Lifetime Predictions for Dimmable Two-Channel Tunable White Luminaires

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ABSTRACT

Two-channel tunable white lighting (TWL) systems represent the next wave of solid-state lighting (SSL) systems and promise flexibility in light environment while maintaining the high reliability and luminous efficacy expected with SSL devices. TWL systems utilize LED assemblies consisting of two different LED spectra (i.e., often a warm white assembly and a cool white assembly) that are integrated into modules. While these systems provide the ability to adjust the lighting spectrum to match the physiology needs of the task at hand, they also are a potentially more complex lighting system from a performance and reliability perspective. We report an initial study on the reliability performance of such lighting systems including an examination of the lumen maintenance and chromaticity stability of warm white and cool white LED assemblies and the multi-channel driver that provides power to the assemblies. Accelerated stress tests including operational bake tests conducted at 75°C and 95°C were used to age the LED modules, while more aggressive temperature and humidity tests were used for the drivers in this study. Small differences in the performance between the two LED assemblies were found and can be attributed to the different phosphor chemistries. The lumen maintenances of both LED assemblies were excellent. The warm white LED assemblies were found to shift slightly in the green color direction over time while the cool white LED assemblies shifted slightly in the yellow color direction. The net result of these chromaticity shifts is a small, barely perceptible reduction in the tuning range after 6,000 hours of exposure to an accelerating elevated temperature of 75°C.

KEY WORDS: LED, Tunable White Light, Lumen Maintenance, Chromaticity, Driver, Reliability

INTRODUCTION

Single-color LED-based luminaires are making significant market penetration in many demanding lighting applications, and LED lighting systems are establishing a level of performance that all future lighting systems must meet or exceed. The next wave of LED lighting technology is likely to be white tunable luminaires (TWL) that can adjust the spectrum of the emitted light between a range of values. This capability allows the light system to produce white light of an appropriate spectrum for the task at hand. For example, a warmer light (i.e., lower correlated color temperature (CCT)) could be used for more relaxed tasks such as conversations, while a cooler light (i.e., higher CCT) could be used for tasks requiring greater concentration and higher visual acuity [1-3].

There are at least two different approaches to making TWL LED lighting systems. In a two-channel TWL system, two separate assemblies containing different colors of white LEDs (e.g., typically assemblies of warm white and cool white LEDs) are used to establish the endpoints of the tuning range as shown in **Figure 1**. Supplying current to only one LED assembly produces illumination at the CCT of that LED (e.g., 2729K and 6471K in Figure 1). Supplying current in varying proportions to both LED assemblies allows CCT values lying on a straight line connecting the end points to be achieved. Each LED assembly is driven by a separate channel on the driver, allowing the current supplied to each to be altered independently. Although lighting produced by two-channel TWL devices does not follow the Blackbody Locus (aka, Planckian Locus), research on lighting preference have found that light sources that lie just below the Blackbody Locus are favored by most observers [4].

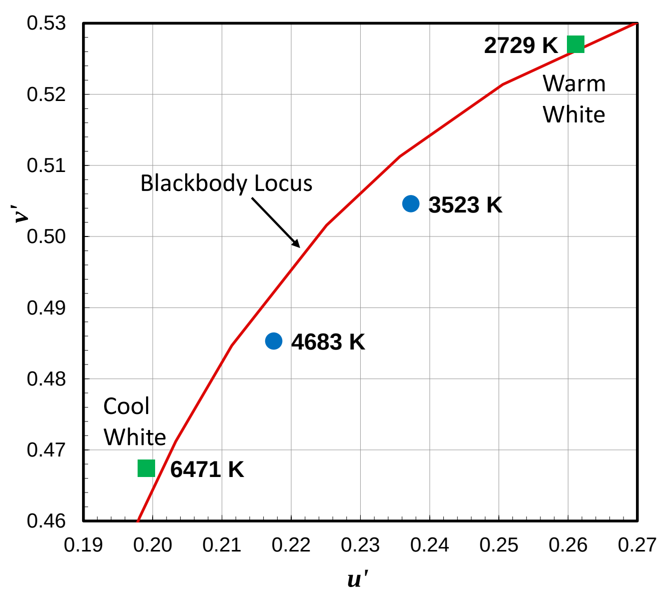

Figure 1: Tunable white system using two different white LED assemblies. The CCT values of the two different white LED assemblies are given as green rectangles in the figure along with two representative intermediate CCT values that are shown as blue circles.

A second approach to TWL systems is to use assemblies of three of more direct emitting LEDs (e.g., red, green, blue). The chromaticity points of the three direct emitting LED assemblies form a triangle on the chromaticity diagram, and the color can be tuned to any point within the triangle by supplying the appropriate current to each LED assembly. In order to achieve this flexibility, every LED assembly is assigned a separate channel in the driver. Consequently, three of more channels are required for tuning of direct emitter devices, adding complexity to the driver and control circuits. However, the primary advantage of this approach to light tuning is the greater flexibility that can be achieved in the color gamut including the ability to produce a lighting source that follows the Blackbody Locus.

A significant benefit of tunable white luminaires is that they provide the ability to create a smart lighting system that matches the lighting conditions to human physiological needs for the task at hand. For example, lighting with higher CCT values is known to reduce the pupil size in the human eye and increase visual acuity, which may be beneficial for concentrating on fine tasks [5]. In contrast, lighting with lower CCT values tends to promote relaxation and elicits a calming response [6].

TWL LED systems are inherently more complex than the conventional one-color LED devices due to the need to accommodate multiple LED assemblies, the inherently higher level of complexity of multi-channel drivers, and the necessity for a user interface to operate the lighting system. In general, the reliability of such lighting systems is excellent if used in appropriate environments. Therefore, identifying failure modes and studying the lifetime and reliability characteristics of such systems requires accelerated stress tests (AST) that speed up the device aging process to practical time scales that can be conveniently measured in the laboratory.

This paper describes AST results and models for the long-term behavior of mid-power LEDs (MP-LEDs) and multi-channel drivers used in two-channel TWL systems. The models are derived from experimental findings produced by AST experiments. The two-channel tunable white approach was chosen for this work due to its relative simplicity, compared to three or more different color LED tunable systems. The educational lighting market is the chosen application for this study due to stringent cost requirements and the expectation that the lighting system will be operable for 20 years. A TWL source would be beneficial in this application since cooler white sources promote greater levels of concentration and visual acuity that would be beneficial in taking tests and individual study [2, 5] while warmer temperatures promote a more relaxed environment that is beneficial to group work and rest periods [3, 6]. The testing protocols and models developed for this application encompass the major elements of the lighting system and including LEDs, lenses, and driver electronics. The use of AST protocols to confirm product reliability is necessary to ensure that the technology can meet the performance and lifetime requirements of the application.

EXPERIMENTAL

The experiments described in this work were divided into studies of MP-LED modules and separate experiments on the drivers used to power the MP-LED modules. The LED modules tested in this work consisted of separate assemblies of 40 warm white and 40 cool white MP-LEDs mounted on a FR-4 circuit board that was covered with a white solder mask. A picture of this LED module is given in **Figure 2**. The assemblies were configured with 10 separate LED strings operating in parallel with each string containing 4 LEDs. Separate populations of the LED modules were tested for 6,000 hours at elevated temperatures of 75°C and 95°C, and a one-hour power duty cycle was used throughout. These test conditions were chosen to be roughly 2.5X and 3X the expected maximum ambient temperature in a typical classroom. During testing of the LED modules, the drivers were kept outside the test chamber to minimize the effect of the elevated temperature environment.

Figure 2: Picture of the tunable white MP-LED module used in this study.

The test population of LED modules consisted of a total of 8 modules for each elevated ambient temperature. There were two LED modules that were operated at 350 mA per channel, two modules were operated at 700 mA per channel, two modules were operated at 1,000 mA per channel, and two modules were operated at 1,500 mA per channel.

After every 500 hours of testing, the LED modules were removed from the test ovens and radiometrically evaluated in a calibrated 1.65 meter integrating sphere (LabSphere). During the radiometric measurements, the full spectral power distribution (SPD) was recorded and lighting properties such as illuminance, chromaticity, and CCT were calculated from the SPD using the LightMtrX software (LabSphere). The warm white and cool white SPDs were recorded separately. All LED modules were operated at 750 mA per channel during measurement in the integrating sphere. A one-hour warm-up was used before the SPD was recorded. A separate, unexposed control LED module was also tested in the integrating sphere and used as a control for the experiment.

In separate experiments, samples of the two different multi-channel driver products were subjected to an environment of 75°C and 75% relative humidity (7575), which has been previously shown to be a good AST environment for LED devices [7]. This wet high temperature operational lifetime (WHTOL) test is generally more aggressive than temperature alone. Two samples of each product were tested in 7575. Product A utilized metal oxide semiconducting field effect transistors (MOSFETs) that were integrated into the same package as the controller chip, while Product B used separate discrete MOSFETs and a controller chip. Both products used dedicated MOSFETs for each channel. We have previously observed that integrating MOSFETs into the controller chip package can produce thermal management issues that in some instances will result in product failure [7, 8].

During testing each driver was connected to identical dummy loads consisting of four LED modules. The LED modules were placed outside of the test chamber throughout to avoid any impacts from heat-induced changes. One channel was connected to all the warm white LEDs, with the LED modules in series, and the other channel was connected to the cool white LEDs. The remaining two channels were not used. During the 7575 test, power to the drivers was cycled on a one-hour duty cycle (i.e., one hour on and one hour off).

The performance of the drivers was periodically characterized using multiple approaches. One approach was simply the change in power consumption and power factor as measured by a Kill-A-Watt meter. The second approach was measurement of the photometric flicker waveform from the LED modules using a GigaHertz handheld flicker meter (Model BTS256-EF).

RESULTS

1. LED Lumen Maintenance

The ability of a light source to produce a consistent level of light, as measured in lumens, is term luminous flux maintenance which will be shortened to lumen maintenance herein. Lumen maintenance is defined as the percentage of luminous flux at a given time divided by the initial luminous flux. This can be expressed mathematically as:

$$Lumen\ Maintenance = \frac{Luminous\ Flux\ at\ Time\ t}{Initial\ Luminous\ Flux} x\ 100\%$$

The lumen maintenance measured from the start of the experiment to 6,000 hours in 500 hour increments is shown for the warm white channel (i.e., ~2750 K) in **Figure 3** for the LED modules exposed to the elevated ambient of 75°C and in **Figure 4** for the cool white channel (i.e., ~6,500 K). The lumen maintenance rises initially for both channels and then decays at a consistent, exponential rate as discussed previously [9]. Lumen maintenance decay rate constants (α) were calculated from an exponential fit to the data for each current in the 75°C exposure experiments, and the results are given in **Table 1**. In calculating α values, data from the first 1,000 hours was discarded as is done in a TM-21-11 analysis [10]; however, it should be noted that the samples size used in the calculation was two modules per current setting, which is below the sample size requirements of TM-21-11.

Table 1. α values for LED modules tested at 75°C.

Current	2750 K Setting	6500 K Setting
350 mA	6.91×10^{-6}	6.21×10^{-6}
700 mA	6.76×10^{-6}	6.18×10^{-6}
1000 mA	8.20×10^{-6}	7.18×10^{-6}
1500 mA	1.21×10^{-5}	1.22×10^{-5}

The measured lumen maintenance for the 8 LED modules exposed to the elevated ambient of 95°C is given in **Figure 5** for the warm white setting (i.e., 2,750 K) and in **Figure 6** for the cool white setting (i.e., 6500 K). The lumen maintenance rises initially and then decays at a consistent, exponential rate as discussed previously [9]. Lumen maintenance decay rate constants (α) were calculated for each current in the 95°C exposure experiments and the results are given in **Table 2**. In calculating α values, the general procedure described in TM-21-11 was used [10]; however, it should be noted that the samples size used in the calculation was two modules per current, which is below the sample size requirements of TM-21-11.

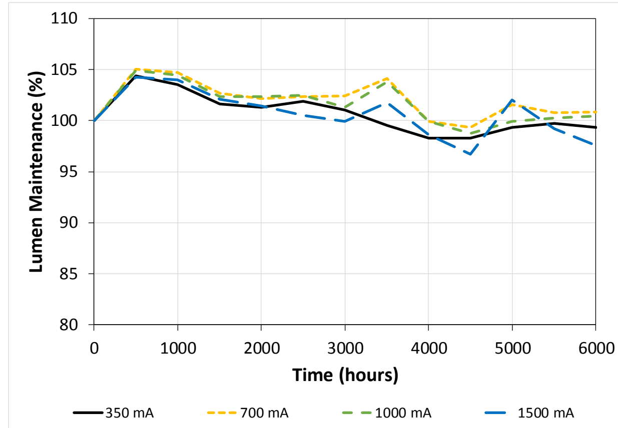

Figure 3: Lumen maintenance of the LED modules with the warm white (2750 K) assemblies energized to different current settings and exposed to an elevated temperature of 75°C.

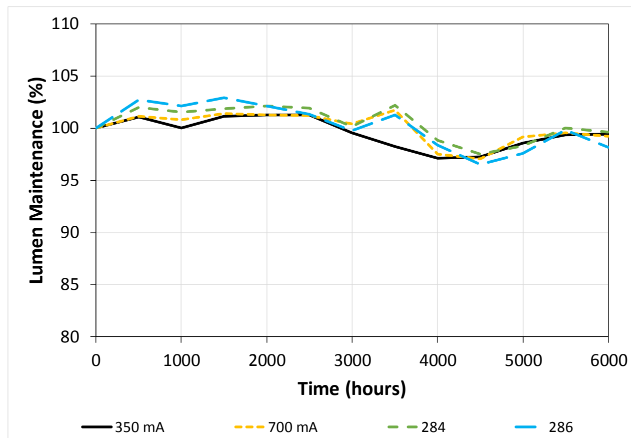

Figure 4: Lumen maintenance of the LED modules with the cool white (6500 K) assemblies energized to different current settings and exposed to an elevated temperature of 75°C.

Table 2. α values for LED modules tested at 95°C.

Current	2750 K Setting	6500 K Setting
350 mA	1.05×10^{-5}	1.11×10^{-5}
700 mA	1.14×10^{-5}	1.13×10^{-5}
1000 mA	1.17×10^{-5}	1.09×10^{-5}
1500 mA	1.68×10^{-5}	1.58×10^{-5}

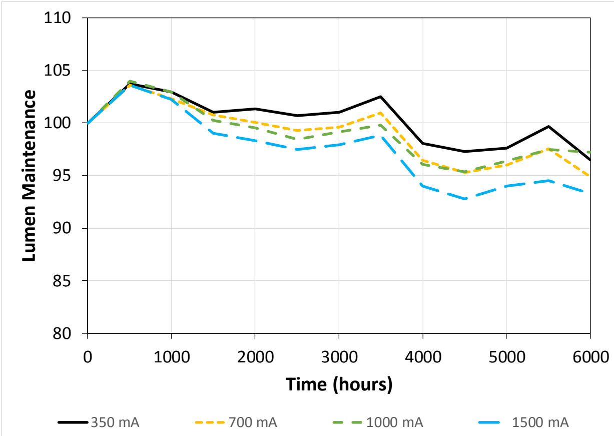

Figure 5: Lumen maintenance of the LED modules with the warm white (2750 K) assemblies energized to different current settings and exposed to an elevated temperature of 95°C.

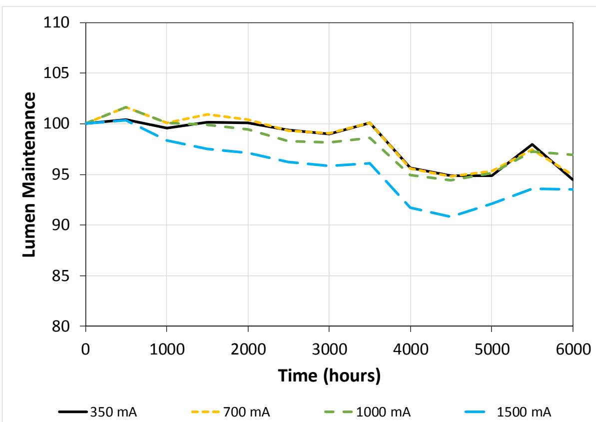

Figure 6: Lumen maintenance of the LED modules with the cool white (6,500 K) assemblies energized to different current settings and exposed to an elevated temperature of 95°C.

A closer examination of the data presented in Figures 3-6 and Tables 1 and 2 shows that there are several overarching trends. First, the lumen maintenance of the samples exposed to the 95°C environment is lower than that of the samples tested at 75°C. While this finding is not unexpected, it does suggests that the data is consistent with larger datasets as required by a TM-21-11 analysis. A second finding is that the range in α values is larger for the 75°C tests than for the 95°C tests, which suggests that ambient temperature may play a more dominant role in determining lumen maintenance at 95°C, whereas another factor (i.e., drive current) may play a bigger role at 75°C. This point will be addressed further in the discussion section.

2. <u>LED Chromaticity Stability</u>

The chromaticity of LED sources can be represented in various color spaces. In this work, we have chosen the 1976 CIE (Commission Internationale de L'Eclairage) color space in which a given color can be represented by two chromaticity coordinates labels u' and v'. A shift in u' component can be represented by $\Delta u'$ while a change in the v' component can be represented by $\Delta v'$. Since a chromaticity shift can involve changes in both u' and v', a vector ($\Delta u'v'$) can also be define to represent the magnitude of the chromaticity shift as represented by the mathematical equation:

$$\Delta u'v' = \sqrt{\left(\Delta u'^2 + \Delta v'^2\right)}$$

It is important to note that Δu′v′ is the magnitude of the chromaticity shift vector, but does not provide any information about the direction of the shift. In some instances, small chromaticity changes (e.g., $\Delta u'v' \sim 0.001$) are barely noticeable by human observers, but in other instances the changes can be quite significant. A chromaticity shift of $\Delta u'v' \geq 0.007$ is one common gauge for maximum allowable chromaticity shift in LED products [1].

Changes in the chromaticity of one or both assemblies of white LEDs in a WTL LED module can change the tuning properties of the luminaires employing these light sources. For the LED modules tested in this study, there was a small shift in the chromaticity point of the source LEDs at both ends of the tuning range, as shown in **Figure 7**. The result of the measured chromaticity shift was to move the chromaticity point of the luminaire slightly closer to the Blackbody Locus over much of the tuning range, although the end points did move slightly away from the Blackbody Locus. Although the data presented in Figure 7 represents a time series for one device under test (DUT), similar observations were made for all DUTs examined in this study although the extent of the chromaticity shift depends on the drive current and test temperature used during exposure.

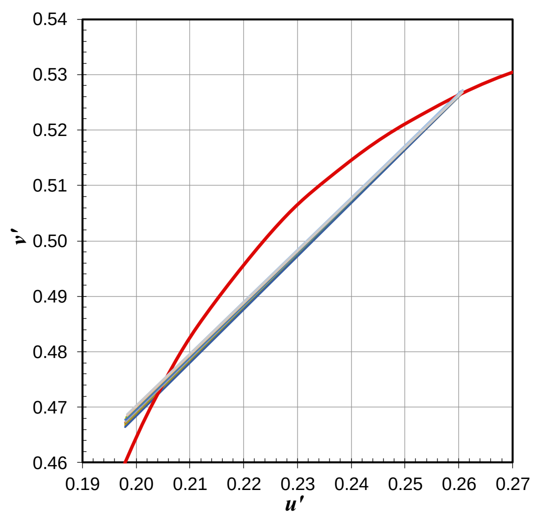

Figure 7: Tuning range of one tunable white LED module examined in this study. This LED module was tested at 75°C and 350 mA during environmental exposure. Each measurement of the device, which was taken at 500 hour intervals, is represented by a separate line in the graph. The Blackbody Locus is shown by the thick red line.

A closer examination of the chromaticity shift occurring in these LED modules is needed to understand the behavior of each white LED source and its impact on the tuning range of the system. **Figure 8** gives an expanded view of the warm white LED end point shown in Figure 7, and the chromaticity shift of the LED modules can be seen to occur generally in the green direction (i.e., u' is decreasing and the change in v' is minimal). This chromaticity shift has previously been shown to arise from changes in the nitride phosphors used for warm white LEDs and an examination of the SPD of the warm white LEDs is consistent with this explanation [11]. Overall, the range of the chromaticity shift that was found for the warm white LEDs in this sample is less than a one-step MacAdam ellipse (i.e., $\Delta u'v' \cong 0.001$), which is barely perceptible by an average observer.

The cool white LEDs in the LED modules were also found to undergo a chromaticity shift, and an expanded view of this region of the chromaticity diagram is shown in **Figure 9**. In contrast to the findings for the warm white LEDs, the cool white LEDs are generally shifting in the yellow direction as characterized by a minimal change in u' and a larger, positive change in v'. This behavior may arise from either increased absorption of blue photons likely due to yellowing of the encapsulant or MP-LED molding resin or microcracks in the phosphor layer [11]. The range of chromaticity shift that was observed for this sample was approximately a two-step MacAdam ellipse (i.e., $\Delta u'v' \cong 0.002$) which may be barely perceptible by a human observer. Although data from only one device is given here, similar trends were found for all tested devices, and the magnitude of the chromaticity shift was generally larger at higher currents and higher temperatures.

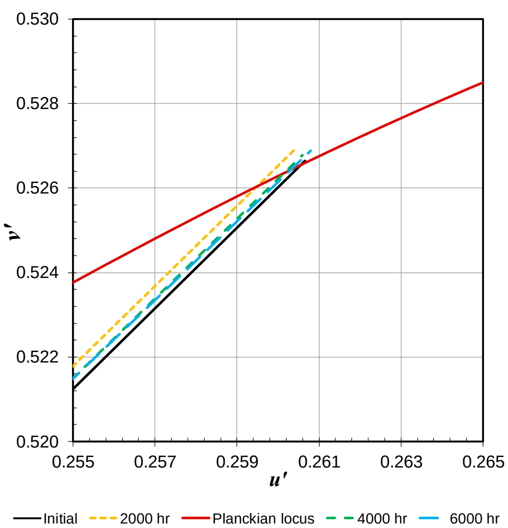

Figure 8: Expanded view of the chromaticity diagram given in Figure 7 showing changes in the warm white LED chromaticity point as the AST experiment progresses. The Blackbody Locus is shown by the thick red line.

Another way to consider the change in the tuning range of a luminaire as it ages is to consider the change in the CCT values of the two source LED assemblies. Figure 10 shows the change in CCT values for both the warm white and cool white sources in the LED module. The change in CCT values of the warm white sources was minimal (< 30 K) and reaches a maximum around 2000 hours, but the change in the CCT of the cool white sources was larger. Consequently, over time there will be a slight reduction in the tuning range of luminaires employing these LED modules. However, the magnitude of the shift is such that the change will likely not be noticeable by most observers.

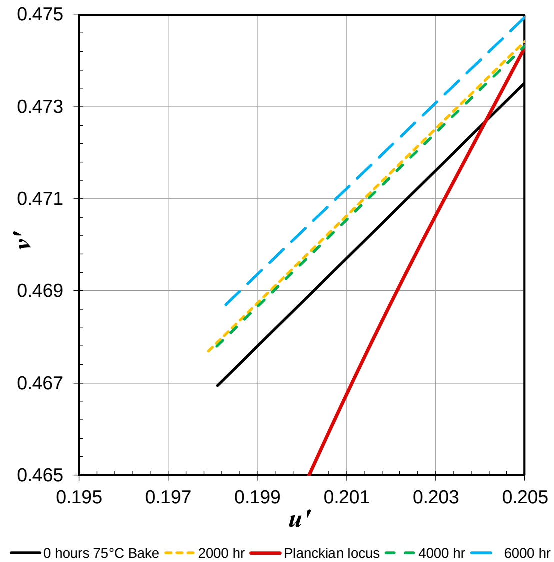

Figure 9: Expanded view of the chromaticity diagram given in Figure 7 showing changes in the cool white LED chromaticity point as the AST experiment progresses. The Blackbody Locus is shown by the thick red line.

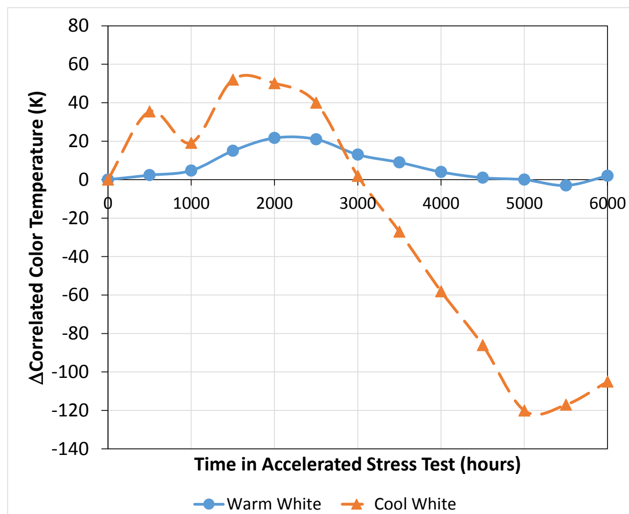

Figure 10: Change in the CCT value of the warm white and cool white LEDs in a WTL LED module. The measurements were taken on a single device at different times during AST experiments conducted at 75°C.

3. Driver Performance

In experiments conducted separately from those on the LED modules, two samples each of two different four-channel driver products with dimming capability were tested in 7575. The drivers were connected to identical loads which consisted of four LED modules per driver, but only two channels on each driver were used. The modules were connected such that one channel was dedicated to the warm white LEDs on the four LED modules and one channel was dedicated to the cool white LEDs.

Through 1,000 hours of testing in 7575, no failures of the drivers were observed and there was no appreciable change in the power consumption and power factor of any driver. In addition, after 1,000 hours of exposure to the 7575 environment, the photometric flicker waveforms of both products exhibited only subtle differences. The photometric flicker waveform can be transformed to a representation in the frequency domain using the Fast Fourier Transform (FFT) technique [12]. The FFT spectra of the photometric flicker waveform from one sample in its initial state and after exposure to 7575 for 1,000 hours is shown in **Figure 11**. The large FFT component at 0 Hz is not included in this analysis. One of the differences between the two spectra is the shift in frequency of the minor FFT components occurring at 1441, 2907, and 4348 Hz. A second difference is that the width of the FFT peaks appears to be different after 1,000 hours of 7575. It should be emphasized that no change in the output of the LED modules was measured in this study. However, the small changes observed in the FFT spectra of the photometric flicker may be indicative of a change in the properties of the electrical components in the drivers. Additional testing is needed to confirm this hypothesis and to determine what level of change is required for failure occurs.

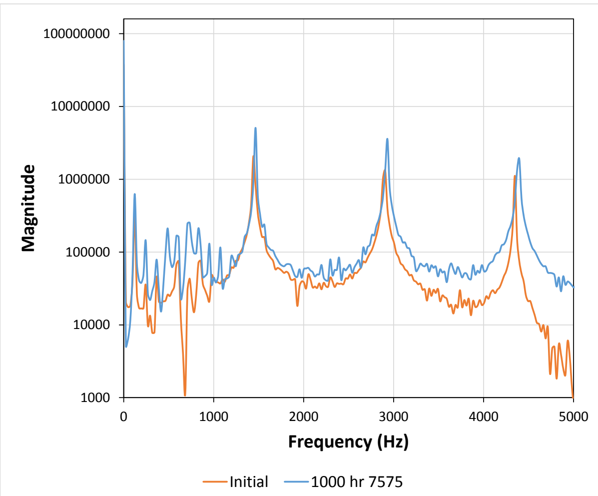

Figure 11: FFT spectrum of the photometric flicker waveform for one of the drivers under test. Orange is the FFT of the initial photometric flicker waveform and blue is the FFT of the photometric flicker waveform after 1,000 hours of 7575.

DISCUSSION

In order for TWL systems to achieve the level of reliability that is becoming common for LED products, all components in this system must achieve high reliability. This includes the different LED assemblies that comprise the LED modules and the multi-channel drivers that provide electrical power to these LED modules. Electrical testing of each LED assembly in the LED module was performed to understand the lumen maintenance and chromaticity stability of this part of the lighting system. For the drivers, WHTOL testing was used to understand the aging of this system component.

As shown in Table 1 and Table 2, the lumen maintenance of the LED modules was found to depend upon several factors including LED type (i.e., warm white or cool white) and ambient operational temperature, at a minimum. Linear regression models that included only LED type and temperature explained only part of the observed effect. The correlation coefficient of such linear models was typically around 0.45 for both cool white and warm white LEDs and the statistical significance of the model were low (i.e., p values ranged between 0.06 and 0.42). In contrast, linear regression models using both temperature and current as independent variables explained more of the observed behavior. The coefficients for both warm white and cool white LED assemblies is shown in **Table 3** along with the corresponding p-value of each model component. The confidence levels of these model components can be seen to be better the 95%. Inspection of the table reveals that temperature has a larger impact on lumen maintenance than current, but both are necessary to include in the model to achieve a meaningful statistical significance.

Table 3: Components of linear regression models, and corresponding p-values, for lumen maintenance of the tested LED modules.

Model Component	Coefficient	p-value
Warm White Intercept	-1.12×10^{-5}	0.0263
Warm White Current	5.03×10^{-9}	0.0038
Warm White Temperature	2.06×10^{-7}	0.0043
Warm White Intercept	-1.23×10^{-5}	0.0430
Warm White Current	4.62×10^{-9}	0.0132
Warm White Temperature	2.15×10^{-7}	0.0089

Although there is some uncertainty in the α values used to construct these models, the high confidence levels of the linear regression modules with both current and temperature as independent variables suggests that the models may be good approximations of lifetime performance. For example, assuming a current of 1000 mA is supplied to a LED module and divided between the two LED assemblies in some fashion, these models indicated that the time required to reach L80 (i.e., decrease in luminous flux to 80% of the initial value) would be in excess of 55,000 hours for all current settings. 55,000 hours of continuous operation is equivalent to 6.3 years of continuous operation. Operating at lower currents and for only 12 hours per day would extend this value significantly.

In addition to the long lumen maintenance calculated for these LED modules, their chromaticity stability was also excellent. The warm white LEDs were found to shift in the green direction, while the cool white LEDs shifted in the yellow direction. The magnitude of the chromaticity shift for the warm white LED assemblies is less than that for the cool white LED assemblies. The chromaticity shifts in the LED assemblies resulted in the loss of less than 150 K in chromaticity tuning range based on the findings in testing at 700 mA. Most of this chromaticity shift is accounted for by the cool white LED assemblies. In general, the loss of 150 K in tuning range is not likely to be observed by the average viewer especially since it occurs mainly within the cool white colors.

The final component of the TWL system to be considered is the driver. Although two different multi-channel driver products were tested, no failures were observed and there was minimal change in the flicker waveforms, even after 1,000 hours of testing in 7575. A closer examination of the FFT spectra from these devices suggests that small changes may be occurring which shift and widen the FFT spectral peaks even though the drivers are working normally. Additional testing is needed to determine if these trends continues and how much degradation must occur before failure occurs in the device.

Summary & Conclusions

Tunable white luminaires are an emerging technology that enables the white light produced by a SSL device to be adjusted to meet the physiology demands of humans performing a given task. White light in this context can be referred to by the CCT value of the luminaire or the SPD of light emissions. The simplest TWLs utilize two assemblies of different white LEDs, often a warm white LED assembly combined with a cool white LED assembly to form an LED module. Each LED assembly is operated by a separate channel in the driver to allow the current supplied to each to be varied independently. By changing the blend of cool white and warm white emissions, CCT values between these endpoints can be produced.

The use of two LED channels of white lights with different CCT values in the device creates potential complexities with managing lumen maintenance and chromaticity stability. As shown in this paper, excellent lumen maintenance can be achieved with the proper choice of both the LEDs used in the modules and operational conditions of the device. Packaging of the LED assemblies into the LED module is also an important element of the design to provide the heat sinking and electrical connections needed to operate the device and to achieve excellent lumen maintenance and chromaticity stability. Since the separate LED assemblies can be operated over a wide current range, depending upon the CCT settings, creating maps of LED lumen maintenance versus current is important to understanding the long-term performance of each LED light source and the luminaire. The analysis reported here demonstrates that with proper design and operational boundaries for the LED modules, the luminous flux produced by tunable white luminaires can exceed 80% of the initial value (L80) after more than 55,000 hours of continuous operation regardless of the chosen CCT profile. At the conclusion of the accelerating tests reported here, a small reduction in CCT tuning range was observed; however, the magnitude of this shift is not likely to be noticeable by an observer. Overall, TWL is the next wave of high reliability SSL technologies and offers the potential for a superior lighting system by providing both high luminous efficacy and the ability to match lighting spectrum to human needs for each task.

Acknowledgments

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