting the amount of acceptable chromaticity shift in LED lighting products, but different certifications have established requirements. For example, to qualify for the ENERGY STAR® label, nine out of 10 samples of an LED lamp must have a measured chromaticity shift ($\Delta u'v'$) of less than 0.007 over the first 6,000 hours of operation. For applications that require high chromaticity stability, a specification may be established on a project-by-project basis.

Beyond the lack of agreement on acceptable levels of chromaticity shift, there is currently no standard methodology for projecting future chromaticity maintenance using standard test procedures like there is for projecting LED package lumen maintenance. Furthermore, there are no established methods for accelerated testing, leaving each manufacturer to develop their own testing methodologies and predictive modeling approaches. A consensus methodology for predicting chromaticity shift will be a challenge as different materials of construction and manufacturing processes can affect the results; however, an IES committee is working to come to accord on this pressing issue (TM-31).

Chromaticity Consistency

Chromaticity stability should not be confused with chromaticity consistency — also referred to as color consistency. Chromaticity stability refers to the ability of a product to maintain a constant chromaticity point over its lifetime, whereas chromaticity consistency refers to the product-to-product variation within a lamp or luminaire type. This lamp-to-lamp consistency is important to provide uniform lighting within a room and building. In LED lighting, the chromaticity consistency from lamp to lamp depends on the consistency of the phosphor-converted LEDs. To counter variability that is inherent in the manufacturing process, white LEDs are binned based on chromaticity, lumen output, and forward voltage. This allows the manufacturers of LED lamps and luminaires to provide a more consistent product.

Figure 4. A room lit with LED lamps with poor chromaticity consistency shows the differing white color appearance when these lamps are placed next to each other. This type of chromaticity variation from product-to-product will lead to customer disappointment in this application.[5]

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[5] Lumileds, *Freedom from Binning and Hot Testing*. Available: http://www.lumileds.com/technology/luxeon-technology/freedom-from-binning.

Figure 4 illustrates the problem of poor chromaticity consistency from lamp to lamp upon installation. Although this case represents a chromaticity consistency challenge, similar effects can be seen with varying chromaticity maintenance over time. Both factors, chromaticity consistency (at time = 0) and chromaticity stability (after thousands of hours in operation), are crucial for the customer.

LED Packages

The LED package construction often drives the performance and long term behavior of the LED light source. The impact of LED package design and materials of construction on performance, color quality, lumen maintenance and chromaticity shift, have been investigated for a variety of LED packages under the DOE SSL Core Technology Research Project awarded to RTI International.[6] One of the goals of this project is to determine failure modes for LED packages and develop software approaches to model failure rates in an effort to correlate package behavior to system reliability results.

Four main LED package platforms have emerged as light sources for LED luminaires:

- High-power packages (1 to 5 W) typically used in products requiring small optical source size (e.g., directional lamps) or high reliability (e.g., street lights)
- Mid-power packages (0.1 to 0.5 W) typically used in products requiring multiple light sources for diffuse emission (e.g., troffers, A-type lamps)
- Chip-on-board (COB) packages typically used in products needing high luminous fluxes from a small optical source or extremely high luminous flux density (e.g., high-bay lighting)
- Chip scale packages (CSPs), also called package-free LEDs or white chips, which have gained attention as a compact, low cost alternative to the high-power and mid-power platforms.

Representative packages from these major LED package platforms are illustrated in Figure 5.

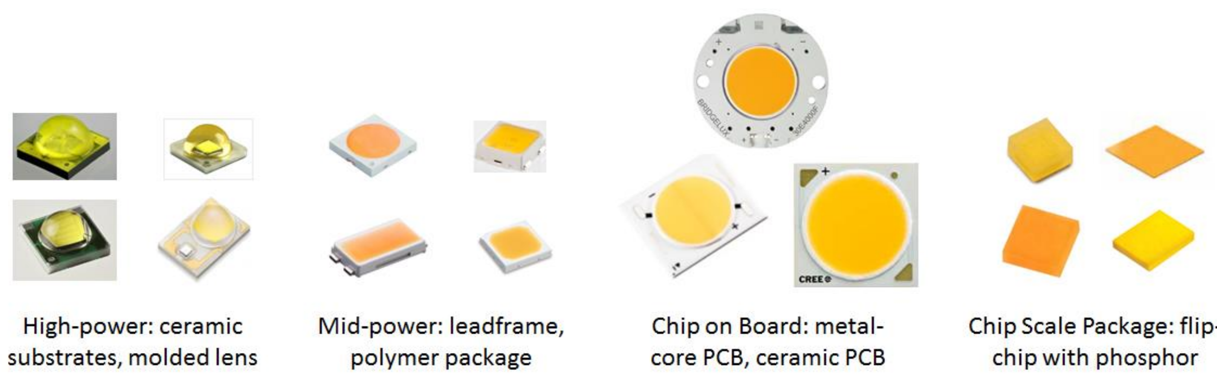

Figure 5. Examples of high-power, mid-power, chip-on-board (COB), and chip scale package (CSP) LEDs (not shown to scale).

6 DOE SSL Program Core Technology Project Update, *RTI International Develops SSL Luminaire System Reliability Model*, May 2016. Available: http://energy.gov/eere/ssl/rti-international-develops-ssl-luminaire-system-reliability-model.

To begin the modeling work of the lumen maintenance and chromaticity shift of LEDs, a methodology was developed to analyze LM-80 data across multiple LED manufacturers to provide new insights into LED-level factors impacting lifetime. Data from more than 200 different LED data sets was analyzed using this methodology combined with TM-21 projections and supplemented with experimental data. This process calculates a decay rate constant (α) that provides a measure of the rate of luminous flux change. Higher α values indicate faster lumen depreciation whereas small α values indicate longer lumen maintenance times. The analysis provided a detailed look at lumen maintenance and chromaticity shift behavior for a range of LED packages with different designs and materials of construction from multiple manufacturers and found that the materials of construction have a direct impact on long-term performance of LEDs.

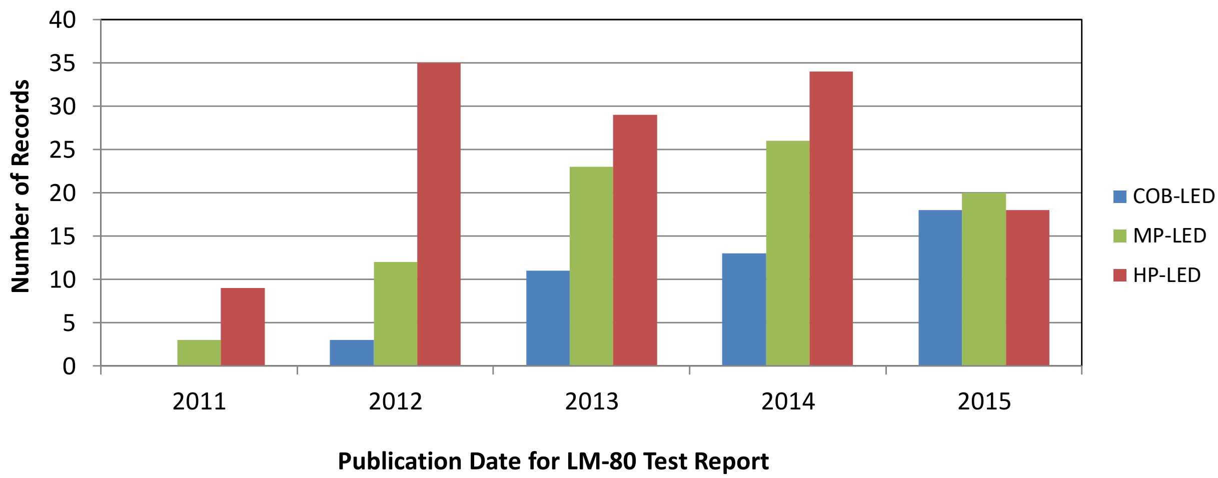

Figure 6. Summary of the LM-80 report records by year and LED platform type.[7]

The different LED package platforms have different intrinsic characteristics based on materials of construction and manufacturing processes, which impact their lumen depreciation and chromaticity point stability. Figure 7 shows the decay rate constants as a function of LED junction temperature for different package platforms. Mid-power LEDs can often exhibit more rapid lumen degradation than high-power LEDs or chip on board LEDs; this faster decay of luminous flux is largely due to degradation of the plastic resin body used in the mid-power LED compared to the more stable ceramic substrate used in the high-power LED. The plastic material most commonly employed in mid-power LED packages is polyphthalamide (PPA), a thermoplastic resin. At high temperatures and long operating times, the materials in the package can discolor, crack, or delaminate, leading to lumen depreciation and chromaticity shift.

Different types of plastic resin, however, have different lumen degradation behavior. Improved plastic resins such as epoxy molding compound (EMC) can reduce the thermal constraints associated with conventional mid-power commodity packages. Mid-power LEDs based on EMC resin are more resistant to degradation than PPA and compatible with higher operating temperatures. Figure 8 compares the

[7] M. Hansen, "Package Impact on Color Shift in LEDs," *Strategies in Light*, Santa Clara, CA, March 2016.

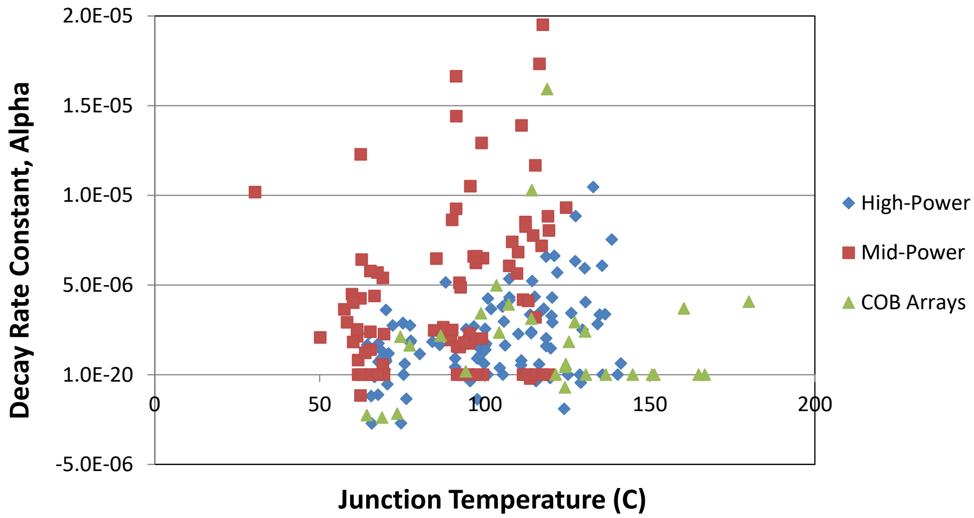

Figure 7. Decay rate constants for high-power, mid-power, and COB LEDs as a function of junction temperature. These were calculated using LM-80 and TM-21 projections combined with the new analysis methodology described.[7]

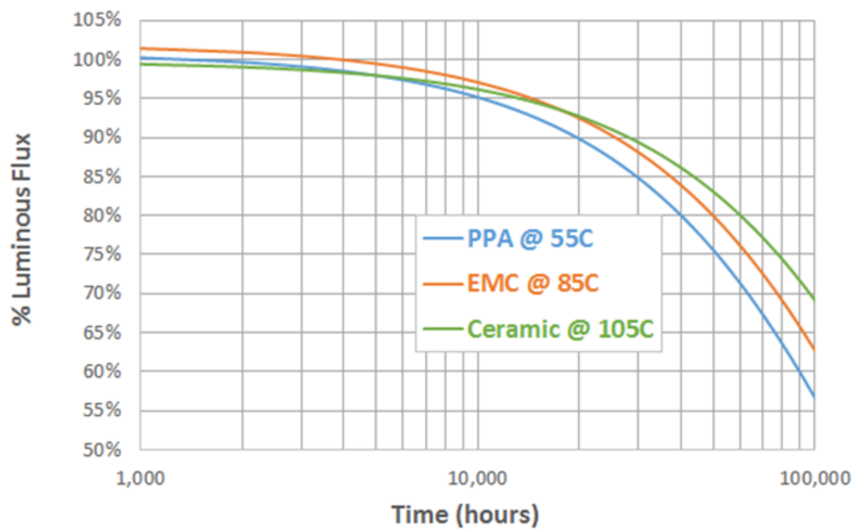

Figure 8. Lumen degradation performance of mid-power packages (PPA and EMC plastic resins) operating at 150 mA and a high-power package (ceramic substrates) operating at 1 A drive current.[8]

lumen degradation performance of mid-power packages using PPA and EMC plastic resins to high power packages using ceramic substrates. While the quality of mid-power packages can vary between LED manufacturers, one commonly seen trend is that EMC-based LED packages can achieve high lumen maintenance at higher temperatures and drive currents than PPA-based LED packages. In addition, it is commonly observed that the ceramic substrates in high power LEDs provide improved heat dissipation and thus result in higher lumen maintenance behavior, especially at high currents and temperatures. Though the various package materials of construction have different lumen maintenance performance,

[8] M. Hansen, "The True Value of LED Packages," *Strategies in Light*, Las Vegas, NV, February 2015.

both PPA and EMC mid-power packages can achieve excellent lumen maintenance performance (e.g., better than 50,000 hours in some cases), as long as their drive currents are kept low enough to stay in a ‘safe operating zone’ (below where that particular resin material discolors and breaks down over time).

While lumen maintenance is important, other forms of parametric failure for LED packages must not be overlooked. Chromaticity shift, for example, may be more detrimental than lumen depreciation for some applications; however, this is sometimes difficult to know in advance. To date, the industry generally quantifies chromaticity shift using Δu'v', which describes the magnitude of chromaticity shift, but it does not capture the direction of the shift. (The actual chromaticity coordinates u’ and v’ are required to know the direction of the chromaticity shift.) The point at which a chromaticity shift becomes noticeable and results in parametric failure will depend on the lighting application. If the chromaticity change occurs slowly over a very long period (e.g., 25,000 hours), it may not be objectionable in the case where the light sources shift by the same magnitude and in the same direction (unlikely in practice).

Factors impacting chromaticity point stability in LEDs include aging-induced changes in the emitter, phosphor, encapsulant materials, and plastic resin. Emitters can exhibit decreases in radiant flux over time; phosphors can experience decreases in quantum efficiency or shifts in emission spectrum due to oxidation; encapsulants can exhibit cracking, oxidation and yellowing, or changes in index of refraction; and resins can discolor and absorb photons. Higher temperatures will accelerate these degradation mechanisms leading to greater color shift, though the magnitude of the color shift as a function of temperature will vary with packaging materials and manufacturing processes. As with lumen maintenance behavior, if the LEDs are operated at low drive currents and lower than normal operating temperatures, these materials changes leading to chromaticity shift will be very slow to develop, if they occur at all.

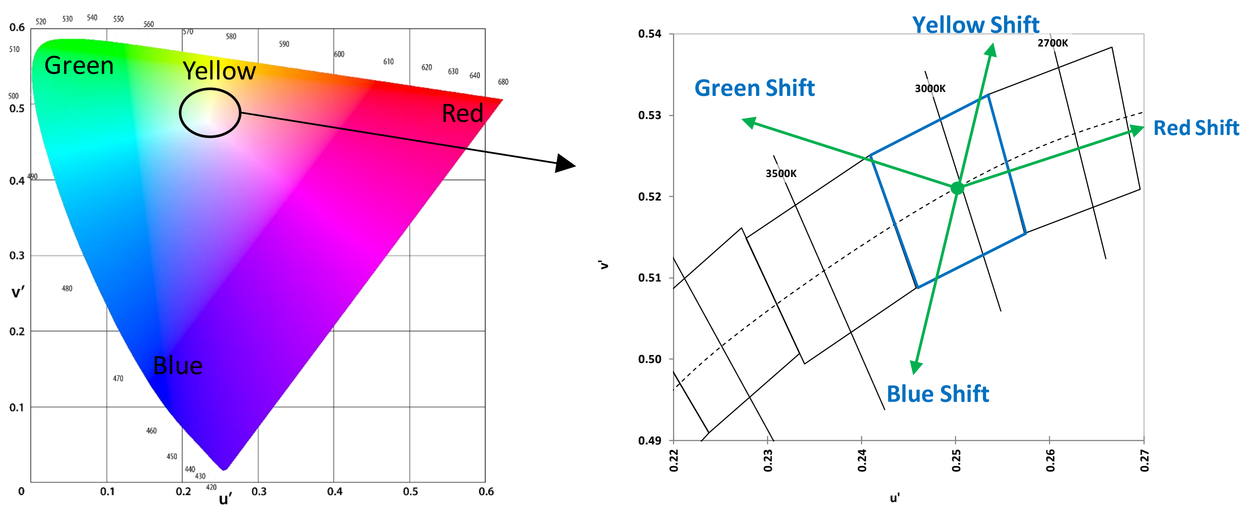

Figure 9. 1976 CIE chromaticity diagram (u', v') illustration the white chromaticity region (denoted by the black circle) and the common directions of chromaticity shift in LED packages. The right figure is an enlargement of the black circle, showing the white chromaticity bins.

The resulting direction of chromaticity shift depends on the dominant degradation mechanisms occurring in the package, which in turn depends on the package materials and methods of construction. The chromaticity shifts can be towards the yellow, blue, green, or red colors as illustrated using the CIE 1976 chromaticity diagram in Figure 9. Different package platforms have shown distinct differences in the chromaticity shift signatures.

Chromaticity Shift Mechanisms

Many different mechanisms can lead to chromaticity shift modes in LED lamps and luminaires. Since the chromaticity shifts can come from various materials and subsystems — from the LED package and its materials to the optical lens or diffusers — the result is many different directions of chromaticity shift. Table 1 summarizes several commonly seen chromaticity shift mechanisms that can occur in LED lighting systems and the root causes of such a shift.

Table 1. Summary of chromaticity shift mechanisms that can occur in LED lamps and luminaires.[9]

Shift Direction	Cause
Blue shift	Loss of phosphor quantum efficiency due to chemical change or temperature effects
	Oxidation of the molding compound in PLCC (plastic leaded chip carrier) or tarnishing of exposed metal surfaces such as lead frames and reflectors
	Operating the phosphor above the saturation flux level, settling and precipitation of the phosphor
	Top-to-bottom fractures of the binder in the phosphor-binder layer, resulting in blue photons bypassing the phosphor layer
Yellow Shift	Increase in phosphor quantum efficiency due to chemical changes or temperature decreases
	Cracking or delamination of phosphor-binder layer, which can lengthen the path of blue photons through the phosphor
	Discoloration/oxidation of the lenses
	Discoloration of the reflector
Green Shift	Chemical changes in the phosphor such as oxidation that shift emission intensity to lower wavelengths
	Reduction in red emissions such as those from a red LED
Red Shift	Shift in emission properties of direct red emitter
	Reduction in the emissions from green phosphors

Beyond the mere direction of the chromaticity shift, other general behavior characteristics of LED lamps shift have been observed. A DOE sponsored study was performed to investigate the different chromaticity shift modes on a series of LED PAR38 lamps. The various characteristic behaviors of these

LED lamps have been measured and then subsequently classified into chromaticity shift modes (CSMs), as summarized in Table 2. Four main CSMs were identified and caused by changes in the LED packaging materials including the behavior of the LED chip, the phosphor and silicone binder, and the plastic molding used as in the package body. More details of this study and its analysis can be found in the CALiPER report titled *Chromaticity Shift Modes of LED PAR38 Lamps Operated in Steady-State Conditions.*[9]

Table 2. Summary of chromaticity shift modes observed in LED PAR38 lamps.[9]

Chromaticity Shift Mode	Characteristic Behavior
CSM-1	Typically involves a continuation of the chromaticity shift in the blue direction (i.e., *u*′ and *v*′ both decrease). This CSM is favored by low operational stress conditions such as low LED board temperatures and low drive currents. It is speculated that longer test times or more-aggressive test conditions may result in the appearance of additional CSMs in these samples
CSM-2	Typically involves a shift in the green direction (i.e., *u*′ decreases and *v*′ remains unchanged or increases slightly). This CSM is also favored by low operational stress conditions and appears to be caused by small shifts (less than 5 nm) in the emission maxima of the phosphor, which may signify phosphor oxidation.
CSM-3	A prolonged shift in the yellow direction (i.e., u′ changes little while v′ may increase significantly) may occur after the initial blue shift. This CSM produces a characteristic hook pattern in the chromaticity coordinates, with the yellow shift characterized by an increase in first *v*′ followed by *u*′. The primary cause is believed to be degradation of the binder in the phosphor-binder composite, resulting in delamination and cracking between the phosphor/binder layer and the LED die. This CSM is seen in high-power LEDs, similar to that shown in Figure 11.
CSM-4	Typically involves a short initial shift in the blue direction, followed by a shift in the yellow direction, followed by a second blue shift. This CSM behavior was only found in samples containing plastic lead frame LED packages (e.g. mid-power LEDs), suggesting that the primary cause of this CSM is oxidation of the molding resin used in LED packages.

The various chromaticity shift modes by package type were summarized for the PAR38 lamps selected in the CALiPER report on Chromaticity Shift Modes. As can be seen in Figure 10, multiple package styles displayed the same chromaticity shift mode. In addition, a package architecture can shift different ways depending on the materials of construction and manufacturing process that a particular manufacturer

[9] DOE SSL Program, *CALiPER Report 20.5: Chromaticity Shift Modes of LED PAR38 Lamps Operated in Steady-State Conditions*, February 2016. Available: http://energy.gov/sites/prod/files/2016/03/f30/caliper_20-5_par38.pdf

uses for that product line. The chromaticity shift modes an LED package product exhibits can change over the product generations due to the use of newer or more robust materials in that product family. The data in Figure 10 represent packages that were manufactured in 2013 or earlier; today's LED packages may not have the same distribution of color shift modes in some cases.

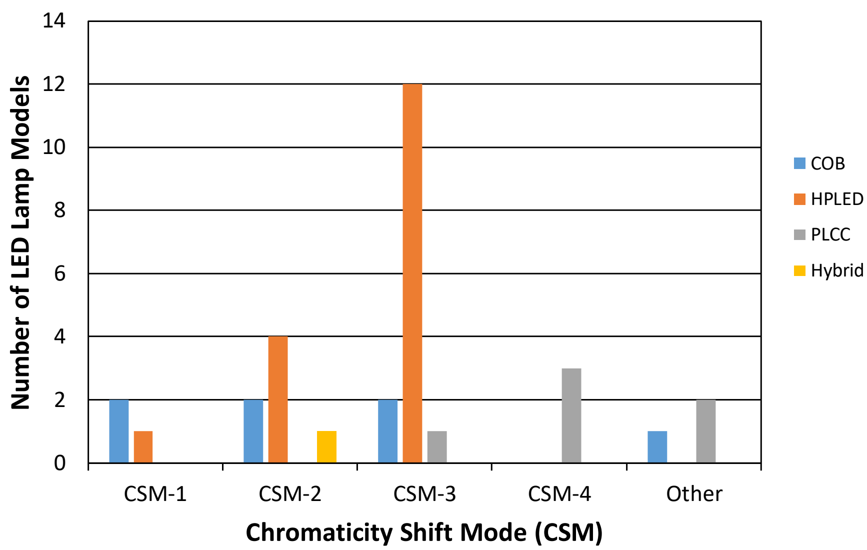

Figure 10. Count of the CSMs found in the LED PAR38 lamp models from the CALiPER report on chromaticity shift modes.[10] Different LED package platforms and similar platforms from different manufacturers exhibited different CSMs.

High-Power LEDs

The high-power LED architecture often produces the most stress to the phosphor and binder materials, because the phosphor is applied directly on the LED chip using an optical-grade binder. The large blue LED chips in high-power packages can operate at very high currents, resulting in high optical flux densities (approximately 1 W/mm^2) hitting the phosphor and binder. In addition, the heat from the LED chip plus the heat generated in the phosphor matrix (from the Stokes losses of the phosphor conversion of the blue [or violet] photon to yellow), creates high thermal stresses. Phosphor temperatures can easily be 30°C to 50°C above the junction temperature of the LED.

With time and high temperatures, the phosphor layer can crack and delaminate from the surface of the LED chip. When phosphor cracking and delamination occurs, a yellow shift in the spectrum arises due to an increase in the distance the blue photons travel through the phosphor to escape.[11] The majority of high-power LED packages exhibit a steady yellow shift over time, as seen in Figure 11, due to phosphor cracking or delamination. This steady yellow shift is the most commonly observed terminal chromaticity shift mechanism for high-power packages and is consistent across a variety of manufacturers and product generations.

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[10] J. Lynn Davis, "The Causes of Color Shift in LED Devices," *Strategies in Light*, Santa Clara, CA, March 2016.

[11] M. Royer, C. Stalker, R. Tuttle, "LED color stability: 10 important questions," DOE webinar, April 15, 2014. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/color-stability-webinar_4-15-2014.pdf.

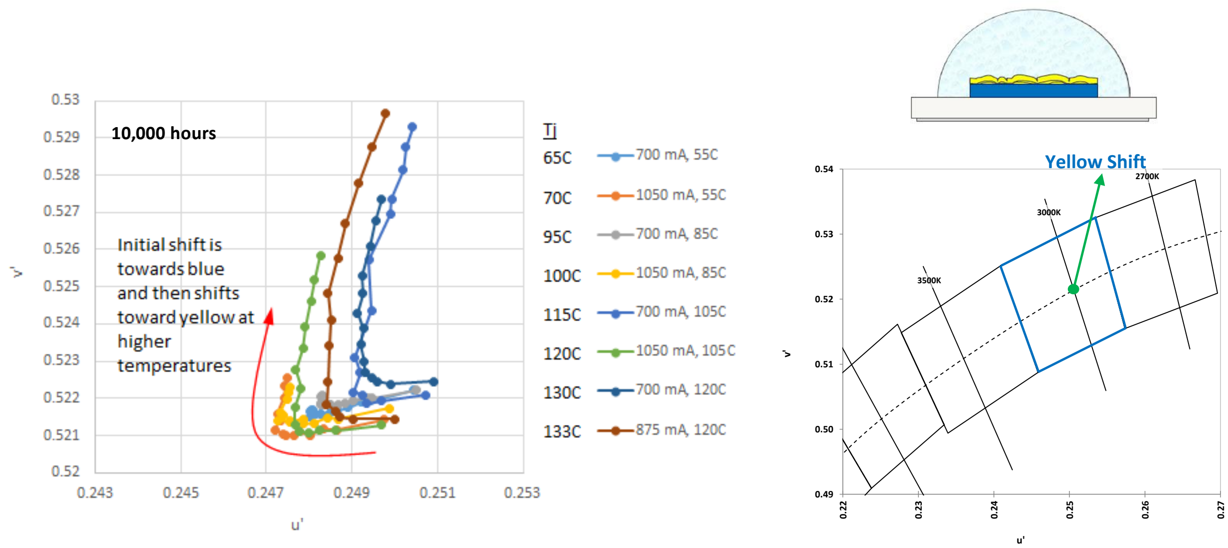


Figure 11. The chromaticity shift of a representative warm white high power package demonstrating a steady yellow shift. This yellow shift results from phosphor delamination from the chip, leading to a longer path-length through the phosphor.[7]

Mid-Power LEDs

Mid-power LED packages typically undergo a different chromaticity shift mechanism than high-power LEDs due to differences in their construction. Discoloration of the plastic resin (illustrated in Figure 12) is a dominant chromaticity shift mechanism in the mid-power LED packages. When a photon hits the reflective package sidewall, it will travel a longer path length through the phosphor matrix, resulting in a warmer color temperature compared to the photons that leave through the top surface of the LED without a sidewall reflection. As the sidewall becomes discolored, the photons creating the warmer white color component are increasingly absorbed, resulting in a blue chromaticity shift as photons taking the shorter path length (cooler white) begin to dominate. The resin discoloration not only leads to chromaticity shift, but also results in reduced lumen output due to light absorption by the sidewalls.

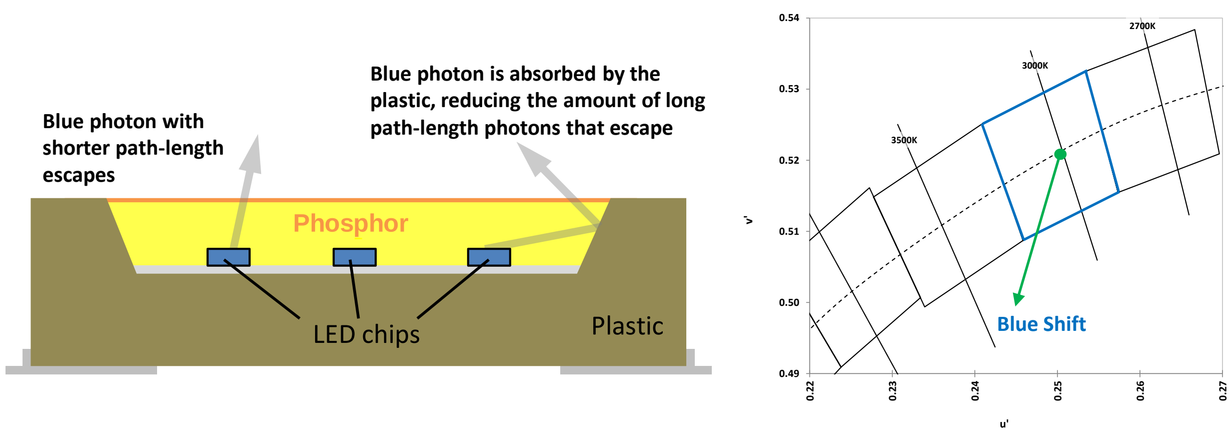


Figure 12. LED package schematics showing sidewall discoloration that absorbs long-path length blue photons resulting in an overall blue chromaticity shift.[8]

While discoloration of the plastic package is a dominant color shift mechanism in many mid-power packages, other factors can lead to color shift. Oxidation of exposed lead frames, phosphor delamination, and selective reduction of emission intensities from one component of the phosphor mix can also produce chromaticity shifts in mid-power packages.

Improved package materials can mitigate the thermal constraints and discoloration. Different types of resin, such as EMC and silicone molding compound, have an improved resistance to discoloration at higher temperatures and thus delay the onset of lumen degradation and chromaticity shift. The decay rate constants are lower for the more thermally stable plastics, as shown in Figure 13.

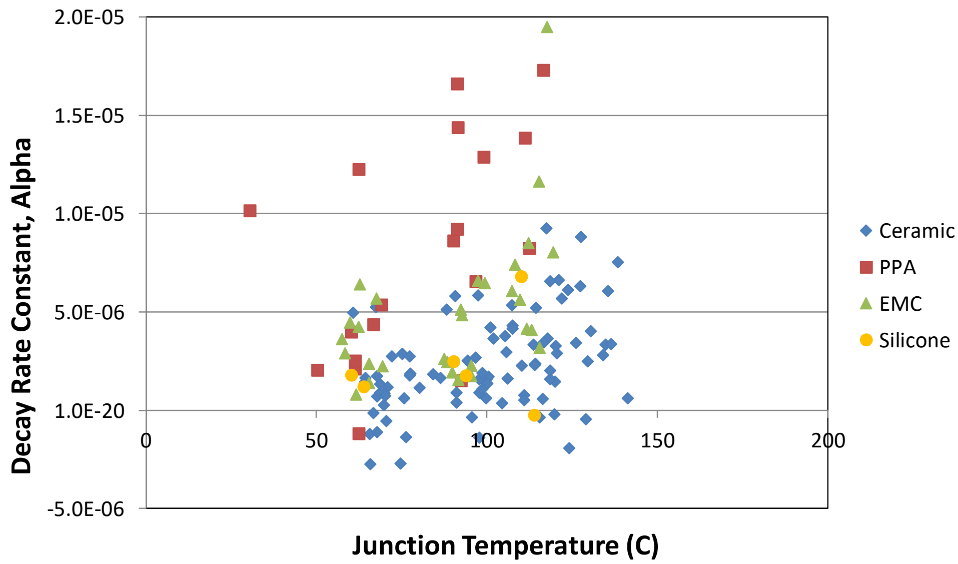


Figure 13. Decay rate constants for LED packages made with different materials of construction including mid-power packages with different resin material such as PPA, EMC and silicone molding compound. These are compared to high power ceramic-based packages.[8]

COB LEDs

The architecture of COB LEDs changes how the materials interact compared to the previously discussed high-power and mid-power LEDs. COBs do not have the strong package sidewall interaction like in mid-power LEDs, nor the heat sinking for the phosphor found in the high-power LEDs, making them a thermally constrained system. If the COB LEDs are not properly heat sunk, the light emitting surface (LES) of the LED will crack catastrophically and lead to failure.

COB LEDs show a chromaticity shift behavior that falls between the blue and green directions, but is predominately shifting green. Figure 14 shows a typical chromaticity shift of a warm white COB LED. A previous analysis of small COB LEDs in PAR38 lamps in the CALiPER Report 20.5 showed several different color shift modes depending on the COB manufacturer.[9] Some shifted blue (CSM-1), some shifted green (CSM-2) and some shifted yellow (CSM-3).

Further study on the color shift behavior of COBs is needed since evidence from the field is indicating changes in the materials properties of the silicone at the LES. Other indications are that the reflective white coating on the printed circuit board (PCB) can degrade and darken slightly, leading to higher absorption and color shift.

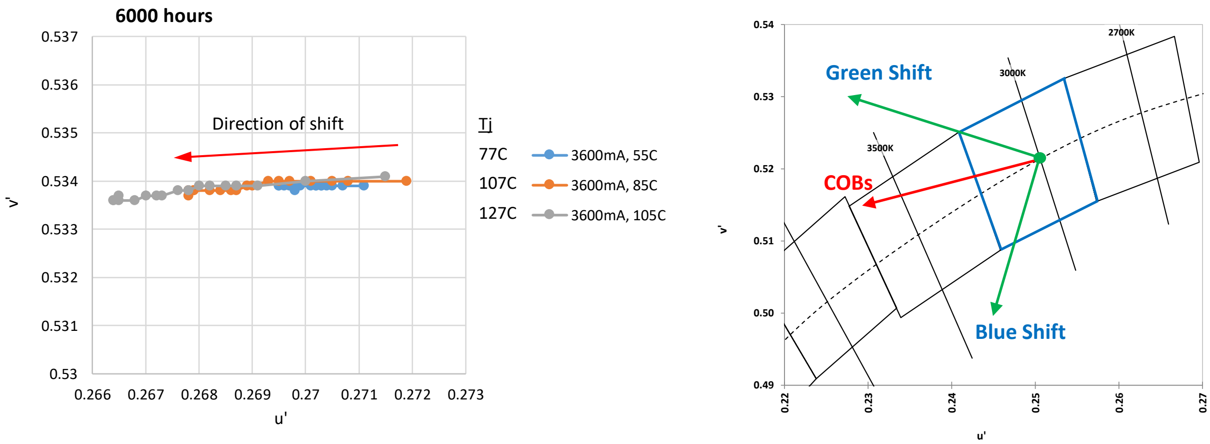


Figure 14. Example of chromaticity shift of a warm white COB LED moving in a stable fashion predominantly in the green direction.[7]

Phosphor Degradation

Experimental studies utilizing accelerated life tests (ALT) performed by RTI International have also provided insights into the impact of LED package materials on color point stability. Commercially available cool white and warm white high-power LEDs were run under wet high temperature operating life (WHTOL) testing at 75°C and 75% relative humidity (75/75). Cool white LEDs showed a lower overall chromaticity shift compared to warm white LEDs. After 3,500 hours of ALT, the cool white LEDs had a Δu'v' shift of 0.012 toward the yellow direction, whereas the warm white LEDs showed a Δu'v' shift of 0.028 towards the green direction. To understand the mechanism of these color shifts, the emission spectra were studied. The cool white LEDs showed a stable yellow peak, with a slight loss in the red wavelength region of the emission spectra.

The chromaticity shift seen in the warm white LEDs after 3,500 hours ALT is attributed to a significant change in the characteristics of the emission spectrum in the red/orange region, with the main peak shifting from approximately 610 nm to 601 nm (Figure 15). This shift in the red peak wavelength will continue to increase under more aggressive ALT conditions. After 4,000 hours of ALT at 85°C and 85% relative humidity (85/85), the peak shifted from 610 nm to 580 nm, as seen in Figure 16. The move from 75/75 to 85/85 corresponds to an acceleration factor of approximately 4X. The study concluded that the spectral shift was due to degradation of the red oxy-nitride phosphor in the presence of oxygen from the moisture present in WHTOL testing, causing the red emission wavelength peak to shift shorter. The shortened red emission ultimately caused chromaticity shift of the warm white LED emission towards the green spectral region.

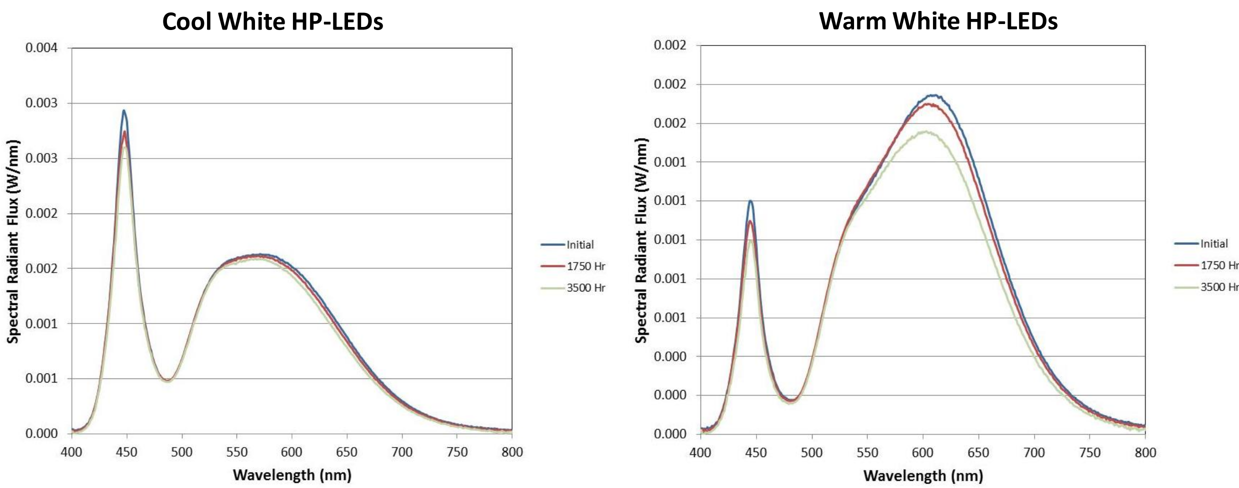


Figure 15. Accelerated testing at 75°C and 75% relative humidity for a cool white high-power LED shows a stable yellow peak from the YAG phosphor (left image). The warm white LED exhibits a shift in red phosphor wavelength from 610 nm to 601 nm after 3,500 hours for the warm white LED (right image), which results in an overall green chromaticity shift.[8]

The different phosphor materials in the LED packages can lead to different chromaticity shift mechanisms. Cool white high-power LEDs with a YAG:Ce phosphor typically exhibit a chromaticity shift towards the yellow direction due to phosphor binder delamination or cracking, which is often the result of the silicone binder degrading under heat and blue flux. Warm white high-power LEDs contain a phosphor blend, typically using a YAG:Ce yellow phosphor and a nitride red phosphor. This red phosphor is not as stable under oxidizing environments and can shift emission wavelength leading to a green shift, as illustrated in Figure 17. While the humidity in the ALT testing drove the red phosphor peak wavelength to shorter values, this chromaticity shift mechanism is also seen in LED lamps in the field.[9]

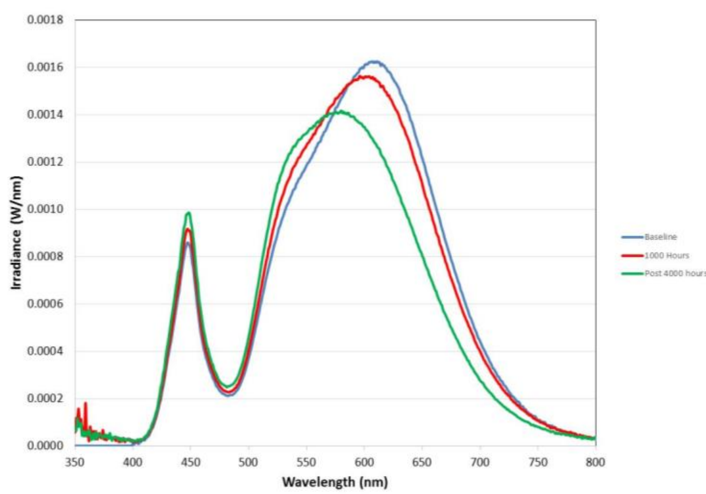


Figure 16. Under accelerated testing at 85°C and 85% relative humidity, the warm white high-power LED exhibits a larger shift in red phosphor wavelength from 610 nm to 580 nm after 4,000 hours, compared to testing at 75°C and 75% relative humidity. This results in an overall green chromaticity shift due to the red phosphor emission peak shifting.

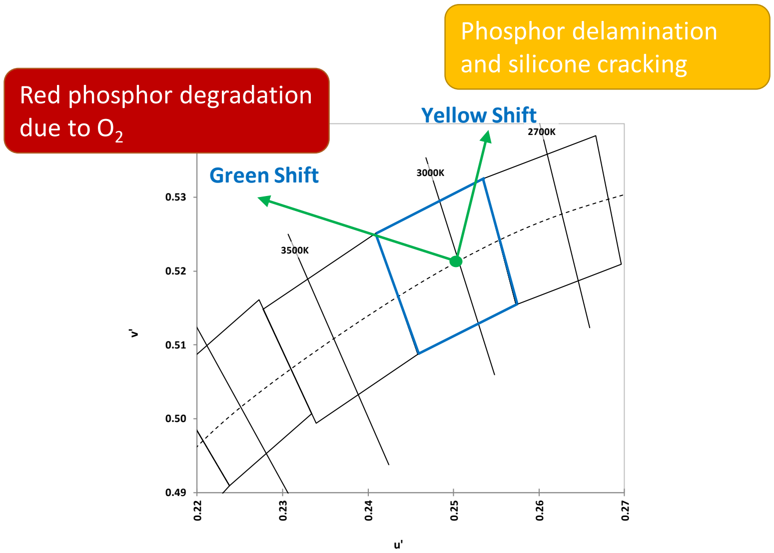


Figure 17. Chromaticity shifts and the commonly associated chromaticity shift mechanisms for the direction of chromaticity shift are displayed.[8]

Remote Phosphor LED Modules

Remote phosphor LED modules exhibit different chromaticity shift behavior compared to discrete LED packages due to their differing architecture. The major difference is that the phosphor matrix is not placed in direct contact with the LED chips, but instead located remotely from the LEDs to minimize direct heat transfer from the LED to the phosphor matrix. The remote location of the phosphor results in lower temperature rises in the phosphor layer, even at high flux levels.

A variety of materials and architectures can be realized using the remote phosphor approach, as seen in Figure 18. A common configuration of the remote phosphor approach involves coating a phosphor onto a glass or polycarbonate disk using a binder for insertion into an LED module or luminaire. Another approach is to embed the phosphor material into polymeric lenses using a molding process.

Coated Remote Phosphor Products

Molded Remote Phosphor Products

Figure 18. Examples of coated remote phosphor configurations and molded remote phosphor configurations.[12]

[12] Intematix ChromaLit product family. Available: http://www.intematix.com/products/chromalit/chromalit-specifications.

Accelerated testing of commercially available remote phosphor disks established that chemical properties of the phosphors and binder materials have a significant impact on lumen maintenance, chromaticity shift, and chromaticity stability.[13] Red nitride phosphors used in warm white LEDs can experience chromaticity point shifts due to oxidation. When this phosphor is combined with silicone binders, it will exhibit larger chromaticity shifts in WHTOL testing due to the high water permeability of silicones. The degree of chromaticity change can be mitigated to some extent by selecting less water-permeable materials, like polyurethane as the binder, though these materials can have their own optical stability issues. In addition to changes in the phosphor material or chemical changes in polymer binder, WHTOL testing can lead to increased absorption at certain wavelengths and altered index of refraction of the remote phosphor. These findings emphasize that understanding the properties of materials used in LED devices is critical to achieving high lumen maintenance and chromaticity stability over the life of the product.

Optical System Impacts

The optical system of the luminaire or lamp contain secondary lenses, diffusers, and reflective layers intended to optimize light extraction and reflections in the mixing chamber and diffuse the light pattern from the LEDs. The optical system of the luminaire or lamp can also impact the chromaticity shift beyond that in the LED package.

Optics and Diffusers

Optical materials such as polycarbonate (PC) or poly-methyl methacrylate (PMMA) are broadly used as secondary lens materials for indoor lighting applications due to their relative low cost and mature manufacturing process. Studies have been carried out to investigate the impact of thermal aging stress and blue irradiation on PC and PMMA lens materials. The observed change in lens color can lead to varying spectral power distributions thus leading to chromaticity shifts. Often, these shifts are in the yellow direction since the discoloration of the lens preferentially decreases the transmission of blue light.

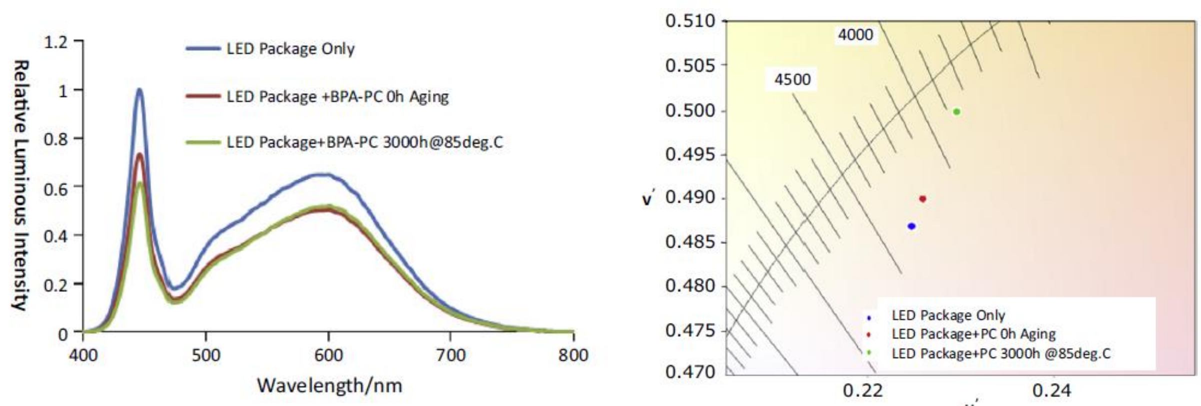
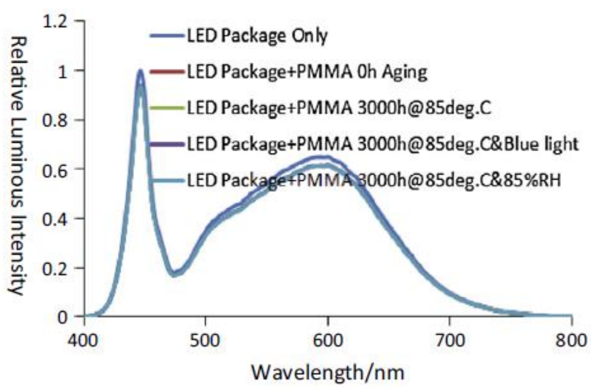


Figure 19. Spectral power distribution (left) and chromaticity diagram (right) of BPA-PC lens after 3,000 hours of aging at 85°C, exhibiting an overall chromaticity shift in the yellow direction.[14]

[13] J. Lynn Davis *et al.,* "The Influence of Phosphor and Binder Chemistry on the Aging Characteristics of Remote Phosphor Products," publication pending, *Solid State Lighting Technology and Application Series*, Springer-Verlag, New York, 2017.

BPA-PC (biphenyl A polycarbonate) is more sensitive to the exposure of temperature and blue irradiation than PMMA. In one study, BPA-PC showed a decrease in the blue spectral peak intensity while the broad yellow peak intensity remained the same after 3,000 hours exposure at 85°C (Figure 19), thus leading to a yellow-shift.[14] When PMMA was tested under similar conditions, no significant change was observed in chromaticity (Figure 20). Further studies on PMMA showed no yellowing under aging of 85°C for 5,000 hours, or with additional blue light irradiation and additional 85% relative humidity (RH) for 5,000 hours. PMMA withstood aging of 100°C for 3,000 hours as well, as seen in the lack of transmittance change in Figure 21.[15] In these experiments, the discoloration of PMMA was not observed until high temperatures (150˚C), thus demonstrating the resistance to oxidation of this material.



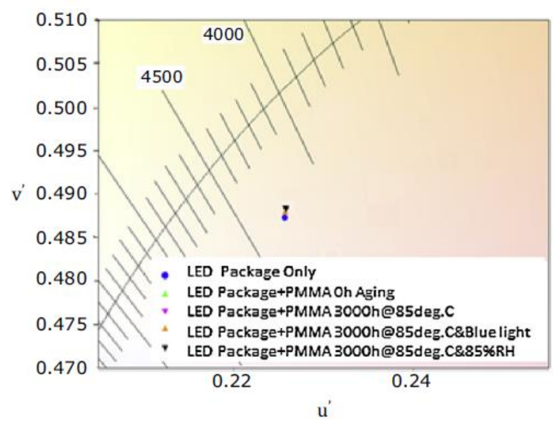


Figure 20. Spectral power distribution (left) and chromaticity diagram (right) of PMMA after 3,000 hours of aging at 85°C, showing minimal chromaticity shift.[14]

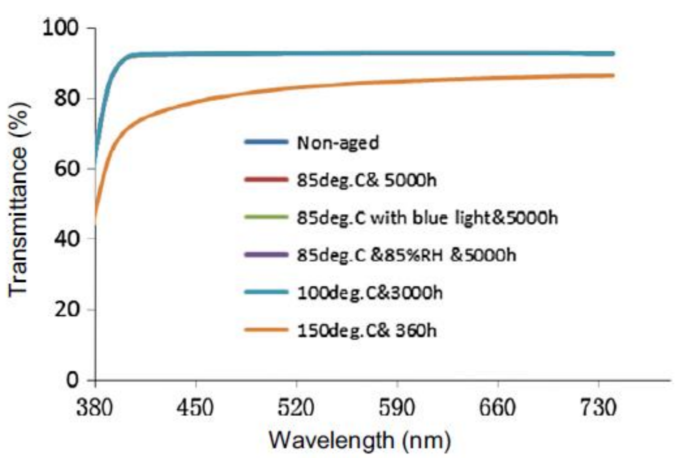


Figure 21. Transmittance behavior of PMMA as a function of wavelength under various thermal aging conditions. PMMA withstood aging of 100°C for 3,000 hours as well.[15]

[14] Guangjun Lu, *et al.,* "Color Shift Investigations for LED Secondary Optical Designs: Comparison between BPA-PC and PMMA," *Optical Materials* vol. 45, p. 37-41, 2015.

[15] Guangjun Lu, *et al.,* "Colour shift and mechanism investigation on the PMMA diffuser used in LED-based luminaires," *Optical Materials* vol. 54, p. 282-287, 2016.

Other studies have observed the same yellowing phenomena when the lens is aged as part of an entire LED system. In a CALiPER study of PAR38 lamps tested for lumen and chromaticity maintenance,[9] a discolored lens was observed upon disassembly of one of the tested lamps, as shown in Figure 22. This secondary lens was in direct contact with an LED board at the elevated temperature, which resulted in oxidation of the lens causing it to yellow. The yellowing of the secondary lens can be contributed to increasing absorbance of blue photons that then produce a shift in the blue-emission-peak shape and shift the emission peak to longer wavelengths (which can be used as an indicator of lens yellowing during use).

Figure 22. Secondary lenses taken from PAR38 LED lamps measured under accelerated testing showing the yellowing of the optic on the right after nearly 14,000 hours of testing due to excessive heat. The clear optic on the left shows the coloration after 2,000 hours of testing before the onset of yellowing.[9]

White Reflective Materials

In addition to secondary lenses and diffusers, spectrally reflective layers are included in many lamps and luminaires to reduce the absorbing surfaces around the LED board to help improve light emission from the system. White reflective materials made from microcellular PET (polyethylene terephthalate) or spun polymer microfibers composites like high density polyethylene (HDPE) embedded with reflective particles have advantages for the luminaire, including high total reflectivity across the visible spectrum, high diffuse reflectivity, and light weight.

The color shift and lumen degradation of microcellular PET (MC-PET) was investigated in a downlight luminaire configuration.[16] The white color of this material arises naturally from the microcellular structure and is not the result of added pigments. After aging for 4,000 hours at 85°C, MC-PET did not show any significant changes in reflectivity under thermal aging or later when combined with blue light irradiation, though when 85% RH was subsequently applied to the aging test, the reflectivity did drop slightly in the low wavelength regime (380-430 nm), as seen in Figure 23. The resulting chromaticity shift under thermal aging of MC-PET was minimal, though it increased a bit when aged at temperature and

[16] Guangjun Lu, *et al.,* "Degradation of Microcellular PET reflective materials used in LED-based products," *Optical Materials* vol. 49, p. 79-84, 2015.

humidity. In addition, the exposure of temperature and humidity reduced the mechanical strength of MC-PET, leading to embrittlement and fracturing during handling.

Some reflector materials use rutile pigments to achieve high reflectance across the visible spectrum. Rutile is a photocatalyst and its absorption band can overlap slightly with the low wavelength side of the main blue emission peak. Depending upon the polymer used in these materials, they may discolor due to activation of the photocatalyst by the combined influence of heat, humidity, and exposure to blue photons.

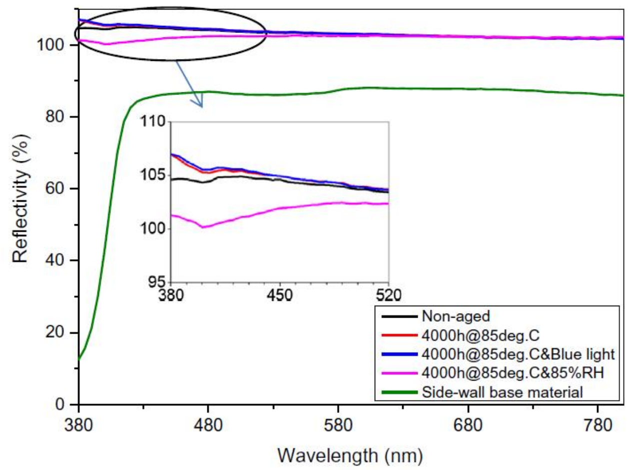


Figure 23. Reflectivity of microcellular PET after 4,000 hours testing under various aging conditions. The material maintains stable reflectivity except under aging with humidity.[16]

Summary

Chromaticity shift in LED packages is very complex, with different mechanisms at play depending on package materials and construction, but the chromaticity shift can progress in a fairly predictable pattern depending on junction temperature. The ambient temperature, optical flux density, and presence of moisture for phosphor particles, and the neighboring binder material also affect the rate of chromaticity shift. Within an LED package, the phosphor temperatures can be 30°C to 50°C above the junction temperature of the LED chip. At high temperatures and long operating times, the materials in the package can discolor, crack, or delaminate — leading to chromaticity shift and lumen depreciation. Red phosphors also can experience a decrease in peak wavelength in the presence of moisture and heat, which can impact the chromaticity of warm white LED packages.

The initial chromaticity shift in many LEDs begins in the blue direction, but then can change direction depending on the particular terminal chromaticity shift mechanism. This initial shift is likely due to changes in the LED and package materials that began during manufacturing and continue for a short time when the LED is first turned on. After this initial incubation period, the chromaticity of the LED package will usually shift according to one of four chromaticity shift modes. For high-power LEDs, often the dominant mechanism is a stable long-term chromaticity shift towards yellow due to phosphor delamination from the chip, silicone micro-cracks or yellowing, or blue LED degradation. For many mid-power LEDs, the chromaticity shift can move in the blue direction when operated at high temperatures and drive currents due to discoloration of the package resin. Shifts in the green and red directions can also occur in mid-power LEDs depending upon the specifics of the phosphor mix, the LED junction temperature, and the drive current. Improved package resin materials can delay the onset of chromaticity shift due to discoloration. COBs exhibit various chromaticity shifts with a common shift predominantly towards the green direction. The chromaticity shift behavior of COB LEDs is still under investigation for correlation to a physical mechanism. One possibility is discoloration on the white reflective layer of the PCB.

Another area of investigation for LED packages is the new chip scale package (CSP) LED platform. CSP LEDs have gained prominence recently due to their lower cost from minimizing materials and manufacturing steps, as well as their small footprint allowing for tighter packing in a luminaire. The number of CSP product offerings continues to grow, as well as the number of manufacturers offering this LED product type. CSP products are finally starting to reach the 6,000 hour test point for LM-80 reports and analysis can begin on this new LED package platform.

In addition to the chromaticity shift behavior from the LED packages, optical materials in the lamps and luminaires tend to yellow or discolor due to oxidation effects, leading to chromaticity shifts in the yellow direction.

While LED chromaticity shift does occur and can impact the performance of LED lighting products, the new understanding summarized in this paper has allowed the industry to manage the negative impact of such a shift. While LED based lighting can exhibit significantly improved color stability compared to conventional lighting products, their long lifetime requires an understanding of how color might shift over this long life. Further research is needed to develop improved predictive models that will enable manufacturers and consumers to understand the tradeoffs and make informed decisions regarding LED lighting performance requirements and product capabilities.

Path Forward

Further work is needed in understanding and projecting the chromaticity shift behavior in LED packages. A TM-31 working group is developing a standard for projecting long-term chromaticity maintenance of LED packages, possibly from LM-80-15 data. Ideally, a chromaticity shift model can be developed for different package types to determine the time to a certain chromaticity shift magnitude (e.g. 7-step MacAdam ellipse) that can be inserted in a system reliability model to predict the behavior of an LED luminaire or lamp. Beyond the efforts of the TM-31 working group, the DOE SSL program has funded R&D on this topic. RTI International has been investigating this topic by analyzing color shift data from LED packages (LM-80 reports), LED lamps (CALiPER 20.5 study), and luminaires from accelerated stress testing. Models are currently being developed and need to be tested. Further research is required to understand the different color shift mechanisms in the different luminaire subsystems and to develop accelerated testing methods and predicative models to further improve the manufacturer’s ability to bring color-stable lighting products to the customer.

List of Acronyms

HDPE	High density polyethylene
IES	Illuminating Engineering Society
LED	Light emitting diodes
LES	Light emitting surface
LSRC	LED Systems Reliability Consortium
MC-PET	Microcellular PET
NGLIA	Next Generation Lighting Industry Alliance
PAR	Parabolic aluminized reflector
PC	Polycarbonate
PET	Polyethylene terephthalate
PLCC	Plastic leaded chip carrier
PMMA	Poly-methyl methacrylate
PPA	Polyphthalamide, a thermoplastic resin
SSL	Solid-State Lighting
WHTOL	Wet high temperature operating life
YAG	Yttrium Aluminum Garnet
YAG:Ce	Yttrium Aluminum Garnet doped with Cerium