U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

CALiPER

Report 20.5:

Chromaticity Shift Modes of LED PAR38 Lamps Operated in Steady-State Conditions

February 2016

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1 Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3] Increasingly, CALiPER investigations also rely on new test procedures that are not industry standards; these experiments provide data that is essential for understanding the most current issues facing the SSL industry.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's web page at the time of purchase.

CALiPER purchases products through standard distribution channels, acting in a similar manner to a typical specifier. CALiPER does not accept or purchase samples directly from manufacturers, to ensure that all tested products are representative of a typical manufacturing run and not hand-picked for superior performance. CALiPER cannot control for the age of products in the distribution system, nor account for any differences in products that carry the same model number.

Selecting, purchasing, documenting, and testing products can take considerable time. Some products described in CALiPER reports may no longer be sold or may have been updated since the time of purchase. However, each CALiPER dataset represents a snapshot of product performance at a given time, with comparisons only between products that were available at the same time. Further, CALiPER reports seek to investigate market trends and performance relative to benchmarks, rather than as a measure of the suitability of any specific lamp model. Thus, the results should not be taken as a verdict on any product line or manufacturer. Especially given the rapid development cycle for LED products, specifiers and purchasers should always seek current information from manufacturers when evaluating products.

To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights Consortium® (DLC) Qualified Products

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[1] IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.iesna.org/.

[2] CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).

[3] CALiPER application reports are available at http://energy.gov/eere/ssl/caliper-application-reports. Detailed test reports for individual products can be obtained from http://www.ssl.energy.gov/search.html.

[4] LED Lighting Facts® is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see http://www.lightingfacts.com.

[5] ENERGY STAR is a federal program promoting energy efficiency. For more information, visit http://www.energystar.gov.

List (QPL),[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, photometric testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully. In the end, the best product is the one that best meets the needs of the specific application.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

[6] The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate-program eligibility. For more information, visit http://www.designlights.org/.

2 Outline of CALiPER Reports on PAR38 Lamps

This study is part of a series of investigations performed by the CALiPER program on LED PAR38 lamps. Each report in the series covers the performance of up to 44 LED PAR38 lamps (some tests were not performed on all of the available samples) that were purchased in 2012 or 2013. Summaries of the testing are covered in each report, as follows:

Application Summary Report 20: LED PAR38 Lamps (November 2012, addendum September 2013)[7]
A sample of 44 LED PAR38 lamps, as well as 8 halogen and 2 compact fluorescent (CFL) benchmarks, underwent photometric testing according to IES LM-79-08. CALiPER Application Summary Report 20 focuses on the basic performance characteristics of the LED lamps compared to the benchmarks, as well as performance relative to manufacturers' claims. This report follows numerous similar reports on different product types, which have been published by the CALiPER program.

Report 20.1: Subjective Evaluation of Beam Quality, Shadow Quality, and Color Quality for LED PAR38 Lamps (October 2013)[8]
This report focused on human-evaluated characteristics, including beam quality, shadow quality, and color quality. Using a questionnaire that included rank-ordering, opinions on 26 of the Report 20 PAR38 lamps were gathered during a demonstration event for members of the local IES chapter. This was not a rigorous scientific experiment, and the data should not be extrapolated beyond the scope of the demonstration. The results suggested that many of the LED products compared favorably to halogen PAR38 benchmarks in all attributes considered. LED lamps using a single-emitter design were generally preferred for their beam quality and shadow quality, and the IES members' ranking of color quality did not always match the rank-order according to the color rendering index (CRI).

Report 20.2: Dimming, Flicker, and Power Quality Characteristics of LED PAR38 Lamps (March 2014)[9]
This report focused on the flicker and power quality performance of the Series 20 lamps at full output and various dimmed levels. All of the Series 20 PAR38 lamps that manufacturers claimed to be dimmable (including all halogen lamps) were evaluated individually (one lamp at a time), both on a switch and under the control of a phase-cut dimmer designed for use with "all classes of bulbs." Measurements of luminous flux, flicker, and power quality were taken at 10 target dimmed settings and compared with operation on a switch.

The dimmed performance of many LED lamps is dependent on the phase-cut dimmer used and the number of lamps that are connected to the dimmed circuit. Some manufacturers recommend specific dimmers that work better with their product(s), as well as the minimum and maximum number of dimmers per circuit. Because only a single unit of each product was evaluated on a single dimmer make and model, which may or may not have been recommended by its manufacturer, Report 20.2 focused on the performance of the products relative to each other, rather than on the best-case performance of each lamp or variation in performance delivered from each lamp. Despite these limitations, the results suggest that LED performance is improving, and performance trends are beginning to emerge, perhaps due in part to the identification of preferred LED driver strategies for lamp products.

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[7] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20_summary.pdf
[8] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20.1_par38.pdf
[9] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20-2_par38.pdf

Report 20.3: Robustness of LED PAR38 Lamps (December 2014)[10]
Most of the Series 20 PAR38 lamps underwent multi-stress testing, whereby samples were subjected to increasing levels of simultaneous thermal, electrical, and mechanical stress. The results do not directly yield expected lifetime or reliability performance, but the LED products can be compared with one another, as well as with benchmark conventional products, to assess the relative robustness of the product designs.

The results showed that there is great variability in the robustness and design maturity of LED lamps. Nonetheless, the LED lamps were generally more robust than the benchmark PAR38 lamps, with a couple of exceptions. More than 25% of the lamps were prone to early failure, indicating that the designs and manufacturing could still be improved.

Almost all of the lamps that failed did so catastrophically rather than parametrically. That is, the lamps stopped working before their lumen output or chromaticity reached unacceptable levels—L_{70} or a Δu'v' of 0.007, respectively. Although a precise failure analysis examining each failed lamp's components was not conducted, this breakdown of failure modes helps to identify areas of weakness for the lamps. In this case, the electronics tended to fail before performance of the LED packages or optical systems degraded, with a few exceptions.

Report 20.4: Lumen and Chromaticity Maintenance of LED PAR38 Lamps (December 2014)[11]
The lumen depreciation and chromaticity shift of 38 different lamps (32 LED, 2 CFL, 1 ceramic metal halide [CMH], 3 halogen) were monitored in a specially developed automated long-term test apparatus (ALTA2) for nearly 14,000 hours. Five samples of each lamp model were tested, with measurements recorded on a weekly basis. The lamps were operated continuously at a target ambient temperature between 44°C and 45°C.

On average, the lumen maintenance of the LED lamps monitored in the ALTA2 was substantially better than the average for the other lamp technologies. After nearly 14,000 hours, the average lumen output for the non-catastrophically failed LED lamps was 94%. In contrast, the CFLs were at 68% and the CMH lamps were at 62%. The halogen lamps typically reached about 80% of the initial output before failing.

While the average lumen maintenance for the LED lamps was very good, there was considerable variation from lamp model to lamp model. At the end of the test period, some lamp models had an average lumen output greater than the initial average, whereas two lamp models had an average output less than 80% of the initial. All but three of the LED lamp models had average relative output between 87% and 101% (only including operating lamps). As with lumen maintenance, on average the LED lamps exhibited superior chromaticity maintenance compared to the conventional benchmark lamps—including the halogen lamps. However, the average Δu'v' of two of the LED lamp models exceeded the ENERGY STAR limit of 0.007 (which is used as a basis of comparison in this report) and would likely be problematic in an application where color stability is important.

Report 20.5: Chromaticity Shift Modes of LED PAR38 Lamps Operated in Steady-State Conditions (February 2016)
This report examines the same LED lamp models covered in CALiPER Report 20.4 but focuses more on the chromaticity maintenance of individual samples rather than the lamp model averages that were emphasized in CALiPER 20.4. This approach was taken to facilitate a classification of the chromaticity-shift modes (CSM) for each sample and a comparison of CSMs across all samples of a particular lamp model and between lamp models with similar characteristics. In general, samples of the same PAR38 lamp model usually exhibited the same

[10] Available at: http://energy.gov/eere/ssl/downloads/report-203-stress-testing-led-par38-lamps
[11] Available at: http://energy.gov/sites/prod/files/2015/02/f19/caliper_20-4_par38_0.pdf

chromaticity-shift behavior, and there were similarities in chromaticity-shift trends between lamp models with similar LED packages. However, the timing of different chromaticity shifts varied somewhat between lamp models and appeared to depend upon lamp design, characteristics of the LED packages used in the lamp model, and lamp operational conditions.

As part of this evaluation, a tear-down analysis was completed on each lamp model, and potentially critical design and operational parameters, such as LED type, LED board temperature, secondary lens structure, and the presence or absence of reflectors, were recorded. PAR38 lamps are relatively simple LED lighting devices that consist primarily of LEDs and a secondary lens. Consequently, the characteristics of the LED packages dominate the lumen and chromaticity maintenance mechanisms of these products

The CSMs of the LED PAR38 lamp models can be classified by the direction of the chromaticity shift. Changes along the blue-yellow line, which connects the chromaticity points of the blue (die) and yellow (phosphor) emitters, involve alteration of the balance of the emissions. Such changes can be attributed to several mechanisms, including a reduction in quantum efficiency of phosphor, changes in the blue photon path through the phosphor layer, and materials degradation. In contrast, shifts in the green or red directions are caused by changes in the emission maximum characteristics of either the phosphor or the die. For example, oxidation of warm-white phosphors will produce a green chromaticity shift.

The PAR38 lamp models examined in this study exhibited a systematic chronology in the chromaticity shift that depended on LED package type and operational conditions, such as LED board temperature and drive current. Nearly all samples in this study were found to initially shift in the blue direction, with $\Delta u'v'$ values of 0.003 or less. After the initial blue chromaticity shift, four primary CSMs were identified that appeared in a sequential fashion depending on design and operational conditions: continued blue shift (CSM-1), green shift (CSM-2), yellow shift (CSM-3), or a complex shift consisting of a yellow shift followed by a blue shift.

3 Introduction

CALiPER Report 20.4, *Lumen and Chromaticity Maintenance of LED PAR38 Lamps*, documented the long-term performance of 32 of the Series 20 LED PAR38 lamps. Specifically, it focused on average chromaticity maintenance, lumen maintenance, and catastrophic failures of the 32 LED lamp models. This report builds on CALiPER Report 20.4 by providing a tear-down analysis of the 32 LED PAR38 lamp models and also performing additional analyses on the spectroradiometric data obtained using the ALTA. The focus of this new report is to investigate causes of chromaticity shift and parametric failures within these lamps.

The 32 LED lamps examined in this study were simultaneously operated for approximately 14,000 hours in the ALTA2, and these LED lamps are identified in **Appendix A**. For a complete description of the apparatus and measurement sequence, see CALiPER 20.4. The data from the earlier analysis is further examined in this report, and additional analyses performed. No additional studies were performed on the benchmark CFLs from CALiPER Report 20.4. The additional analysis provided in this report focuses on two key areas: chromaticity shift and physical degradation of failed lamps.

This report builds on the findings in CALiPER report 20.4 by focusing on the causes of chromaticity shift in the LED PAR38 lamps. In addition, **Appendix B** provides detailed data on the chromaticity-shift performance of each sample, including pictures of each lamp model, measurements of LED board temperatures, and chromaticity changes for each sample. The goals of this report are to examine the causes of parametric failure in these lamp models and to provide insights into the performance and limitations of LED lighting lamp models.

Physical Characteristics of LED PAR38 Lamps

PAR38 lamps project light in the forward direction, as do LEDs, and hence take advantage of the intrinsic forward emission pattern of white-light-emitting LEDs. Consequently, the optical design of LED PAR38 lamps is relatively straightforward, and a secondary lens is often the only optical element needed in the device to achieve the desired light level and beam pattern. As a result, analysis on PAR38 lamps primarily provides insights in changes occurring at the LED level during aging. In contrast, other SSL devices, such as A Lamps and luminaires, often use a more complex optical structure consisting of reflectors and diffusers to achieve a broader light beam pattern, and analysis of these LED models is more complex.

Examples of designs of some of the PAR38 lamps examined in this study are shown in **Figures 1–3**. The most common design was LEDs fitted with a molded, one-piece secondary optic; 25 out of 32 lamp models tested

Individual Secondary Lenses

Figure 1. An example of an LED PAR38 lamp using individual secondary lenses.

One-Piece Secondary Lenses

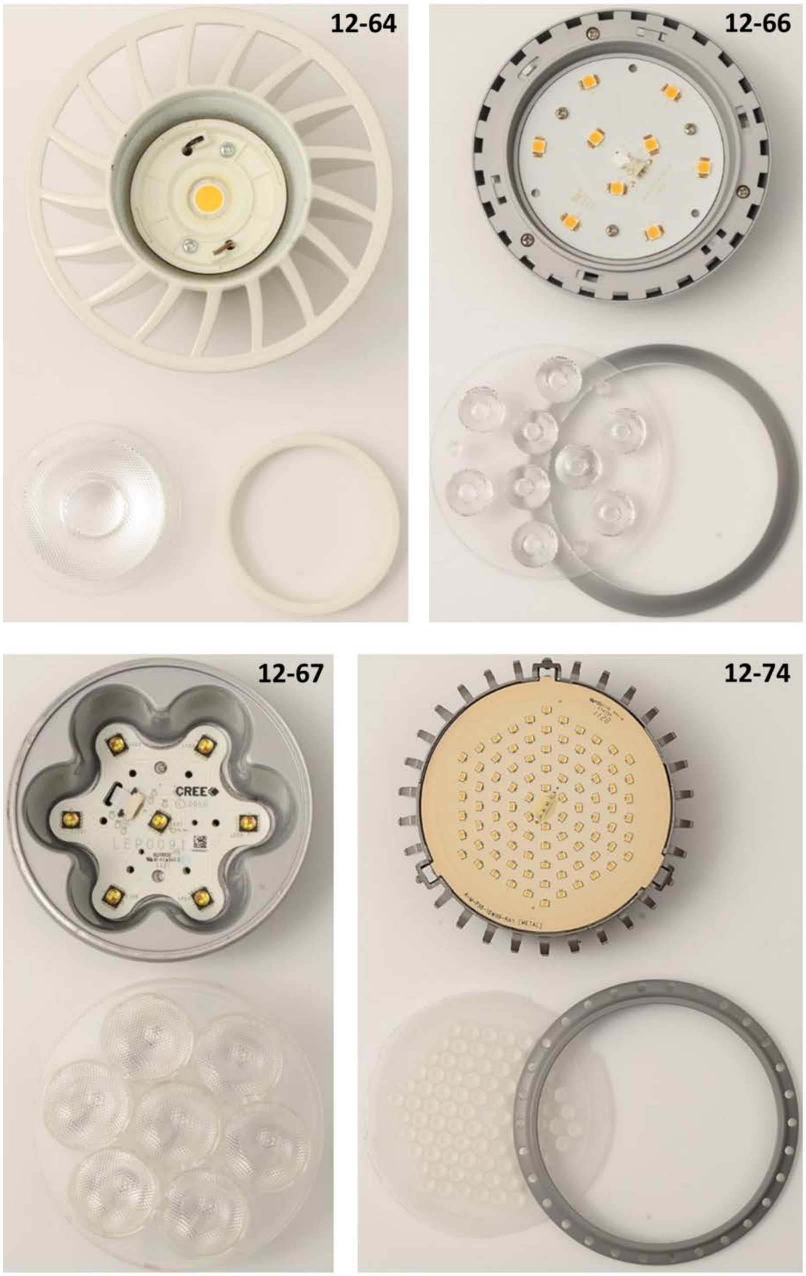


Figure 2.
Four examples of LED PAR38 lamps using one-piece secondary lenses.

were of this type. A derivative of this approach is to use individual molded lenses for each LED, with a retaining ring holding the lenses in place. Three tested lamp models (12-89, 12-100, and 12-148) were of this type. In most cases, the secondary lens changed little during the tests, suggesting that the behavior of the LEDs dominated the observed lumen and chromaticity maintenance behavior. There was one notable exception, however; lamp model 12-96 demonstrated a yellowing of the secondary optic (see **Appendix B**), and the impact of this change in lens transmittance on chromaticity will be discussed in detail.

While all of the lamps used a secondary lens, only six products (12-75, 12-89, 12-90, 12-100, 12-135, 12-144) utilized a design that required a significant amount of light reflection prior to exiting the lamp. The reflectors that are used in these lamp models included molded white polymer cones (12-89 and 12-100), metallized plastic cones (12-75), and formed aluminum (12-90, 12-135, and 12-144). In addition, lamp models 12-135 and 12-144

Reflector & Secondary Optic

Figure 3. Three examples of LED PAR38 lamps using a reflector and secondary optic.

used a design that mimicked the traditional PAR lamp structure with a metal housing as the reflector and a glass lens as the secondary optic, with the LEDs at the base of a large reflector cavity. These lamp models also differed in that 12-144 had an additional secondary optic over the LEDs, whereas lamp model 12-135 did not. Lamp models that utilized reflectors as part of the optical design experienced minimal reflector degradation during the measurement period, further supporting the hypothesis that LED behavior is the dominant influence on lumen and chromaticity maintenance in PAR38 lamps.

LED Packages Used in PAR38 Lamps

Nearly all of the LED PAR38 lamps examined in this study utilized phosphor-converted LEDs (pcLEDs) to generate white light. Representative light engines (including LEDs) from the products examined in this study are shown in **Figure 4,** and a breakout of the number of products with the different LED package types is given in **Table 1**. The LEDs can be classified into four main groups, based on packaging materials and LED structure:

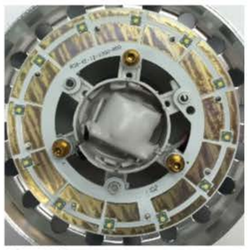
- High-powered LEDs (HP LEDs), consisting of a single die, usually mounted on a ceramic chip carrier. The power consumption of HP LEDs is > 1 W. The number of HP LED packages in each product examined in this report varied between 6 and 13.
- Plastic leaded chip carriers (PLCC), consisting of at least one die contained at the bottom of a molded plastic well. The power levels for PLCC packages varied from < 0.5 W for mid-powered LEDs (MP LEDs) to > 1 W for multi-chip PLCCs. The number of PLCC packages in the samples examined in this report varied between 7 and 90, with the lower number of packages indicative of larger die and possibly a multi-die molded package, while a higher (> 20) number of packages is indicative of the use of lower luminous flux, mid-power LED packages.
- Chip-on-board (COB) LEDs, consisting of multiple small die mounted on a common substrate that is either ceramic or a metal-core printed circuit board (PCB). In all of the samples tested in this study, there is only one COB LED package per lamp.
- Hybrid LED array, consisting of greenish pcLEDs and a red direct-emitting LED in the same package. Only one tested lamp model in this analysis used a hybrid LED array configuration, and this light engine consisted of seven LED packages with four LEDs (i.e., three yellow-green and one red direct emitter) in each package.

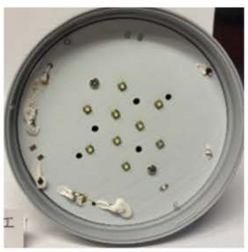
Table 1. Count of the package types used in the LED PAR38 lamps examined in this report.

Package Type	Number of Products
HP LED	18
COB	7
PLCC	6
Hybrid LED	1

HP LED Packages

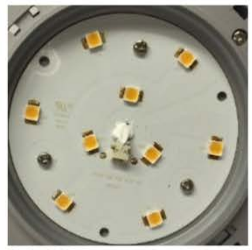

12-78

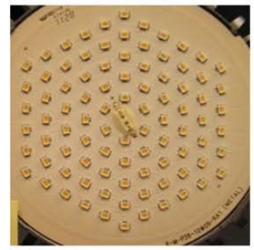

12-82


12-86


12-89

PLCC LED Packages


12-66


12-74


12-80


12-147

COB LED Packages


12-64


12-79


12-81


12-85

Hybrid LED Packages

12-67

Figure 4. Examples of the package types used in the LED PAR38 lamps examined in this report.

Representations of Chromaticity and Chromaticity Shift

Chromaticity of light sources can be expressed as coordinates in one of several different diagrams developed by the Commission Internationale de l'Eclairage (CIE); full details on the different CIE chromaticity diagrams can be found elsewhere.[12] In this report, chromaticity is plotted using the CIE 1976 chromaticity diagram (u', v'). The u' and v' chromaticity coordinates used in the CIE 1976 chromaticity diagram can be calculated directly from the spectral radiant flux (i.e., the spectral power distribution [SPD]) of a light source. Although they are a distillation of more complex spectral information, chromaticity coordinates provide a convenient means to represent spectral changes over time.

The CIE 1976 chromaticity diagram was developed to provide a more uniform representation of chromaticity differences compared to older schemes; that is, numerical differences are more similar to perceptual differences. This makes it better suited for calculating chromaticity shift. The magnitude of measured chromaticity shift, $\Delta u'v'$, can be calculated as the geometric distance from one chromaticity point (u'_i, v'_i) to a subsequent chromaticity value (u', v') as shown in **Equation 1**. It is important to note that $\Delta u'v'$ provides the magnitude of the chromaticity shift but not the direction. The direction of shift must be determined from other photometric and radiometric parameters, such as the chromaticity coordinates, other metrics such as ΔCCT and ΔD_{uv}, or the spectral data.

$$\Delta u'v' = \sqrt{(u' - u'_i)^2 + (v' - v'_i)^2} \qquad \textbf{(Equation 1)}$$

There are no standards that establish an unacceptable chromaticity shift for LEDs or any other type of light source; unlike L_{70} for lumen maintenance, there is no value of $\Delta u'v'$ that IES suggests constitutes a parametric failure. In the analysis described in CALiPER Report 20.4, the lamps were evaluated in the context of the ENERGY STAR criterion, which is a $\Delta u'v'$ of 0.007. Importantly, this level of difference is readily noticeable in many interior lighting settings, if two lamps with that level of difference are viewed simultaneously. If all the lamps in a room undergo a change of that magnitude—and in the same direction—over the course of several years, the occupants may not detect that the lighting has changed, at least not until one or more of the lamps is replaced. In the information given in CALiPER 20.4, there were 13 individual samples out of the LED test population of 160 LED lamps that were considered to be parametric failures, with $\Delta u'v'$ exceeding 0.007.

Chromaticity Shift Modes (CSM) in LED PAR38 Lamps

White light is made from pcLEDs by combining a blue LED and a yellow phosphor, such as Ce:YAG.[13] Using the CIE 1976 chromaticity diagram, **Figure 5** demonstrates that if a blue emitter (i.e., the LED) and a yellow emitter (i.e., the phosphor) are combined, any chromaticity value lying along the line connecting those two emission points can be achieved simply by varying the relative contributions of blue and yellow emissions. Due to the intrinsic importance of the line connecting the blue LED emission point and the phosphor emission point in understanding chromaticity shift, this line will be referred to as the blue-yellow line throughout this report.

In order for the chromaticity to shift away from the blue-yellow line, the peak wavelength of at least one of the emitters (i.e., blue LED and phosphor) has to shift. Therefore, the potential chromaticity-shift directions of a light source with chromaticity given by the white dot in **Figure 5** can be characterized as follows:

[12] See DOE Solid-State Lighting Technology Fact Sheets on "LED Color Characteristics" (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-color-characteristics-factsheet.pdf) and "LED Color Stability" (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/color-shift_fact-sheet.pdf).

[13] For more information on generating white light with LEDs see the DOE Solid-State Lighting Technology Fact Sheet on "LED Color Characteristics"(http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-color-characteristics-factsheet.pdf).

- Blue shift may result from an increase in blue emission or a decrease in yellow emission. This chromaticity change produces a decrease in both *u*' and *v*' (see **Figure 5**).
- Yellow shift may result from an increase in yellow emission or a decrease in blue emission. This chromaticity change produces an increase in both *u*' and *v*' (see **Figure 4**).
- Green shift occurs when the chromaticity moves off of the blue-yellow line and proceeds toward the green direction. A green shift is indicative of a change in the emission properties of either the blue or yellow emitter. This chromaticity change produces a decrease in *u*' and a minimal change, and possibly an increase in some cases, in *v*' (see **Figure 5**).
- Red shift occurs when the chromaticity moves off of the blue-yellow line and proceeds toward the red direction. A red shift is indicative of a change in the emission properties of either the blue or yellow emitter. This chromaticity change produces an increase in *u*' and a minimal change in *v*' (see **Figure 5**).

There are multiple causes for chromaticity shift in lamps and luminaires, and a summary of common chromaticity-shift causes is provided in **Table 2**. This list is not intended to be exhaustive, but is representative of the most common chromaticity-shift mechanisms. For the PAR38 lamps examined in this analysis, the chromaticity shift is dominated by the characteristics of the LED, since the optical materials changed little in most samples.

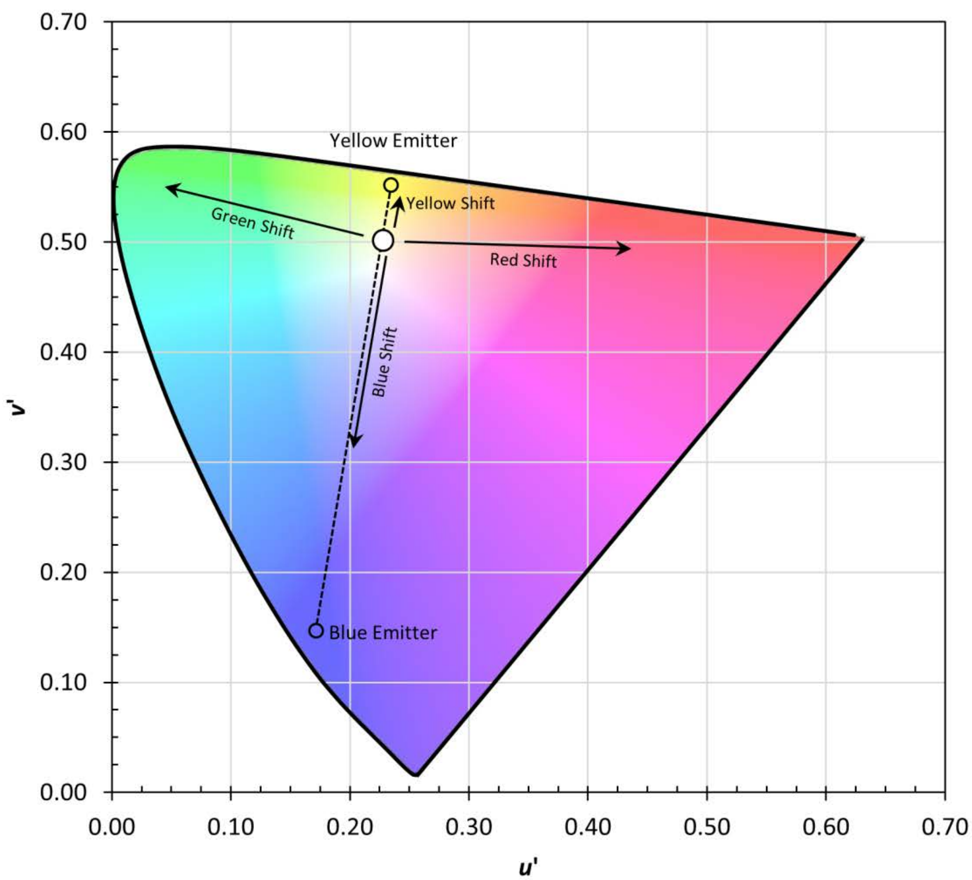


Figure 5. CIE 1976 chromaticity diagram (*u*', *v*') showing a hypothetical chromaticity point (white circle) and the directions of chromaticity change for blue, yellow, green, and red shifts. A blue and yellow emitter can be mixed to any point in between the chromaticity of the two components (i.e., the dashed blue-yellow line). The colored background is shown for orientation purposes only.

Table 2. Potential chromaticity-shift mechanisms in LED lamps and luminaires.

Shift Direction	Cause
Blue shift	Loss of phosphor quantum efficiency due to chemical change or temperature effects
	Oxidation of the molding compound in PLCC[a]
	Operating the phosphor above the saturation flux level
	Settling and precipitation of the phosphor[b]
	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[c]
	Discoloration/oxidation of the lenses[d]
	Discoloration of the reflector[d]
Green shift	Oxidation of phosphor[d]
Red shift	Shift in emission properties of direct red emitter[d]

a. Ralph Tuttle and Mark McClear, "Understanding the true cost of LED choices in SSL systems, LEDS Magazine, February 2014, p. 43.
b. M. Royer, R. Tuttle, S. Rosenfeld, and N. Miller, "Color maintenance of LEDs in laboratory and field applications," DOE Gateway Report, September 2013. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_color-maintenance.pdf accessed November 28, 2015).
c. Michael Royer, Chad Stalker, and Ralph Tuttle, "LED Color Stability: 10 Important Questions," DOE Webinar, April 15, 2014. Available at http://energy.gov/eere/ssl/led-color-stability-10-important-questions.
d. J. Lynn Davis et al., "System reliability for LED-based products," 2014 15th International Conference on thermal, mechanical, and multi-physics simulation and experiments in microelectronics and microsystems (EuroSimE), p. 1.

4 Analysis

CALiPER Report 20.4 provided an analysis of the average lumen maintenance and chromaticity stability for the 32 different LED PAR38 lamp models; the present report focuses on measured chromaticity instead of $\Delta u'v'$, with greater emphasis on individual lamp samples rather than per-model averages. While many of these products exhibited excellent chromaticity and lumen maintenance, there were some that did not. In evaluating the lumen and chromaticity maintenance of these lamps, it is important to remember that these products were manufactured in the 2011–2012 timeframe.[14] More recent products are likely to have improved performance, because the knowledge of SSL technologies has increased significantly in the past four years.

Even though these lamps are older examples of SSL technology, outstanding performance was still observed for many of the products. CALiPER Report 20.4 stated:

> *"The lumen maintenance of the LED lamps monitored in the ALTA2 was substantially better than the average for the other lamp technologies. After nearly 14,000 hours, the average lumen output for the non-catastrophically failed LED lamps was 94%. In contrast, the CFLs were at 68% and the CMH lamps were at 62%. The halogen lamps typically reached about 80% of the initial output before failing.*
>
> *While the average lumen maintenance for the LED lamps was very good, there was considerable variation from lamp model to lamp model. At the end of the test period, some lamp models had an average lumen output greater than the initial average, whereas two lamp models had an average output less than 80% of the initial."*

CALiPER Report 20.4 examined the chromaticity maintenance of the lamp models both as the average performance for each lamp model, and somewhat on the behavior of individual samples. The ENERGY STAR chromaticity shift requirement of $\Delta u'v' \leq 0.007$ was used; samples exceeding that criterion were considered to be parametric failures. While there is no accepted standard for allowable chromaticity shift, and the level of tolerable chromaticity shift can be strongly application-dependent, the $\Delta u'v' \leq 0.007$ criterion provides a reasonable approach to evaluating chromaticity maintenance in these samples. Some key findings captured in CALiPER Report 20.4:

- Figure 8 in CALiPER Report 20.4 demonstrated that the average chromaticity maintenance of the LED PAR38 lamps was significantly better than for lamps using other lighting technologies (i.e., CFL, CMH, and halogen).
- Figure 9 in CALiPER Report 20.4 demonstrated that the average chromaticity shift of the LED PAR38 lamps was typically less than 0.006 during the test period, although two lamp models (12-74 and 12-85) displayed average chromaticity shift values exceeding 0.007.
- Figure 11 in CALiPER Report 20.4 demonstrated that three lamp models (12-73, 12-89, and 12-145) exhibited a large range in the chromaticity shift between individual samples in the test population.

CALiPER Report 20.4 also provided a measure of the parametric failure rates of the LED PAR38 lamps under the test conditions (i.e., constant operation at an ambient temperature of 45°C) for the period of time that the test was performed (i.e., 13,925 hours). There were a total of 13 parametric failures for excessive chromaticity shift (i.e., $\Delta u'v' > 0.007$). These failures occurred in 5 of the 32 lamp models examined, as reported in **Table 3**. All parametric failures were from excessive chromaticity shifts, and none were for lumen maintenance.

[14] Date of manufacture was determined based on LED board codes found during the tear-down analysis of each LED PAR38 model.

Table 3. **Number of parametric failures, time to failure, and final Δu'v' value for the LED PAR38 lamp samples that exhibited parametric chromaticity shift.**

ID	No. of Failures	Time of Parametric Failure (hours)	Final Δu'v' Value[a]	Final Chromaticity Shift Direction
12-73	1	4,686	0.0147	Yellow
12-74	5	10,255; 11,910; 11,574; 12,246; 12,246	0.0126; 0.0090; 0.0094; 0.0087; 0.0088	Blue (All)
12-85	5	4,857; 5,194; 5,694; 6,032; 5,866	0.0156; 0.0165; 0.0146; 0.0149; 0.0142	Yellow (All)
12-89	1	8,380	0.0114	Yellow
12-145	1	5,865	0.0171	Yellow

a. The lamps continued to operate after exceeding the parametric failure threshold. The final Δu'v' value is the measured chromaticity shift at the end of the test (i.e., 13,925 hours).

Chromaticity Shift Behavior of LED PAR38 Lamps

An examination of the chromaticity coordinates of the 32 LED PAR38 lamp models examined in CALiPER 20.4 revealed that the initial direction of the chromaticity shift in all instances was in the blue direction. Since a blue shift is characterized by a decrease in both *u*' and *v*', the duration of this initial blue shift can be followed by examining the chromaticity coordinates. In this analysis, the average data for all 32 lamp models was examined for the time when *u*' and *v*' first began to increase. For the purposes of this analysis, changes in *u*' and *v*' were examined separately, and either chromaticity coordinate was deemed to be increasing when two consecutive readings showed a higher value. These changes were often small (i.e., Δu' or Δv' < 0.0001), which is why consecutive readings were used to confirm that a change in chromaticity shift was beginning. The findings from this analysis are shown in **Figure 6**.

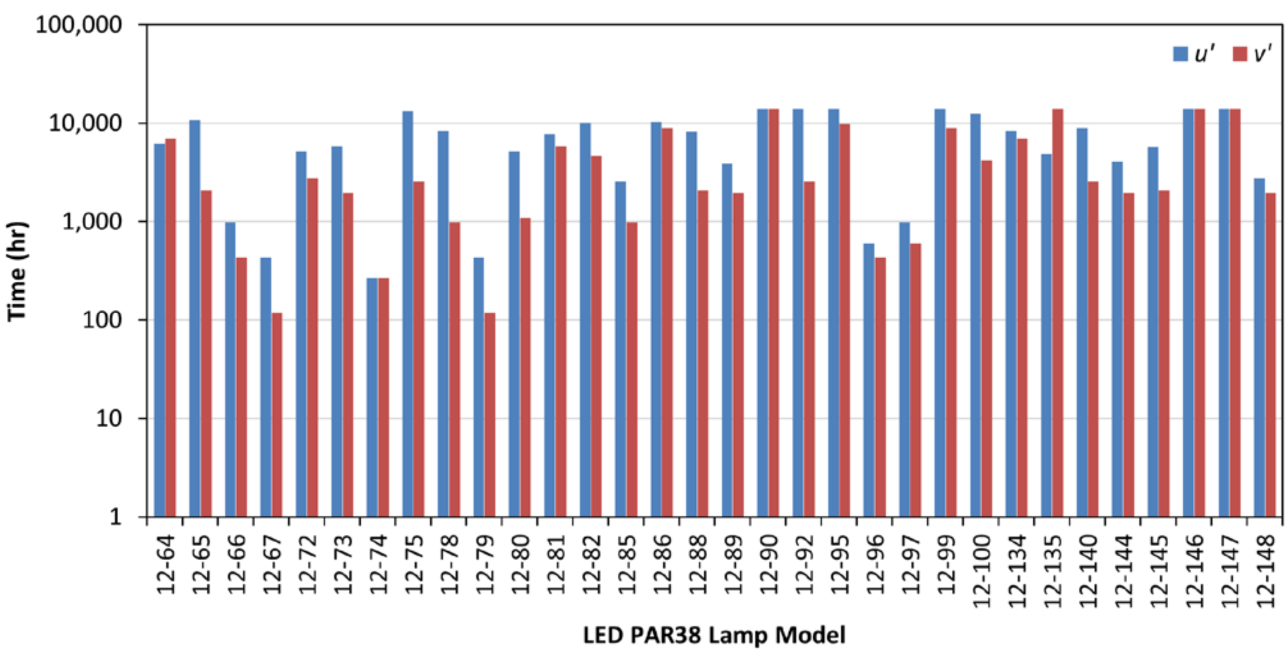


Figure 6. **Time required for *u*' and *v*' chromaticity coordinates of the 32 LED lamp models studied in CALiPER 20.4 to show an increase. The initial chromaticity shifts for the LED lamp models examined in this study were always in the blue direction (i.e., both *u*' and *v*' decrease), but increases in both *u*' and *v*' eventually occurred.**

This data demonstrates that all lamp models examined in this study exhibited a blue shift when first turned on, but the duration varied between 100 hours (LED lamp model 12-79) and greater than the 13,925 hours of the test (LED lamp model 12-90). The magnitude of the initial blue shift was small in all cases and typically produced a chromaticity change (Δu'v') of less than 0.003. The *v*' chromaticity coordinate generally began to increase before the *u*' coordinate, suggesting that the end of the initial blue chromaticity shift can be signaled by *v*'.

Following the initial blue chromaticity shift, four different chromaticity-shift modes were found in the LED PAR38 lamp models:

- Chromaticity Shift Mode 1 (CSM-1): Continuation of the chromaticity shift in the blue direction.
- Chromaticity Shift Mode 2 (CSM-2): Shift in the blue and green directions.
- Chromaticity Shift Mode 3 (CSM-3): Shift in the yellow direction.
- Chromaticity Shift Mode 4 (CSM-4): A complex shift consisting of a shift in the yellow direction followed by a second blue shift.

Chromaticity Characteristics of CSM-1

Three out of 32 LED PAR38 lamp models (12-64, 12-86, and 12-90) exhibited CSM-1 behavior during the test period, or a continual shift in the blue direction relative to the initial starting point. As shown in **Figure 7**, the

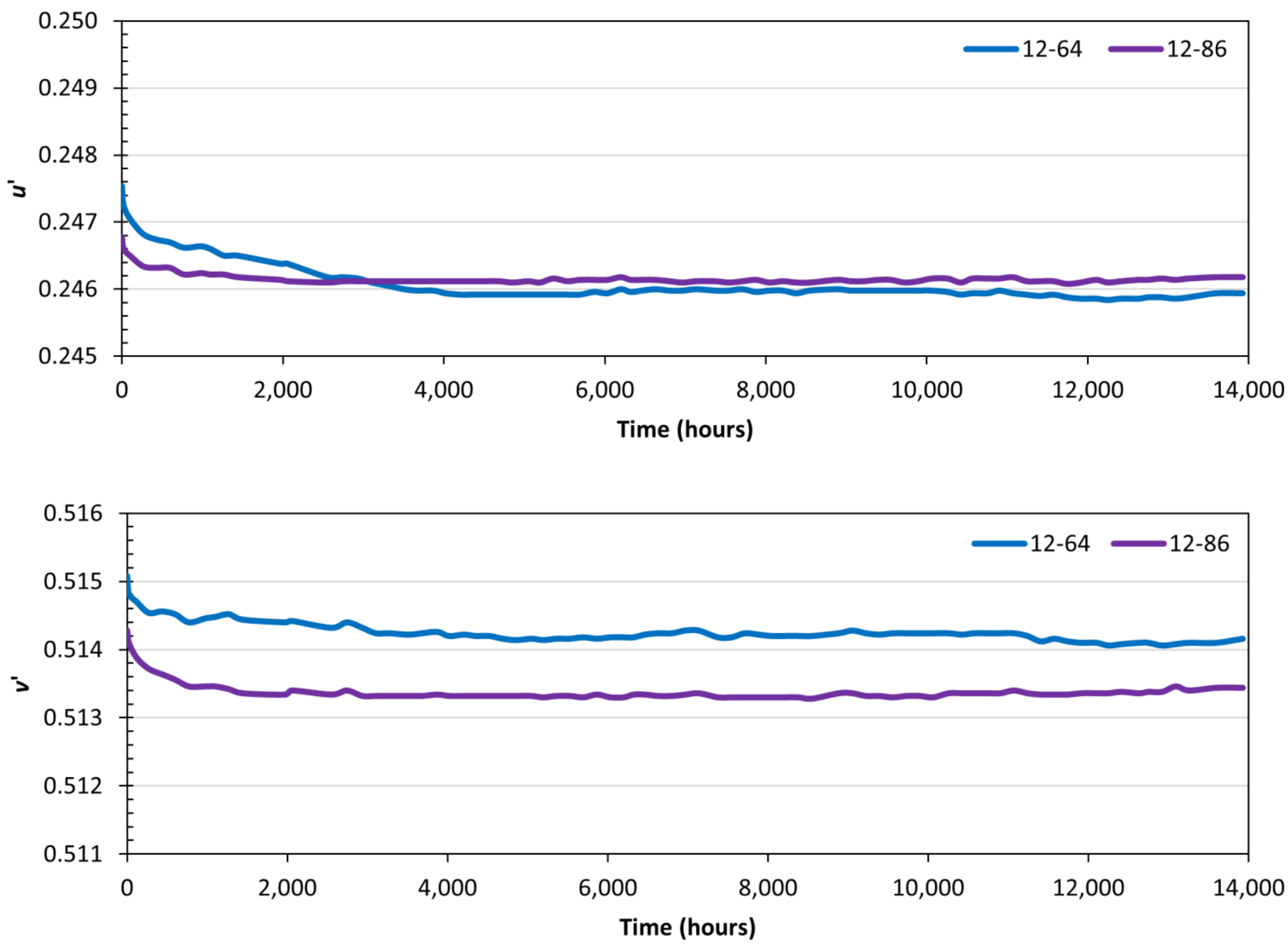


Figure 7. Time-based change in average *u*' and *v*' values for lamp models 12-64 and 12-86 during testing at an ambient temperature of 45°C in ALTA2. Both of these LED models exhibited a blue chromaticity shift during the test period. The reported values are the averages for the five samples tested for each lamp model.

values of both *u*' and *v*' decrease rapidly when the lamp is first turned on (12-64 and 12-86 are shown as representative examples). The chromaticity shift continues in the blue direction (i.e., *u*' and *v*' decreasing), but at a slower rate between 100 and 4,000 hours for lamp model 12-64. There were minimal changes in chromaticity after 4,000 hours for this lamp model. Likewise, for lamp model 12-86, a sharp drop in chromaticity was observed in the first 50 hours, followed by a more gradual blue shift until around 2,000 hours. At that point, no significant change in *u*' is observed, although *v*' appears to increase slowly, suggesting that another chromaticity-shift mechanism is starting to occur at a low level. A sample-by-sample analysis of the chromaticity shift for these lamp models is given in **Appendix B**. The spectral changes accompanying this chromaticity-shift mode are also discussed in subsequent sections.

Chromaticity Characteristics of CSM-2

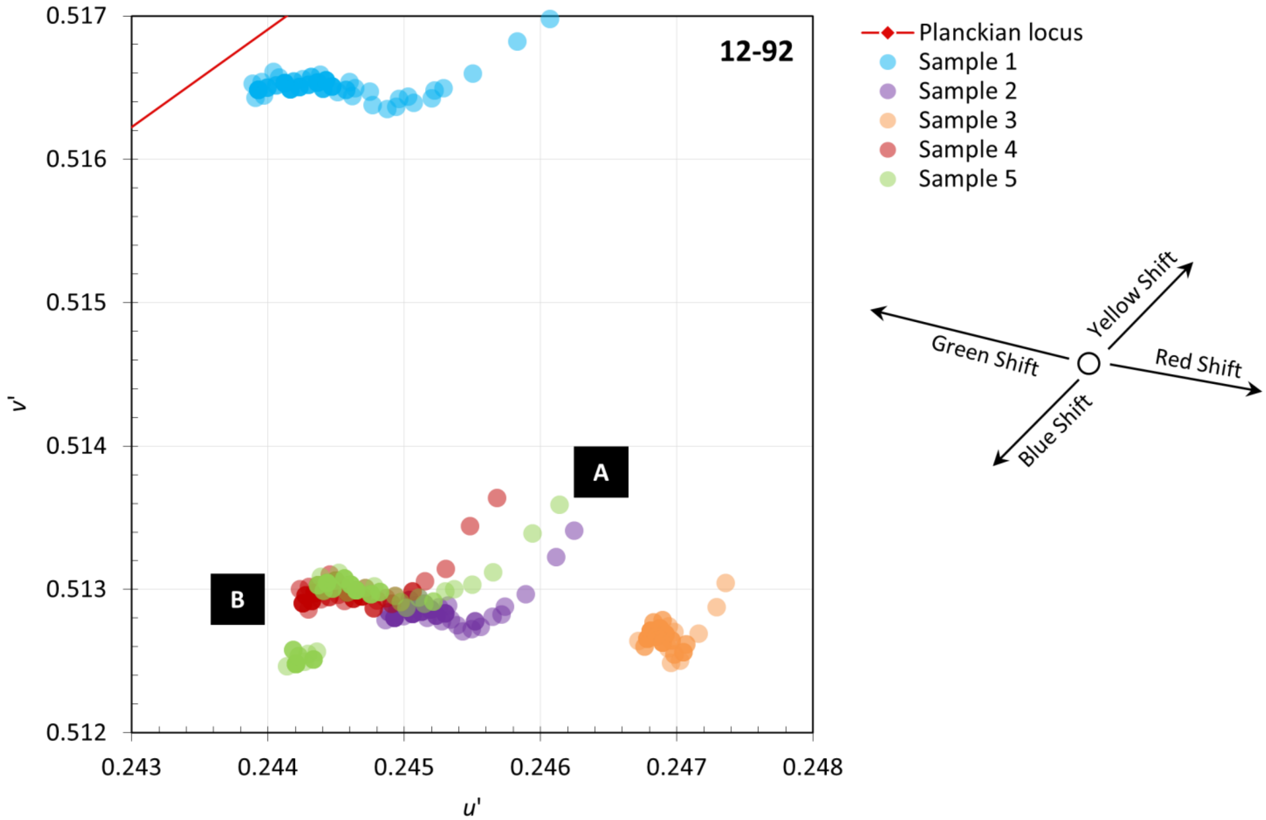
CSM-2 involves the introduction of a green shift in conjunction with the initial blue shift, and 8 out of 32 LED lamp models displayed this behavior. In general, a green chromaticity-shift mode has the effect of changing the lamp chromaticity in a manner that does not exactly follow the blue-yellow line. The effect is best observed by examining the chromaticity coordinates; two representative examples are shown in **Figure 8**. For lamp model 12-92, the emergence of the green chromaticity-shift results is visible as a sharp change from the blue-yellow line, whereas the change is more gradual for lamp model 12-99.

Chromaticity Characteristics of CSM-3

CSM-3, which was the most common chromaticity shift for the LED PAR38 lamps tested in this study, consisted of prolonged period of shifting in the general direction of the yellow emitter, following the initial blue shift. This change may not follow exactly on the blue-yellow line suggestive of the introduction of some green shift as well. The behavior is characterized by a continual increase in both the *u*' and *v*' chromaticity coordinates after the initial blue chromaticity shift has halted. Usually, this chromaticity-shift mode is first observed in the *v*' coordinate, and the magnitude of the shift is also greater for *v*' than for *u*'. **Figure 9** shows the average chromaticity shift for the five samples of lamp models 12-75, 12-85, and 12-100. Lamp model 12-85, which was a parametric failure for chromaticity shift, exhibited an initial blue shift lasting less than 500 hours, followed by a sharp yellow shift that lasted for the remainder of the test period. At the end of the test period, the average chromaticity shift for the 12-85 lamp model was $\Delta u'v'$ = 0.0152, which was above the failure criterion. Likewise, lamp model 12-100 exhibited an initial blue shift followed by a sharp yellow shift that was first visible in the *v*' coordinate at 4,000 hours. At the end of the test period, the average chromaticity shift for lamp model 12-100 was $\Delta u'v'$ = 0.0053, which was below the failure criterion. Finally, lamp model 12-75 also exhibited a yellow chromaticity shift after the initial blue shift. This change is demonstrated by the very slow increase in the *v*' coordinate starting at around 2,000 hours. At the end of the test period, the average chromaticity shift for lamp model 12-75 was 0.001. A sample-by-sample analysis of the chromaticity shifts for these lamp models is given in **Appendix B**, and the spectral changes accompanying this chromaticity shift mode is discussed in Section 2.2.3.

The reversal of the chromaticity shift from blue to yellow that occurs in CSM-3 is also readily apparent when examining the chromaticity for samples displaying this behavior. As shown in **Figure 10**, this reversal in chromaticity gives a characteristic hook pattern, with the bottom of the hook being the time when the direction of chromaticity shift begins to change from a blue shift to a yellow shift. The width of the hook is also an indication that some degree of green shift is also occurring, although blue and yellow chromaticity shifts are dominant. The observed chronology of these chromaticity shifts indicates that the blue shift occurs first, followed by a green shift and ending with a yellow shift. For convenience, the initial chromaticity values will be referred to as Point A, the values at the maximum blue shift will be referred to as Point B, and the values at the end of the test as Point C, as shown in **Figure 10**.

A deeper understanding of the changes that are occurring in the LED during CSM-3 can be gained by using the maximums of the blue and yellow emissions as an indicator of chromaticity (see **Table 4**). The maximum radiant



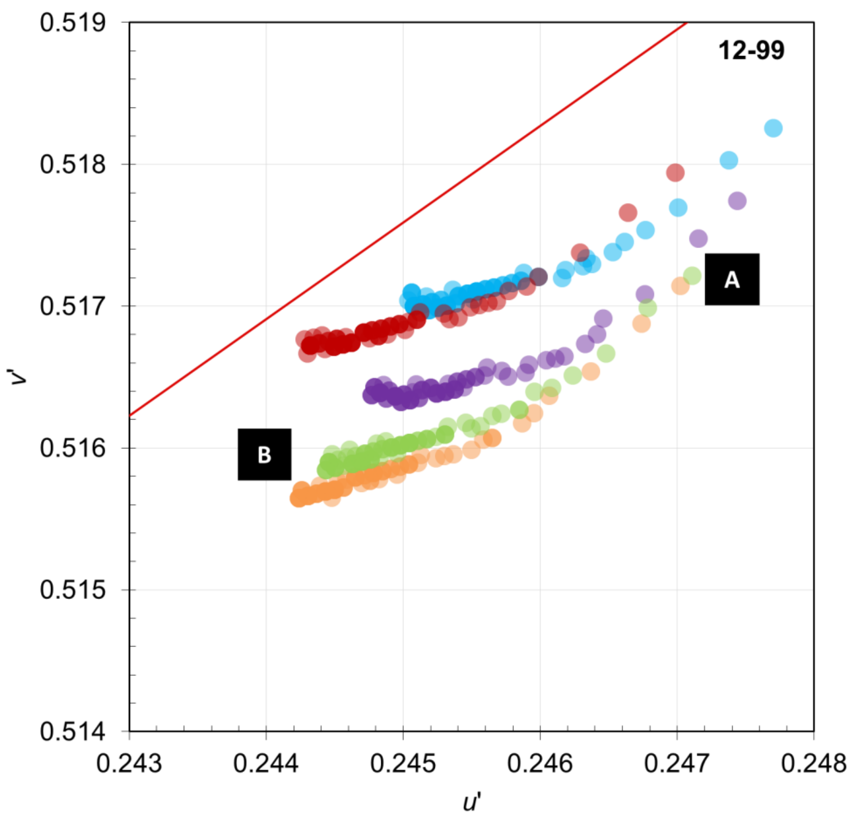


Figure 8. Sequential measurements of chromaticity coordinates for the five samples in the test populations for lamp model 12-92 (top) and 12-99 (bottom). All samples initially demonstrated a blue shift. The green shift appeared later and moved the chromaticity shift off of the blue-yellow line (CSM-2).

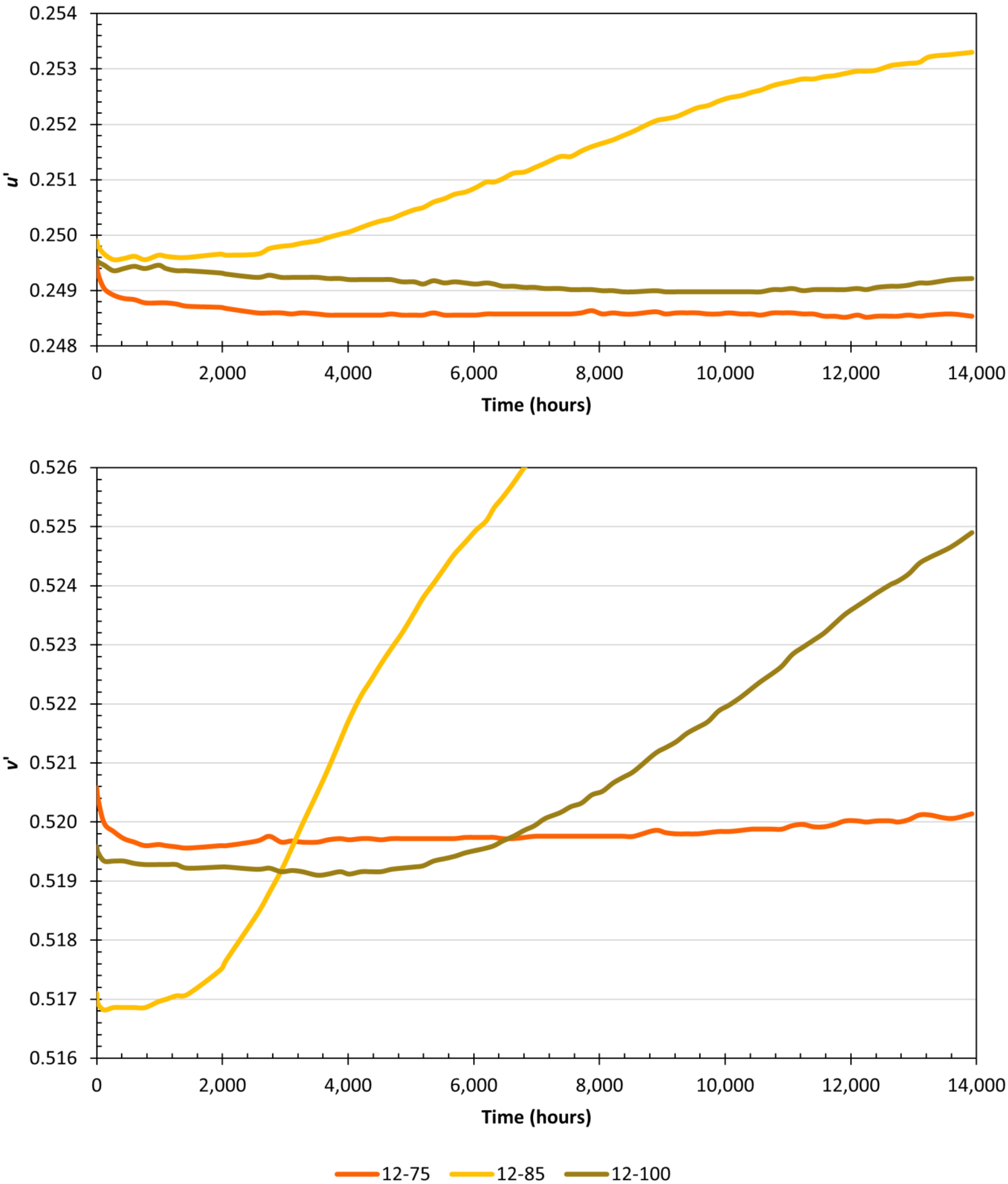


Figure 9. Time-based change in *u*' and *v*' for lamp models 12-75, 12-85, and 12-100. The lamp models all initially exhibited a blue shift and then shifted in the yellow direction. The reported values are the averages for the five samples tested for each lamp model.

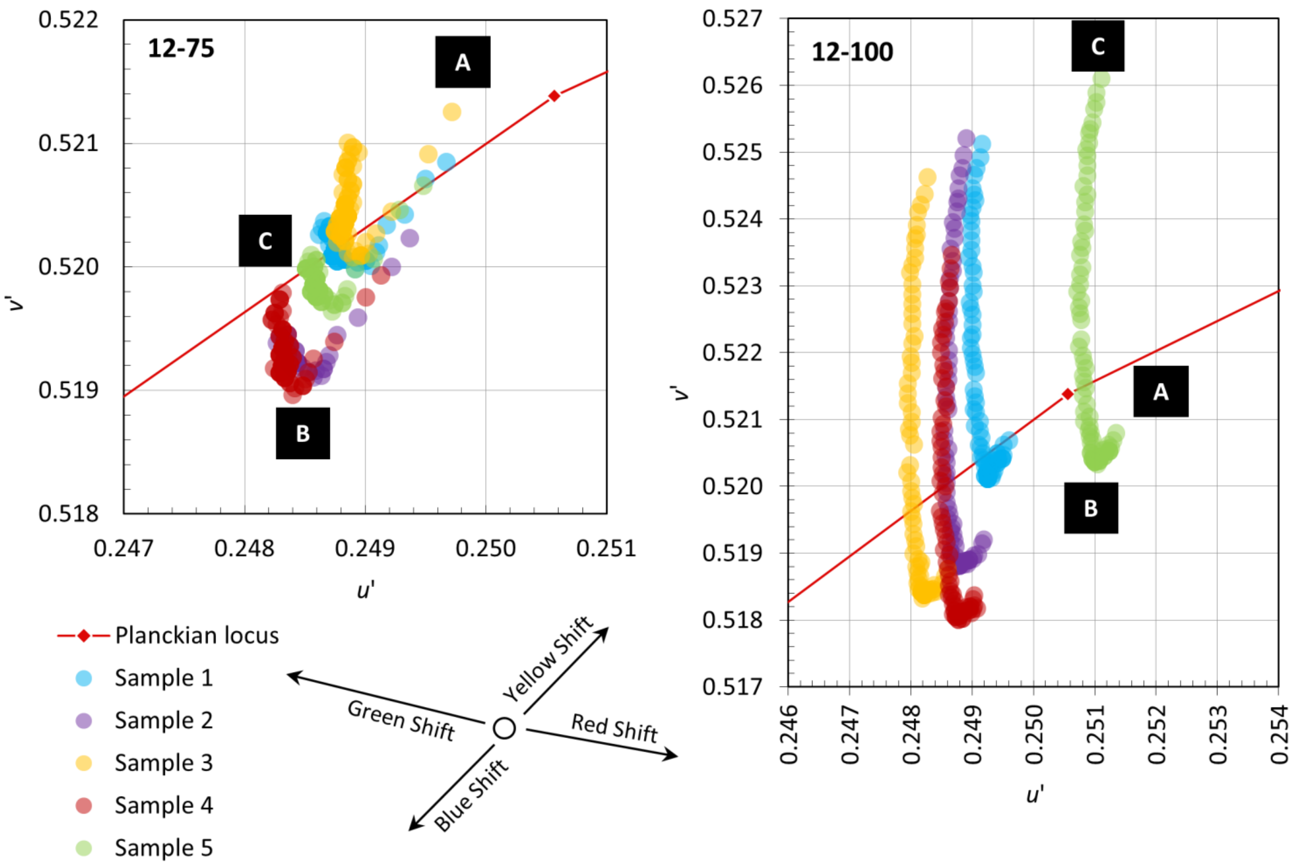


Figure 10. Change in chromaticity coordinates for the five samples of lamp models 12-75 (left) and 12-100 (right). All samples initially demonstrated a blue shift followed by a yellow shift (CSM-3).

flux of the blue emission peak at Point A, Point B, and Point C are denoted as B_A, B_B, and B_C, respectively. Likewise, Y_A, Y_B, and Y_C denote the maximum radiant flux value of the yellow emission at Point A, Point B, and Point C, respectively. By taking the ratio of B_B and B_A and B_C and B_B, the change in maximum radiant flux for blue emission can be followed along the B-A and C-B segments of the chromaticity diagram. For example, if the ratio B_B/B_A is greater than one, then the blue emission was increasing in moving from Point A to Point B. Likewise, if B_B/B_A is less than one, blue emission was decreasing. A similar analysis can be performed for Y_A, Y_B, and Y_C to study the changes in yellow radiant flux emission along the B-A and C-B arcs. This information is presented in **Table 4** for three representative lamp models. (Similar information for lamp model 12-85, which also exhibited CSM-3, is provided later in **Table 10**.)

This analysis shows that blue emission increases along the B-A arc, as evidenced by the finding that B_B/B_A is greater than one in all three cases. However, the yellow emission did not demonstrate the same increase on the B-A arc, suggesting that there may be a small loss in phosphor efficiency. The situation is significantly different along the C-B arc (i.e., the yellow chromaticity shift), as the ratio of blue radiant flux maxima drops (i.e., B_C/B_B) and is now less than the ratio of yellow radiant flux maxima (i.e., Y_C/Y_B). In particular, lamp model 12-100 shows a precipitous drop in blue emission and a much smaller drop in yellow. An increase in the conversion of blue photons by the phosphor would account for the drop in blue emission and the rise in yellow emission along the C-B arc.

Table 4. Comparison of the maximum blue and yellow radiant flux at points A, B, and C on the chromaticity diagram for three LED PAR38 lamp models. The chromaticity coordinates for models 12-75 and 12-100 are shown in Figure 10.

	B_B/B_A		B_C/B_B		Y_B/Y_A		Y_C/Y_B	
ID	**Average**	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**
12-75	1.026	0.005	0.974	0.012	0.978	0.004	0.983	0.006
12-81	1.010	0.007	0.963	0.012	0.923	0.010	0.977	0.005
12-100	1.019	0.005	0.779	0.022	1.001	0.004	0.928	0.009

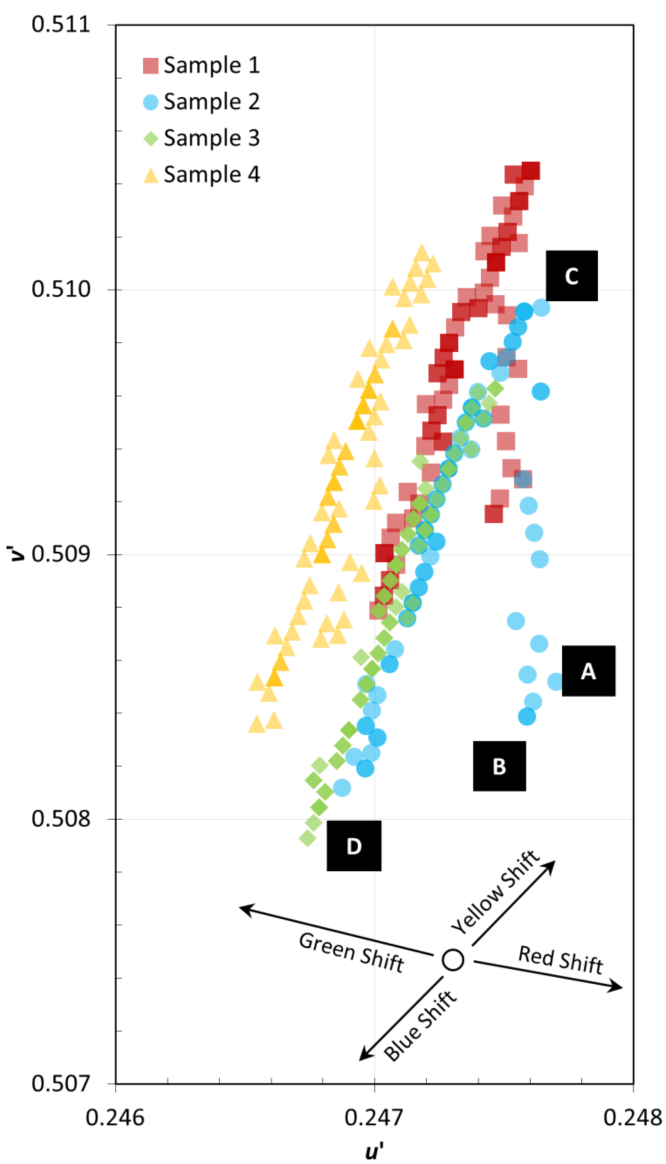


Figure 11. Change in chromaticity coordinates for the four samples of lamp model 12-66. All samples initially demonstrated a short blue shift between points A and B, followed by a yellow shift between points B and C, followed by a second blue shift between points C and D (CSM-4). This lamp model uses PLCC LED packages in the light engine.

Chromaticity Characteristics of CSM-4

CSM-4 consisted of a very short blue shift, often less 100 hours, followed by a nearly linear change in chromaticity in the yellow direction, followed by a change back toward the blue direction. A typical example of the chromaticity shift mode is shown in **Figure 11**, where the chromaticity can be seen to shift in the blue direction (i.e., both *u*' and *v*' decrease along the A-B segment) for the first 50 hours, followed by a yellow shift (i.e., both *u*' and *v*' increase along the B-C segment) up to roughly 3,000 hours, followed by a second blue shift (i.e., both *u*' and *v*' decrease along the C-D segment).

CSM Behavior by LED Package Type

Using the chromaticity-shift mode classification discussed above, a more detailed analysis of the chromaticity shift by lamp model can be conducted. A summary of this information is given in **Figure 12,** broken out by the LED package type in each lamp model. Several major trends can be observed from this analysis. First, there was some difference in the dominant chromaticity-shift mode for the various LED package types. Lamps that used HP LEDs most commonly exhibited CSM-3 behavior, although CSM-1 and CSM-2 were also observed less frequently. Lamps that utilized COB packages were distributed equally among CSM-1, CSM-2, and CSM-3 behavior. The CSM-1 and CSM-2 mechanisms are potential precursors to the CSM-3 behavior, and continuation of the test, or testing under

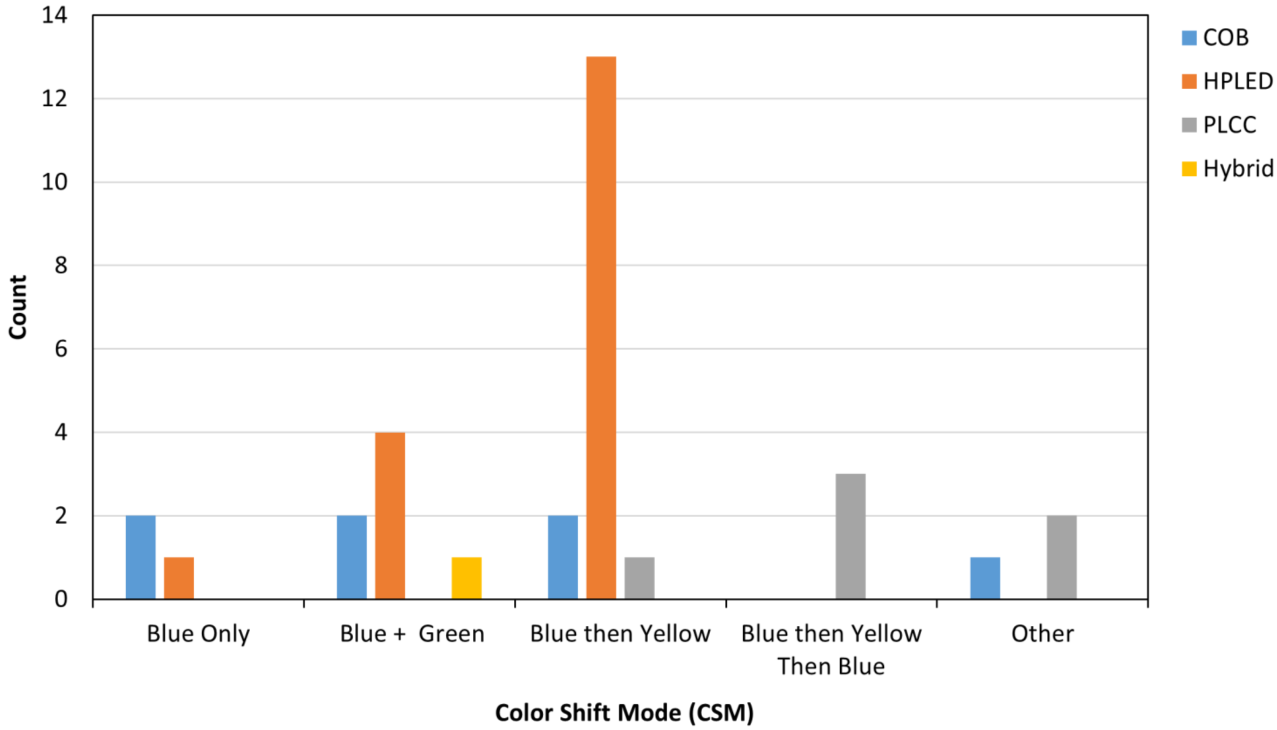


Figure 12. Count of the chromaticity-shift modes found in the LED PAR38 lamp models. Different LED packages exhibited different chromaticity shifts.

more-extreme conditions, would likely produce the yellow-shift characteristics of CSM-3.

Lamp models containing LEDs in PLCC packages predominantly exhibited CSM-4 behavior, as shown in **Figure 12**. None of the other package types exhibited this CSM, suggesting that the cause of this chromaticity-shift mode may be due to the chemistry of the molding resin used in the PLCC packages. Since these lamp models were manufactured in the 2012 timeframe, the PLCC molding resin is likely to be polyphthalamide (PPA), which has been shown to undergo photo-oxidation under some conditions, resulting in a blue shift.[11] We speculate here that elimination of the resin oxidation will shut down the CSM-4 mechanism and will produce a CSM-3 shift, as found for LED model 12-80.

Spectral Changes Associated with Chromaticity-Shift Modes

Physical and Spectral Changes Occurring During CSM-1

All of the lamp models examined in CALiPER 20.4 exhibited a blue shift when first energized. However, based on an examination of the data in **Figure 6** and **Appendix B**, only three lamp models (12-64, 12-86, and 12-90) did not exhibit another significant chromaticity-shift direction during the test period. As shown in **Table 5**, these lamp models, on average, exhibited three characteristics of low-stress operation for the LEDs: low LED board temperatures, high lumen maintenance, and small chromaticity shifts. Based on these observations, it can be speculated that longer test times or more-severe conditions would produce additional chromaticity shifts, likely in the yellow direction. A closer look at the individual samples for lamp model 12-64 (see Appendix B) shows some part-to-part variation in chromaticity shift. As a result, some samples (i.e., samples 4 and 5) exhibited a slight deviation from a straight blue shift during the test, which is suggestive of the onset of other chromaticity-shift modes in these samples.

Table 5. Changes in average photometric properties of LED PAR38 lamps exhibiting Chromaticity Shift Mode 1 (i.e., pure blue shift). Change is measured as the difference between final reading and initial reading for each photometric property. Values shown for photometric properties are the average from five samples of each lamp model. LED board temperature was measured on a single lamp model at an ambient temperature of 22°C.

ID	LED Type	Average Lumen Maintenance	$\Delta u'v'$	ΔCCT (K)	LED Board Temp. (°C)
12-64	COB	0.92	0.0019	50	53
12-86	HP LED	1.01	0.0010	23	48
12-90	COB	0.94	0.0013	33	64

The SPD for one sample each from lamp models 12-86 and 12-90 are given in **Figure 13**. A blue shift is characterized by an increase in blue emission relative to yellow and no changes in the emission-peak shape of either the LED or the phosphor. As is especially visible for lamp model 12-90, the phosphor emission decreased more rapidly than the emission from the blue LED, producing the net blue shift. This difference could be attributed to several factors, but the most likely cause is a drop in the quantum efficiency of the phosphor, because blue emission is virtually unchanged.

An initial increase in LED efficiency, resulting in higher radiant and luminous flux, is often seen in the test samples, especially in the first 1,000 hours of operation. This increased efficiency has been attributed to several effects, including annealing of the epitaxial layer and reduction of contact resistances.[15] Only a handful of samples were able to maintain such an increase in emission over the test lifetime, as found for 12-86. Whenever this occurs, the blue emission often increases proportionally more than the yellow emission, resulting in the net blue shift. There are two possible causes for proportionately less phosphor emission: operating above the phosphor saturation point, or a reduction of phosphor quantum efficiency. Since the phosphors are unlikely to be operated exactly at the saturation point in so many instances, a small initial drop in phosphor quantum efficiency is a more plausible explanation for the initial blue shift.

Physical and Spectral Changes Occurring During CSM-2

A deviation from a chromaticity shift along the blue-yellow line occurs when the emission properties of either the phosphor or the blue LED change. In general, this shift is in the green direction and was found to occur for many of the LED PAR38 lamps. When this effect is combined with the general blue shift that also occurs when the lamps are first energized, the result is a combined blue and green shift that deviates from the blue-yellow line. As shown in **Table 6**, these lamp models, on average, exhibited three characteristics of low-stress operation for the LEDs: low LED board temperatures, high lumen maintenance, and small chromaticity shifts. Based on these observations, it can be speculated that longer test times or more-severe conditions would give rise to additional chromaticity-shift modes, likely in the yellow direction (i.e., CSM-3).

An examination of the SPD for these lamp models provides insights into the emission changes occurring during the tests. Representative examples are shown in **Figures 14** and **15**. The observed green shift observed corresponds to a shift to lower wavelengths of the phosphor emission by 2-5 nm. In addition, some samples showed an increase in emission in the 500 nm to 600 nm range (relative to the peak), further indicating that the green shift was caused by a change in the phosphor emission characteristics. As is evident in **Figures 14** and **15**,

[15] E. Zanoni *et al.*, "GaN-based LEDs: state of the art and reliability limiting mechanisms," 2014 15th International Conference on thermal, mechanical, and multi-physics simulation and experiments in microelectronics and microsystems (EuroSimE).

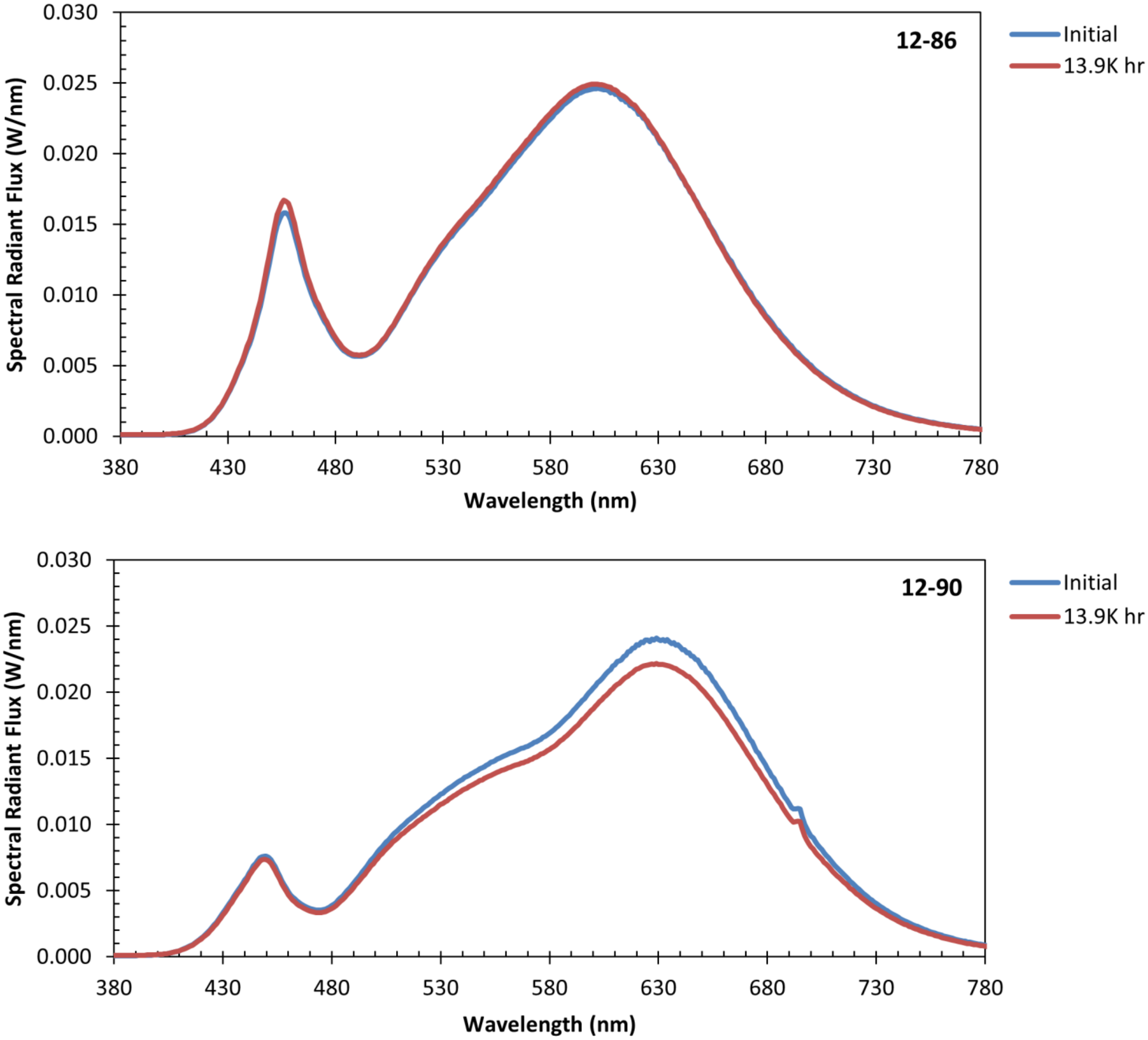


Figure 13. Spectral radiant flux plots for one sample each of LED PAR lamp models 12-86 and 12-90. The spectra were recorded when the device was first energized, and again after 13,925 hours of operation.

the peak shape and location of the blue LED emission are not changing, further indicating that the observed green shift is due to the phosphors. Previous studies have shown that changes in the chemistry of nitride phosphors used in warm-white LEDs results in a shift to lower emission wavelengths. These chemical changes include oxidation of the dopants and changing the crystal field of the nitride phosphor.[16]

Physical and Spectral Changes Occurring During CSM-3

By far the most common chromaticity-shift mode found in these LED PAR38 lamps was an initial blue shift followed by a prolonged yellow shift. Nearly all of the tested lamp models continued to shift in the yellow direction, once this chromaticity shift began. The only exceptions were some of the lamp models using PLCC LED

[16] C.-W. Yeh *et al.*, "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* vol. **134** (2012) p. 14108 – 14117.

Table 6. Changes in average photometric properties of LED PAR38 lamps exhibiting Chromaticity Shift Mode 2 (i.e., blue and green shift). Change is measured as the difference between final reading and initial reading for each photometric property. Values shown for photometric properties are the average from five samples of each lamp model. LED board temperature was measured on a single lamp model at an ambient temperature of 22°C.

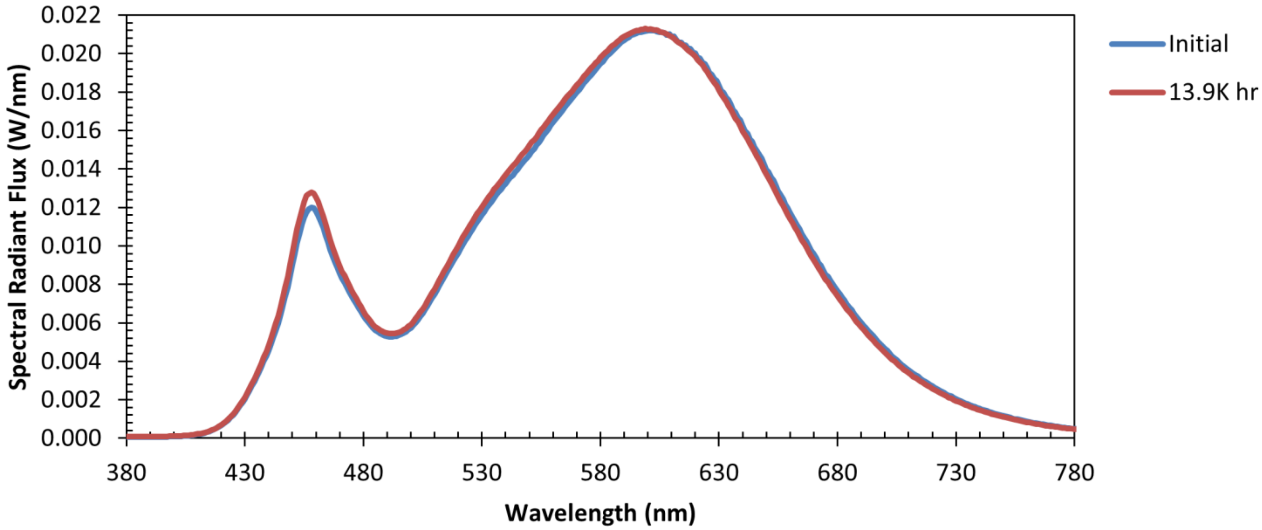
ID	LED Type	Average Lumen Maintenance	Δu'v'	ΔCCT (K)	LED Board Temp. (°C)
12-65	COB	0.97	0.0019	43	64
12-67	Hybrid Array	1.01	0.0012	32	50
12-72	COB	0.96	0.0020	54	45
12-92	HP LED	1.05	0.0016	46	45
12-99	HP LED	1.01	0.0029	81	48
12-134	HP LED	0.86[a]	0.0029[a]	87[a]	N/A[a]
12-146	HP LED	0.95	0.0040	106	55

a. The last surviving sample of lamp model 12-134 was operational when the test ended at 13,926 hours, but was not operation when attempts were made to measure the board temperatures. Tests for lamp model 12-134 ended at 13,926 hours due to the catastrophic failure of all samples. Changes in the photometric measurement values are based on the reading when the last lamp model was functioning and the initial reading. Board temperature could not be measured for these lamp models because they were non-functional at the end of testing.

packages. In general, the rate of chromaticity shift in the yellow direction was often linear over the test period, as demonstrated by the Δu'v' plots for these lamp models provided in CALiPER Report 20.4. A summary of the average physical and photometric properties of the LED PAR38 lamp models exhibiting this chromaticity-shift mode is given in **Table 7**. Compared to the other chromaticity-shift modes, there is a much broader range of physical properties (e.g., board temperature) and photometric performance (lumen maintenance, ΔCCT, and Δu'v') for lamp models displaying CSM-3 behavior. In addition, 8 out the 13 samples (62%) that exhibited parametric failure due to excessive chromaticity shift demonstrated CSM-3 behavior. These samples covered 4 out the 5 lamp models (80%) that had a sample failure due to excess chromaticity shift. Based on these observations, it can be speculated that once the yellow chromaticity-shift mode begins in ceramic-based LED packages, it will continue until the chromaticity shift and/or lumen maintenance exceeds the applicable failure criteria.

Spectral power distributions for two representative lamp models (12-75 and 12-100) that display CSM-3 behavior are shown in **Figures 16** and **17**. The time-based changes in chromaticity coordinates for these lamp models are also given in **Figure 10**, which shows the characteristic hook pattern indicative of a reversal in the chromaticity shift.

For the tested lamp models, blue emission increased relative to the initial values, as shown in **Figures 15b** and **16b**, up until the reversal of the chromaticity shift direction occurs. During this time, phosphor emission did not remain proportional (as shown in **Figures 15c** and **16c**), so there was a net shift in the blue direction. Once the chromaticity shift in the yellow direction began, the blue emission from the LED decreased at a faster rate than the phosphor emission. The observed spectral changes indicate that blue photons were being lost faster than the photons emitted by the phosphor, potentially due to increased conversion of blue photons by the phosphor. This is reinforced by **Table 4**, which documents that the peak maximum ratio for yellow (Y_C/Y_B) decreases significantly less than the corresponding ratio for blue emission (B_C/B_B).



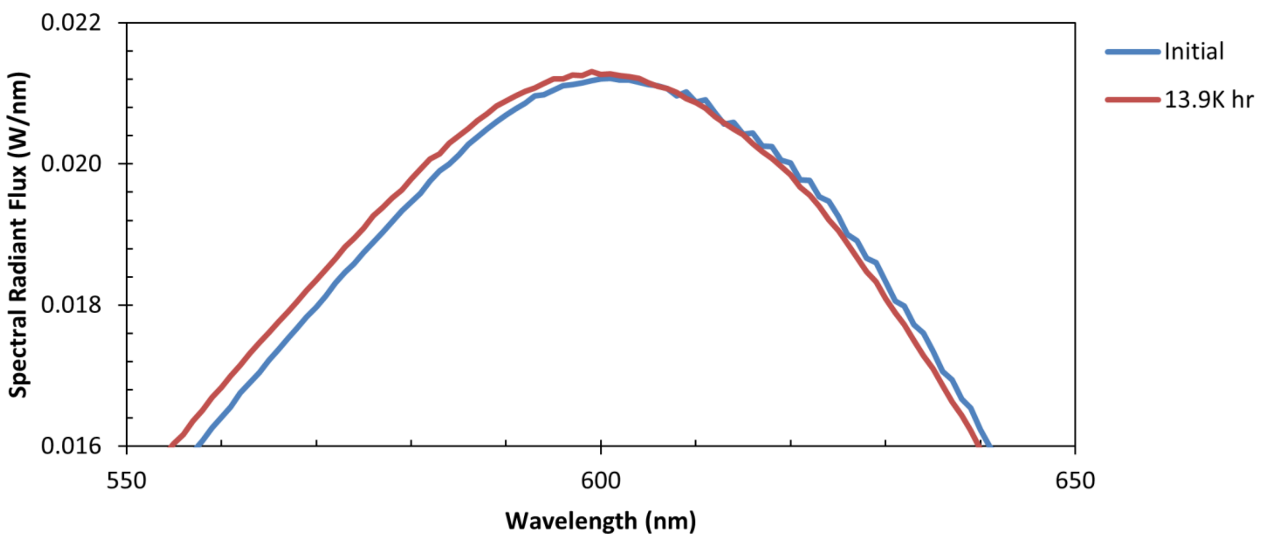


Figure 14. Spectral radiant flux plots for one sample of model 12-99. The spectrum was recorded when the lamp was first energized, and again after 13,925 hours of operation. The graph on the top shows the entire visible-spectrum response, whereas the graph on the bottom focuses on the region between 550 nm and 650 nm where phosphor emission is at its highest levels.

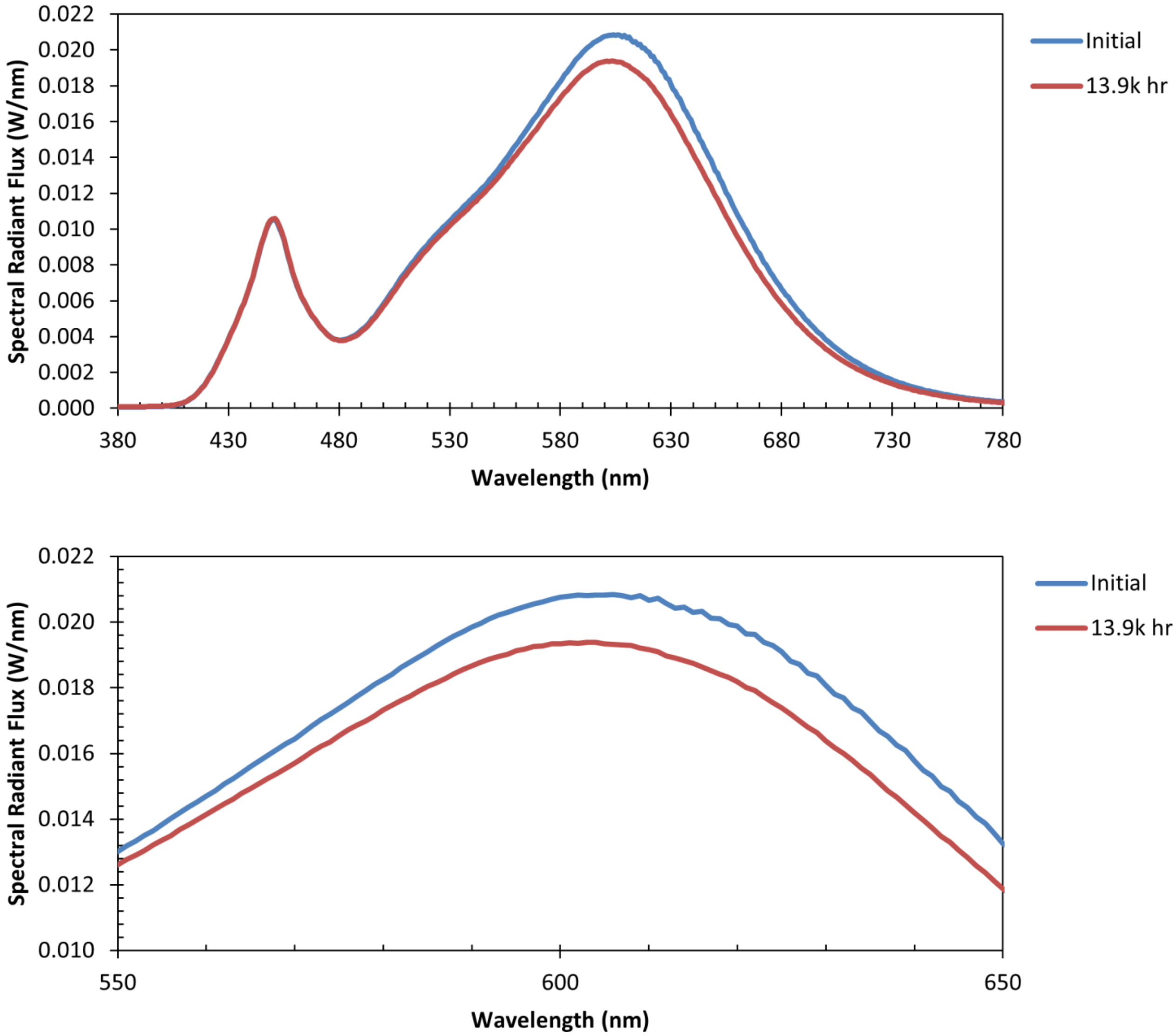


Figure 15. Spectral radiant flux plots for one sample of model 12-146. The spectrum was recorded when the lamp was first energized, and again after 13,925 hours of operation. The graph on the top shows the entire visible spectrum, whereas the graph on the bottom focuses on the region between 550 nm and 650 nm where phosphor emission is at its highest levels.

Table 7. Changes in average photometric properties of LED PAR38 lamps exhibiting Chromaticity Shift Mode 3 (i.e., blue then yellow shift). Change is measured as the difference between final reading and initial reading for each photometric property. Values shown for photometric properties are the average from five samples of each lamp model. LED board temperature was measured on a single lamp model at an ambient temperature of 22°C.

ID	LED Type	Average Lumen Maintenance	Δu'v'	ΔCCT (K)	LED Board Temp. (°C)
12-73	HP LED	0.94	0.0050[a]	0	51
12-75	HP LED	0.97	0.0011	27	54
12-78	HP LED	0.94	0.0046	23	53
12-80	PLCC	0.98	0.0006	16	62
12-81	COB	0.92	0.0031	82	54
12-82	HP LED	0.96	0.0036	-1	52
12-85	COB	0.76	0.0152[a]	-169	66
12-88	HP LED	0.97	0.0007	-3	42
12-89	HP LED	0.92	0.0049[a]	-30	49
12-95	HP LED	0.98	0.0031	88	41
12-96	HP LED	0.91	0.0060	-94	92
12-100	HP LED	0.93	0.0053	-25	45
12-140	HP LED	0.98	0.0028	74	61
12-144	HP LED	0.90	0.0042	-100	65
12-145	HP LED	0.93	0.0052[a]	-8	46
12-148	HP LED	0.93[b]	0.0004[b]	2[b]	N/A[b]

a. The samples from these lamp models had at least one parametric failure, which is included in the average. Lamp models 12-73, 12-89, and 12-145 had one parametric failure due to excessive chromaticity shift. All five samples for lamp model 12-85 were classified as parametric failures due to excessive chromaticity shift.

b. Tests for lamp model 12-148 ended at 10,061 hours, due to the catastrophic failure of all samples. Changes in the photometric values are based on the reading when the last lamp model was still functional, and the initial reading. Board temperature could not be measured for lamp models, because they were non-functional at the end of testing.

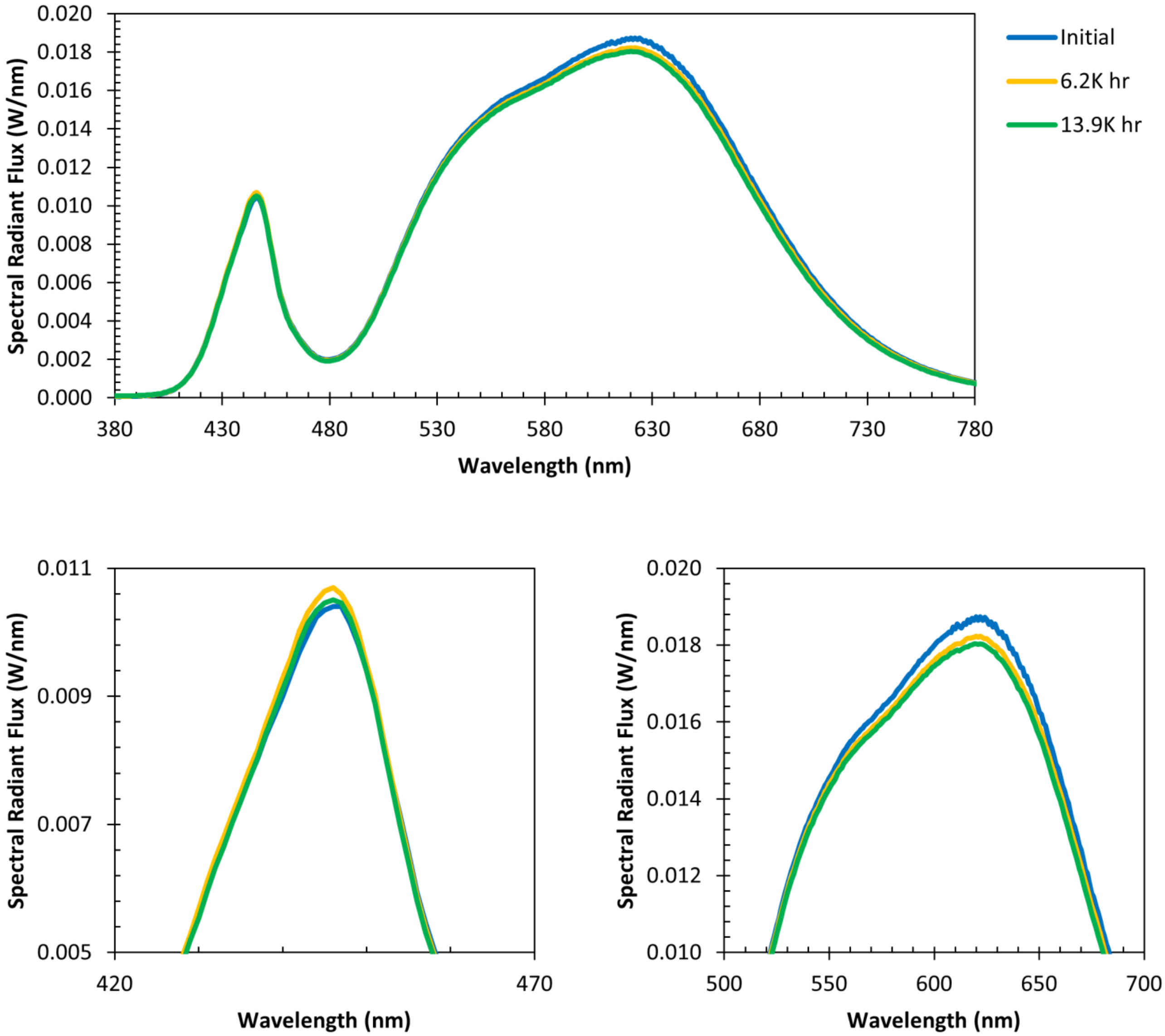


Figure 16. Spectral radiant flux plots for one sample of model 12-75. The spectrum was recorded when the device was first energized, after 6,198 hours (when the chromaticity starts to shift in the yellow direction), and after 13,925 hours of operation. The top graph displays the entire visible spectrum, the bottom left graph shows an expanded view of the change in the blue LED emission peak, and the bottom right graph shows an expanded view of the change in the phosphor emission peak.

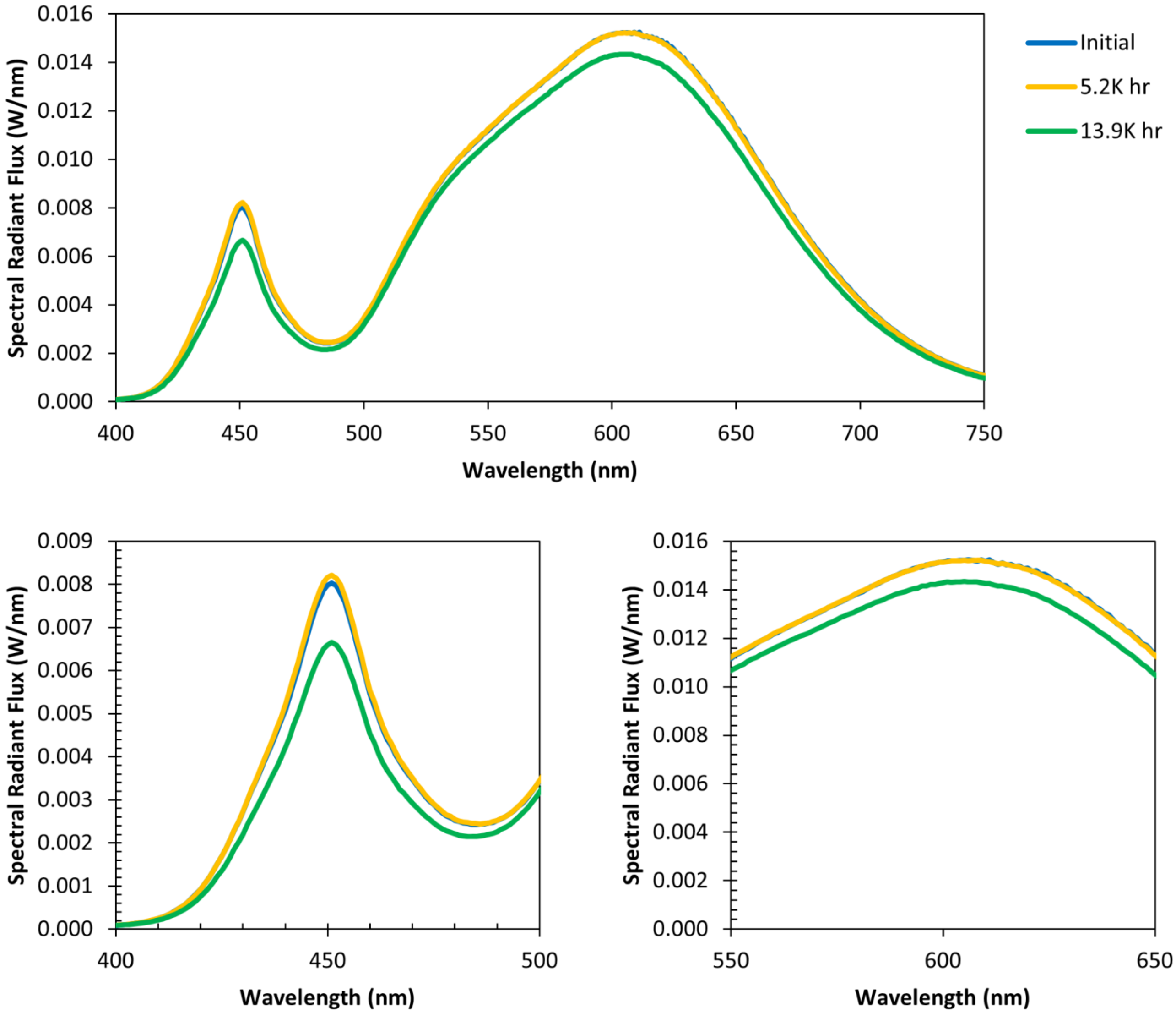


Figure 17. Spectral radiant flux plots for one sample of model 12-100. The spectrum was recorded when the device was first energized, after 5,194 hours (when the chromaticity begins to shift in the yellow direction), and after 13,925 hours of operation. The top graphic displays the entire visible spectrum, the bottom left graph shows an expanded view of the change in the blue LED emission peak, and the bottom right graph shows an expanded view of the change in the phosphor emission peak.

A mechanism has been put forward by Tuttle to explain the yellow chromaticity shift in LEDs, such as observed in these tests.[17] This mechanism attributes the yellow chromaticity shift to cracking of the phosphor-binder layer and delamination of this composite from the top of the blue LED. The introduction of cracks and physical delamination in the phosphor-binder layer introduces a defect into the optical path and allows air—a low-refractive-index material—to fill the void. The introduction of the low-refractive-index material will increase the optical path level of photons emitted by the blue LED and traveling through the phosphor. The longer optical path level will increase photon conversion by the phosphor and produce light with a proportionately higher yellow content, as shown in **Figure 18**.[18] The introduction of these defects can also adversely affect light-extraction efficiency, resulting in an overall reduction in photons.[19]

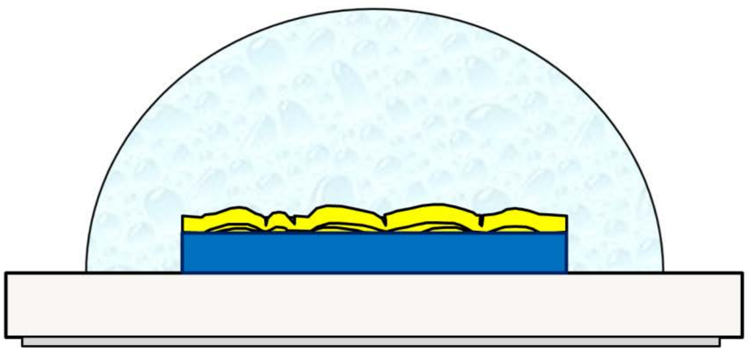


Figure 18. Cracking and delamination of the binder/phosphor composite layer arises due to stress at the interfaces during use. The phenomenon introduces air into the optical path, which increases the optical path of photons through the phosphor, which in turn increases down conversion.[18]

In addition to the cracking/delamination chromaticity-shift mechanism, a second mechanism was also observed to cause a yellow shift in model 12-96. As shown in **Table 7**, this lamp model had the highest board temperature of the devices that were measured in this study. At the 45°C ambient temperature used in the ALTA2 tests, the LED board temperature is expected to have been roughly 115°C. Since the secondary lens is in direct contact with this board, this elevated temperature is sufficient to cause oxidation of the lens,[20] and a discolored lens was observed upon disassembly of the lamp, as shown in **Figure 19**. No other lamp models were found to exhibit lens yellowing during the tear-down analysis, consistent with the lower operational temperatures of the LED boards. Based on previous results, yellowing of the secondary lens can be expected to increase the absorbance of blue photons, especially at lower wavelengths. This is expected to 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.

An examination of spectral power distributions from one of the four 12-96 samples that survived the complete test is shown in **Figure 20**. At the end of the test, a disproportionate reduction in blue emission produced a pronounced yellow shift, although the total magnitude of the shift was below the failure criterion. Absorbance

[17] M. Royer, R. Tuttle, S. Rosenfeld, and N. Miller, "Color maintenance of LEDs in laboratory and field applications," DOE Gateway Report, September 2013. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_color-maintenance.pdf accessed November 28, 2015).

[18] M. Royer, C. Stalker, R. Tuttle, "LED color stability: 10 important questions," DOE webinar, April 15, 2014. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/color-stability-webinar_4-15-2014.pdf (accessed November 28, 2015).

[19] B. Wu *et al*. "Effect mechanisms of moisture diffusion on LED reliability," 2010 3rd Electronic System-Integration Technology Conference (ESTC) (2010).

[20] M. Y. Mehr *et al.,* "Lifetime assessment of Bisphenol-A Polycarbonate (BPA-PC) plastic lens, used in LED-based products," *Microelectronics Reliability* vol. 54 (2014) p. 138 – 142.

Figure 19.

Lenses taken from two samples of model 12-96. The lens on the left is from the lamp model that failed catastrophically after 2,059 hours of continuous operation at 45°C. The lens on the right is from a lamp model that survived the entire test (13,925 hours) and showed significant discoloration due to excessive heat. The discoloration is especially pronounced in the center of the lens.

of blue emission by the lens also shifted the peak emission maximum, which can be clearly seen in the normalized LED emission spectrum given in **Figure 20**. Normalization of the blue part of the spectrum was performed to study both peak shape and location of the peak maximum. This process highlights the change in peak shape and peak maximum that resulted from the yellowing of the secondary lens.

Physical and Spectral Changes Occurring During CSM-4

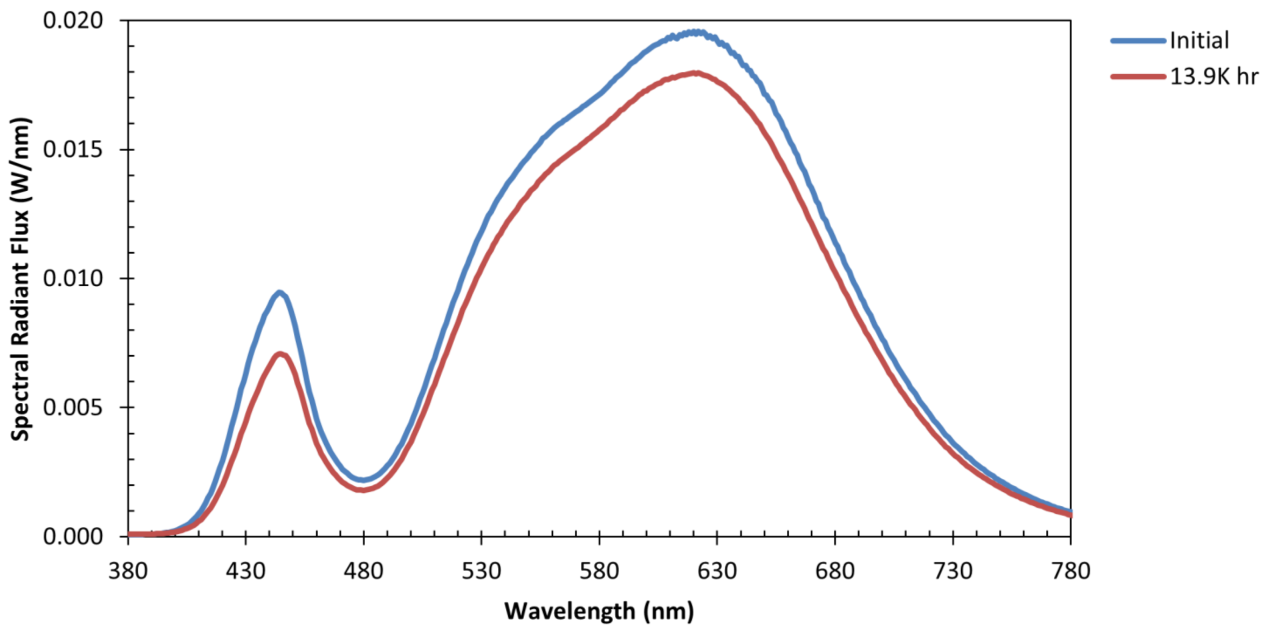
Some of the LED PAR38 lamps using PLCC LED packages exhibited a complex shift mode that consisted of a short (< 150 hours) blue shift, then a yellow shift, then a second blue shift. This chromaticity-shift mode was only observed with lamp models using PLCC packages, and may be due to discoloration of the molding resin used to form the package.[21] As shown in **Table 8**, the three lamp models that exhibited this behavior all underwent a positive change in CCT, consistent with a blue chromaticity shift. In addition, all five samples of 12-74 were parametric failures for excessive chromaticity shift and will be discussed further below.

Additional insights on CSM-4 can be gained by examining the spectrum from a representative sample of lamp model 12-66 (see **Figure 21**). In the time between 0 and 118 hours (purple line in **Figure 21**), there is a notable increase in blue emission and only a slight change in phosphor emission. This behavior is indicative of an increase in efficiency of the LED, due to annealing effects that increase production of blue photons. The phosphor undergoes a small drop in efficiency (for an unknown cause), so phosphor emission is proportionately less and there is a net blue shift. Between 118 and 3,270 hours, phosphor emission from the lamp was clearly

Table 8. Changes in average photometric properties of LED PAR38 lamps exhibiting Chromaticity Shift Mode 4 (i.e., blue then yellow then blue shift). Change is measured as the difference between final reading and initial reading for each photometric property. Values shown for photometric properties are the average from five samples of each lamp model. LED board temperature was measured on a single lamp model at an ambient temperature of 22°C.

ID	LED Type	Average Lumen Maintenance	Δu'v'	ΔCCT (K)	LED Board Temp. (°C)
12-66	PLCC	0.96	0.0007	17	54
12-74	PLCC	0.74	0.0097	143	54
12-97	PLCC	0.93	0.0018	40	50

[21] Ralph Tuttle and Mark McClear, "Understanding the true cost of LED choices in SSL systems, LEDS Magazine, February 2014, p. 43.



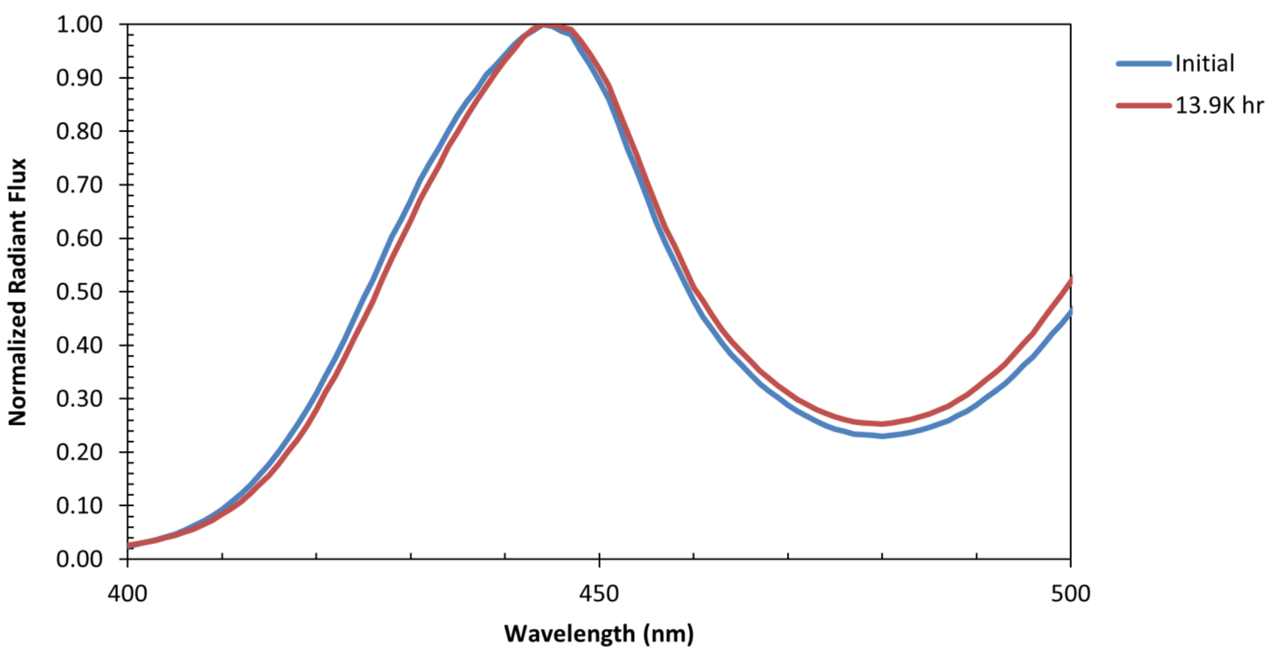


Figure 20. Spectral radiant flux plots for one sample of model 12-96. Similar results were found for the other three samples that were functional at the end of the test period. The spectra were recorded when the device was first energized, and again after 13,925 hours of operation. The top graph displays the entire visible spectrum, whereas whereas the bottom graph shows an expanded view of the change in the blue LED emission peak. The graph on the bottom is normalized so that the maximum of both blue emission peaks is 1.

increasing, while blue emission decreased slightly. This produced the yellow shift in chromaticity for this lamp model. After 3,270 hours, emission from the phosphor began dropping proportionately more than blue emission, producing a second blue shift from the lamp.

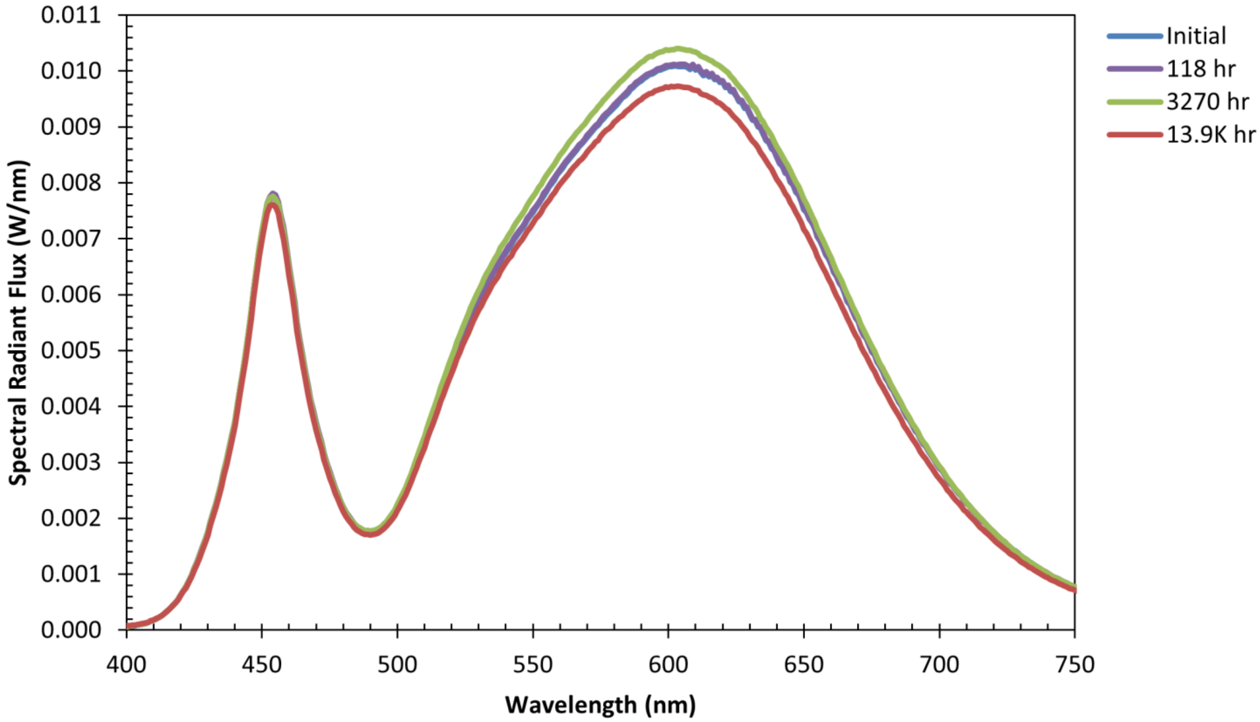


Figure 21. Spectral radiant flux plots for one sample of model 12-66. Similar results were found for the other four samples that were functional at the end of the test period. The spectra were recorded when the device was first energized, after 118 hours of operation (i.e., end of the first blue shift), after 3,270 hours of operation (end of yellow shift), and after 13,925 hours of operation.

A mechanism for CSM-4 has been proposed previously and is illustrated in **Figure 22**.[21] In PLCC packages, photons take many different paths through the phosphor layer, and a portion of the blue photons reflect off the white molding compound used in the PLCC package. As the resin in the molding compound ages, reflectance drops at blue wavelengths, and there is increased photon absorption, resulting in lower contributions from the light rays reflecting off of the package walls to the overall light emission. These longer optical path level light rays are significant contributors to the yellow content of the overall light emission, and reducing their contributions will produce a shift in the blue direction. As noted previously, CSM-4 was only observed in PLCC packages in this study. Since only the PLCC packages use molding compounds containing resins such as PPA, this finding is consistent with the molding resin playing a role in this chromaticity shift.

Parametric Failures for Excessive Chromaticity Shift

A total of 13 samples were classified as parametric failures due to excessive chromaticity shift at the conclusion of the ALTA2 test (i.e., 13,925 hours). Ten of these failures occurred in two lamp models (12-74 and 12-85), while the other three failures were individual samples of LED lamp models 12-73, 12-89, and 12-145 that exhibited significant deviation from the other samples of these models.

The five failures for LED PAR38 lamp model 12-74 were due to excessive chromaticity shift in the blue direction. This lamp model uses mid-power LEDs in a PLCC package, and the terminal blue chromaticity shift is consistent with the chromaticity behavior of CSM-4. A comparison of the blue and yellow emission maxima found that the blue emission maxima decreased by only 8% during the test, whereas the yellow emission maxima decreased by 25%. This finding indicates that the large blue shift observed for these samples is due to a proportionately larger

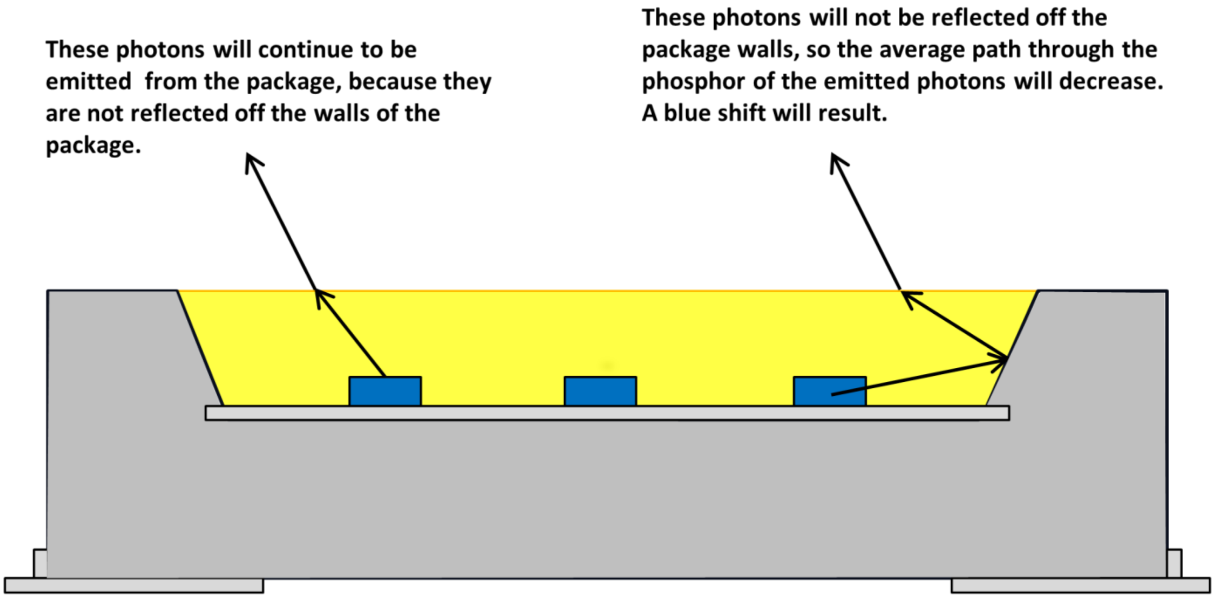


Figure 22. Schematic illustration of the CSM-4 chromaticity shift observed in PLCC LED packages.[21]

decrease of yellow emission than blue during the tests. The reduction in yellow emission, which is characteristic of CSM-4 behavior, is attributed to increased absorption by the molding resin in the PLCC package.

The five failures for LED PAR38 lamp model 12-85 were due to excessive chromaticity shift in the yellow direction. This lamp model used an early-generation LED array package in which separate pcLED die were placed on a common substrate. A comparison of the blue and yellow emission maxima found that the blue emission maxima decreased by more than 50% during the test, whereas the yellow emission maxima decreased by only 24%. This finding indicates that the large yellow shift observed for these samples is due to a proportionately larger decrease of blue emission than yellow during the tests, which is characteristic of CSM-3 behavior.

The other three parametric failures were individual samples from lamp models 12-73, 12-89, and 12-145 that exhibited excessive chromaticity shift in the yellow direction. The other four test samples of these lamp models also exhibited CSM-3 behavior, but the magnitude of the yellow chromaticity shift remained well below the chromaticity shift failure criterion (i.e., $\Delta u'v' < 0.007$). A sample-by-sample comparison of the performance of these lamp models is given in **Appendix B**.

The three lamp models that exhibited only one parametric failure for excessive chromaticity shift provide additional insights into the physical changes responsible for chromaticity shift. A summary of the photometric properties of samples from the same LED models, comparing those that had parametric failures and those that did not, is given in **Table 9**. Included in this table are the maximum radiant flux spectral readings for the blue LED emission (B) and yellow phosphor emission (Y) from the LED PAR38 lamps. This information can be used to calculate the ratio of yellow and blue peak maximum (Y/B ratio) at the beginning of the test (t = 0 hours) and at the conclusion of the test (t = 13,925 hours). Since the test included both parametric failures and non-failures from the same lamp model, a ratio of the peak maximum for blue emission can also be calculated for the initial and final values (B_f/B_i) of a given sample. A similar ratio can also be calculated for yellow emission (Y_f/Y_i).

Table 9. Comparison of photometric properties of selected LED PAR38 lamps.

ID	Sample #	Condition	Parametric Failure	Blue Flux Max (B) (W/nm)	Yellow Flux Max (Y) (W/nm)	Y/B Ratio	B_f/B_i	Y_f/Y_i
12-73	1	Initial	No	0.00860	0.01657	1.927	0.942	0.965
12-73	1	Final		0.00810	0.01598	1.974		
12-73	5	Initial	Yes	0.00960	0.01656	1.725	0.540	0.854
12-73	5	Final		0.00518	0.01414	2.729		
12-89	2	Initial	No	0.01038	0.01736	1.672	0.956	0.977
12-89	2	Final		0.00992	0.01696	1.710		
12-89	5	Initial	Yes	0.00960	0.01500	1.563	0.540	0.845
12-89	5	Final		0.00518	0.01268	2.447		
12-145	5	Initial	No	0.00623	0.01308	2.100	0.925	0.954
12-145	5	Final		0.00576	0.01247	2.166		
12-145	4	Initial	Yes	0.00428	0.01160	2.711	0.325	0.738
12-145	4	Final		0.00139	0.00857	6.150		

From this table, several significant observations can be made:

- The Y/B ratio of all the samples in **Table 9** was higher at the conclusion of the test than at the beginning. This finding is consistent with a yellow chromaticity shift.
- The Y/B ratio was higher in all the parametric-failure samples than in the non-failed samples for the same lamp model. This is also consistent with a large yellow chromaticity shift for the parametric failures.
- The ratio of final and initial yellow emission (Y_f/Y_i) is higher than the corresponding ratio for blue emission (B_f/B_i) in all cases. This indicates that blue photons were being lost faster than photons emitted by the phosphors, possibly due to increased blue photon conversion.
- The B_f/B_i and Y_f/Y_i ratios for the parametric failures were significantly lower than corresponding ratios of the non-failed samples for the same lamp model. This finding indicates a significant reduction in light emission observed for these samples, consistent with the lumen maintenance findings presented in CALiPER 20.4.
- Although both the B_f/B_i and Y_f/Y_i ratios were lower in the parametric-failure samples than in the non-failed samples of the same lamp model, the drop in B_f/B_i was much more precipitous than the drop in Yf/Yi. This finding is also consistent with increased down-conversion of blue photons by the phosphor layer.

The findings summarized in **Table 9** are consistent with a drop in LED photon production in the samples that exhibited parametric failure due to reduced light-extraction efficiency. While this drop in LED photon production reduces total luminous flux from the lamp, there is also a pronounced yellow shift that compensates to a degree and maintains luminous flux above the failure criterion for lumen maintenance (less than 0.70). Since the Y_f/Y_I ratio dropped less than the B_f/B_i ratio, there appears to have been increased down-conversion of blue photons, resulting in the large yellow chromaticity shift. All of these findings are suggestive of the formation of cracks, voids, and delamination in the phosphor/binder layer and at the phosphor/binder-LED die interface.

Since all five samples of 12-74 and 12-85 exhibited parametric failure during the test period, the B_f/B_i and Y_f/Y_i ratios can be calculated for each lamp model, along with the standard deviations. As shown in **Table 10**, the small standard deviations demonstrate that all five samples of each lamp model exhibited roughly the same behavior. For lamp model 12-74, the B_f/B_i ratio indicates minimal reduction (about 9% on average) in blue emission during the test period, but the Y_f/Y_i ratio decreased by greater than 26%, indicating a sharp drop in yellow emission. The reduction in yellow photon emission could be due to a mechanism such as increased absorption by the molding compound of the PLCC package as it ages[21] or a drop in the quantum efficiency of the phosphor. Since this lamp model exhibited the CSM-4 behavior that is only observed in PLCC packages, it is likely that increased absorption by the molding compound as aging occurs is at least partially responsible for the observed behavior.

In contrast, the B_f/B_i ratio for Lamp model 12-85 was much smaller than the corresponding Y_f/Y_i ratio consistent with the observed yellow chromaticity shift. The large difference in these two numbers suggests that blue photons are being converted by the phosphor at a higher ratio as the testing proceeds. This is consistent with a mechanism in which cracking and delamination of the silicone binder in the phosphor layer introduces a low-index substance (i.e., air) into the light path in the LED, reducing extraction efficiency and changing the path of blue photons through the phosphor.

Table 10. Comparison of the photometric properties of the lamp models where all five samples exhibited parametric failure for excess chromaticity shift.

	B_f/B_i		Y_f/Y_i		$\Delta u'v'$	
ID	**Average**	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**
12-74	0.910	0.009	0.733	0.022	0.0097	0.0016
12-85	0.464	0.011	0.767	0.025	0.0152	0.0009

5 Conclusions

This report examines the same LED lamp models covered in CALiPER Report 20.4, but focuses more on the design and operational conditions impacting chromaticity maintenance of individual samples, rather than on lamp model averages. This approach was taken to facilitate a classification of the CSMs for each sample, and a comparison of chromaticity-shift modes across all samples of a particular lamp model and between lamp models with similar characteristics. In general, samples of the same PAR38 lamp model usually exhibited the same chromaticity-shift behavior, and there were similarities in chromaticity-shift trends between lamp models with similar LED packages. However, the timing of different chromaticity shifts varied somewhat between lamp models and appears to depend upon lamp design, characteristics of the LED packages used in the lamp model, and lamp operational conditions.

The PAR38 lamp models examined in this study exhibited a systematic chronology in the chromaticity shift that depended on LED package type and operational conditions such as LED board temperature and drive current. All samples in this study were found to initially shift in the blue direction, with $\Delta u'v'$ values of 0.003 or less. Subsequent shifts tended to be first in the green direction followed by a shift in the yellow direction. This led the creation of a chronology for the four different chromaticity-shift modes to describe the behavior found in these samples:

- <u>Chromaticity Shift Mode 1</u> (CSM-1) involves a continuation of the chromaticity shift in the blue direction (i.e., u' and v' both decrease) roughly along the blue-yellow line. This chromaticity-shift mode 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 would result in the appearance of additional CSMs in these samples.
- <u>Chromaticity Shift Mode 2</u> (CSM-2) involves a shift off of the blue-yellow line and in the green direction (i.e., u' decreases and v' remains unchanged or increases slightly). This chromaticity-shift mode 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.
- <u>Chromaticity Shift Mode 3</u> (CSM-3) involves a prolonged shift in the yellow direction after the initial blue shift. This chromaticity-shift mode produces a characteristic hook pattern in the chromaticity coordinates, with the yellow shift characterized by an increase in first v' followed by u'. The primarily cause of CSM-3 behavior 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. CSM-3 behavior was prevalent in HP LEDs and occurred during the test period in 72% of the samples using this LED package, and in most of the parametric failures for excessive chromaticity shift.
- <u>Chromaticity Shift Mode 4</u> (CSM-4) involves a short initial shift in the blue direction, followed by a shift in the yellow direction, followed by a second blue shift. This chromaticity-shift mode produces a characteristic double-hook pattern in the time-based profile of chromaticity coordinates. CSM-4 behavior was only found in samples containing PLCC LED packages, suggesting that the primary cause of this chromaticity shift mode is oxidation of the molding resin used in PLCC devices. All of the parametric failures for excessive chromaticity shift in samples with PLCC LEDs occurred through a CSM-4 behavior, indicating that this type of chromaticity shift can produce parametric failure in PLCC devices.

The findings from this study provides a means to understand the chronology of chromaticity shifts in relatively simple LED lighting devices such as PAR38 lamps. While the applicability of these findings to more complex LED products, such as luminaires and lamps with isotropic radiation patterns is not known, this approach may provide a convenient starting point for analyzing chromaticity shifts in more-complex SSL products.

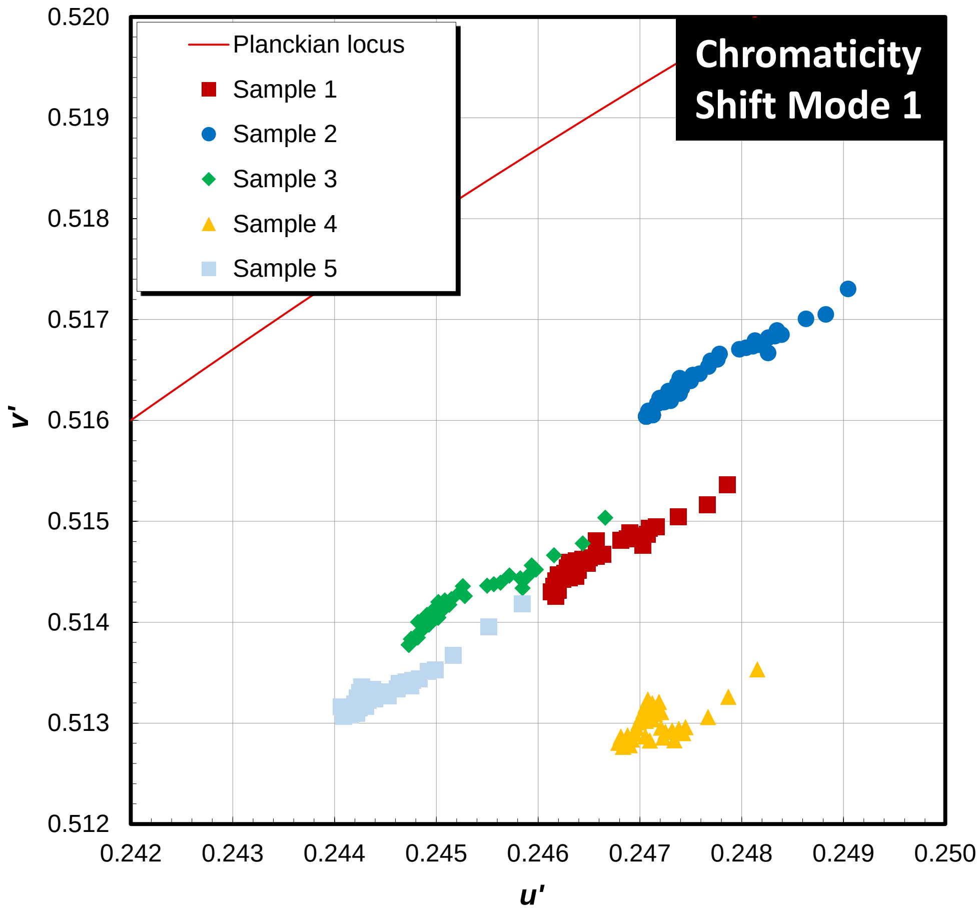
6 Appendix A: Lamp Identification and Rated Lifetime

Table A1. Identifying information for the lamps included in the CALiPER PAR38 long-term performance investigation. For additional product performance information, see CALiPER Application Summary Report 20.

ID	Brand	Model	Rated Lifetime (hours)	ENERGY STAR
12-64	TCP	LED17E26P3830KNFL	50,000	Yes
12-65	Lighting Science Group	DFN 38 W27 V2 NFL 120	50,000	Yes
12-66	Eiko	LEDP-11WPAR38/SP/830-DIM	40,000	Yes
12-67	Cree LED Lighting	LRP38-10L-30K-12D	50,000	Yes
12-72	Sylvania	LED21PAR38/DIM/P/930/FL30 (78745)	25,000	Yes
12-73	Feit Electric	PAR38/HP/LED	30,000	No
12-74	Satco Products, KolourOne	S8853	30,000	No
12-75	GE Lighting	LED17P38S830/17 (64035)	50,000	Yes
12-78	Toshiba E-CORE	19P38/835SP8 (LDRB2035NE6USD)	40,000	Yes
12-79	Westinghouse	18PAR38/LED/DIM/30 (03434)	30,000	No
12-80	MaxLite MaxLED	SKR3817SPDLED30	25,000	Yes
12-81	Halco Lighting ProLED	PAR38/16WW/NFL/LED (80034)	35,000	No
12-82	Litetronics	LP15566FL4D (64350)	50,000	Yes
12-85	LEDnovation	LED-PAR38-90-1WD-1WF	50,000	No
12-86	Solais Lighting	LR38/10/30K/18W/1025/GY	50,000	No
12-88	Lumena	MS-PAR38-120V60-27	50,000	No
12-89	NuVue	NV-PAR38I20W26C (NV/PAR38/9.2 WW NFL 26 CR)	40,000	No
12-90	Acculamp	ALSP38 900L R9	50,000	Yes
12-92	Samsung	SI-P8V181DB0US (SLA0-PAR38-75-AYD-830-25R)	40,000	No
12-95	MSI Solid State Lighting	IPAR3830101D	50,000	Yes
12-96	Array Lighting	AE26PAR38183010	25,000	No
12-97	Havells	16W/LED/PAR38/FL (48541)	15,000	No
12-99	LEDirect NaturaLED	LED17PAR38/DIM/NFL/30K	40,000	Yes
12-100	aleddra	PAR38-S-D-45-30	25,000	No
12-134	Duracell	DL-P38F-60-30K-WH	50,000	Yes
12-135	Axiom	AP10W27V120	50,000	No
12-140	Philips	BC19.5PAR38/AMB/3000K/ FL25 DIM 120V	25,000	Yes
12-144	Solais Lighting	LRP38/25/30	50,000	Yes
12-145	Seesmart	15W Warm White 45° LED PAR 38 (180025)	30,000	No
12-146	Zenaro	SL-PAR38C/H/P16/50/E30/TD/26/LAC	25,000	Yes
12-147	Lights of America	2213DLEDNP38 - LF3-8	25,000	No
12-148	LEDWaves	LW10-NYC-008-WW-DM	30,000	No
BK09-111	Philips	CDM-i 25W/PAR38/FL/3K	15,000	
BK12-63	Philips	EL/A PAR38 23W 2PC (9292689721102)	10,000	
BK12-68	GE	60PAR/HIR/FL30 (18626)	3,000	
BK12-69	Sylvania	75PAR/CAP/SPL/WSP12 120V	2,500	
BK12-71	Philips	75PAR38/HAL/SP10	3,000	
BK12-141	Feit Electric	ESL23PAR/ECO	10,000	

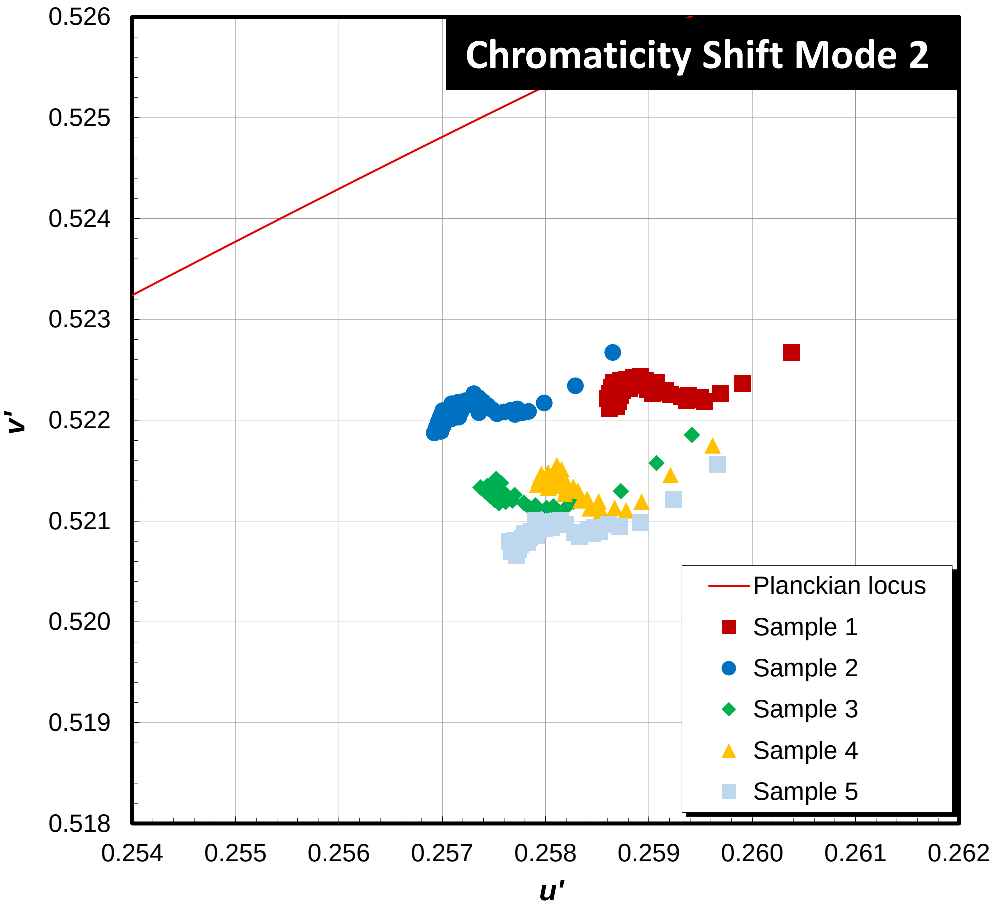
7 Appendix B: Individual Sample Performance

Sample 12-64: TCP PAR 38



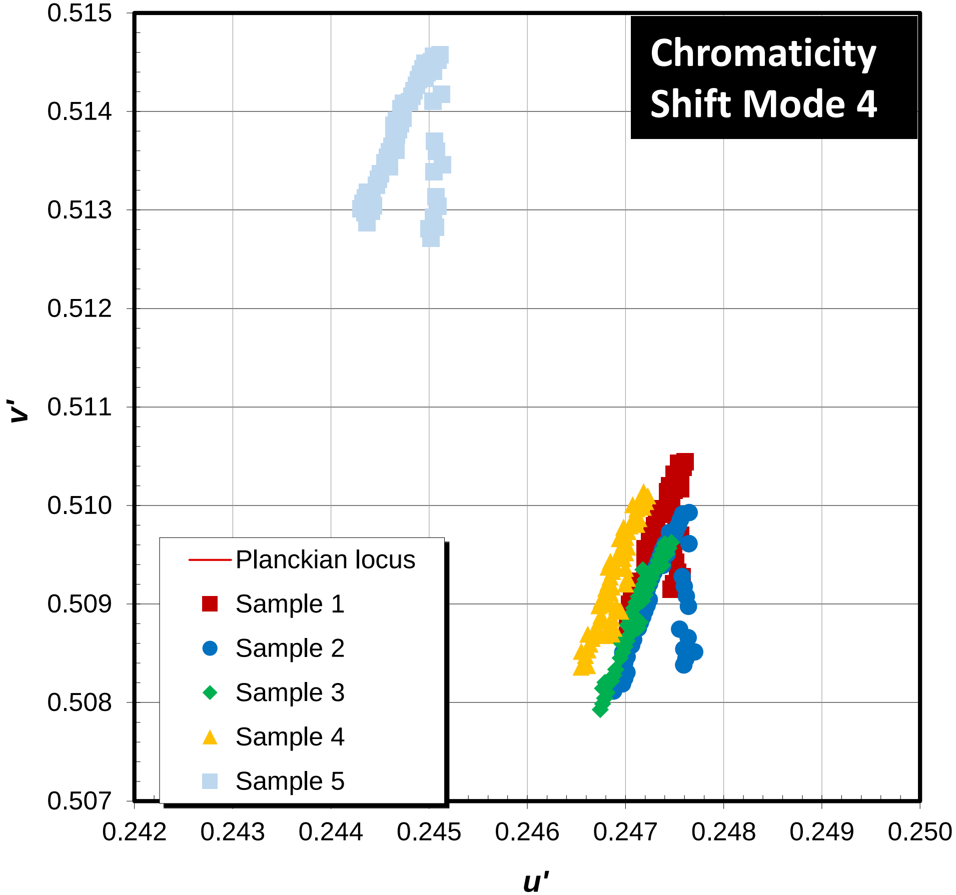
LED Type: COB
Number of LED Packages: 1
Power: 17 Watts
Initial Luminous Flux: 1384 lumens
Lumen Maintenance @ 13.9K hr: 0.92
Initial CRI: 83
Average Initial CCT: 3123 K
Average Final CCT: 3173 K
T_{sp} (@ 45°C ambient): 78°C
Date of Manufacture: Unknown
Final Color Shift: $\Delta u'v' = 0.0018$

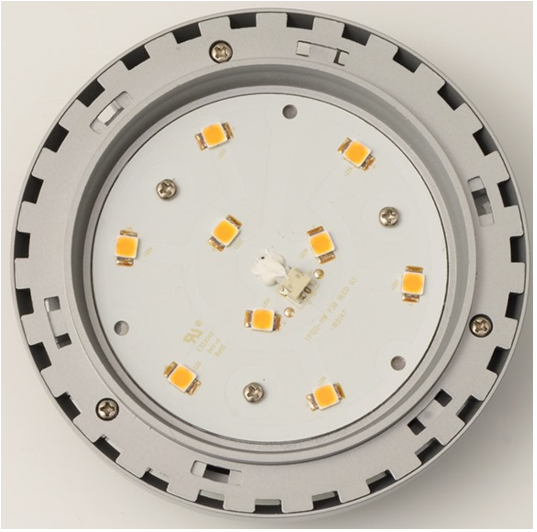
Sample 12-65: Lighting Science Group Definity PAR38



LED Type: COB
Number of LED Packages: 1
Power: 24 Watts
Initial Luminous Flux: 1295 lumens
Lumen Maintenance @ 13.9K hr: 0.97
Initial CRI: 84
Average Initial CCT: 2785 K
Average Final CCT: 2828 K
T_{sp} (@ 45°C ambient): 87°C
Date of Manufacture: Unknown
Final Color Shift : $\Delta u'v' = 0.0019$

Sample 12-66: Eiko PAR38

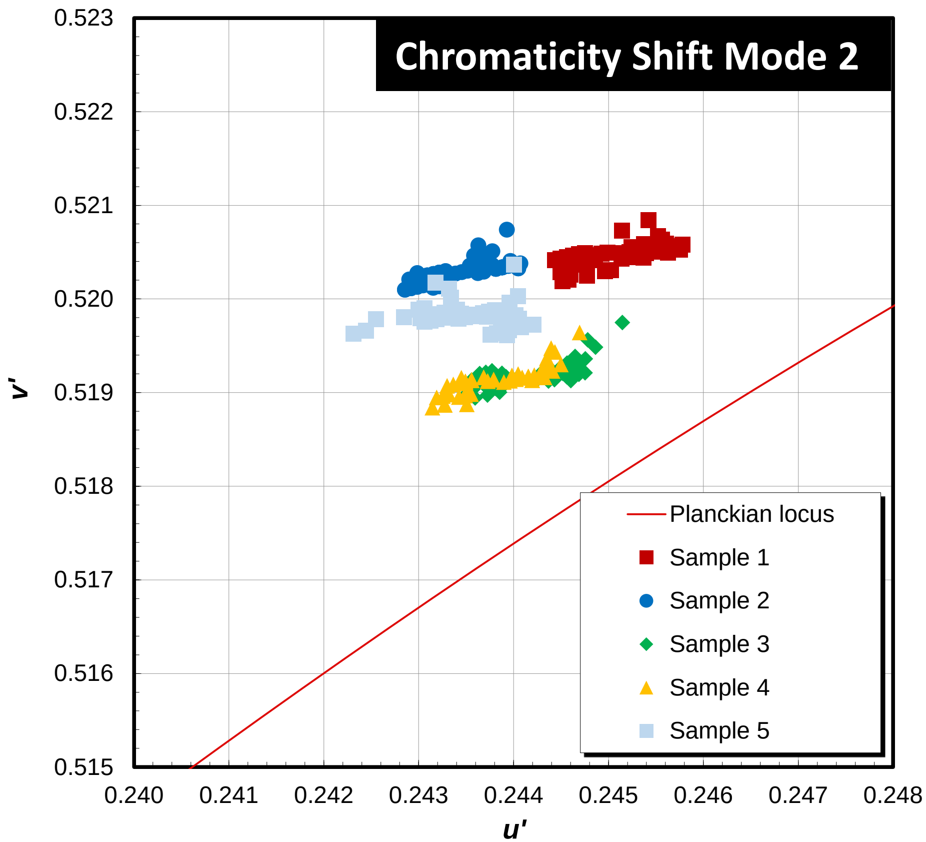




LED Type: PLCC
Number of LED Packages: 9
Power: 11 Watts
Initial Luminous Flux: 536 Lumens
Lumen Maintenance @ 13.9K hr: 0.96
Initial CRI: 83
Average Initial CCT: 3186 K
Average Final CCT: 3203 K
T_j (@ 45°C ambient): 83°C
Date of Manufacture: October 4th, 2010
Final Color Shift : $\Delta u'v' = 0.0006$

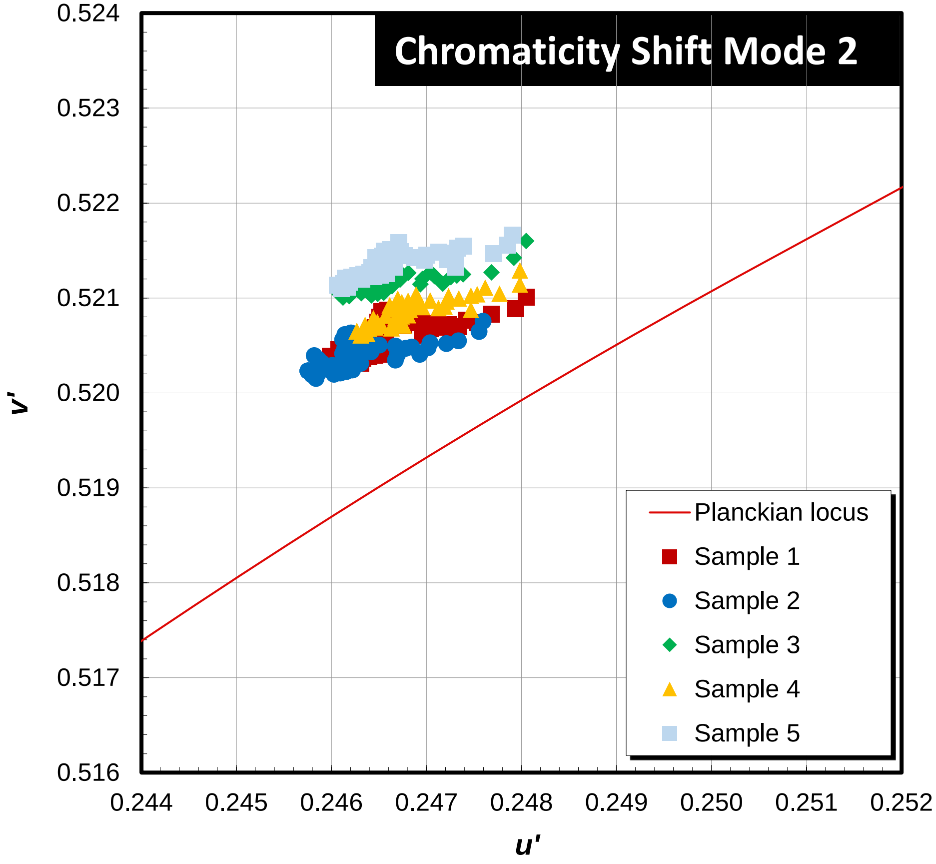
Three stage color shift:
- Small blue shift
- Yellow shift to 3000 hours
- Second blue shift

Sample 12-67: Cree LRP38-10L PAR38



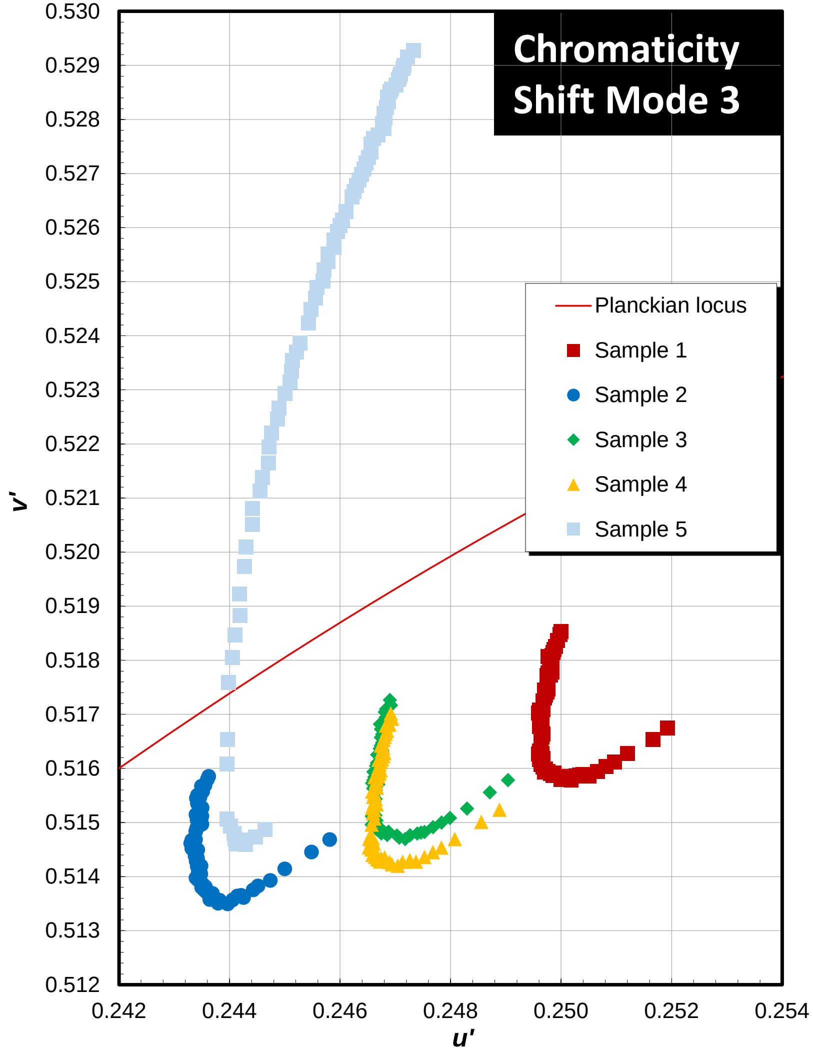
LED Type: Hybrid LED Package
Number of LED Packages: 7
Power: 11 Watts
Initial Luminous Flux: 1132 Lumens
Lumen Maintenance @ 13.9K hr: 1.01
Initial CRI: 96
Average Initial CCT: 3159 K
Average Final CCT: 3191 K
T_j (@ 45°C ambient): 78°C
Date of Manufacture: June 2011
Final Color Shift : $\Delta u'v' = 0.0012$

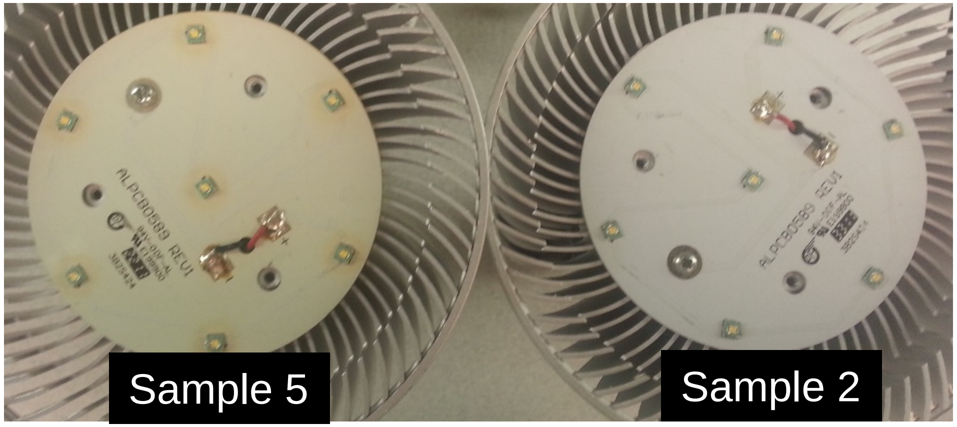
Sample 12-72: Sylvania LED21 PAR38



LED Type: COB
Number of LED Packages: 1
Power: 20 Watts
Initial Luminous Flux: 1378 Lumens
Lumen Maintenance @ 13.9K hr: 0.96
Initial CRI: 94
Average Initial CCT: 3066 K
Average Final CCT: 3120 K
T_{sp} (@ 45°C ambient):
Date of Manufacture: Unknown
Final Color Shift: $\Delta u'v' = 0.0002$

Sample 12-73: Feit PAR38



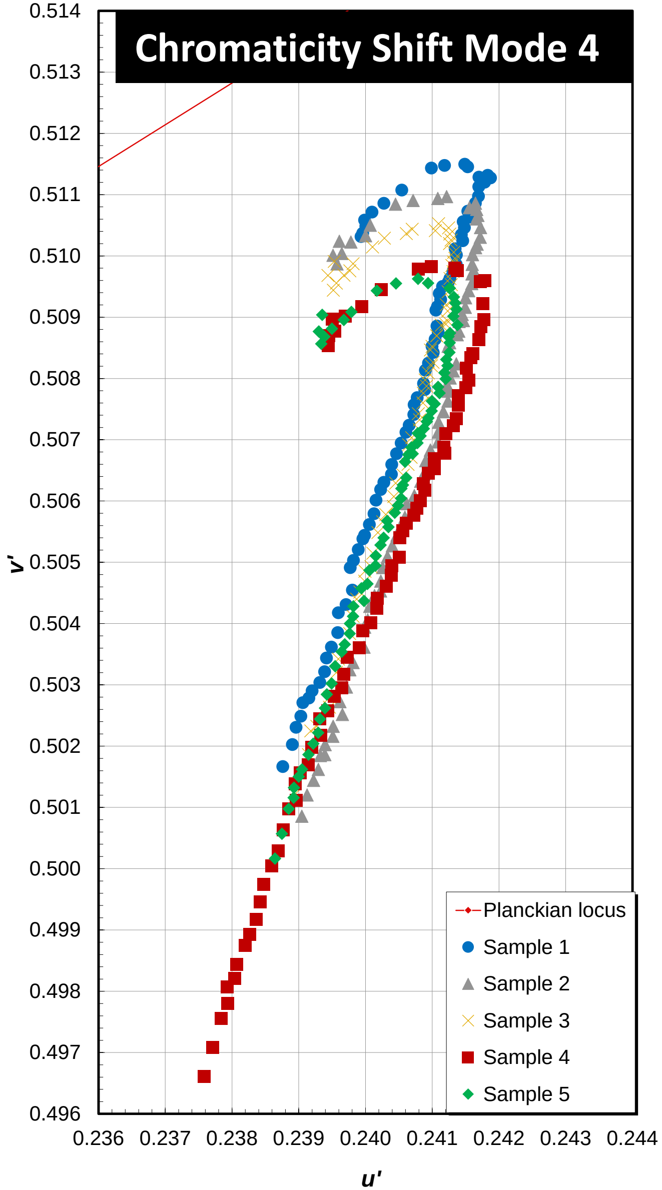


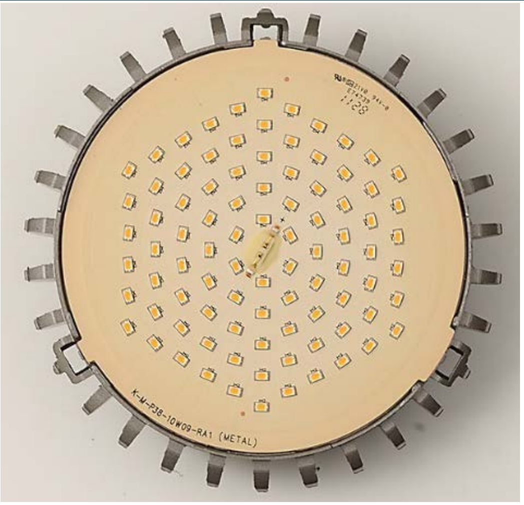
Average Final CCT: 3106 K
LED Type: HP-LED
Number of LED Packages: 7
Power: 15 Watts
Initial Luminous Flux: 844 Lumens
T_j (@ 45°C ambient): 95°C
Date of Manufacture: Mid 2011
Final Color Shift: Δu′v′ = 0.0026 (4 stable lamps) Δu'v' = 0.0147 (outlier)
Stable lamps: Generally blue shift followed by gradual yellow shift.
Other lamp: Small blue shift followed by sharp yellow shift. Sharp loss of blue flux.

Lumen Maintenance @ 13.9K hr: 0.97 (4)
Lumen Maintenance @ 13.9K hr: 0.84
Initial CRI: 83
Average Initial CCT: 3106 K

Sample 12-74: Satco Products, KolourOne – Model S8853

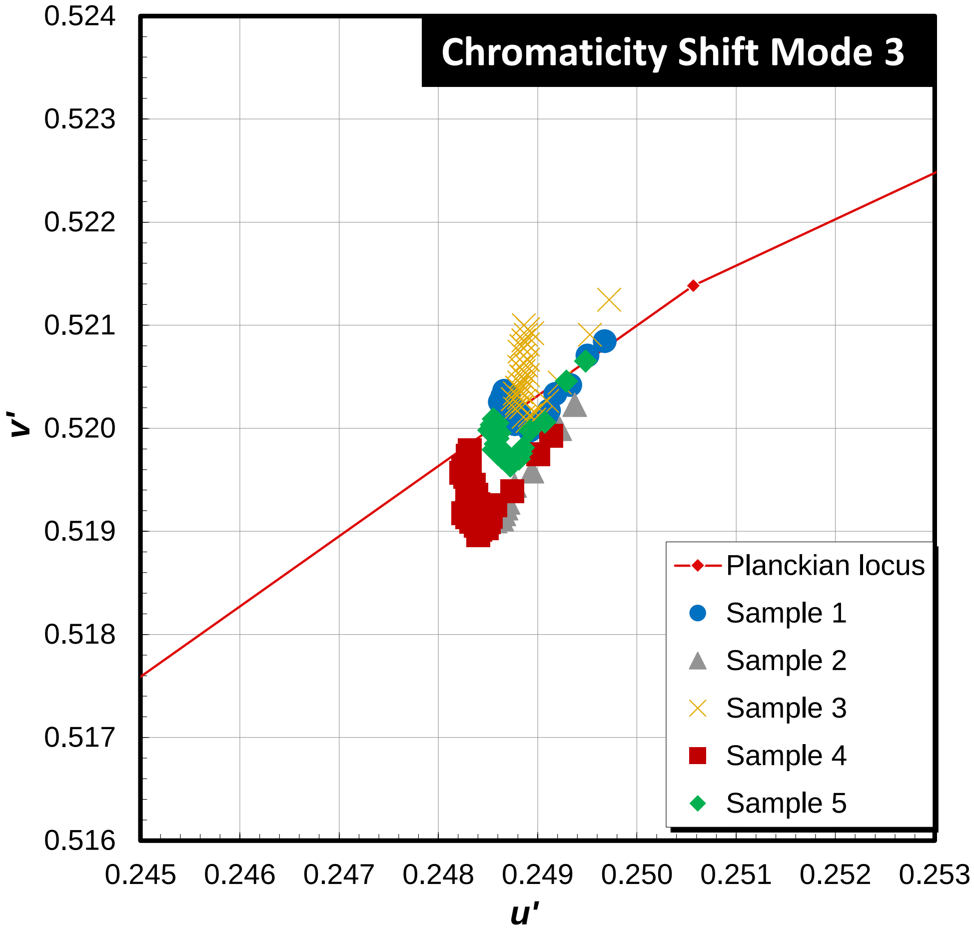
5 Parametric Failures for Color Shift

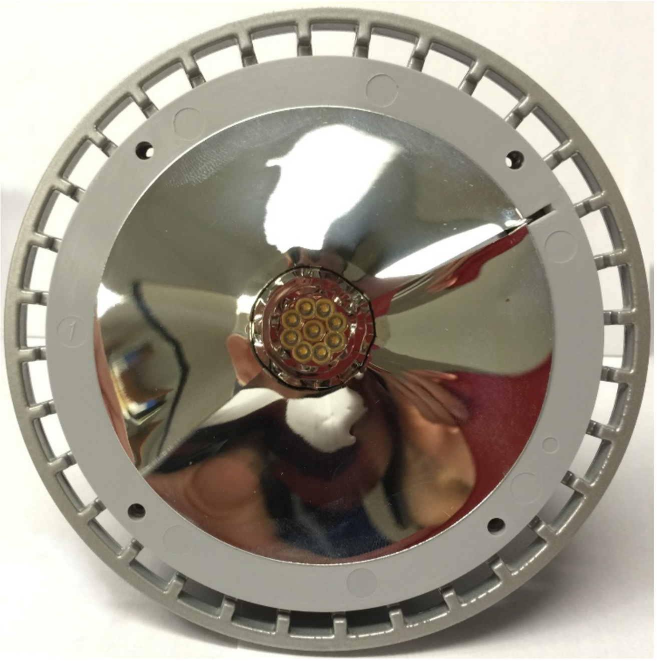




LED Type: PLCC
Number of LEDs: 90
Power: 17 Watts
Initial Luminous Flux: 1128 Lumens
Lumen Maintenance @ 13.9K hr: 0.74
Initial CRI: 84
Average Initial CCT: 3397 K
Average Final CCT: 3540 K
T_j (@ 45°C ambient): 81°C
Date of Manufacture: July 2011
Cause of Failure: Discoloration of interior walls of MPLEDs.
Final Color Shift: $\Delta u'v' = 0.0097$. Significant discoloration of solder mask.

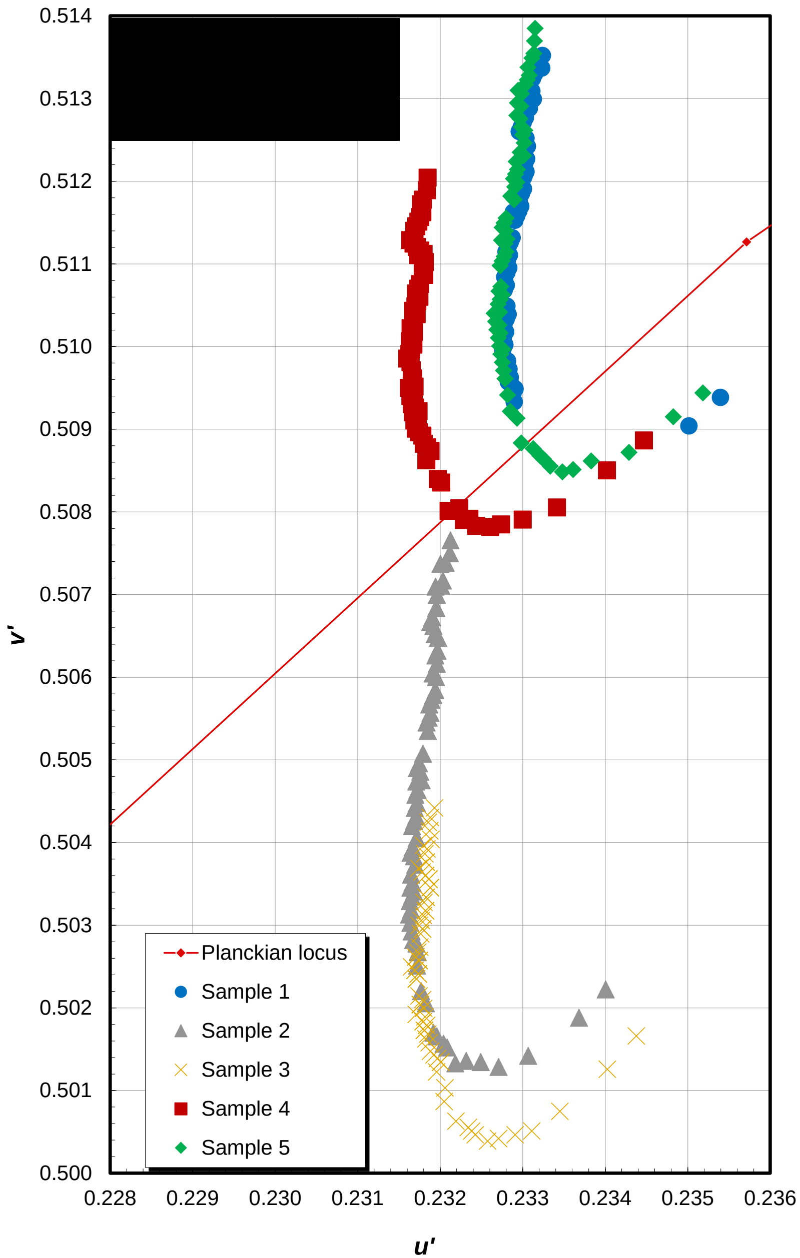
Sample 12-75: General Electric PAR38





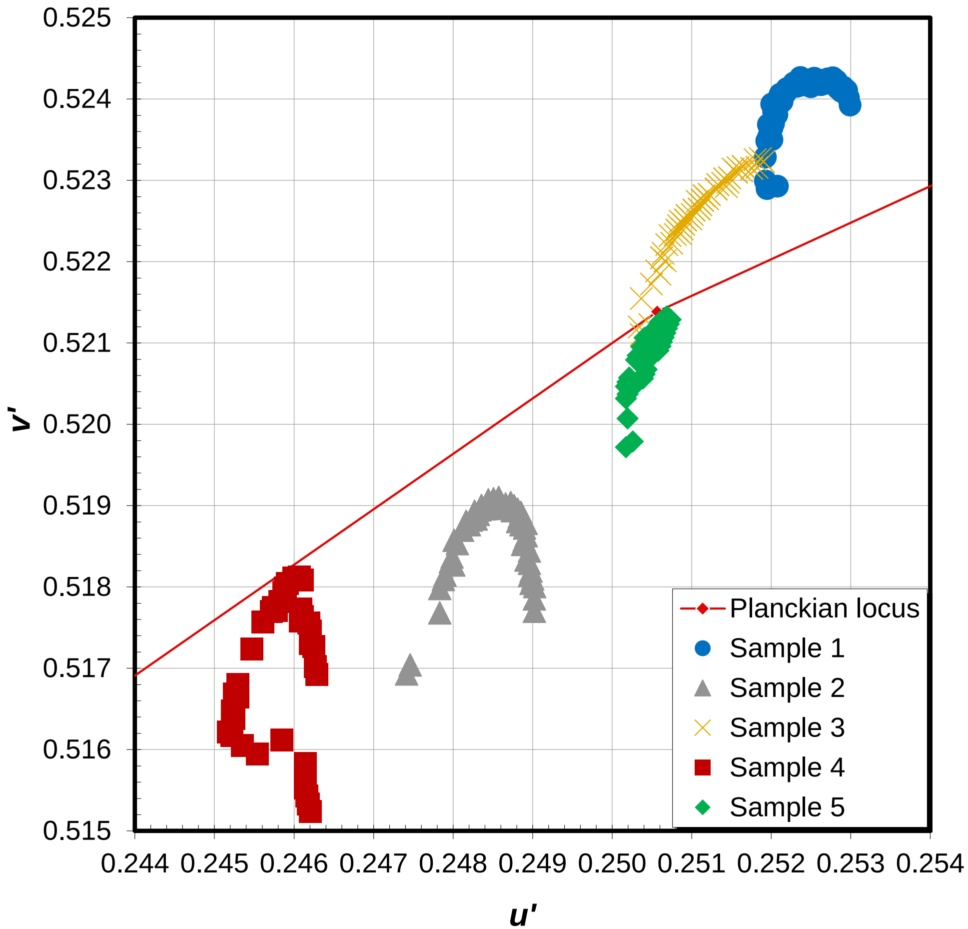
LED Type: HP-LED
Number of LEDs: 9
Power: 16 Watts
Initial Luminous Flux: 997 Lumens
Lumen Maintenance @ 13.9K hr: 0.97
Initial CRI: 82
Average Initial CCT: 3032 K
Average Final CCT: 3059 K
T_j (@ 45°C ambient): 88°C
Date of Manufacture: Dec. 2010
Final Color Shift: $\Delta u'v' = 0.0011$

Sample 12-78: Toshiba E-CORE PAR38



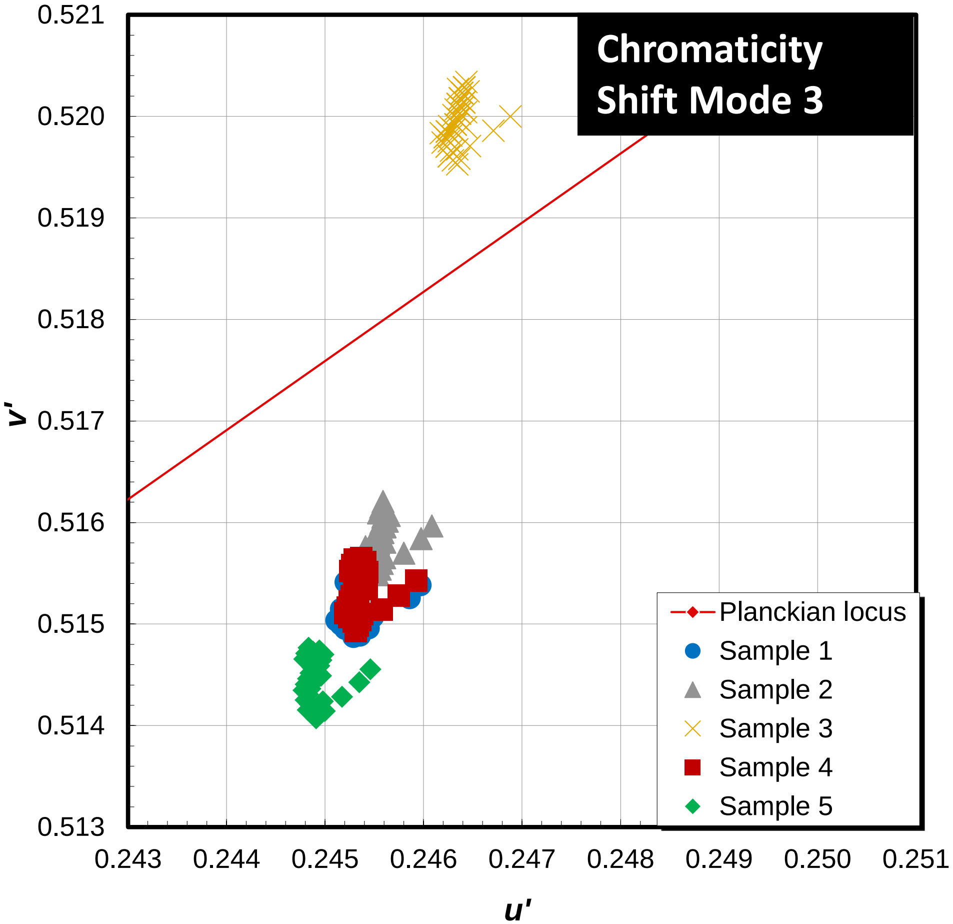
LED Type: HP-LED
Number of LED Packages: 10
Power: 18 Watts
Initial Luminous Flux: 1042 Lumens
Lumen Maintenance @ 13.9K hr: 0.94
Initial CRI: 85
Average Initial CCT: 3594 K
Average Final CCT: 3617 K
T_j (@ 45°C ambient): 94°C
Date of Manufacture: Feb. 2011
Final Color Shift: $\Delta u'v' = 0.0046$

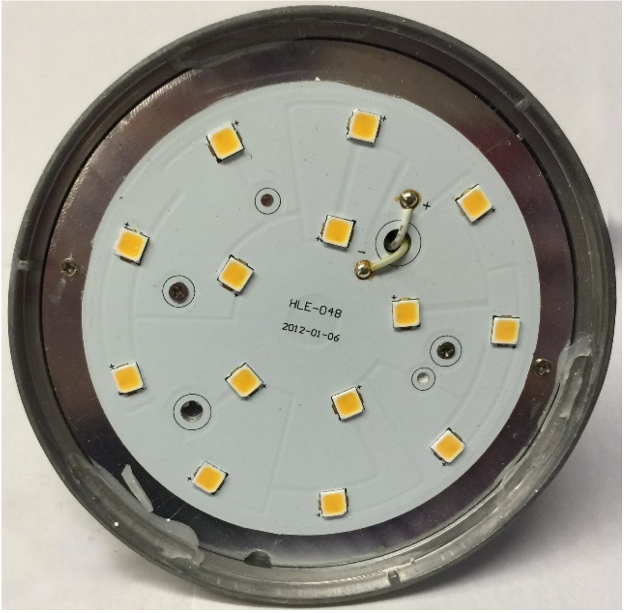
Sample 12-79: Westinghouse PAR38



LED Type: COB
Number of LED Packages: 1
Power:
Initial Luminous Flux: 938 Lumens
Lumen Maintenance @ 13.9K hr: 0.85
Initial CRI: 83
Average Initial CCT: 3048 K
Average Final CCT: 3027 K
T_{sp} (@ 45°C ambient): 67°C
Date of Manufacture: June 2012
Final Color Shift: $\Delta u'v'$ = 0.0009 (Average)
Wide variation in initial color point and color shift direction.

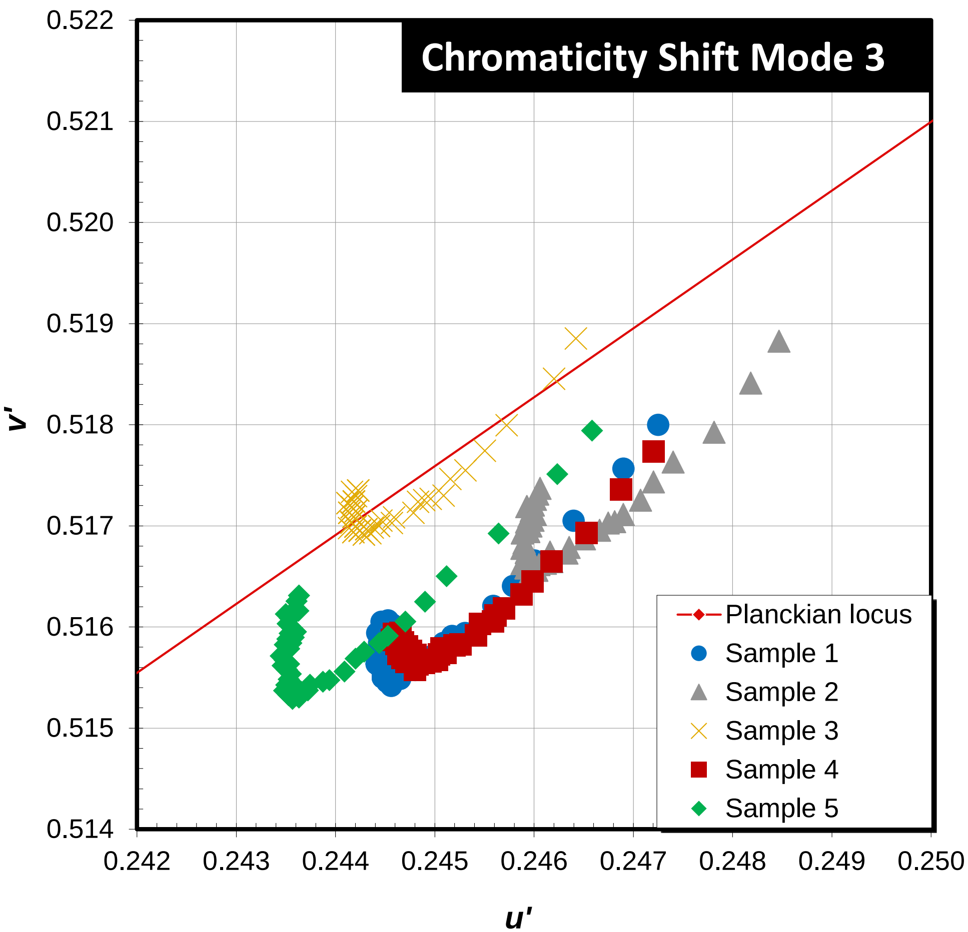
Sample 12-80: MaxLite MaxLED PAR38





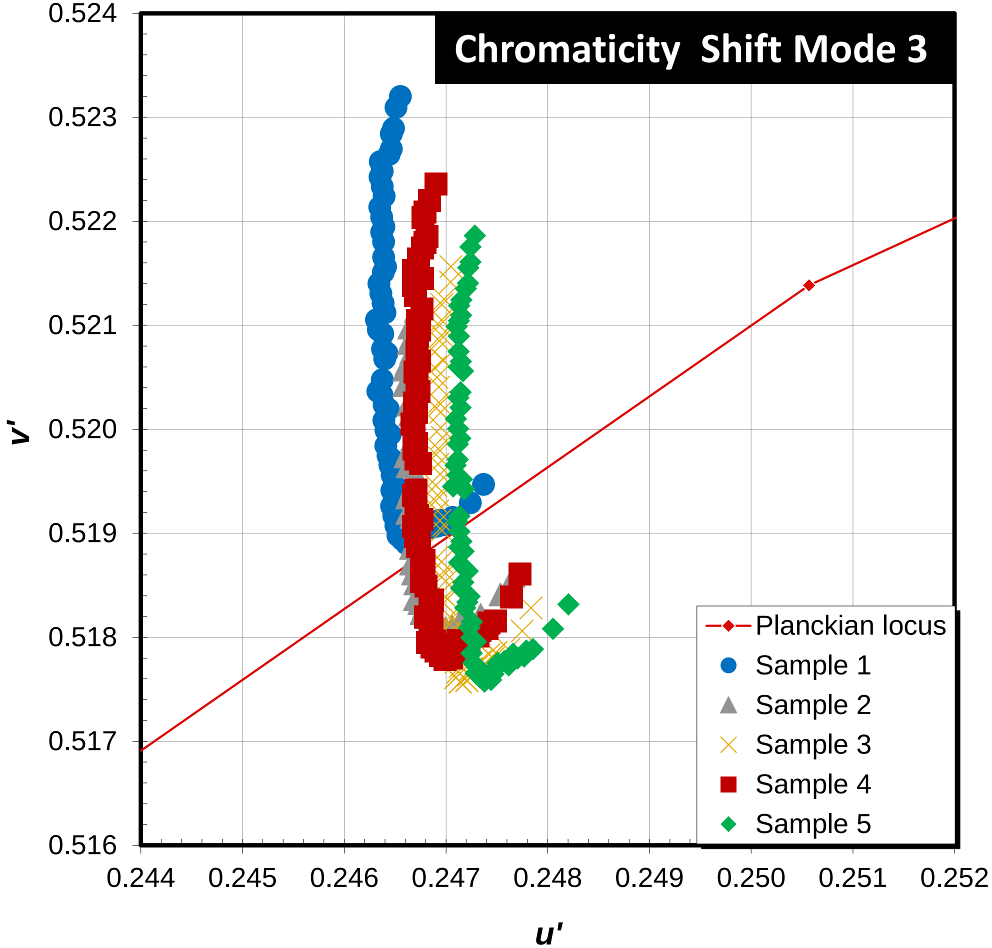
LED Type: PLCC
Number of LED Packages: 14
Power: 16 Watts
Initial Luminous Flux: 1321 Lumens
Lumen Maintenance @ 13.9K hr: 0.98
Initial CRI: 86
Average Initial CCT: 3152 K
Average Final CCT: 3168 K
T_j (@ 45°C ambient): 85°C
Date of Manufacture: Jan. 2012
Final Color Shift: $\Delta u'v' = 0.0006$ (Average)

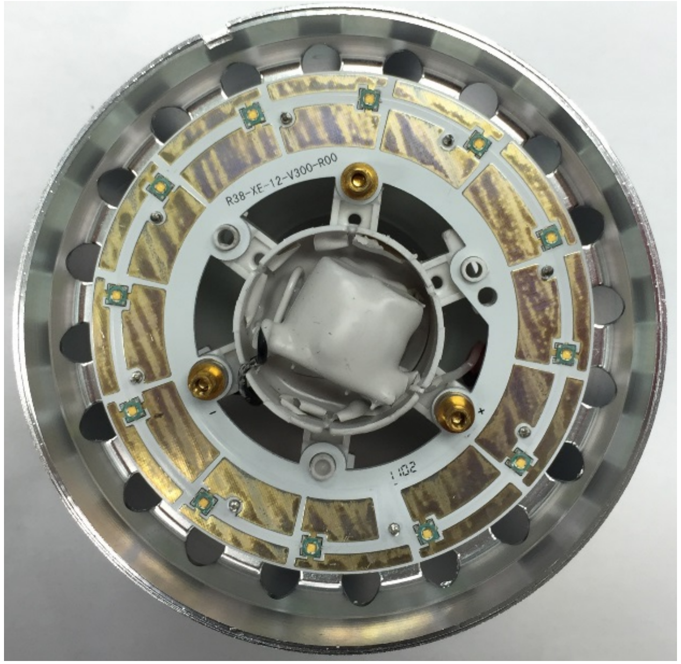
Sample 12-81: HALCO ProLED PAR38 Lamp



LED Type: COB
Number of LED Packages: 1
Power: 15 Watts
Initial Luminous Flux: 1294 Lumens
Lumen Maintenance @ 13.9K hr: 0.92
Initial CRI: 82
Average Initial CCT: 3107 K
Average Final CCT: 3189 K
T_{sp} (@ 45°C ambient): 77°C
Date of Manufacture: Unknown
Final Color Shift: Δu′v′ = 0.0031 (Average)
Initial blue shift followed by yellow.

Sample 12-82: Litetronics PAR38 Lamp

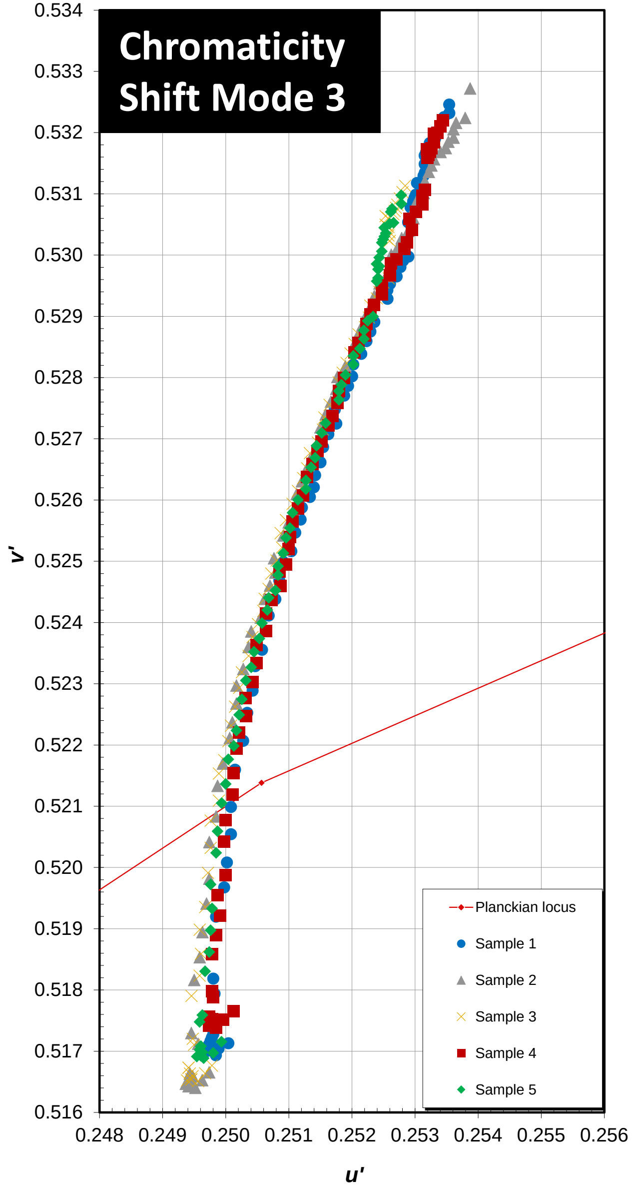




LED Type: HP-LED
Number of LED Packages: 12
Power: 14.5 Watts
Initial Luminous Flux: 993 Lumens
Lumen Maintenance @ 13.9K hr: 0.96
Initial CRI: 83
Average Initial CCT: 3089 K
Average Final CCT: 3088 K
T_j (@ 45°C ambient): 87°C
Date of Manufacture: June 2011
Final Color Shift: $\Delta u'v' = 0.0036$ (Average).

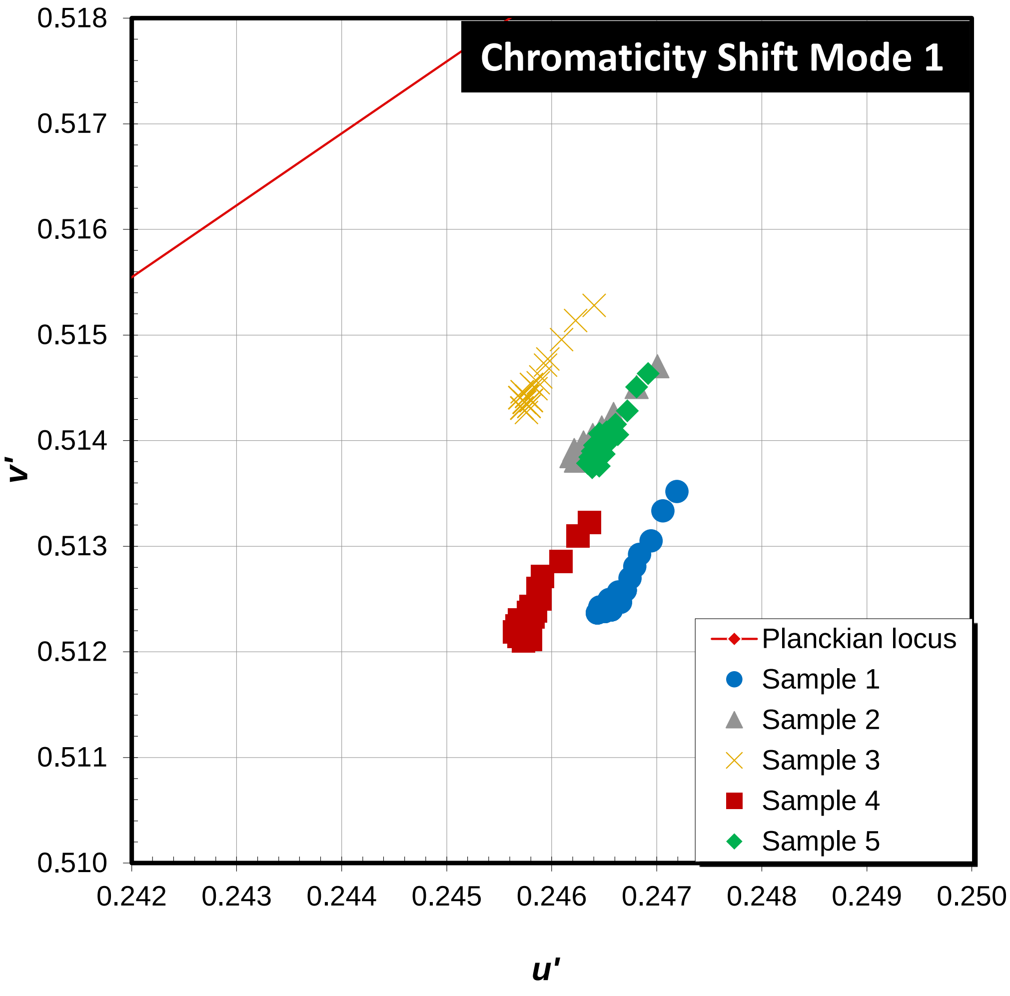
Sample 12-85: LEDnovation PAR38 Lamp

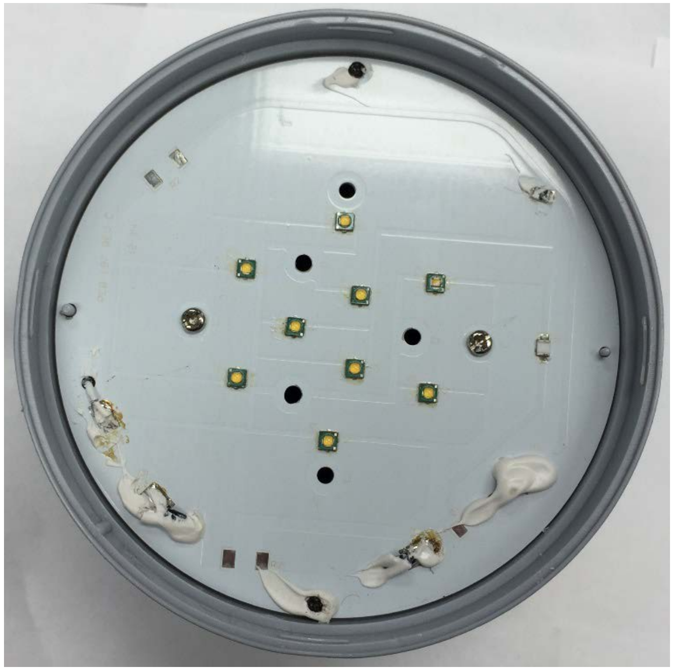
5 Parametric Failures for Color Shift



LED Type: COB
Number of LED Packages: 1
Power: 16 Watts
Initial Luminous Flux: 1048 Lumens
Lumen Maintenance @ 13.9K hr: 0.76
Initial CRI: 82
Average Initial CCT: 3045 K
Average Final CCT: 2876 K
T_{sp} (@ 45°C ambient): 89°C
Date of Manufacture: May 2010
Cause of Failure: Unknown but magnitude of yellow color shift is suggestive of encapsulant aging.
Final Color Shift: $\Delta u'v' = 0.0152$ (Average)

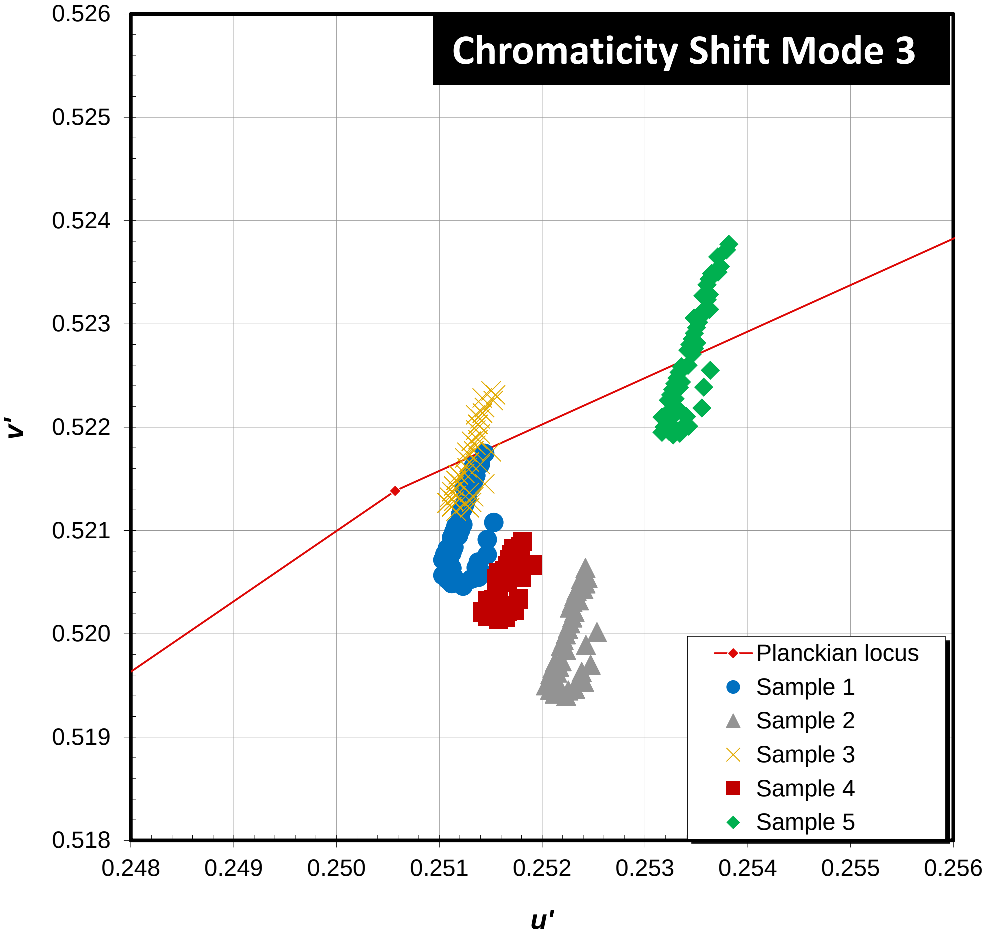
Sample 12-86: Solais PAR38 Lamp

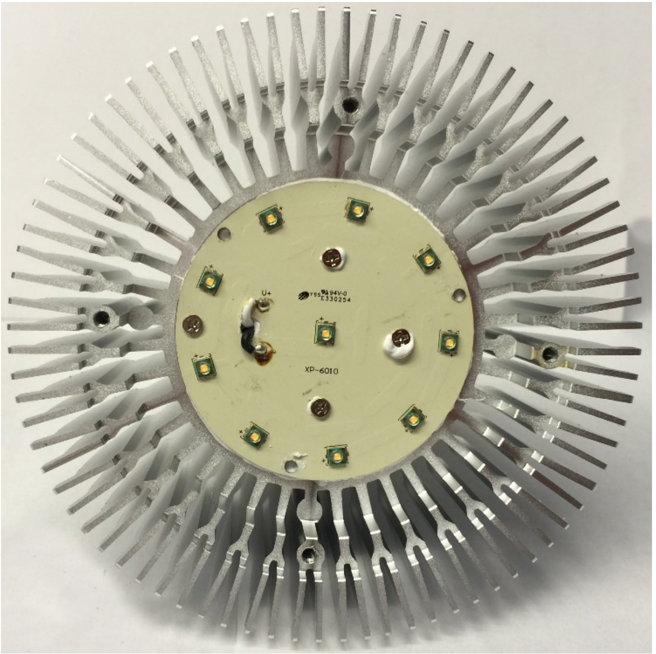




LED Type: HP-LED
Number of LED Packages: 9
Power: 18 Watts
Initial Luminous Flux: 1307 Lumens
Lumen Maintenance @ 13.9K hr: 1.01
Initial CRI: 82
Average Initial CCT: 3148 K
Average Final CCT: 3171 K
T_j (@ 45°C ambient): 78°C
Date of Manufacture: Aug. 2012
Final Color Shift: $\Delta u'v'$ = 0.0010 (Average)

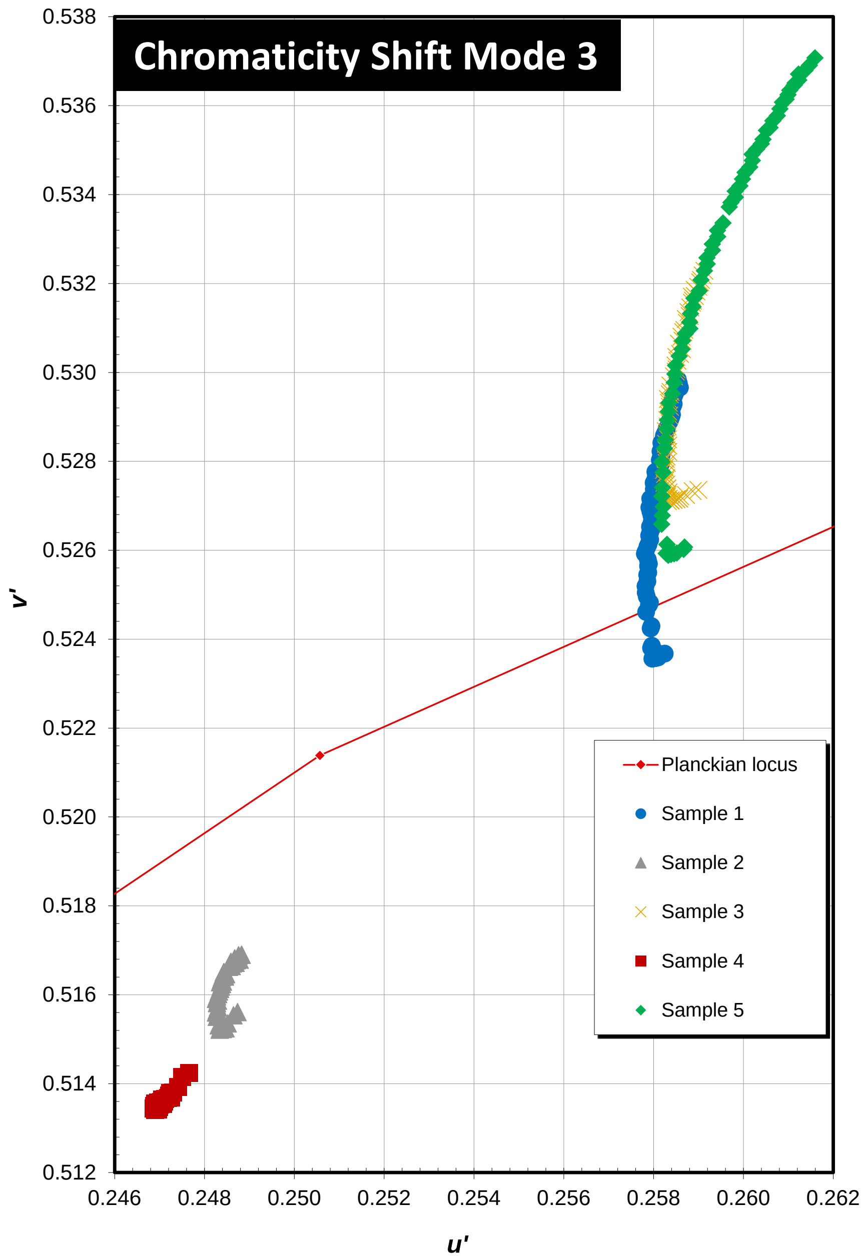
Sample 12-88: Lumena PAR38 Lamp

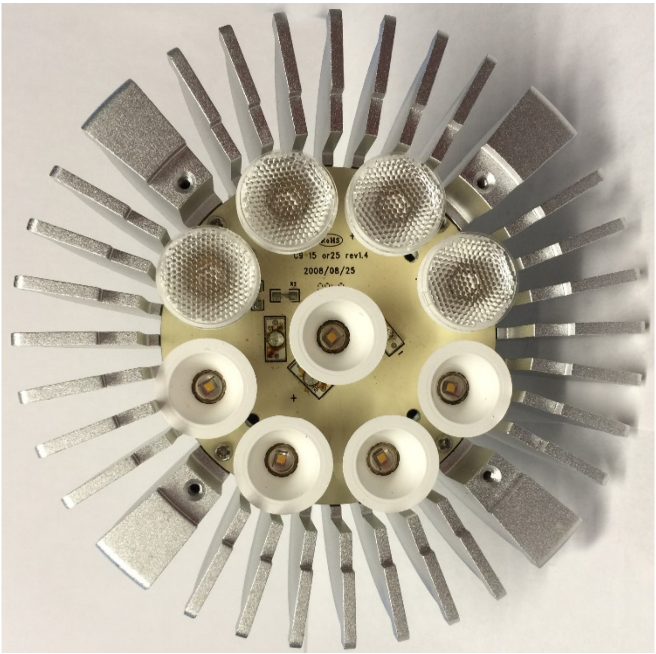




LED Type: HP-LED
Number of LED Packages: 10
Power: 15 Watts
Initial Luminous Flux: 1090 Lumens
Lumen Maintenance @ 13.9K hr: 0.97
Initial CRI: 80
Average Initial CCT: 2960 K
Average Final CCT: 2957 K
T_j (@ 45°C ambient): 80°C
Date of Manufacture: Sep. 2012
Final Color Shift: $\Delta u'v' = 0.0007$ (Average)

Sample 12-89: NuVue PAR38 Lamp

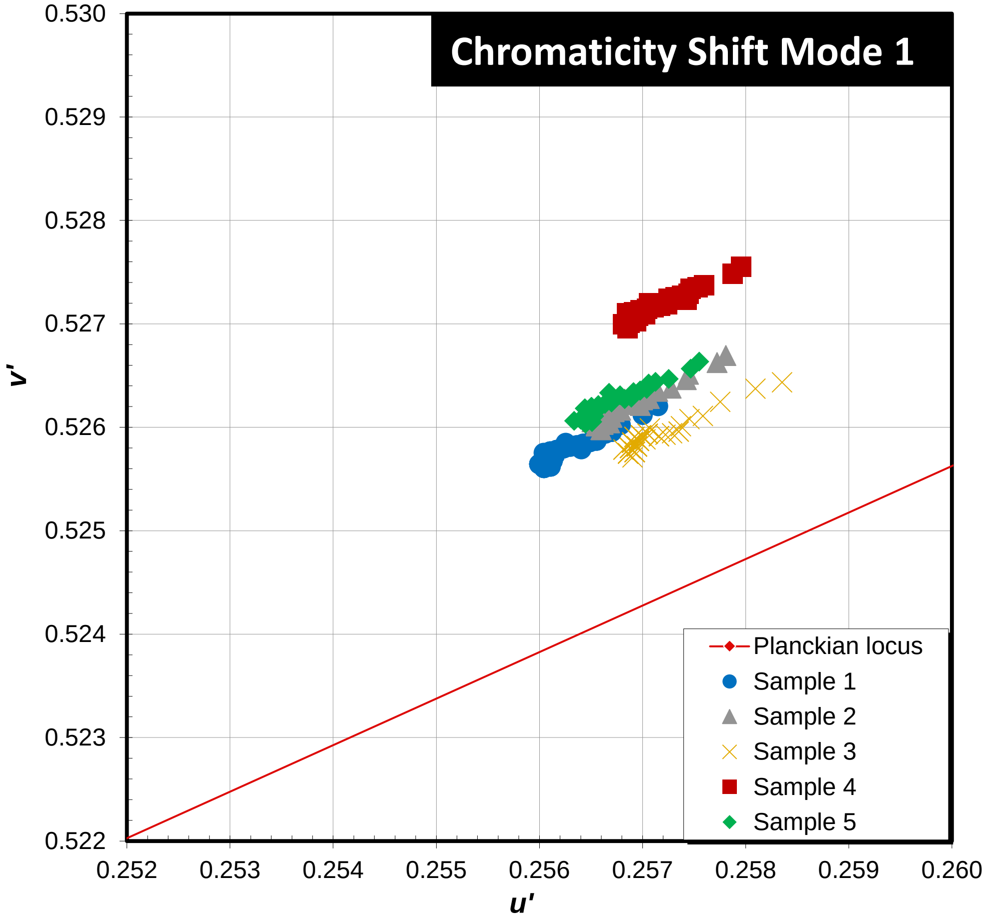




LED Type: HP-LED
Number of LED Packages: 9
Power: 14 Watts
Initial Luminous Flux: 818 Lumens
Lumen Maintenance @ 13.9K hr: 0.92
Initial CRI: 82
Average Initial CCT: 2915 K
Average Final CCT: 2885 K
T_j (@ 45°C ambient): 85°C
Date of Manufacture: Aug. 2008
Final Color Shift: $\Delta u'v'$ = 0.0045 (Average)

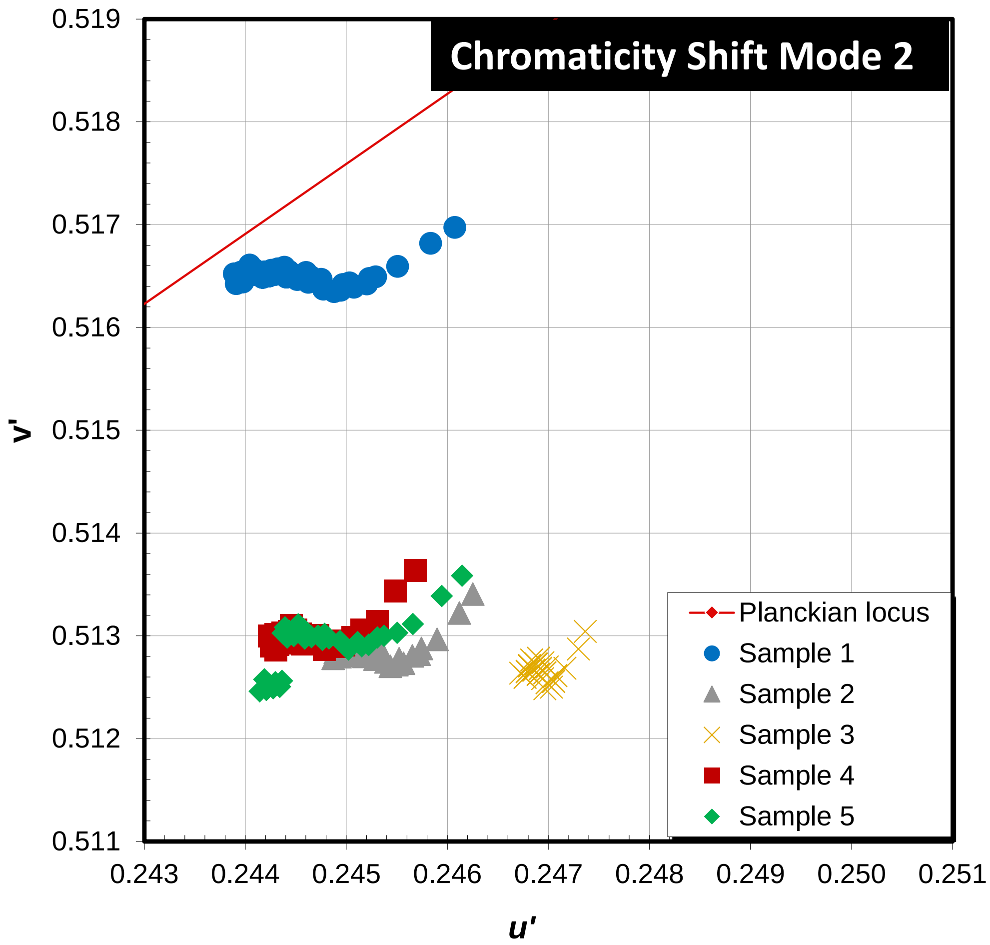
Sample 12-90: Acculamp PAR38 Lamp

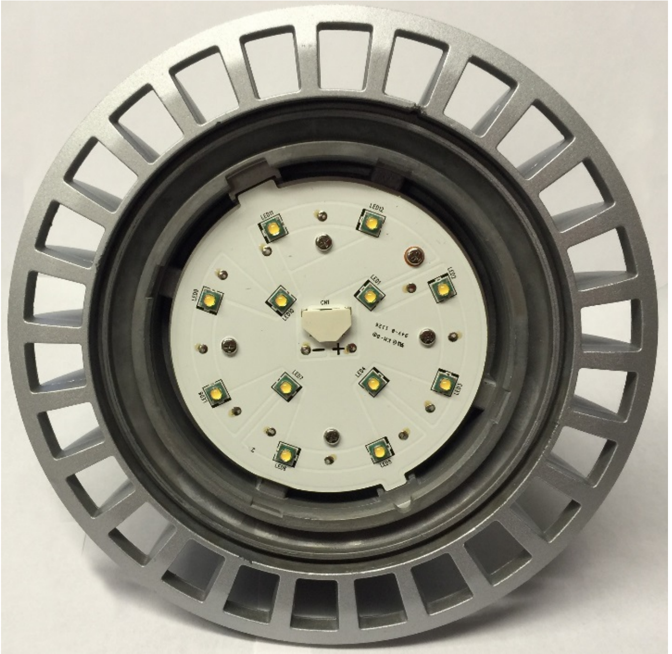
1 Catastrophic Failure



LED Type: COB
Number of LED Packages: 1
Power: 17 Watts
Initial Luminous Flux: 1096 Lumens
Lumen Maintenance @ 13.9K hr: 0.94
Initial CRI: 95
Average Initial CCT: 2803 K
Average Final CCT: 2836 K
T_{sp} (@ 45°C ambient): 86°C
Date of Manufacture: Mar. 2009
Final Color Shift: $\Delta u'v' = 0.0015$ (Average)

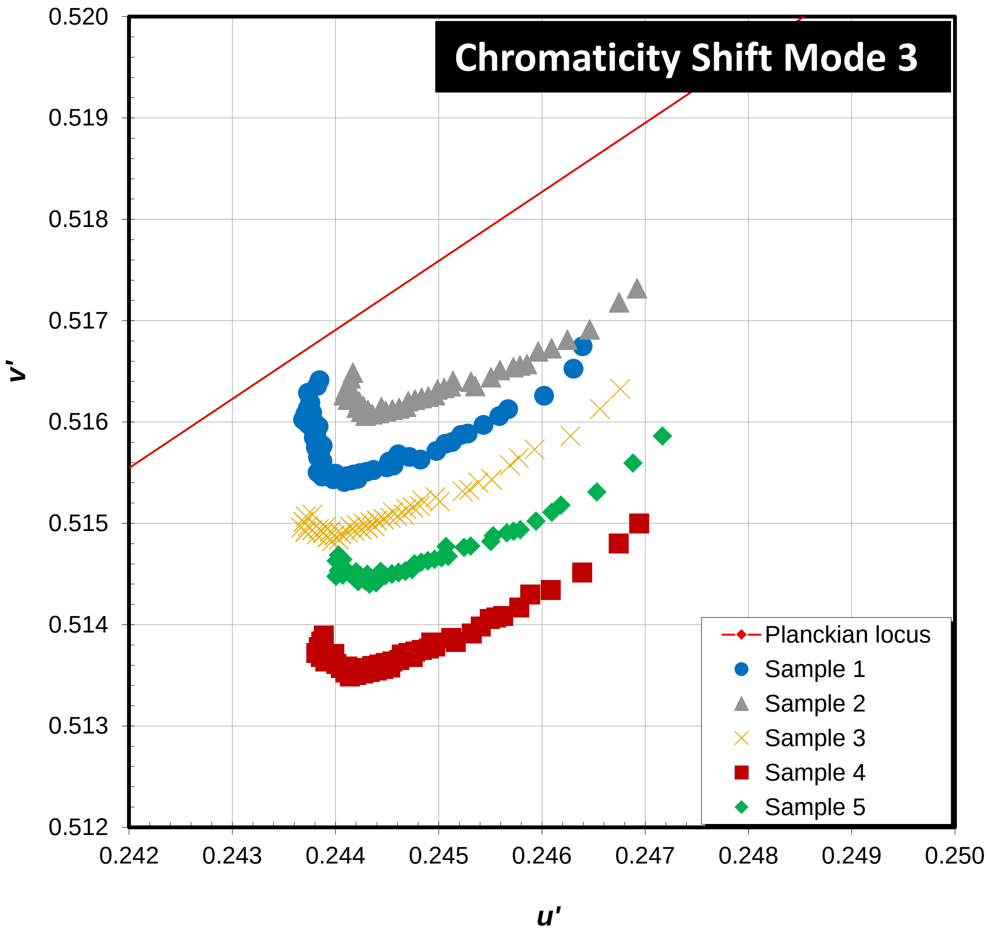
Sample 12-92: Samsung PAR38 Lamp





LED Type: HP-LED
Number of LED Packages: 12
Power: 16 Watts
Initial Luminous Flux: 1286 Lumens
Lumen Maintenance @ 13.9K hr: 1.05
Initial CRI: 83
Average Initial CCT: 3162 K
Average Final CCT: 3208 K
T_j (@ 45°C ambient): 75°C
Date of Manufacture: Jun 2011
Final Color Shift: Δu′v′ = 0.0016 (Average)

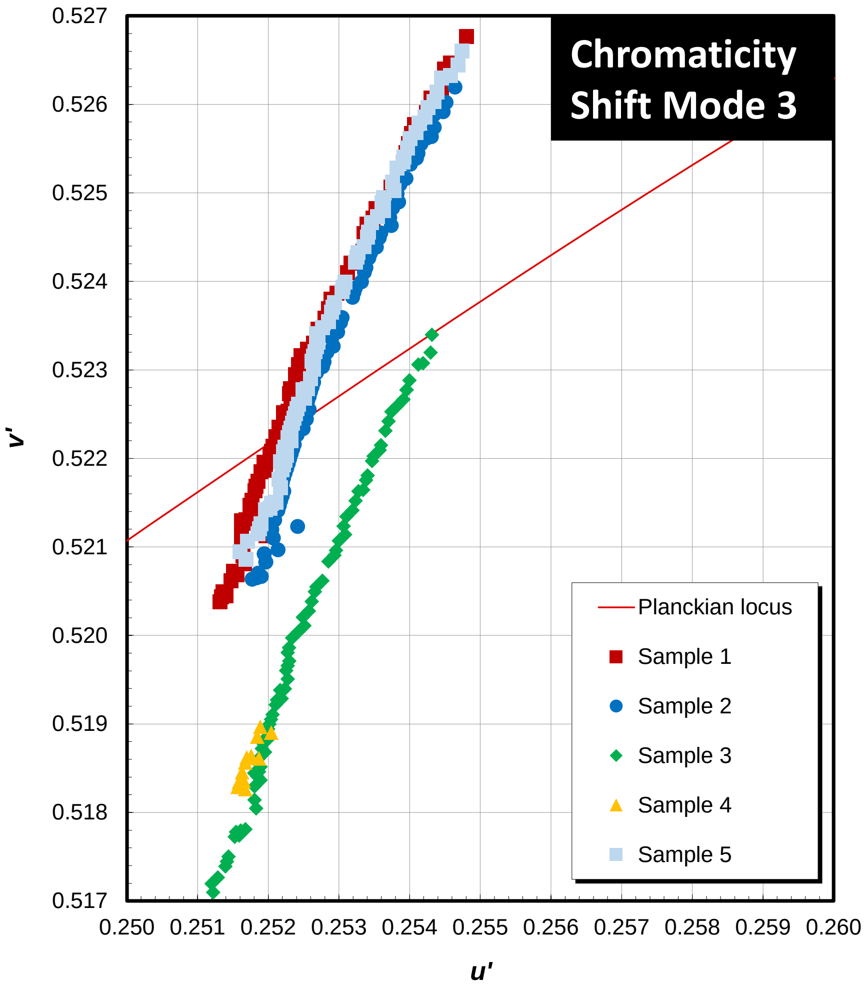
Sample 12-95: MSI PAR38 Lamp

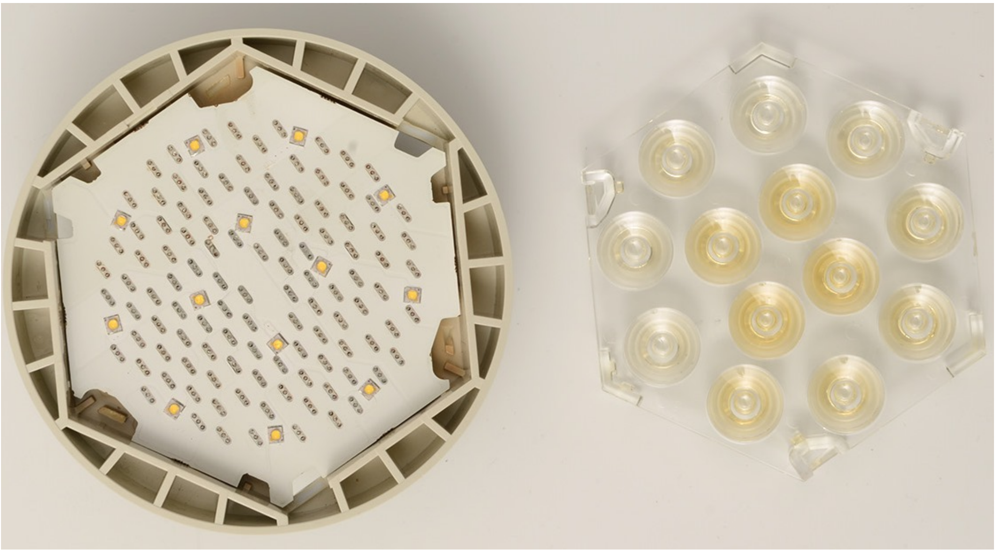


LED Type: HP-LED
Number of LED Packages: 9
Power: 12 Watts
Initial Luminous Flux: 775 Lumens
Lumen Maintenance @ 13.9K hr: 0.98
Initial CRI: 82
Average Initial CCT: 3131 K
Average Final CCT: 3219 K
T_j (@ 45°C ambient): Unknown
Date of Manufacture: Unknown
Final Color Shift: $\Delta u'v' = 0.0031$ (Average)

Sample 12-96: Array PAR38 Lamp

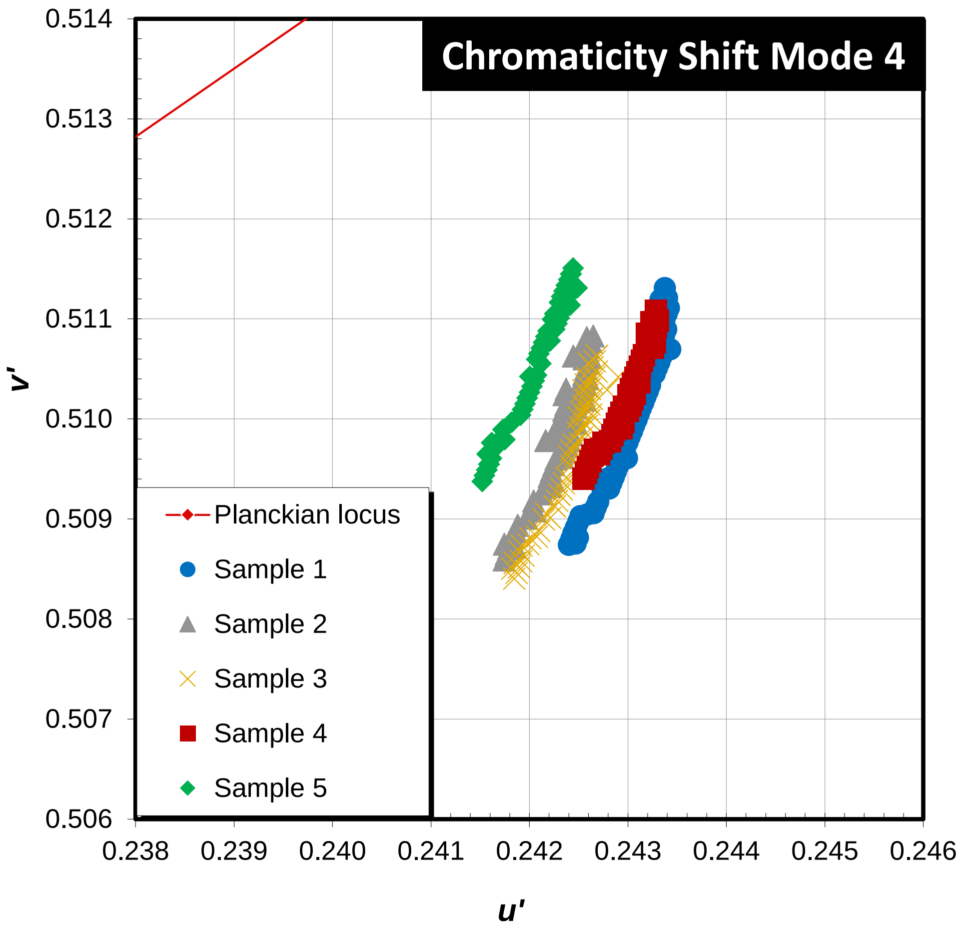
1 Catastrophic Failure

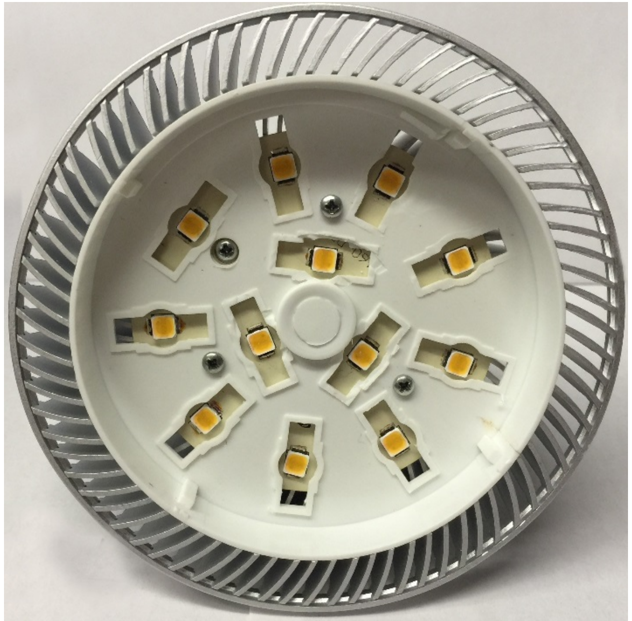




LED Type: HP-LED
Number of LED Packages: 13
Power: 21 Watts
Initial Luminous Flux: 1060 Lumens
Lumen Maintenance @ 13.9K hr: 0.91 (4)
Initial CRI: 82
Average Initial CCT: 2972 K
Average Final CCT: 2878 K
T_j (@ 45°C ambient): 129°C
Date of Manufacture: Oct. 2010
Final Color Shift: $\Delta u'v'$ = 0.0062 (Average).
Yellowing of lenses produces sharp yellow shift.

Sample 12-97: Havells PAR38 Lamp

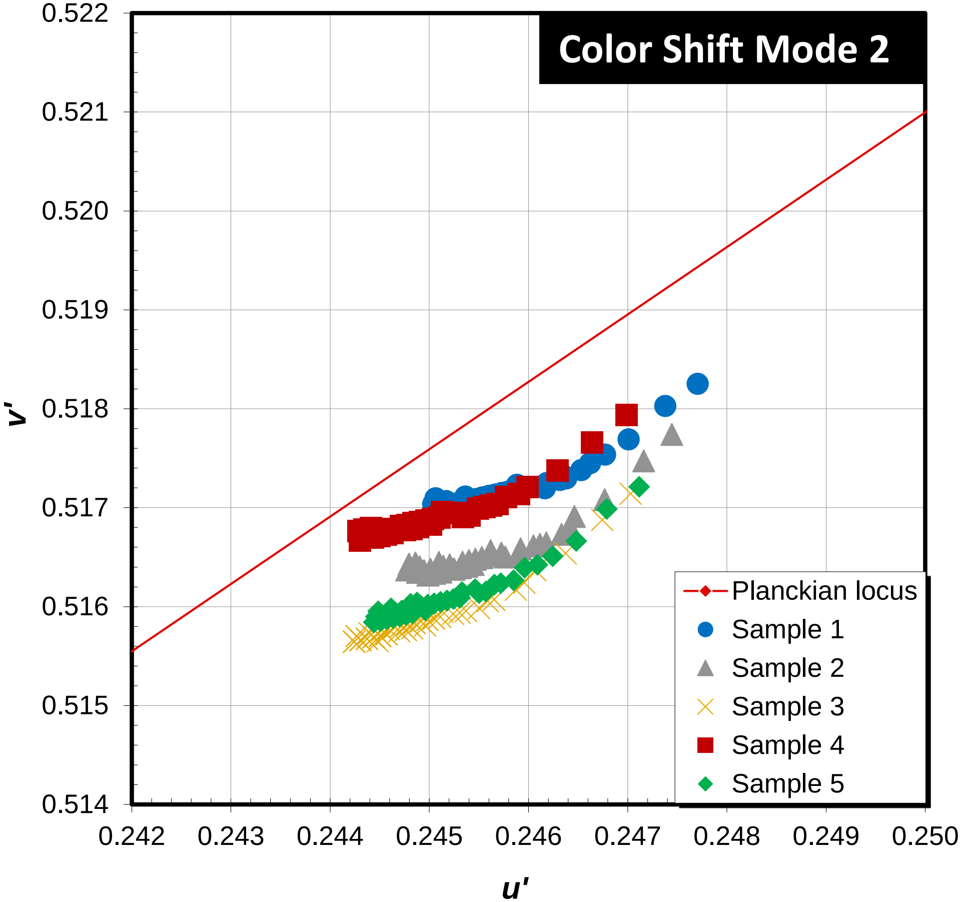


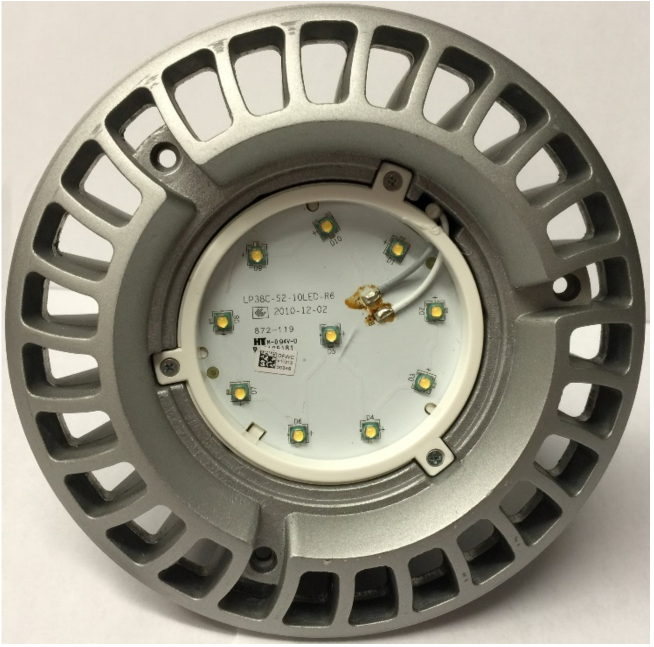


LED Type: PLCC
Number of LED Packages: 12
Power: 16 Watts
Initial Luminous Flux: 865 Lumens
T_j (@ 45°C ambient): 81°C
Date of Manufacture: Unknown
Final Color Shift: $\Delta u'v'$ = 0.0018 (average)
Three stage color shift:
- Blue shift for 1^{st} 267 hr
- Yellow shift to 1969 hr
- Blue shift for the remainder of time

Lumen Maintenance @ 13.9K hr: 0.93
Initial CRI: 80
Average Initial CCT: 3292 K
Average Final CCT: 3332 K

Sample 12-99: LEDirect NaturaLED PAR38 Lamp





LED Type: HP-LED

Number of LED Packages: 10

Power: 16.5 Watts

Initial Luminous Flux: 1115 Lumens

Lumen Maintenance @ 13.9K hr: 1.01

Initial CRI: 82

Average Initial CCT: 3110

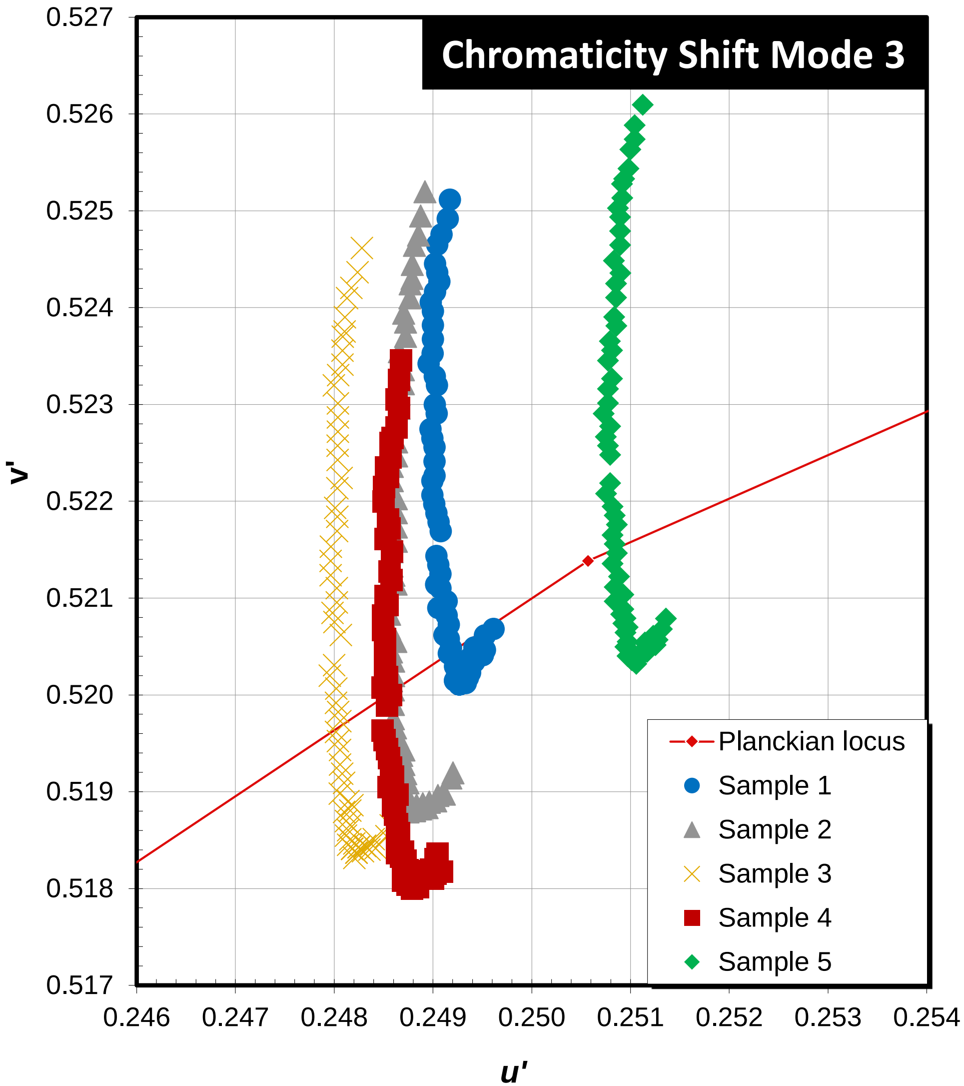
Average Final CCT: 3191 K

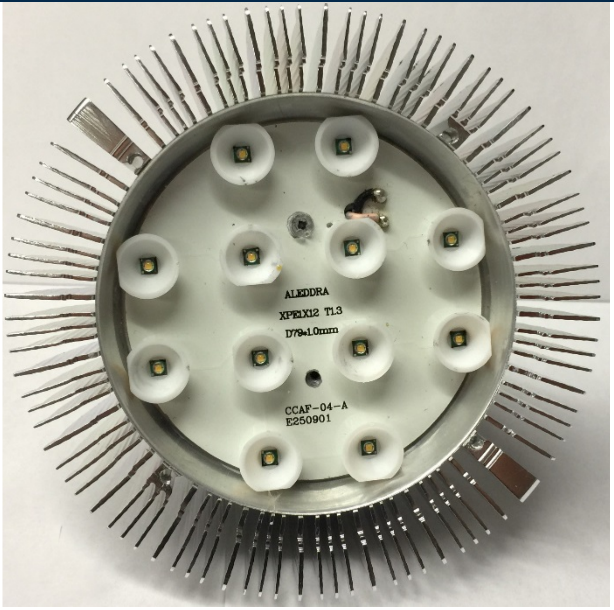
T_j (@ 45°C ambient): 78°C

Date of Manufacture: Dec. 2010

Final Color Shift: $\Delta u'v'$ = 0.0029 (Average)

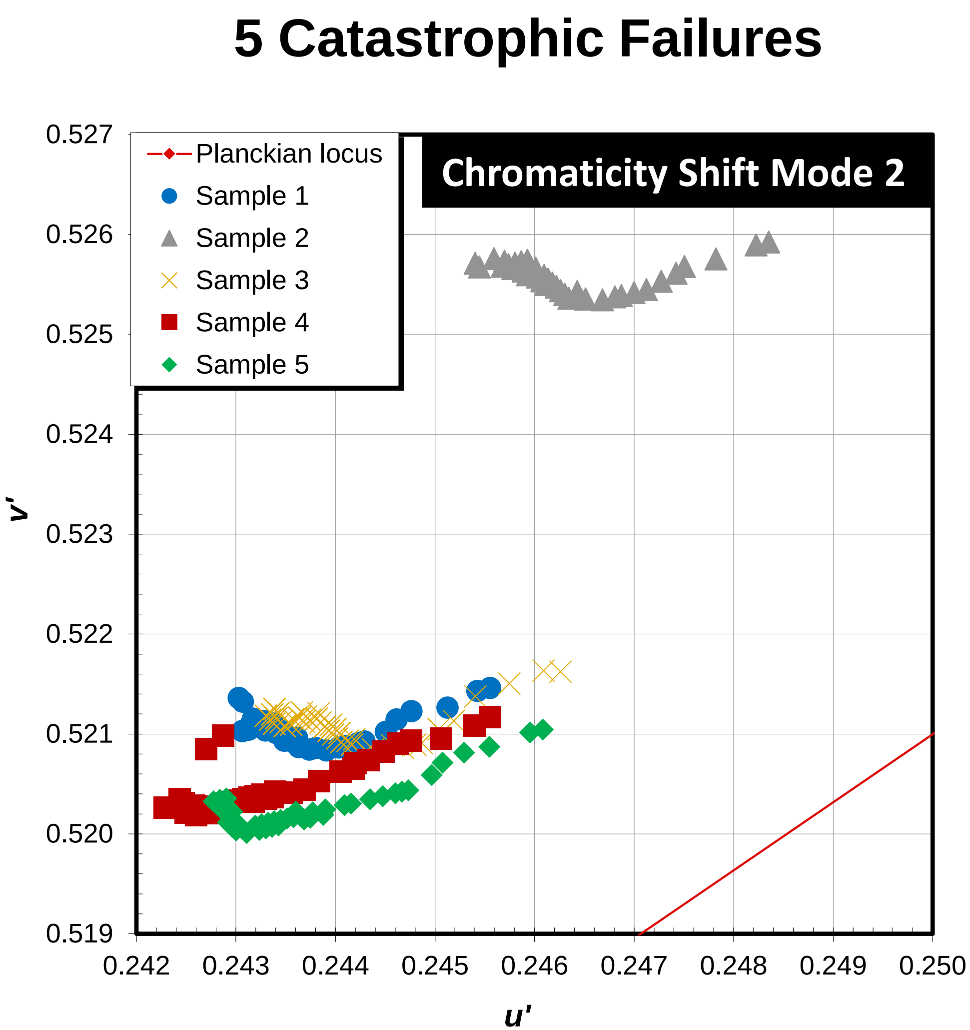
Sample 12-100: Aleddra PAR38 Lamp





LED Type: HP-LED
Number of LED Packages: 12
Power: 12 Watts
Initial Luminous Flux: 780 Lumens
Lumen Maintenance @ 13.9K hr: 0.93
Initial CRI: 82
Average Initial CCT: 3036 K
Average Final CCT: 3011 K
T_j (@ 45°C ambient): 79°C
Date of Manufacture: April 2012
Final Color Shift: $\Delta u'v'$ = 0.0053 (Average)
Sharp and prolonged yellow shift suggests either optical material oxidation or secondary optic aging.

Sample 12-134: Duracell PAR38 Lamp



LED Type: HP-LED

Number of LED Packages: 12

Power: 17 Watts

Initial Luminous Flux: 1172 Lumens

Lumen Maintenance @ 11.2K hr: 0.84

Initial CRI: 81

Average Initial CCT: 3100 K

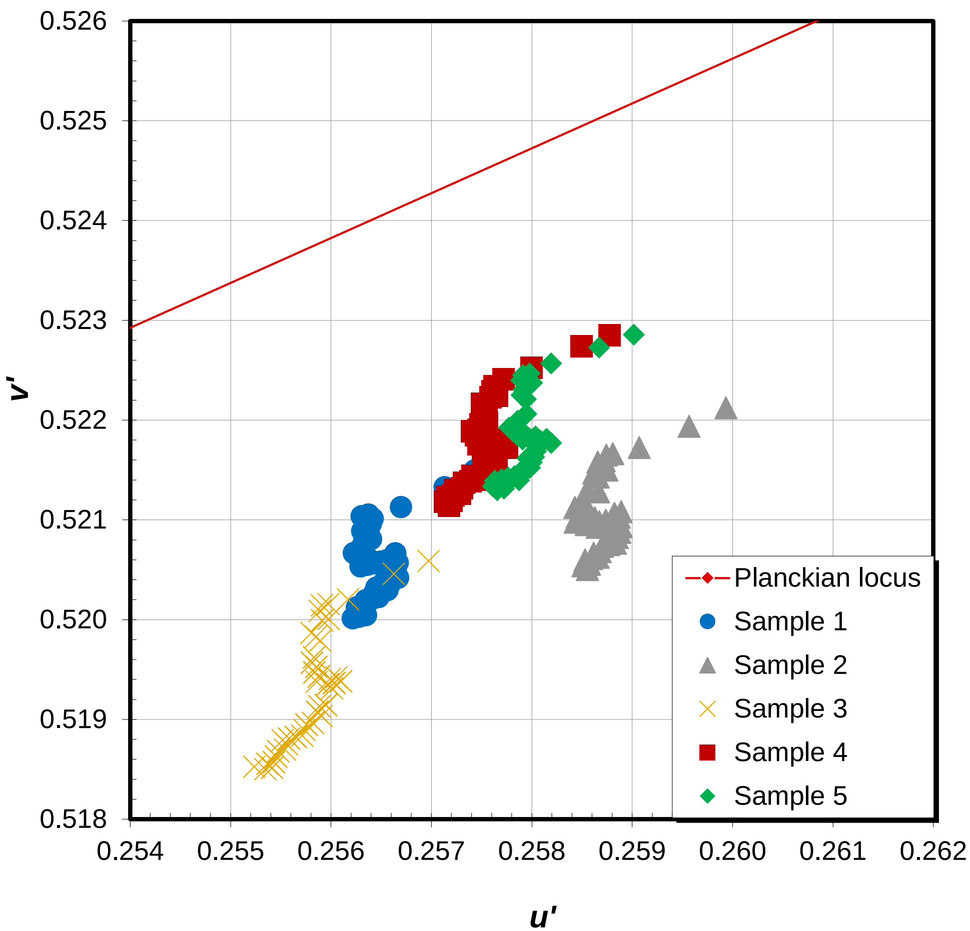
Average Final CCT: 3187 K

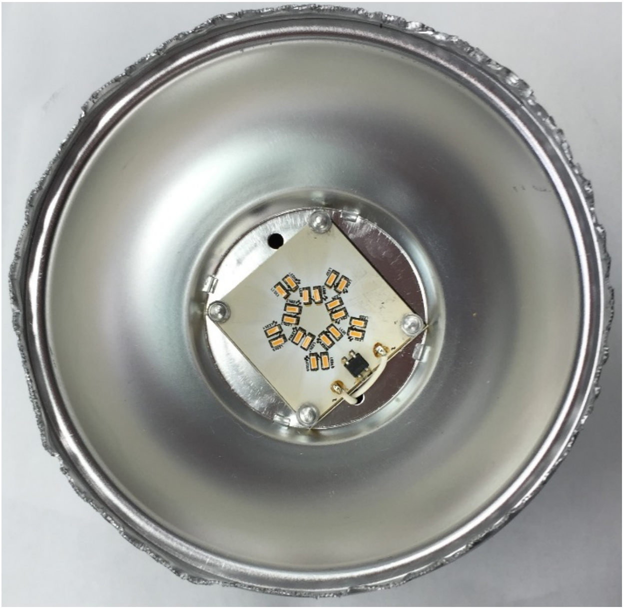
T_j (@ 45°C ambient): N/A (All Catastrophic)

Date of Manufacture: September 2012

Final Color Shift: $\Delta u'v'$ = 0.0032 (Average)

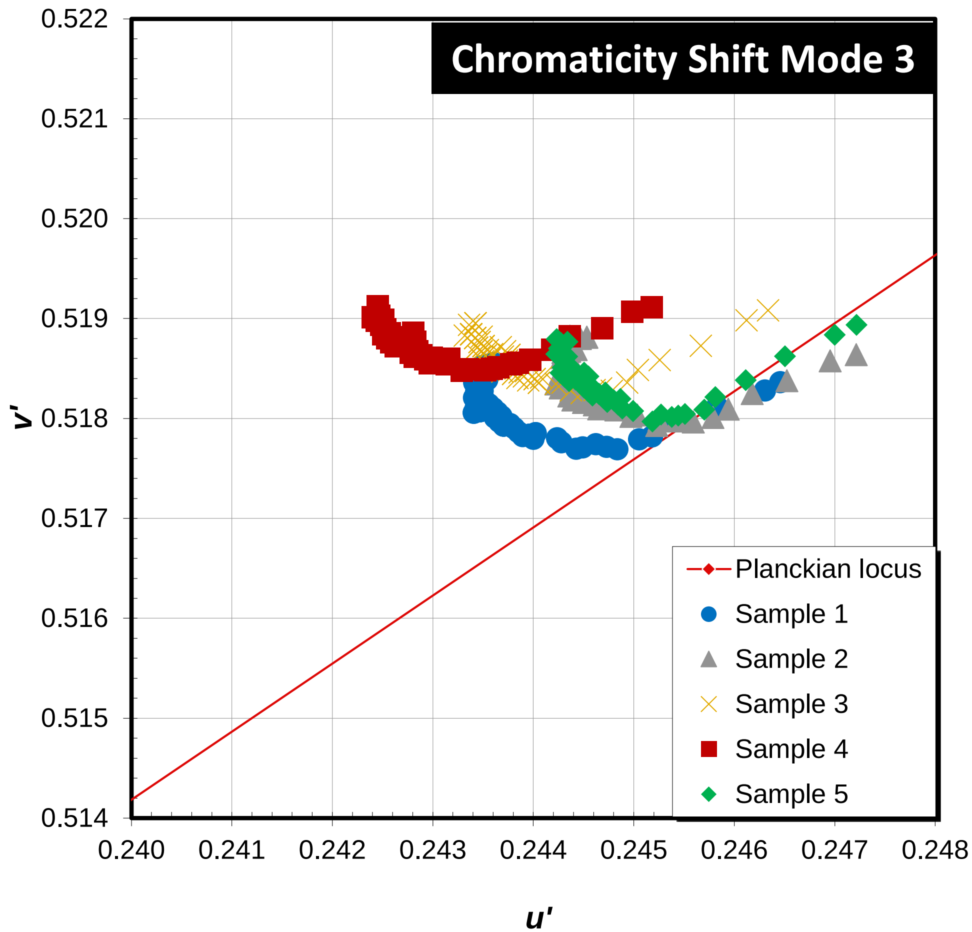
Sample 12-135: Axiom PAR38 Lamp





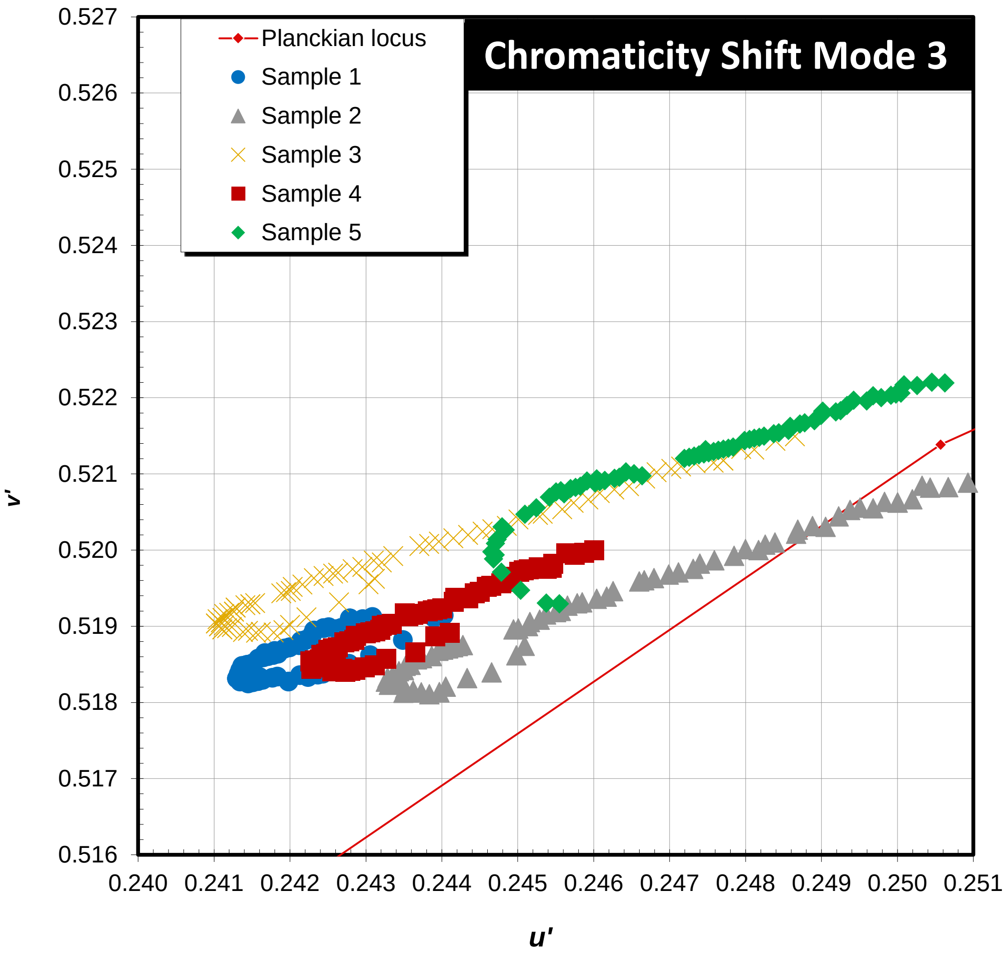
LED Type: PLCC
Number of LED Packages: 20
Power: 9 Watts
Initial Luminous Flux: 442 Lumens
Lumen Maintenance @ 13.9K hr: 0.87
Initial CRI: 81
Average Initial CCT: 2811
Average Final CCT: 2853 K
T_j (@ 45°C ambient): ~ 82°C
Date of Manufacture: Unknown
Final Color Shift: Δu′v′ = 0.0022 (Average)
Complex color shift with mid-power

Sample 12-140: Philips PAR38 Lamp



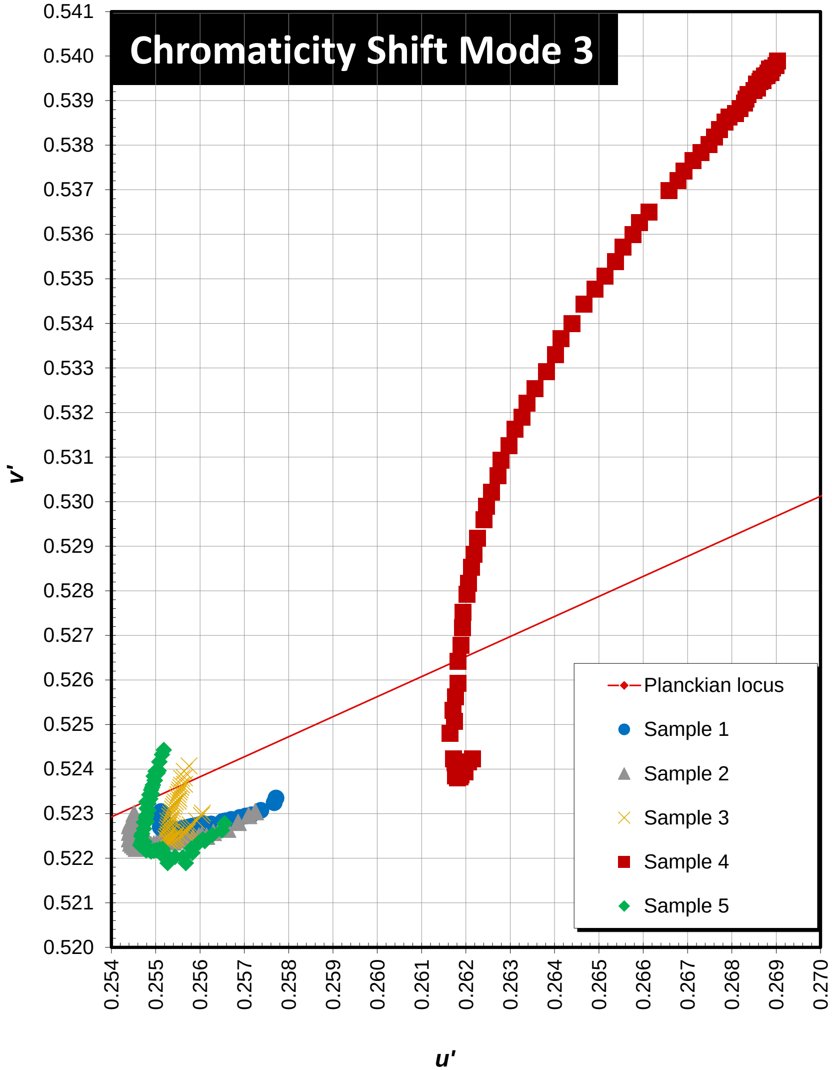
LED Type: HP-LED
Number of LED Packages: 10
Power: 19.5 Watts
Initial Luminous Flux: 1532 Lumens
Lumen Maintenance @ 13.9K hr: 0.98
Initial CRI: 86
Average Initial CCT: 3122 K
Average Final CCT: 3196 K
T_j (@ 45°C ambient): 104°C
Date of Manufacture: Apr. 2012
Final Color Shift: Δu′v′ = 0.0028 (Average)

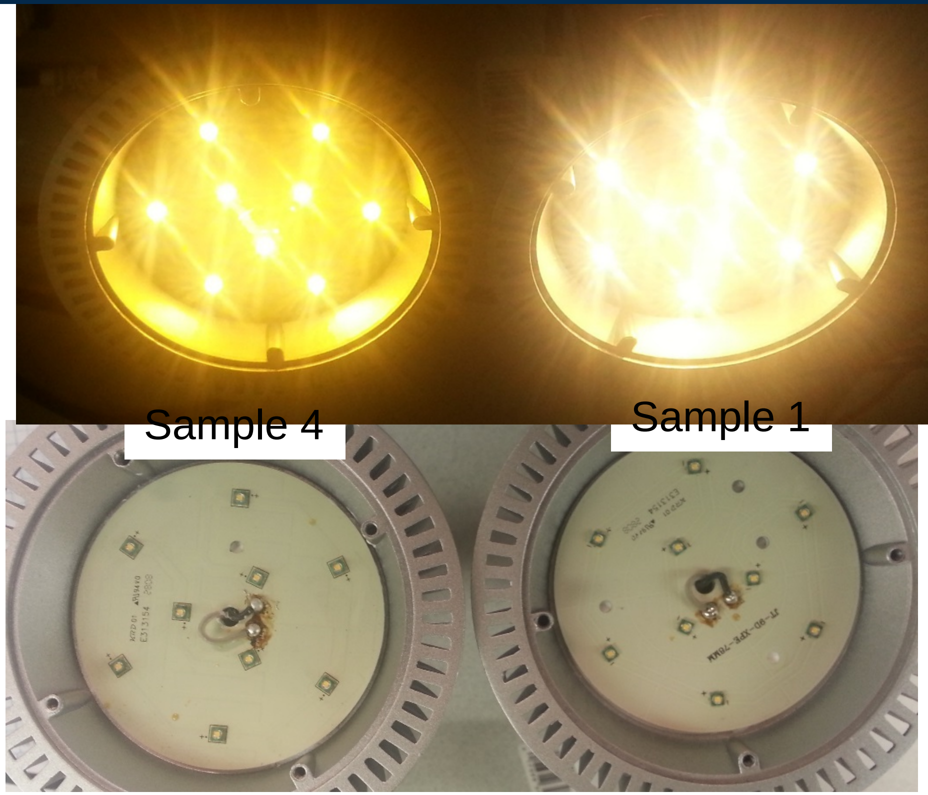
Sample 12-144: Solais PAR38 Lamp



LED Type: HP-LED
Number of LED Packages: 7
Power: 16 Watts
Initial Luminous Flux: 1200 Lumens
Lumen Maintenance @ 13.9K hr: 0.90
Initial CRI: 85
Average Initial CCT: 3174 K
Average Final CCT: 3074 K
T_j (@ 45°C ambient): 111°C
Date of Manufacture: May 2012
Final Color Shift: $\Delta u'v'$ = 0.0038 (Average)

Product 12-145: Seesmart PAR38 Lamp

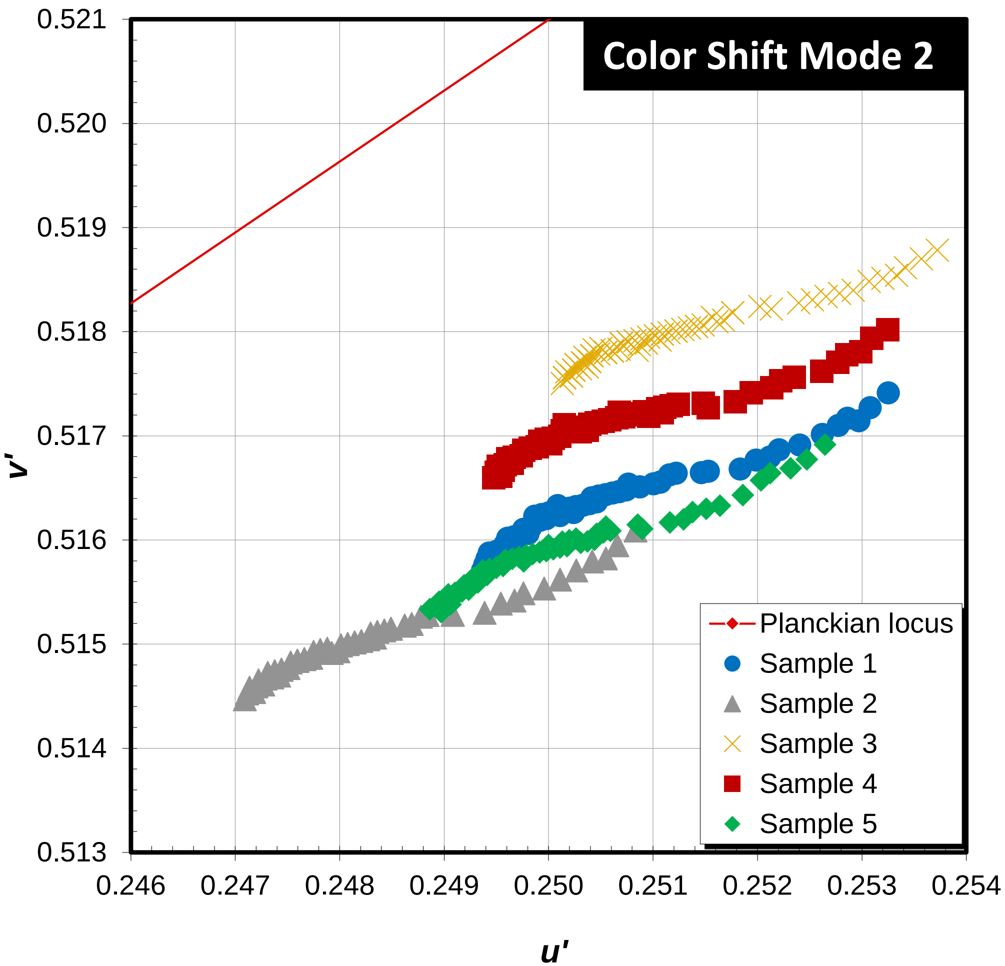


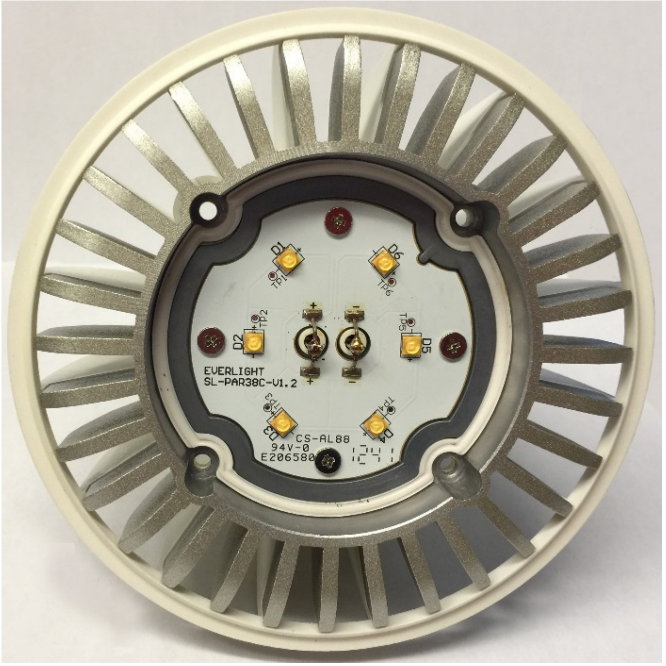


Lumen Maintenance @ 13.9K hr: 0.93
Initial CRI: 81
Average Initial CCT: 2816 K
Average Final CCT: 2808 K

LED Type: HP-LED
Number of LED Packages: 9
Power: 11 Watts
Initial Luminous Flux: 615 Lumens
T_j (@ 45°C ambient): 82°C
Date of Manufacture: March 2012
Final Color Shift: Δu′v′ = 0.0022 (Best 4 Average)
Behavior of Sample 4 is strongly suggestive of encapsulant photo-oxidation.

Product 12-146: Zenaro PAR38 Lamp

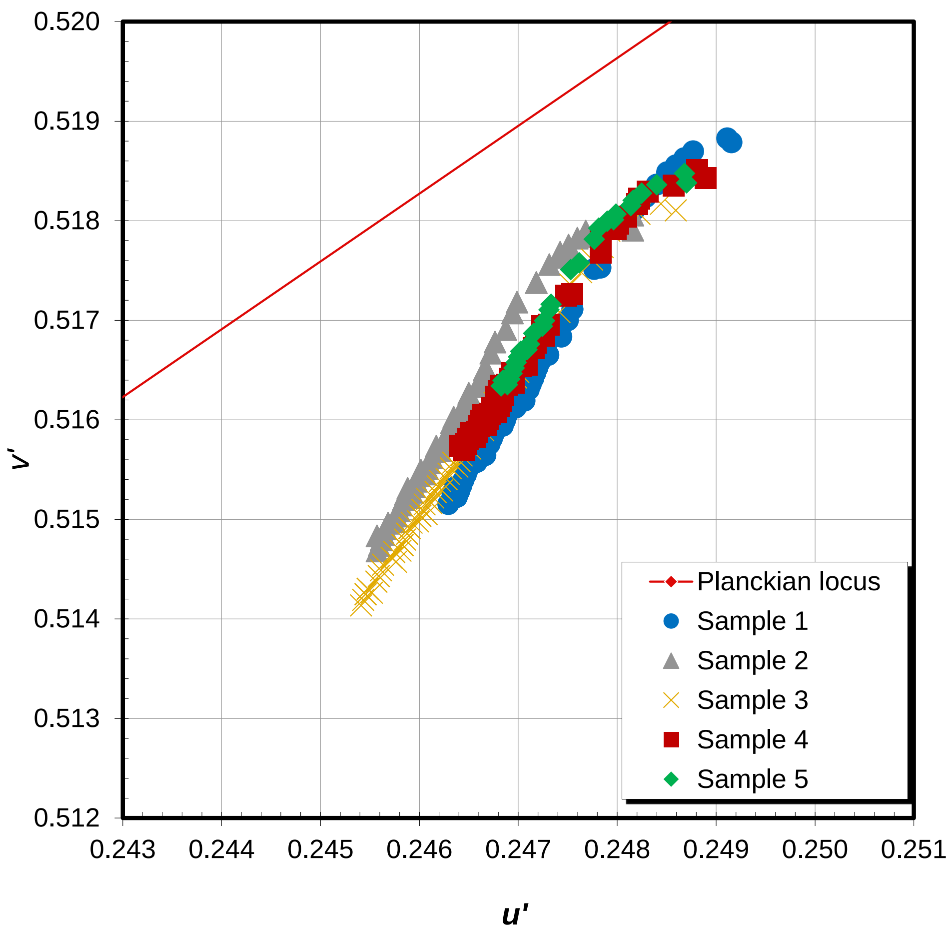




LED Type: HP-LED
Number of LED Packages: 6
Power: 16 Watts
Initial Luminous Flux: 1027 Lumens
Lumen Maintenance @ 13.9K hr: 0.95
Initial CRI: 82
Average Initial CCT: 2971 K
Average Final CCT: 3077 K
T_j (@ 45°C ambient): 93°C
Date of Manufacture: October 2012
Final Color Shift: $\Delta u'v' = 0.0040$ (Average)

Product 12-147: Lights of America PAR38 Lamp

2 Catastrophic Failures



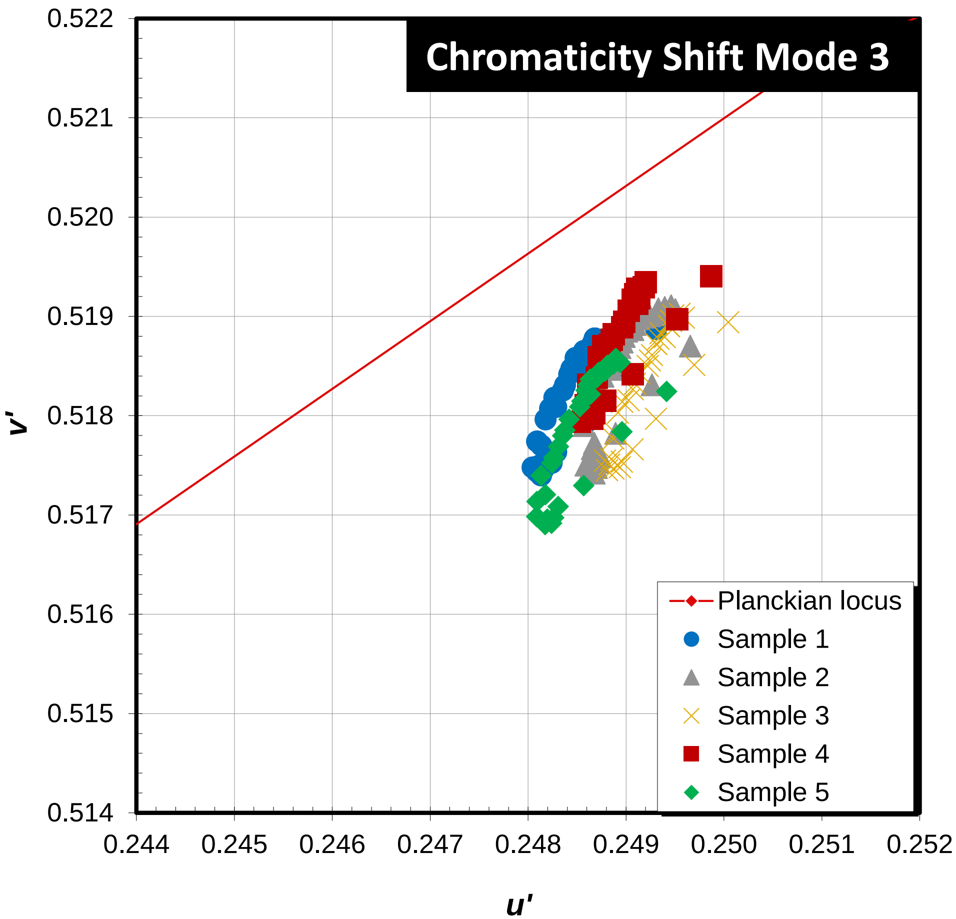
Lumen Maintenance @ 13.9K hr: 0.94
Initial CRI: 85
Average Initial CCT: 3067 K
Average Final CCT: 3173 K

LED Type: PLCC
Number of LED Packages: 7
Power: 20 Watts
Initial Luminous Flux: 950 Lumens
T_j (@ 45°C ambient): 83°C
Date of Manufacture: August 2011
Final Color Shift: $\Delta u'v'$ = 0.0046 (Average)

Small initial green shift followed by prolonged blue shift. Also some clouding of the lens is occurring.

Product 12-148: LEDWaves PAR38 Lamp

5 Catastrophic Failures



LED Type: HP-LED
Number of LED Packages: 12
Power: 14 Watts
Initial Luminous Flux: 744 Lumens
Luminous Flux @ 6.2k hr: 0.97
Initial CRI: 82
Average Initial CCT: 3039 K
Average Final CCT: 3041 K
T_j (@ 45°C ambient): Couldn't Capture (All Catastrophic)
Date of Manufacture: August 2011
Final Color Shift: $\Delta u'v'$ = 0.0004 (Average)

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