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AN INVESTIGATION OF CATASTROPHIC FAILURE IN SOLID-STATE LAMPS EXPOSED TO HARSH ENVIRONMENT OPERATIONAL CONDITIONS

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ABSTRACT

Today's lighting technology is steadily becoming more energy efficient and less toxic to the environment since the passing of the Energy Independence and Security Act of 2007 (EISA) [1]. EISA has mandated a higher energy efficiency standard for lighting products and the phase out of the common incandescent lamp. This has led lighting manufacturers to pursue solid-state lighting (SSL) technologies for consumer lighting applications. However, two major roadblocks are hindering the transition process to SSL lamps: cost and quality. In order to cut cost, manufactures are moving towards cheaper packaging materials and a variety of package architecture construction techniques which may potentially erode the quality of the lamp and reduce its survivability in everyday applications. Typically, SSL lamps are given product lifetimes of over twenty years based off of the IES TM-21-11 lighting standard which does not include moisture effects or large operational temperatures [2]. A group of recently released off-the-shelf lamps have undergone a steady-state temperature humidity bias life test of 85°C/85%RH (85/85) to investigate the reliability in harsh environment applications.

The lack of accelerated test methods for lamps to assess reliability prior to introduction into the marketplace does not exist in literature. There is a need for SSL physics based models for the assessment and prediction of a lamp's lifetime which is being spearheaded by the DOE [3]. In order to be fully accepted in the marketplace, SSL lamps must be able to perform similarly to incandescent lamps in these environments, as well as live up to the lifetime claims of manufacturers.

A lamp's package architecture must be designed with performance factors in mind, as well as address some of the known and published package related failure mechanisms, such as carbonization of the encapsulant material, delamination, encapsulant yellowing, lens cracking, and phosphor thermal quenching [4]. Each failure mechanism produces the similar failure mode of lumen degradation predominately due to two contributing factors: high junction temperature and moisture ingress. The current state-of-the-art has focused on individual areas of the lamp, such as the LED chip, substrate material, electrical driver design and thermal management techniques. [5] – [16] Looking at the lamp as a whole is a novel approach and has not been seen before in literature.

This work followed the JEDEC standard JESD22-A101C of 85/85 with a one hour interval of applied voltage followed by a one hour interval of no applied voltage [17]. This test was performed continuously for each SSL lamp until it became nonoperational, i.e. did not turn on. Periodically, photometric measurements were taken following the IES LM-79-08 standard at room temperature using an integrating sphere, a spectrometer, and lighting software. The overall health of the SSL lamps was assed using the relative luminous flux (RLF), correlated color temperature (CCT) and the color difference (Δu`v`) using the

Euclidean distance of the CIE 1976 color space coordinates. Finally, a Weibull analysis was completed to compare the characteristic lifetime of the SSL lamp to the actual rated lifetime. An important result from this work shows that the rated lifetime does not come close to the actual lifetime when the SSL lamps are used in a harsh humid environment which is fairly common in outdoor applications across the U.S. Also, the photometric results are presented for the entire lifetime of each SSL lamp under test.

KEY WORDS
Solid-State Lighting, LED, Luminous Flux, Correlated Color Temperature, Color Shift

MOTIVATION

The U.S. Department of Energy (DOE) has made a long-term commitment to advance R&D breakthroughs in efficiency and performance of SSL. The DOE has developed a comprehensive national strategy that encompasses Basic Energy Sciences, Core Technology Research, Product Development, Manufacturing Research and Development (R&D) Initiative, Market Development Support, SSL Partnerships, and Standards Development [3]. The lack of accelerated test methods for LEDs to assess reliability prior to introduction into the marketplace does not exist. There is a need for SSL physics based PHM modeling indicators for assessment and prediction of LED life.

INTRODUCTION

SSL technologies are beginning to replace today's less energy efficient incandescent bulbs which are currently being phased out of the marketplace. Since incandescent bulbs will no longer be available, SSL lighting technologies will become more prevalent in everyday consumer applications, as well as numerous harsh environment applications, such as automotive, aerospace and marine. In order to be fully accepted in the marketplace, SSL lamps must be able to perform similarly to incandescent lamps in these environments, as well as live up to the lifetime claims of manufacturers.

SSL lamp's package architecture must be designed with performance factors in mind, as well as address some of the known and published package related failure mechanisms, such as carbonization of the encapsulant material, delamination, encapsulant yellowing, lens cracking, and phosphor thermal quenching [4]. Each failure mechanism produces the similar failure mode of lumen degradation predominately due to two contributing factors: high junction temperature and moisture ingress. The current state-of-the-art has focused on individual areas of the lamp, such as the LED chip, substrate material, electrical driver design and thermal management techniques. [5] – [16] Looking at the lamp as a whole is a novel approach and has not been seen before in literature.

This work has focused on the entire SSL lamp instead of specific components inside the package architecture. It has been well documented that temperature and moisture degrade SSL lamp components, but an investigation into the entire SSL lamp has not been reported in literature. This work characterizes the failures of SSL replacement bulbs using Photometry and Colorimetry calculations.

PHOTOMETRY & COLORIMETRY

Photometric and colorimetric values are obtained for SSL lamps using an integrating sphere and a spectrometer. The integrating sphere uses what is called 4π geometry for SSL lamps that emit light omnidirectional or forward directional by utilizing the entire surface of the integrating sphere. Figure 1 depicts the measurement system used to gather photometric and colorimetric data.

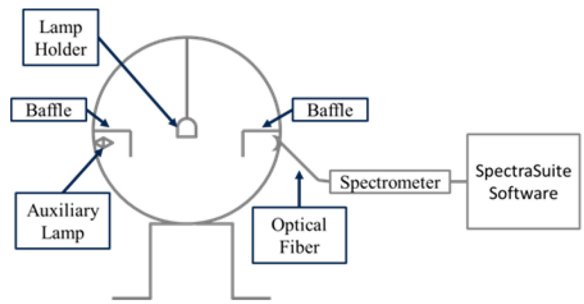

Figure 1: Photometric & Colorimetric Measurement System.

The IES LM-79-08 standard states that the total spectral radiant flux, $\Phi_{test}(\lambda)$, of a SSL product under test can be obtained by comparison to a known reference or calibration standard, $\Phi_{ref}(\lambda)$, spectral radiant flux [18]. It is determined using equation (1) where $y_{test}(\lambda)$ and $y_{ref}(\lambda)$ are the spectrometer readings of the lamp under test and the reference lamp found using the integrating sphere, respectively.

$$\Phi_{test}(\lambda) = \left[\Phi_{ref}(\lambda) \cdot \frac{y_{test}(\lambda)}{y_{ref}(\lambda)}\right] \cdot \alpha_{CCF} = \Phi_{m}(\lambda) \cdot \alpha_{CCF}$$
$$\alpha_{CCF}(\lambda) = \frac{y_{aux,REF}(\lambda)}{y_{aux,TEST}(\lambda)} \quad (1)$$

Once the integrating sphere has been calibrated with the known calibration standard, the bracketed term in equation (1) is calculated internally by the SpectraSuite software with the measured spectral radiant flux, $\Phi_m(\lambda)$, of the test lamp becoming the output of the software. The self-absorption factor, αCCF, can be found through a comparison of an auxiliary lamp measurement with the test lamp inside the integrating sphere, $y_{aux,Test}(\lambda)$, and an auxiliary lamp measurement with the calibration lamp standard inside the sphere, $y_{aux,REF}(\lambda)$ [18]. Both the test lamp and calibration lamp standard are off during the auxiliary measurements. The self-absorption factor is a critical parameter since SSL products typically have a different physical size, shape and absorption characteristics when compared to the calibration lamp standard used to calibrate the integrating sphere and the spectrometer. The total luminous flux, Φ_{test}, in lumens [lm] of the SSL product under test can now be found using the total spectral radiant flux found from equation (1) with equation (2) [18].

$$\Phi_{test} = K_m \cdot \int_{380}^{780} \Phi_{test}(\lambda) \cdot V(\lambda) \cdot d\lambda \tag{2}$$

$$K_m = 683\,\text{lm/W}$$

The spectral luminous efficiency function for photopic vision, $V(\lambda)$, is well documented in literature and K_m is the maximum spectral luminous efficacy. [18]

The tristimulus values for the lamp under test are computed using the spectral radiant flux obtained from equation (1) and the CIE 1931 color matching functions from a standard 2° observer. [19] – [22]

$$X = k \cdot \int_{380}^{780} \Phi_{test}(\lambda) \cdot \bar{x}(\lambda) \cdot d\lambda$$
$$Y = k \cdot \int_{380}^{780} \Phi_{test}(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda \tag{3}$$
$$Z = k \cdot \int_{380}^{780} \Phi_{test}(\lambda) \cdot \bar{z}(\lambda) \cdot d\lambda$$

The color matching functions ($\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$) are provided with seven significant figures by the CIE in tabular form at 1nm intervals over the visible light spectrum [22]. The variable k is known as the normalizing factor and is shown in equation (4). [19] – [22]

$$k = \frac{100}{\int_{380}^{780} E(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda} \tag{4}$$

In this equation, $E(\lambda)$ is the relative spectral power distribution of a CIE standard illuminant. For this work, the CIE standard illuminant A was chosen because it's correlated color temperature (CCT) of 2856K is close to the rated CCT values of the warm-white test specimens. Once the tristimulus values are obtained, the CIE 1931 color space coordinate system can be calculated. [19] – [22]

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z} \tag{5}$$

The coordinate system is then transformed to the CIE 1976 color space because the chromaticity of this space is more uniform compared to the CIE 1931 color space. [23]

$$u` = \frac{2x}{6y - x + 1.5}$$
$$v` = \frac{4.5y}{6y - x + 1.5} \tag{6}$$

The CCT of a lamp under test is the temperature of an ideal black-body radiator with a comparable hue. The isotemperature line that denotes the CCT of the lamp is perpendicular to the Planckian locus. This can be approximated with a high degree of certainty using the McCamy polynomial shown in equation (7). [23] [24]

$$CCT_{PL} = 449n^3 + 3525n^2 + 6823.3n + 5520.33$$
$$n = \frac{x - 0.332}{0.185 - y} \tag{7}$$

The color shift or color difference of a lamp can be determined in any color space coordinate system but is typically shown using the CIE 1976 color space. This is simply the Euclidean distance between the measurement coordinates and the pristine coordinates. [19]

$$\Delta u`v` = \sqrt{\left(u' - u_0'\right)^2 + \left(v' - v_0'\right)^2} \tag{8}$$

WEIBULL DISTRIBUTION

The Weibull distribution is an extensively used tool in industry to evaluate product life. Two important parameters obtained from a Weibull analysis are the characteristic life, α, and the shape parameter, β. The characteristic life describes the time at which 63.2% of the devices will fail. The shape parameter describes the failure rate, such as decreasing (e.g. infant mortality), stable (e.g. constant) and increasing (e.g. wear-out). [25] – [26]

The method of best linear unbiased estimates (BLUEs) is used to estimate the values of α and β [25].

$$\alpha = \exp\left(\sum_{i=1}^{n} a_i \cdot \ln(t_i)\right)$$
$$\beta = 1/\left(\sum_{i=1}^{n} b_i \cdot \ln(t_i)\right) \tag{9}$$

The coefficients a, b and t are the BLUEs coefficient for characteristic life, the BLUEs coefficient for the shape parameter and the failure time of the lamp under test. [25]

TEST VEHICLE

Three sets of off-the-shelf SSL replacement bulbs were used in this experimental work to investigate life characteristics. At the time of this experimentation, the SSL replacement bulbs were the state-of-the-art in the marketplace. The useful rated characteristics of each bulb are given in the Table 1.

Table 1: Rated Parameters of SSL Bulbs.

Parameter	ChWW	CWW	PWW
# of Samples	10	10	10
Luminous Flux [lm]	800	800	830
CCT [K]	3000	2700	2700
Power [W]	9	9.5	11
Efficacy [lm/W]	88.9	84.2	75

TEST ENVIRONMENT

The test vehicles were placed inside a temperature/humidity chamber in order to conduct a steady-state temperature humidity bias life test of 85/85 with an applied one hour electrical bias cycle per JEDEC standard JESD22-A101C [17]. The specimens were removed approximately every 240 hours in order to conduct photometric and colorimetric testing as described in the IES LM-79-08 standard [18]. The SSL bulbs were measured at room temperature and relative humidity at every time step T_i as shown in Figure 2.

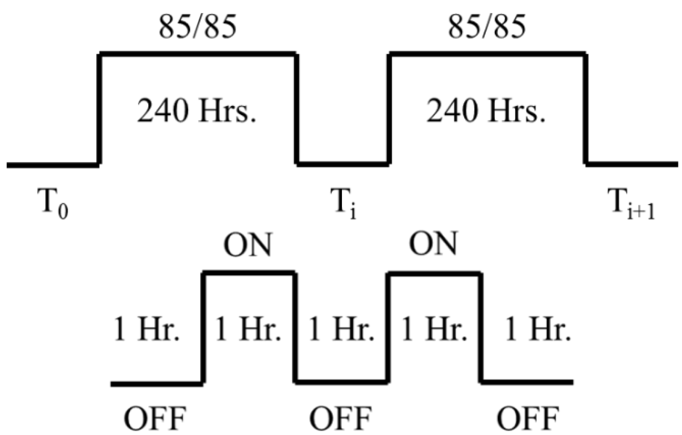

Figure 2: Temperature/Humidity and Power Bias Test Conditions for the SSL Bulbs.

RESULTS

As previously mentioned, the SSL replacement bulbs were removed from the chamber and measured at every time step until complete failure occurred so the reliability in harsh environment applications could be investigated. In order to compare the bulbs, the measurements were placed in relative terms, i.e. measurement divided by the original measurement. The currently accepted standard, TM-21, states that the failure threshold for lamps is a 30% reduction in RLF or lumen maintenance from the original measurement [2]. The time for the lamp to reach this threshold is called lumen maintenance life or L70. The RLF values for the test vehicles, as well as a line denoting L70 are shown in Figure 3 – Figure 5.

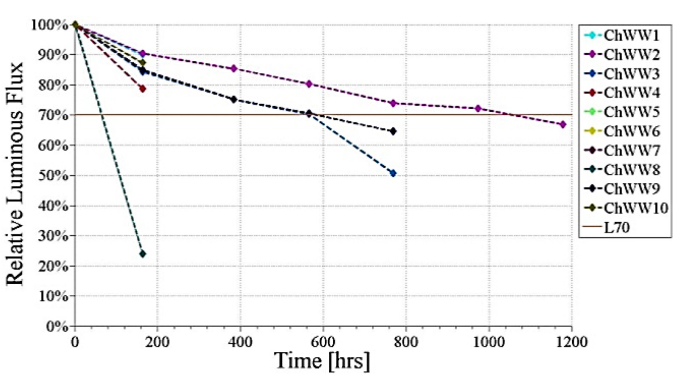

Figure 3: RLF of ChWW.

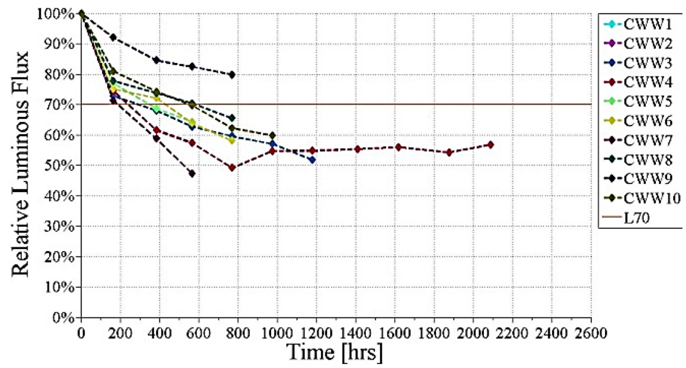

Figure 4: RLF of CWW.

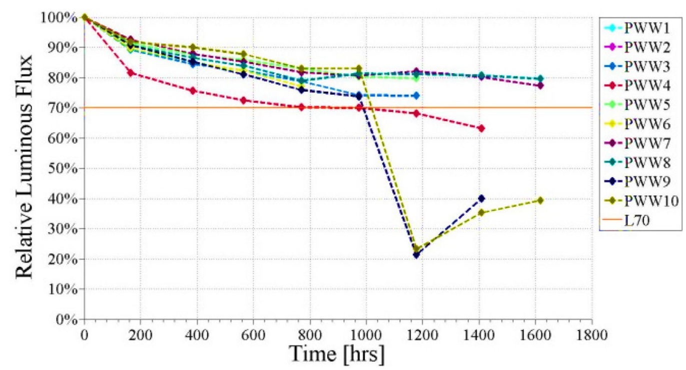

Figure 5: RLF of PWW.

From Figure 3, 30% of the ChWW test vehicles failed before measurements were taken at the first time interval, T1, and an additional 40% failed before the second time interval, T2. The remaining bulbs failed at about 800 hours and 1200 hours.

From Figure 4 and Figure 5, CWW and PWW survived much longer than ChWW in the 85/85 accelerated testing but were still susceptible to catastrophic failure due to the ingress of moisture.

The relative CCT values for each test vehicle can be seen in Figure 6 – Figure 8.

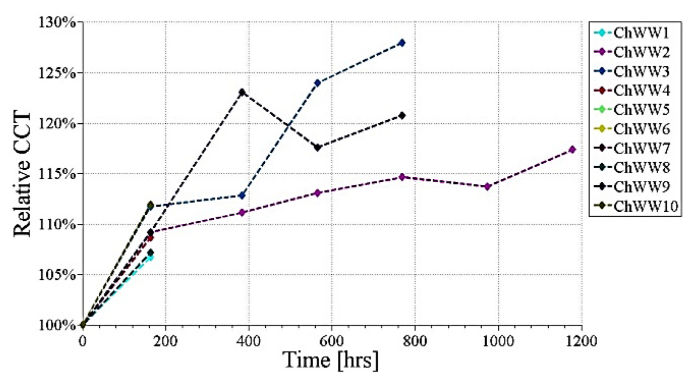

Figure 6: Relative CCT of ChWW.

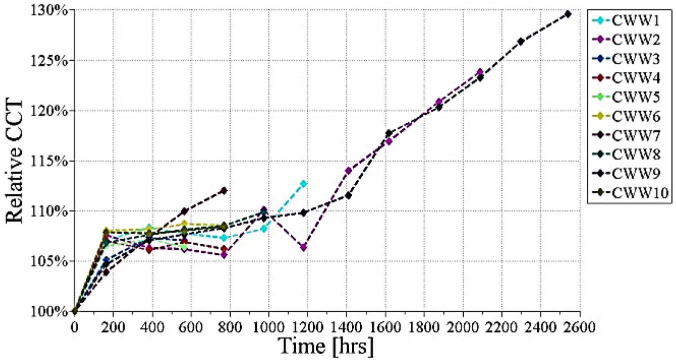

Figure 7: Relative CCT of CWW.

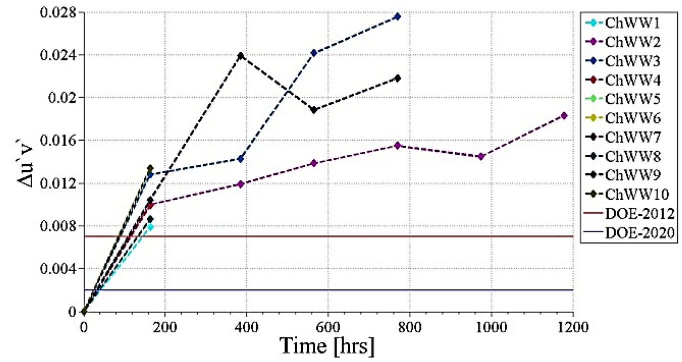

Figure 9: Δu`v` of ChWW.

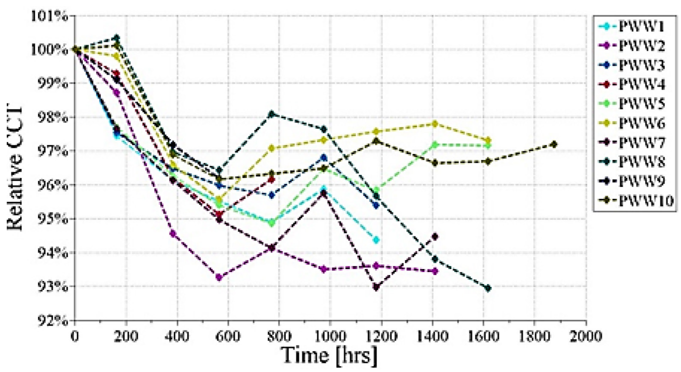

Figure 8: Relative CCT of PWW.

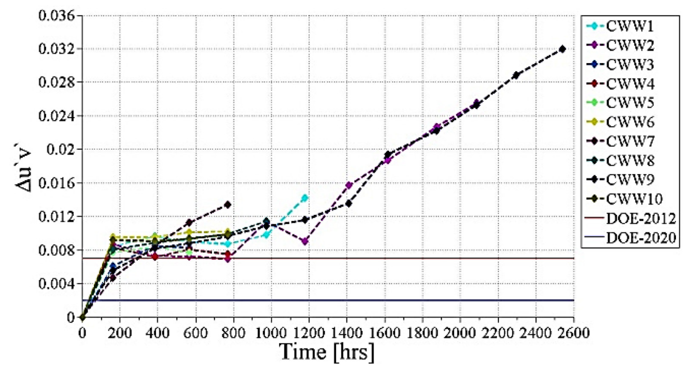

Figure 10: Δu`v` of CWW.

This parameter describes the "direction" the visible light's color coordinates are drifting. The increase in the relative CCT shown in Figure 6 and Figure 7 describes the color coordinates drifting towards the smaller wavelengths of visible light (i.e. blue light) along the Planckian locus. Figure 8 depicts an entirely different trend. The relative CCT of PWW is drifting towards the larger wavelengths of visible light (i.e. red light) along the Planckian locus. This is most likely due to the difference in construction type of these lamps. ChWW and CWW use white LEDs which have phosphor directly on top of the LEDs, while PWW uses blue LEDS with phosphor remotely placed from the LEDs to produce white light. The different designs correlate to the direction the color coordinate drift will occur.

The color shift or color difference of a lamp can be determined in any color space coordinate system but is typically shown using the CIE 1976 color space. The DOE had a 2012 target for lamps not to shift past 0.007 after 6000 hours and a new 2020 target of 0.002 over the lifetime of the lamp. Figure 9 – Figure 11 depict the color shift of each lamp, as well as lines denoting the DOE 2012 and 2020 targets.

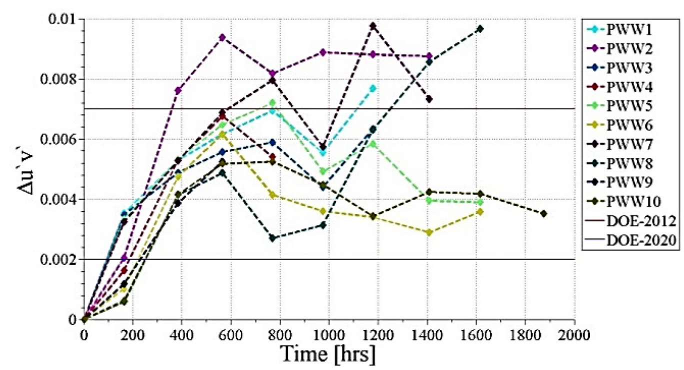

Figure 11: Δu`v` of PWW.

The color stability of the lamps exhibits different behaviors for each set of test vehicles. ChWW and CWW both produced large amounts of color drift, but at different rates with each lamp surpassing the DOE targets after the first time step. PWW saw a smaller color shift with the majority of the lamps staying under the DOE 2012 target. This may be due to the varying construction types, i.e. direct phosphor and remote phosphor.

Each lamp presented in this study has a rated life time of 22.8 years at 3 hours of use per day at normal operating conditions. However, the lamps failed catastrophically well before the rated life with the longest recorded time to failure being just over 2500 hours or about 0.29 years. This can be attributed to the ingress of moisture at the elevated temperature. The Weibull parameters are given in Table 2.

Table 2: Weibull Parameters.

Parameter	ChWW	CWW	PWW
α [hrs.]	212.28	1255.42	1476.19
β	0.48	1.79	3.82

ChWW has a characteristic life that is an order of magnitude lower than CWW and PWW. The shape parameter is less than one which means that the population of this test vehicle exhibits an early "infant mortality" failure rate that decreases with time.

CWW and PWW both have a similar characteristic life with shape parameters larger than one. This means the population for both test vehicles exhibits a wear-out failure rate which increases with time.

SUMMARY AND CONCLUSIONS

An investigation of off-the-shelf lamps using a steady-state temperature humidity bias life test of 85/85 with an applied one hour electrical bias cycle has been conducted following JEDEC standard JESD22-A101C in order to investigate reliability in harsh environment applications. Photometric and colorimetric test data was collected approximately every ten days as described in the IES LM-79-08 standard.

The RLF and CCT have been presented for each set of test vehicles, as well as the chromatic color shift. It was observed that the ingress of moisture had drastic effects on the lamps. The lamps that utilized the direct phosphor approach exhibited chromatic drift towards lower wavelengths of light along the Planckian locus, while the lamps using remote phosphor produced a chromatic drift towards higher wavelengths of light along the Planckian locus.

The Weibull analysis designated a small characteristic life and a shape parameter for ChWW indicating premature failure. CWW and PWW produced a similar characteristic life with shape parameters representing the presence of wear-out failure mechanisms.

In conclusion, the ingress of moisture from a harsh environment application decreased the lifetime of the lamps drastically. ChWW proved to be a much inferior SSL lamp compared to CWW and PWW. Additionally, the rated lifetime proved to be insufficient for actual lifetime when SSL lamps are exposed to large amounts of humidity from a harsh environment application.

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NOMENCLATURE

EISA	Energy Independence and Security Act
SSL	Solid-State Lighting
85/85	85°C/85%RH
RLF	Relative Luminous Flux
CCT	Correlated Color Temperature
$\Delta u`v`$	Color Shift of Chromaticity Coordinates
DOE	Department of Energy
$\Phi_{test}(\lambda)$	Corrected Radiant Flux
$\Phi_{ref}(\lambda)$	Reference Standard Radiant Flux
$y_{test}(\lambda)$	Test Lamp Radiant Flux
$y_{ref}(\lambda)$	Reference Lamp Radiant Flux
$y_{aux,TEST}(\lambda)$	Auxiliary Lamp with Test Lamp Radiant Flux
$y_{aux,REF}(\lambda)$	Auxiliary Lamp with Reference Lamp Radiant Flux
$\Phi_m(\lambda)$	Measured Spectral Radiant Flux
α_{CCF}	Absorption Correction Factor
Φ_{test}	Luminous Flux
$V(\lambda)$	Spectral Luminous Efficiency Function
K_m	Maximum Spectral Luminous Efficacy
k	Normalizing Factor
$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$	CIE 1931 Standard 2° Observer Color Matching Functions
X, Y, Z	Tristimulus Values
$E(\lambda)$	Relative Spectral Power Distribution of a CIE Standard Illuminant
x, y	CIE 1931 Chromaticity Coordinates
u`, v`	CIE 1976 Chromaticity Coordinates
CCT	Correlated Color Temperature
α	Characteristic Life
β	Shape Parameter
BLUEs	Best Linear Unbiased Estimates
a	BLUEs coefficient for α
b	BLUEs coefficient for β
t	Failure Time