Accelerated Testing Based Lifetime Performance Evaluation of LEDs in LED Luminaire Systems

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ABSTRACT LED luminaires have taken over other traditional lighting solutions in all possible lighting applications due to advances such as high lifetime, power efficiency, adaptability in size, shape, and different color generations. The reliability of the LED luminaire as a system was determined by the lifetime performance of the driver electronics. The advancements in power electronics led to more reliable components and products. The LED luminaire’s reliability is determined by the light output and color appearance quality, and quantity. The importance of single LEDs performance in the LED luminaires is most recently realized and needs to be explored. The manuscript presents the analyses of the lumen output and Duv based life estimation, the variations in color appearance in terms of xy chromaticity, and spectral power distribution of two luminaires having same electrical and optical specifications employing different type of LEDs subjected to different accelerated operating conditions. The results identify the predominant failure indicators for lumen and color changes, and show that LED physics & device packaging also play a significant role in the reliability study of an LED luminaire. The results of the manuscript are helpful for LED luminaire manufacturers to enhance the lifetime of LED luminaires by suitable moderation in the LED package design in terms of lumen output and color quality maintenance as per specific application requirements.

INDEX TERMS LED, L70, color-consistency, reliability, Duv, xy-chromaticity, spectral power distribution, Ag mirror tarnish.

I. INTRODUCTION
LED lighting is one of the most popular lighting technologies of the current era due to its variable physical designs, low power consumption and very high reliability compared to other traditional lighting solutions [1], [2]. Generally, the LED luminaire lighting system contains two main subsystems, the LED light engine, and the LED power electronic driver. The LED light engine consists of multiple/single LEDs arranged in series/parallel combinations of connections placed on a PCB. The PCB is further physically placed on a heat sink to dissipate the additional heat generated by the LEDs. The entire system is enclosed in a fiber/metal structure. A secondary optics made of acrylic will be used as a diffuser to eliminate glare or high brightness from the LED light [3]. The power electronic driver provides constant current to the LED circuitry to glow the LEDs at specific light levels. The LED driver consists of an AC-DC converter, and a DC-DC constant current converter with an electrolytic capacitor placed parallel to output to reduce the ripples to the LED luminaire [4]. One of the most popular reasons for LED technology to have overtaken all other lighting technology is its ability to have a long lifetime of approximately 50,000 hours [5]. The general public illumination has seen the slow lumen depreciation of LED luminaires and, consequently, their long life span. However, recent literature [6], [7] suggests that LED luminaire as a system would have a shorter lifetime than a single LED alone, as the failure of driver electronics would fail the LED luminaire system. The claim was valid and accepted over the last decade, and therefore the life of an LED luminaire is mainly compared to its driver electronics. But, due to the latest advancement in the power electronics components field, specifically higher resilient components, better control over the harmonics, power factor corrections and induced ripple mitigation, etc., the LED luminaire driver electronic systems offer similar or comparable...
performance to that of a single LED in terms of lifetime [8]. Recent studies in [9], [10], claimed that the primary reason for LED luminaire failure are the LEDs themselves, and then secondary reason can be driver electronics failure. The lighting market is currently taken over by many start-ups and new LED luminaire manufacturing companies, and the market strategy is to sell their products at a lower price. The quality of LEDs used is substandard, reducing the cost and the entire system’s lifetime performance. Thus, the study on the quality of LEDs used and their performance as a system is essential to have a long-term lifetime performance understanding of LED luminaires.

LED luminaire lifetime is dominated by the operating temperature condition of single LEDs inside the light engine referred to as junction temperature of LEDs and affects the lumen output and color characteristics. Conventional lifetime testing for LEDs lasts approximately 6000 hours. However, accelerated life testing to assess LED quality and faults quickly is essential [11]. Several highly accelerated degradation tests are analyzed under different high levels of temperature and humidity. The thermal degradation kinetics of LED lamps as a system is studied in [12] using step-down and step-up stress accelerated degradation test (ADT) to compare the decay mechanisms due to different thermal stress loads in both experiments. The results suggest that the LED package and phosphor play a significant role in the degradation of the entire LED system. A step-down aging test is performed with a stopping rule as per IES TM-28 in [13]. An equivalent time from one temperature to another is determined, and a two-stage method is adopted to establish the reliability model of LED lamps under accelerated temperature conditions. The methodology and experimental results are then used to deduce the lifetime for ambient temperature using the Arrhenius model. Degradation in optical properties of the LEDs found during ADT of high power LEDs is evaluated in [14]. Experimental methodology is developed for in-situ measurements during ADT and, the results were compared with general ADT and validated. [15] performs accelerated degradation tests to establish a thermal stress limit for LEDs such that the accelerated conditions depict the degradation of LEDs for practical conditions. The thermal stress limit is established to be approx 100°C. [16] performs experiments on seven different types of LED lamps to determine the effect of junction temperature on the performance of the LEDs during step stress accelerated degradation testing. Junction temperature is related to the ratio of white light power to blue light power. In addition, changes in lumen output under different temperature condition and during aging is also presented. [17] performs short-term accelerated life testing on high-brightness LEDs from various LED manufacturers. The exponential law and activation energy describe the decay of light output due to thermal influence. Visible changes of darkening of epoxy color are also observed with time. [18] develops a methodology for future predictions of characteristics of LEDs based on electrical signature observed in the first 100 hours of ADT. The aging protocol is mentioned, and current-voltage and capacitance-voltage measurements were used to perform the predictions, and results are validated statistically. The degradation behavior of a mid-power LED is studied by analyzing and simulating the spectral power distribution in [19]. Different types of LED lamps are aged under accelerated conditions and room temperature conditions to analyze the variation in the performance and predict the lifetime in [20]. The variations in terms of reduction in lumen maintenance are computed for different temperatures. [21] presents a review of possible scenarios failing GaN-based LED lights. Few observations included degradation of LED chip active layer due to driving current stress, degradation of interconnect points, degradation of the optical layer of white LEDs, catastrophic failure due to electrostatic discharge, etc. The weak points identified can be further tried to be improved for better performance of the LEDs.

The work presented in this paper compares the lifetime performance of two different types of LEDs used in precisely the same LED luminaire system driven by the same driver electronic configurations. Thereby analyzing the lifetime performance of both LED luminaire systems to confer the importance of selecting the appropriate type of LEDs for an LED luminaire based on application-specific requirements. The work presented mainly focuses on LED luminaire failure criteria analysis, such as lumen or light output and color-based lifetime performance. They are of utmost importance in many general applications such as households, colleges, public places, health care, retail, etc. This paper is organized as follows; the general methodology is presented in section II. In Sections III is the modeling of the lifetime performance, analysis, and discussions of the results. Section IV draws the conclusion, followed by References.

II. METHODOLOGY

The methodology starts with selecting the LED luminaire readily available in the market. The sample for the study is chosen among the most common LED down-lighter configuration from a leading LED luminaire manufacturing company. Two types of LEDs with exact replicas of PCB are selected, and the luminaire is reconfigured. Everything other than LEDs, all other physical and electrical characteristics, is the same in both types and is referred to as LED P and LED N, as shown in Figure 1. The internal package level diagram of individual phosphor converted white LED used in the light engine of the LED luminaire is as shown in Figure 2. The LED package includes LED chip connected to lead terminals using bond-wire for electrical connections. The reflective Ag mirror is at the bottom to reflect the indirect light from LED chip through the phosphor layer to increase the light-output in-addition to direct light from the LED chip. Multiple combinations of such LEDs arranged in series parallel combinations would form LED light engine of the LED luminaire. The technical specifications of the LEDs under the study is shown in Table 1. Two LED luminaire samples of LED P and LED N for each of the accelerated testing conditions are...
chosen for the analysis. Since the objective of the study is to determine the performance of the LEDs used in the LED luminaires, and each LED luminaire light engine has 64 LEDs and two such samples (128 LEDs) is the sample size for the analysis. The experimentation involves two levels of constant stress conditions; 80°C/80%RH stress testing is represented as Highly Accelerated Degradation Test (HADT) and accelerated constant stress level of 60°C/80% RH is designated as Accelerated Degradation Test (ADT) for further reference. The flowchart briefly describing the methodology is as shown in Figure 3. The first part of the analysis is the experimentation, where the LED luminaires (inclusive of LED driver) under the study are placed in the thermal chamber 24 × 7 continuously under the conditions of constant stress defined for the study. The second part is the regular optical measurements, where the LED luminaires were removed from the chamber at regular intervals for short time (2mins) and is placed inside the integrating sphere for photometric and colorimetric measurements. The spectrometer setup to integrating sphere measures the lumen output which in normalized to the measurements before the beginning of ADT/HADT. The colorimetric measurements such as Duv is also determined and normalization to zero for initial condition is established. The uncertainty in the measurements is limited to 1% under calibrated conditions with k = 2 (95% level of confidence). The normalized measurements of lumens and Duv at regular intervals of time is plotted, and using the curve fitting technique, the best fit is established considering minimum root-mean-square-errors and R-square value to statistically justify the model. The experimentation is continued, and the measurements are taken at regular intervals, until either lumen maintenance or Duv have reached the end of lifetime indicator. As per the standards for general illumination [5], for lumen maintenance, the L70 and for Duv, a limit of ±0.007 is considered as the end of lifetime indicators respectively. Further to reason with the color shift, various performance indicative characteristics such as xy chromaticity shift and changes in spectral power distribution curves are analyzed and reasoned with the nature of LED light output behavior and characteristics with time. The LED packages are compared before and after the HADT and ADT to investigate the effect of degradation qualitatively. The LEDs are carefully dismantled to reveal the internal arrangements to expose the critical components, and their characteristic changes with degradation are observed with scanning electron microscope (SEM) and energy dispersion spectroscopy (EDS) analysis. The results and the performance indicators are analyzed to compare and determine the reliability of the LEDs under study.

III. RESULT ANALYSIS AND DISCUSSIONS

The LED luminaries selected for the study are subjected to HADT and ADT conditions. The photometric and colorimetric characteristics of the LED luminaires are measured at regular intervals and are presented. Many meaningful inferences and conclusions are drawn from the measurements to analyze the role of LED in the reliability lifetime performance of the LED luminaires.
A. LUMEN OUTPUT ANALYSIS

The lumen output raw data measured at different intervals is modeled with a general exponential model as described by IES-LM-80 for lumen maintenance is given by equation 1.

\[ LM = A \times \exp(-B \times t) \]  

(1)

LM represents normalized lumen maintenance, \( t \) is time allotted in hours, \( A \) is the initial coefficient and \( B \) is the degradation coefficient, respectively. The raw data set from the experiments and the estimated lumen maintenance is shown in Figure 4.

![Figure 4. L70 lumen maintenance of LED P and LED N under HADT and ADT.](image)

The coefficients of the lumen maintenance model and corresponding to test samples and average lifetime are shown in Table 2. To verify the exponential model selection, R-square value is determined and as observed from the Table 2 the values are close to one. As seen, the lifetime under HADT and ADT is more for LED N than LED P. As observed, LED N offers L70 lifetime \( \approx 2.38 \) times more than L70 of LED P under both HADT and ADT conditions. The reason for this is the physical structure of the LED and the Silver(Ag) mirror inside it. The role of Ag mirror in LED lumen degradation is further addressed in section III-C describing the LED package level analysis.

B. COLOR CONSISTENCY ANALYSIS

The color consistency of the light output from LED luminaire with aging can be determined by Duv computation, observations from xy chromaticity, and SPD analysis to determine the characteristics of color shift of LED luminaire.

1) DUV ANALYSIS

The Duv results from HADT/ADT are subjected to the curve fitting technique to model for Duv variation with time. The model selected was linear model fit as a better model with fewer errors and R-square values closer to one. The equation representing Duv is shown in (2), where \( t \) is time in terms of hours, \( S \) and \( I \) are the slope and intercept coefficients of the model. The goodness of fit analysis with 95% confidence interval is also performed and the R-square value is found to be \( \geq 0.9 \) for all the samples under the study as seen in Table 3, thus justifies the linear model selection for the analysis.

\[ Duv = S \times t + I \]  

(2)

| Test | LED | A   | B   | \( R^2 \) | Hours |
|------|-----|-----|-----|-----------|-------|
| HADT | P1  | 0.87| -2.98 \times 10^{-4} | 0.98   | 729   |
|     | P2  | 0.85| -2.98 \times 10^{-4} | 0.95   | 669   |
|     | Avg | 0.87| -2.98 \times 10^{-4} | -       | 699   |
| ADT | P1  | 0.99| -1.21 \times 10^{-4} | 0.99   | 2868  |
|     | P2  | 0.98| -1.26 \times 10^{-4} | 0.99   | 2685  |
|     | Avg | 0.98| -1.24 \times 10^{-4} | -       | 2775  |

![Table 2. Duv coefficients and lifetime under degradation tests.](image)

The experimentally obtained raw data set with the estimated Duv for both the degradation conditions for LED luminaires LED P and LED N are shown in Figure 5. From the observation of Duv profiles in Figure 5, the Duv shift is more along with positive values for LED N. Still, for LED P, the transition is observed in the opposite direction, that is, towards the negative values. These results are observed to be consistent with all the test samples for all the accelerated degradation conditions. The properties that contribute to the color shift accounted by Duv are mainly the phosphor material degradation and the LED chip degradation. The Duv estimation model coefficients \( S \) and \( I \) of the equation (2) along with R-square values are shown in Table 3. The LED N Duv based lifetime is \( \approx 4.7 \) and \( \approx 6.2 \) times more than LED P luminaire for HADT and ADT degradation tests, respectively.
2) XY CHROMATICITY ANALYSIS

$xy$-chromaticity gives the color palette for quantifying the color of an LED light. The study of variations in the $xy$-chromaticity during degradation helps understand and support the direction of color shift and thus the shade of LED color changes. Figure 6 shows the $xy$ chromaticity diagram throughout the degradation process for HADT and ADT conditions. It can be seen from $xy$ chromaticity that with time, the variation of color shift is towards the blue color and moving downwards away from the Planckian-locus for LED P. The direction of color shift can also be supported by Duv results, which increased more negatively with degradation time. During aging, the potential of the yellow phosphor to convert the blue light to white decreases on account of phosphor degradation, and thus, the color shifts towards the blue region in the $xy$ color chromaticity diagram. The $xy$ chromaticity variations with time as observed in 6 shows, the direction of movement is towards green-red shade, crossing over and above the Planckian-locus for LED N for all the conditions. The positive Duv values for LED N support the observations of color shift. From these observations for LED N, it is inferred that the LED chip degradation is more intense than the LED phosphor degradation and, thus, lesser blue components in the white light with time. The theory of the color shift towards the blue region due to degradation of phosphor and away from the blue region due to chip degradation can also be accounted for using the analysis of the spectral power distribution curve of the luminaire.

3) SPD ANALYSIS

SPD curve variations with time will provide modifications to the optical properties of the white light due to degradation as it is known that all the optical characteristics are extracted from the SPD [22]. Thus SPD curve analysis forms an effective method to determine the visual changes in an LED and the results of SPD for both luminaire under the study, prior and post degradation tests are shown in 7.

It can be noticed that for all the LED luminaires, the optical power has lessened exceptionally indicating severe lumen degradation after the degradation test relative to the beginning of the test. For a cool white LED spectrum, SPD can be visually marked to consist of two regions, the dominant blue wavelength ($\approx 450$nm) and the yellow wavelength region ($\approx 550$nm) referred to as blue SPD and yellow SPD part, respectively. The reduction in the blue and yellow peaks of the SPD curves of LED P prior and post the ADT analysis is determined as 71% and 62%, respectively, relative to its initial conditions normalized to 100%. Similar computations are made for HADT, and all conditions of LED N luminaires, and the results are presented in Table 4. The relative change on the blue peak proportional to the change in the yellow region for LED P is 14% to 18% while for LED N it is $-1.3\%$ to $-2.4\%$ for ADT and HADT respectively. The results for LED P indicate that post degradation, the amount of blue component in the white light is increased, thereby indicating dominant phosphor degradation. On the contrary, for LED N, both blue and yellow part degradation were comparable, but the blue part showed marginally more reduction compared to the yellow part. Thus, it indicates dominant LED chip degradation relative to phosphor degradation in LED N. An alternate approach to analyzing the SPD curves is by comparing the Blue peak/Yellow peak (B/Y) ratio of the spectral power distribution. The B/Y ratio for the LED luminaires under the study before and after the degradation test are shown in Table 5. LED P has the B/Y ratio before the test less than after the test under both the degradation...
TABLE 4. SPD relative ratio of blue & yellow part under degradation.

| LED     | Blue peak % degradation before HADT ADT | After degradation |
|---------|----------------------------------------|-------------------|
| LED P   | 100                                    | 52 71            |
| LED N   | 100                                    | 65 71            |

C. LED PACKAGE ANALYSIS

The single LEDs of the luminaires are analyzed individually for package level analysis to ascertain the possible reasons for failure with the LED package. A darker yellow shade of phosphor and very distinctive black/brown layers is observed at the outset for the LEDs that underwent degradation by HADT/ADT in comparison to new LEDs, which had lime yellow color phosphor as seen in Figure 8.

![LED package discoloration before and after degradation tests.](image)

The phosphor layer discoloration is identified as one of the contributor for the LED failure. However, to further analyze, the LED package is dismantled to expose the Ag reflective mirror and the phosphor layer as shown in Figure 9. On SEM analysis, it is observed that an additional physical blackening layer is formed, which is the silver mirror tarnish due to chemical reaction and deposition of the corrosive material and byproducts of chemical reactions with silver. This deposition of materials and silver mirror corrosion will minimize the reflectivity of the Ag mirror present at the bottom of the LED package. Due to reduced reflectivity, the light from the LED does not get reflected back to the phosphor layer and thus brings about extreme lumen output degradation. In comparing LED P and LED N, the surface area of the Ag mirror of LED P is larger; hence more Ag mirror tarnish was observed, while LED N had a smaller surface area; thus, relatively lesser is the degradation with time. The spread and deposition of tarnish are severe in HADT compared to ADT, as expected. HADT is at higher-temperature conditions resulting in extreme chemical reactions inside the package allowing an extensive tarnish and early failure. The results of SEM-EDS are shown in Figure 10, which exhibits the pile-up of additional layer in the form of Ag mirror tarnish alongside LED chip. Similar observations of tarnish dispersion underneath the phosphor layer are also observed. Thus, it is an indication that Ag mirror tarnish also affects the LED chip performance and the phosphor layer, thereby contributing to color variations and lumen depreciation. The EDS analysis in Figure 10 reveals supplementary elements like chlorine and sulfur in the Ag-mirror tarnish region, which are considered harmful for Ag-mirror. The tarnish results from oxidation reactions between the Ag metal and chemicals released in the environment and during the packaging process, reactivated at increased junction temperature condition during LED operation.

Thus, the primary reason for lumen degradation is Ag mirror tarnish, and severity is dependent on the operating conditions.
temperature and the Ag mirror area exposed for degradation. From analyzing multiple governing indicators and observing similar inferences from each parameter, the reflective Ag mirror tarnish, LED chip degradation, and phosphor degradation contributes significantly to the LED luminaires reliability and lifetime performance.

IV. CONCLUSION
The LED luminaire life estimation and the role of LEDs in the light engine are analyzed experimentally, considering lumen and color-based performance analysis. Appropriate and optimum LED type selection is essential. As observed in the study, LED N based luminaire tends to impact the lifetime over and above a minimum of 2.5 times in L70. The LED selection becomes more critical in color consistency-based applications. As seen, LED N-based luminaires had a color shift away from blue and gave a lifetime of beyond 4 times that of LED P-based luminaires that shifted toward blue. The reason for lumen degradation is dominated by the Ag mirror tarnish of the LED package. The color-based degradation can be dominated by LED chip level degradation or yellow phosphor degradation. The work also provides future scope to determine the optimum internal characteristics of LEDs to have the best possible design to overcome Ag mirror tarnish, blue chip, and phosphor-based degradation, thereby improving the overall lifetime performance of LEDs and LED luminaire as a system. The analysis provides a generalized approach to determine the reliability of LED luminaire systematically. The methodology helps the LED luminaire manufacturers to provide appropriate details of lifetime performance testing and also improve the product design with respect to LED selection and luminaire design development.

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