IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 6 May 2024, accepted 16 June 2024, date of publication 24 June 2024, date of current version 1 July 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3418020

RESEARCH ARTICLE

Design of Test Method for Analysis and Estimation of LED Luminaire Lifetime Performance Under Cycle Based Realistic Operating Conditions

ANJAN N. PADMASALI, J. LOKESH, AND SAVITHA G. KINI
Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Udupi 576104, India
Corresponding author: Savitha G. Kini (savitha.kini@manipal.edu)

ABSTRACT LED-based lighting technology is widely adopted as it offers a range of benefits, including energy efficiency, durability, and flexibility in design. LED luminaires' performance during their lifetime is always a concern as several subsystems are in play. The best-adopted strategy yet is accelerated degradation testing with continuous hours of operation. This assumes that the LED luminaire is turned ON through out its life and as in reality the LED luminaires are turned ON and OFF constantly after certain hours of operation. The primary problem is that it doesn't take into account how LED luminaire lifespan performance is impacted by ON and OFF cycles. The work presented adopts modified testing where LED luminaires are turned ON/OFF after the LED luminaire temperature is settled to a steady value. The LED light engine and associated LED driver are operated continuously in three different environmental conditions. The results are analyzed considering lumen maintenance and equivalent series resistance of the electrolytic capacitor of the LED driver. Spectral power distribution and SEM-EDS analysis also revealed the reason for the deterioration of LEDs. An empirical model to predict the lifetime performance for different operating conditions is presented, and the cycle-based lifetime is estimated. Overall, the work offers a realistic performance testing, analysis and estimation technique considering all the possible scenarios the LED luminaire might encounter in a real-world application.

INDEX TERMS LED luminaire, performance analysis, cycles test, accelerated degradation test.

I. INTRODUCTION

LED luminaires are considered to be highly reliable and durable, with a long lifespan of 50,000 to 100,000 hours and low maintenance requirements [1]. However, the actual lifespan of an LED luminaire is affected by various factors, such as the quality of the LED chips, the quality of the driver, the thermal management of the luminaire, and the environmental conditions in which the luminaire operates [2]. Earlier, the LED luminaire lifetime was determined by the performance of the LED driver [3]. But, due to the advancements in LED driver electronics [4], [5] the lifetime of the LED driver is now comparable to better than the LED. The general illumination white LEDs are typically made using a phosphor coating that converts the blue light emitted by the LED chip into white light. This phosphor coating can degrade over time due to exposure to heat and other environmental factors, leading to a reduction in light output. The lifetime of an LED luminaire is typically defined as the time (L70) it takes for the light output to degrade to a certain level, such as 70% of the initial light output [6]. An electrical-thermal-luminous-chromatic model is developed by [7] to predict the light performance under operating temperature. The analysis is carried out for phosphor converted white LED packages. The research in [8] proposes, luminous flux degradation model to determine the optimal number

The associate editor coordinating the review of this manuscript and approving it for publication was Wenxin Liu.

of lamps to replace, maintenance schedules, and brightness dimming level, subsequently considers users' lighting needs, maintenance budget, and energy savings. Work presented in [9], discusses the life cycle assessment of an suspended LED luminaire and the impact on the installation of lighting in an office/classroom set-up.

Accelerated degradation testing of LEDs involves subjecting the LEDs to harsh conditions in order to accelerate the aging process and assess their long-term lifetime performance. The work in [10] presents a review of possible failure mechanisms of LEDs in real-world applications. High and Mid power LEDs are studied, and electrical overstress, assembly issues and chemical contamination are considered as the most common reasons for the failure of the LEDs. Another literature [11] presents a review on various generalized accelerated life testing procedure, different types of modelling, extrapolations, and statistical tools for lifetime prediction based on the accelerated test. The research in [12] adopts a spectral power density-based modelling technique to identify the process of mid-power white LED deterioration. According to the findings, there is a significant decline in the packaging materials properties, which led to LED deterioration. Deterioration of the phosphor layer and blue LED chip are two additional elements that contribute to the overall degradation of the LED light output. In [13], a step-down aging test is carried out with a stopping rule in accordance with IES-TM-28. To develop the dependability model of LED bulbs under accelerated temperature, a two-stage technique is used to calculate the equivalent time from one temperature to another. The work in [14] develops an accelerated test method at elevated temperature to reduce the testing hours to 2000 hours. Acceleration factor for degradation is determined based on the exponential degradation model and the Arrhenius model. The subsystem isolation method is employed in [15], to perform step-stress accelerated degradation test (ADT) on high power LEDs. The LED driver, light engine, and mechanical fixtures are the subsystems considered, and step stress test is conducted only on LED light engine. Higher operating conditions resulted in faster deterioration, and step stress life under multiple test settings is determined using a classified extrapolation of data from a single experiment. High-brightness LEDs from different LED manufacturers are subjected to short-term accelerated life testing by [16]. The exponential law and activation energy are used to illustrate how light output degrades as a result of temperature effect. It is also possible to witness the epoxy's color shifting and darkening over time. The studies with greater current stress are also carried out, and it is discovered that they rise junction temperature, accelerating LED deterioration. The work in [17] performs analysis in terms of defect growth in LED package using a systematic non-destructive approach. The results reveal that under accelerated test circumstances, the parasitic resistance associated with the LEDs varies. A study on optical degradation of the LED package due to high-temperature aging is performed in [18]. It is found that the encapsulant and delaminations do not affect the degradation process. The main reason is the LED junction temperature, and chemicals from the LED lead frame results in intense degradation. The most dominant failure mechanism of LED packages is identified with the help of Scanning Electron Microscope(SEM) and Energy Dispersive Spectroscopy (EDS) analysis. Modifications in the LEDs' optical characteristics that were discovered during the ADT of HPLEDs are assessed in [19]. For in-situ measurements during ADT, experimental technique is devised and the results are confirmed by comparison to generic ADT. Reference [20] proposes a highly accelerated degradation (HADT) methodology based on sub-system isolation method to determine thermal stress limit (TSL) for a LED lamp. The obtained TSL is applied to step-stress accelerated degradation testing(SSADT) to verify the uniform decay mechanism at different stress levels. The TSL limit for any LED lamp is estimated to be approximately 100C to 110C. Step-Down stress accelerated degradation test (SDSDT) analysis is proposed in [21]. The thermal degradation kinetics of LED lamps as a system is studied using SDSADT and step-up stress ADT (SUSADT) to compare the decay mechanisms due to different thermal stress loaded in both the experimentations. The results suggest that the LED package and phosphor play a significant role in the degradation of the entire LED package.

Work in [22] discusses five major mechanisms that contribute to the degradation of LED. The percentage effect of each in quantified and the most influential mechanism is identified as the main reason for failure. Approximately 42% of failure is due to chemical elements deposition on the surface of the Ag reflective layer resulting in severe light degradation. Reference [23] performs a parametric study on the life estimation of the LED-based lamps. LEDs are operated under constant dc current conditions and On-Off testing conditions to determine the effects of possible variations on the performance of LEDs. Power cycle based investigation on flip-chip type of LED module is presented in [24]. The thermal resistance of the LED under investigation is computed and the effect of temperature on the number of cycles of operation of the LED is determined for lifetime analysis. A supply switching test is performed in [25], where LED is subjected to a predefined thermal profile. Based on the analytical model developed and thermal transient measurements carried out, performance analysis of the LED model under cycles of test is determined.

As projected in the literature, continuous testing is carried out under various stress levels, and the LED luminaire performance depends on its operating hours, failing the entire system. But, in practice, the luminaire is also continuously switched ON and OFF, necessitating research into how the operation cycles affect the performance of LED luminaires. Limited study on the cycle-based operation is observed, and those LEDs are turned ON/OFF instantaneously without considering settling time for temperature stability. The temperature is the most dominating factor in determining the performance of the LED luminaire. As a result, cycles-based testing with regulated ON-OFF duration based on temperature stabilization is critical. So, real-world operating scenarios may be examined and a more realistic lifetime is predicted. Thus, the work presented in this manuscript addresses the above-stated concerns, determines the effect of operating cycles on the performance of LED luminaires, and indicates lifetime in terms of operating cycles under accelerated and real operating scenarios. Also, the works in literature predict the lifetime only at the accelerated test conditions, but in practice, LEDs can have a different operating temperature based on environmental conditions. The effectiveness obtained from restricting the experimental procedure to just three conditions is another noteworthy advantage. This approach conserves time and energy by reducing the need for extensive equipment usage, particularly in accelerated conditions, to ascertain results for additional conditions. By focusing resources on a streamlined process, researchers can expedite data collection and analysis, facilitating quicker insights and conclusions. Ultimately, this optimization enhances the overall productivity and effectiveness of the experimental procedure. Thus, a novel model is presented to estimate the lifetime for any desired conditions with a limited number of degradation tests.

II. METHODOLOGY

The LED samples chosen for the study are from leading LED luminaire manufacturers that are widely available in local market used for general illumination [26] and the technical details are as shown in Fig. 1. For reference the three models are named as LED M1, LED M2 and LED M3. One of the objectives of the proposed solution to determine the cycle-based lifetime is to reduce the number of experiments/degradation test to as minimum as possible and thereby provide an estimate of lifetime for other desired conditions. The degradation test involves subjecting the LED luminaires into three different environmental conditions. Four samples from each make/model is chosen for the analysis for each degradation condition. So in total 12 LED luminaires are subjected to each degradation test. The test conditions are as shown in Table 1. The behavior of performance indicators of the LED luminaire are analyzed using three different levels of degradation test conditions. The LED luminaires are subjected to different levels of ambient temperature(T_a) conditions, and constant humidity conditions for the analysis and are referred to as DT-A, DT-B and DT-C as shown in Table 1. The maximum junction temperature(T_j) of the LEDs inside the LED light engine is determined and is classified as shown in the remarks. The LED luminaire system(light engine + driver) is placed inside the thermal chamber for degradation analysis and measurements are taken at regular intervals of time. The connection diagram for the experimentation and measurement test setup is as shown in Fig. 2. The luminaires under test are turned ON and

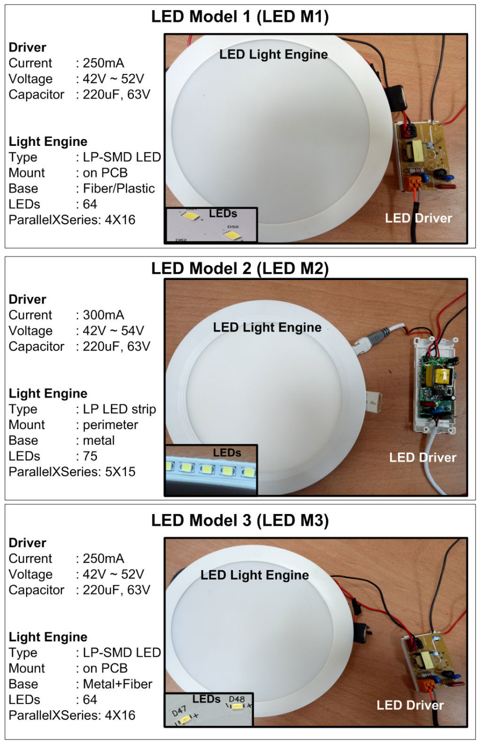

FIGURE 1. The LED make-models and its specifications for the degradation analysis [26].

TABLE 1. Specifications of test conditions under degradation analysis.

Test	Temperature(T_a)	Humidity	remarks
DT-A	80°C	80% RH	LED $T_j > 100°C$
DT-B	60°C	80% RH	LED $T_j < 100°C$
DT-C	$\approx$ 30°C	$\approx$ 80% RH	practical conditions

OFF every 20 minutes with help of micro-controller setup to study the effect of switching cycles on LED luminaire performance. The duration of 20 minutes is selected such that junction temperature is settled to a constant and thus lumen output is stabilized. At regular intervals of time the measurements are carried out with help of integrating sphere, spectrometer and sensors for photometric and electrical measurements [26] and [27], as shown in Fig. 2 and a model to determine the cycle based lifetime is developed. The integrating sphere and spectrometer set-up is calibrated for every set of measurements with standard calibration lamp and standard calibration procedures. The images of the environmental chambers and the test setup is shown in Fig. 3. DT-A, DT-B and DT-C test analysis are performed, and light engine parameters - lumen maintenance and equivalent series resistance (ESR) of driver capacitor is recorded at regular intervals of cycles. Lumen degradation and ESR increase with cycles of operation were observed. Thus, lumen maintenance and ESR change based analysis are performed. A flowchart in Fig. 4 describes the procedure adopted for cycle-based performance prediction and estimation for any other desired conditions. Three degradation levels of tests are performed, and the colorimetric and electrical measurements

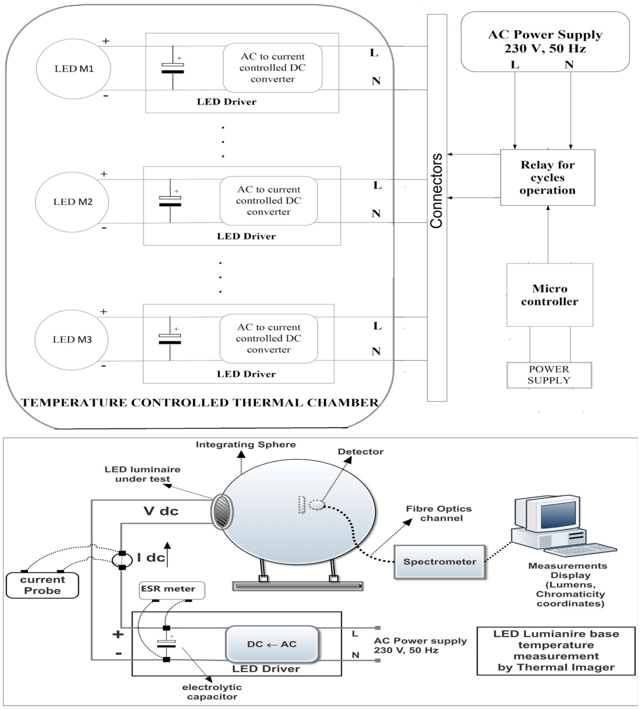

FIGURE 2. The connection diagram for degradation and measurement test setup.

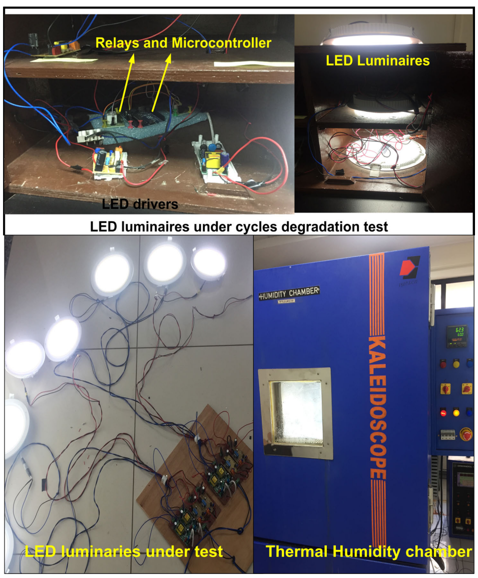

FIGURE 3. The degradation and measurement experimental test setup.

are recorded and the results projected as an average of four samples for each case. In terms of lumen maintenance and ESR, the cycle-based lifetime is projected for the three test settings. Analysis of Spectral Power Distribution (SPD) and SEM-EDS is also done to identify the reasons for failure. A novel multiplication factor-based empirical model is defined to estimate the lumen and ESR degradation profiles, giving the lifetime for any desired temperature conditions. The estimation is done for various temperature conditions and compared with experimental results for validation.

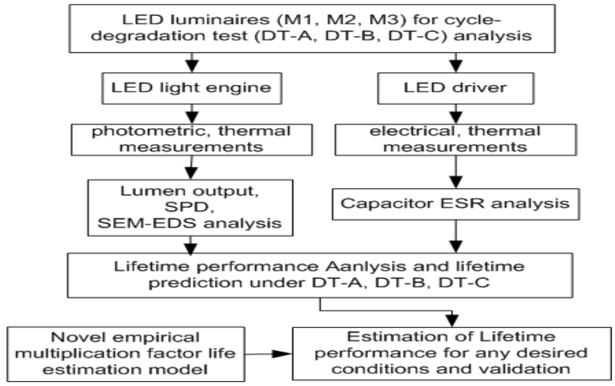

FIGURE 4. Flowchart for cycle based degradation test analysis and life prediction.

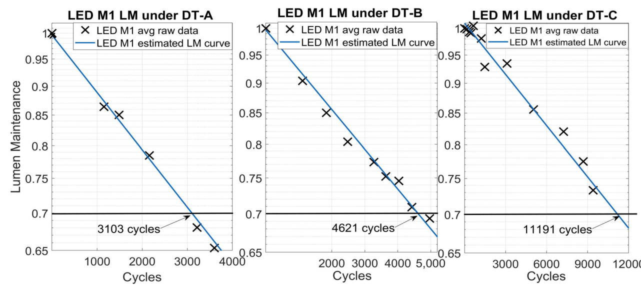

FIGURE 5. Lumen estimation of LED M1 under cycles degradation tests.

III. RESULT ANALYSIS AND DISCUSSIONS

For lumen maintenance and other photometric measures, measurements are obtained at regular intervals for all samples. Similarly, capacitor ESR measurements for LED drivers and other electrical measurements are undertaken. The Lumen maintenance threshold is chosen as L70 (70% of initial light output) as per the lighting standards, and the maximum value for ESR is limited to 1Ω for LED luminaires [28]. Thus, based on nature of the degradation, a suitable model is adopted to determine the lifetime of LED luminaires in terms of cycles of operation.

A. LED LIGHT ENGINE-LUMEN MAINTENANCE ANALYSIS

The LED luminaires are subjected to three temperature level conditions named DT-A, DT-B and DT-C. The measurements were carried out until one of the failure criteria is met which is the lumen maintenance based L70. The averaged lumen maintenance as a relation with the number of switching cycles is obtained and is shown in Fig. 5 for DT-A, DT-B and DT-C conditions of LED M1. Similarly the cycles based lumen performance for LED M2 and LED M3 are shown in Fig. 6 and Fig. 7 respectively. The experimentally obtained lumen maintenance is modeled as an exponential model as a function of cycles of operation, similar to hours of operation, as shown in equation (1).

$$LM = A \times exp(-B \times c) \tag{1}$$

A and B are the coefficients of the model and c represents cycles. The value of R^2 is greater than 0.85, such that the

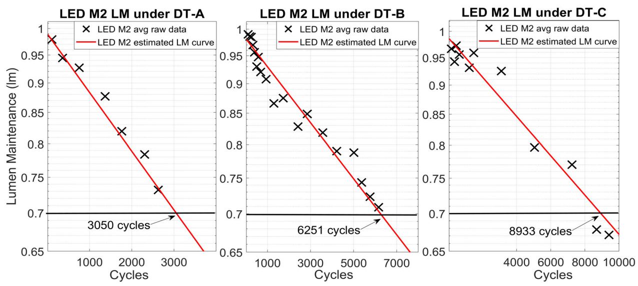

FIGURE 6. Lumen estimation of LED M2 under cycles degradation tests.

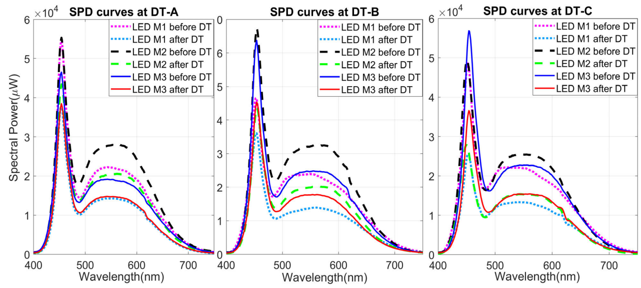

FIGURE 8. SPD of the LED luminaires under cycles degradation tests.

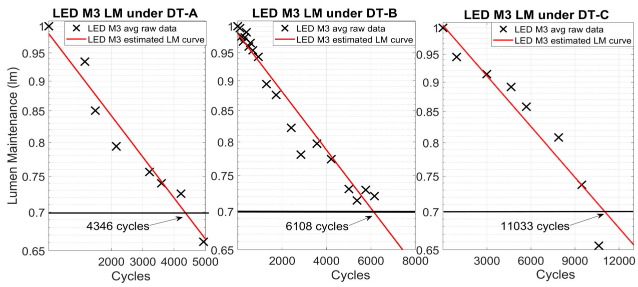

FIGURE 7. Lumen estimation of LED M3 under cycles degradation tests.

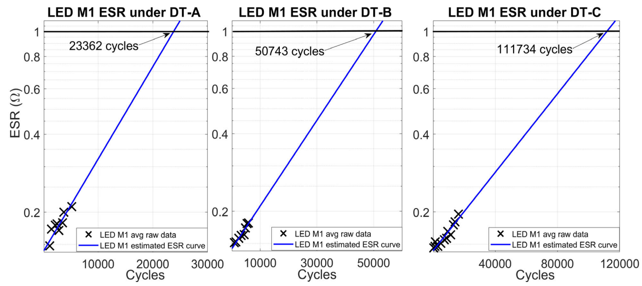

FIGURE 9. ESR estimation of LED M1 under cycles degradation tests.

TABLE 2. Lumen maintenance coefficients and life of LED luminaires.

	DT-A		
LED	A	B	cycles
M1	0.99	-11.37×10-5	3103
M2	0.99	-11.36×10-5	3050
M3	0.99	-7.88×10-5	4346
	DT-B		
M1	0.99	-7.65×10-5	4621
M2	0.98	-5.41×10-5	6251
M3	0.99	-5.61×10-5	6108
	DT-C		
M1	1.01	-3.28×10-5	11191
M2	0.99	-3.85×10-5	8933
M3	1	-3.28×10-5	11033

model and coefficients are accurate for life estimation. The averaged values of coefficients and corresponding cycles for L70 of all the luminaires under the test are shown in Table 2. It is observed that the LED luminaires have a lifetime of ≈ 3000 to 4000 cycles under DT-A, and while testing for DT-B showed a lifetime of ≈ 5000 to 6000 cycles and lifetime under practical operating conditions are expected to be around ≈ 10000 cycles.

B. LED LIGHT ENGINE-SPECTRAL POWER DISTRIBUTION ANALYSIS

Spectral Power Distribution is the distribution of power or energy emitted by a light source at different wavelengths across the visible spectrum. All the photometric and colorimetric measurements are derived from the SPD. The SPD for the LED luminaires under the degradation test conditions before the start of test and after completion of the tests are shown in Fig. 8. In every instance, it is observed that the SPD curves after the degradation test have reduced spectral power due to the reduction of lumen output. It is also to be observed that the peak wavelength is maintained the same throughout the degradation tests. Thereby indicating that the color characteristics are not changed in the cycles-based degradation test, and the lumen maintenance is the only degradation failure mechanism for the LED light engine subsystem.

C. LED DRIVER ANALYSIS

The ESR of the electrolytic capacitor is considered as the lifetime performance factor of the LED driver, as it dictates the quality of constant current fed to the LED light engine and is considered as the weakest link in the LED driver. During every switching cycle the electrolytic capacitor charges and discharges there by the degradation of the capacitor is significant. Thus ESR is measured at regular intervals of time and the averaged ESR as a relation with the number of switching cycles is obtained in similar lines as that of lumen maintenance and is shown in Fig. 9, Fig. 10 and Fig. 11 for LED M1, LED M2 and LED M3 respectively. Since the experiments were carried out until the first failure criterion is met in terms of lumen maintenance, the ESR values measured during the experiments are used to estimate life of driver. The ESR based life estimation is modeled as an exponential function of cycles and is shown in the equation (2). A' and B' are the coefficients and c represents cycles of operation.

$$ESR = A' \times exp(B' \times c) \tag{2}$$

The coefficients and cycles for ESR estimation of all the luminaires under the test for all the conditions are shown in Table 3. From the estimation, the approximate number of cycles to determine the life of LED luminaires under DT-A is ≈ 25,000 cycles. Similarly, the approximate cycles based

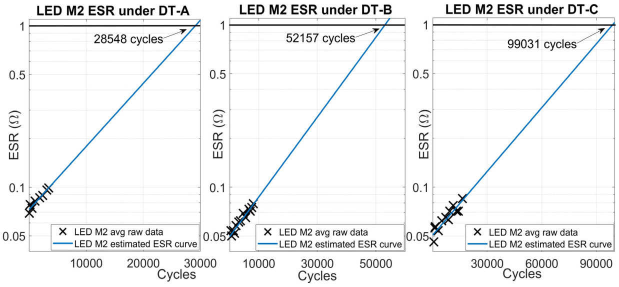

FIGURE 10. ESR estimation of LED M2 under cycles degradation tests.

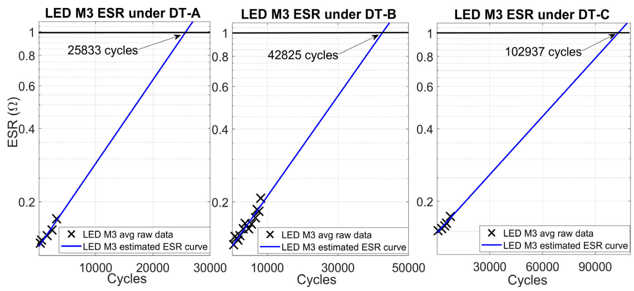

FIGURE 11. ESR estimation of LED M3 under cycles degradation tests.

TABLE 3. ESR coefficients and life of LED luminaires.

	DT-A		
LED	A'	B'	cycles
M1	0.143	8.32×10-05	23362
M2	0.071	9.26×10-5	28548
M3	0.129	7.92×10-5	25833
	DT-B		
M1	0.143	3.84×10-5	50743
M2	0.051	5.7×10-5	52157
M3	0.133	4.71×10-5	42825
	DT-C		
M1	0.141	1.75×10-5	111734
M2	0.05	3.02×10-5	99031
M3	0.148	1.86×10-5	102937

life of LED luminaires under DT-B and practical conditions are found to be ≈ 47,000 cycles and ≈ 1,00,000 cycles respectively.

D. LUMEN MAINTENANCE BASED PERFORMANCE ESTIMATION FOR DESIRED CONDITIONS

To analyse the LED luminaire performance in terms of lumen output variations at desired conditions, an accelerating multiplication factor based model is proposed. The proposed model uses the results of various degradation tests presented, to determine the novel life prediction model coefficients and then the degradation profile for different temperatures in the operating range is determined. The lumen maintenance model for L70 prediction based on cycles of operation as shown in equation (1) is used and the predicted coefficients is determined as shown in equation (3)

$$A_{use} = A_{acc} \quad B_{use} = B_{acc} \times MF \tag{3}$$

here, $A_{use} = A_{acc}$ is not impacted by degradation variations as it is the initial value at zero cycle operation. However, B_{use} is the degradation factor deciding the shape of degradation curve, this factor is majorly dependent on temperature as influencing the shape of the degradation profile. Therefore $B_{use} = B_{acc} \times MF$, where MF is the multiplication factor dependent on temperature which gives relative contribution of degradation effect to the accelerated test obtained B_{acc}. One such model that is used widely is the Coffin-Manson model applied for thermal-induced fatigue failures [29]. The Acceleration Factor (AF) using Coffin-Manson model is shown in equation 4 below.

$$AF = \left(\frac{\Delta T_H}{\Delta T_L}\right)^b \times \left(\frac{f_L}{f_H}\right)^{-a} \times exp\left(\frac{Ea}{K} \times \left[\frac{1}{T_{KL}} - \frac{1}{T_{KH}}\right]\right) \tag{4}$$

where, AF = Acceleration Factor; $\Delta T_H = \Delta T$ of high stress level temperature cycle; $\Delta T_L = \Delta T$ of low stress level temperature cycle, f_L = cycles per day at the low stress level temperature cycle; f_H = cycles per day at the high stress level temperature cycle; T_{KL} = max absolute temperature at the low stress level temperature cycle, in K; T_{KH} = max absolute temperature at the high stress level temperature cycle, in K; a and b are constants. The model is applied for determining the reliability for electronic packaging under accelerated temperature cycle test [29],and thus it is possible to modify and use the Coffin-Manson model for cycle-based reliability of LED luminaire as LEDs degradation is predominantly affected by the temperature. For cycles of operation analysis, the temperature-induced multiplication factor model is derived from modifying the Coffin-Manson model applied for thermal-induced fatigue failures, as shown in the equation (5). Since the frequency at all the accelerated temperature conditions are same the ratio $\frac{f_L}{f_H}$ is one for all measurements and $\frac{Ea}{K}$ is represented as constant a.

$$MF = \left(\frac{\Delta T_{acc}}{\Delta T_{use}}\right)^n \times exp\left(a \times \left[\frac{1}{T_{use}} - \frac{1}{T_{acc}}\right]\right) \tag{5}$$

In the equation, MF is multiplication factor, n is power factor, ΔT_{acc} and ΔT_{use} are $T_{max} - T_{min}$ under accelerated and practical use conditions respectively. Similarly a is thermal coefficient and T_{acc} and T_{use} are maximum temperature under accelerated and desired use conditions given in kelvins.

The LED boundary temperature under cycle operation are the stabilized junction temperature, which is the maximum temperature(T_{max}) and the ambient temperature, which is the minimum temperature(T_{min}). The difference of these temperatures is the temperature change with cycles represented as ΔT. The temperature of the LED light engine for all three luminaires under the study is shown in Table 4 for DT-A, DT-B and DT-C conditions. Using the equation (5), the coefficients of the multiplication factor are computed using DT-A - DT-B and DT-A - DT-C experiments and are shown in Table 4.

TABLE 4. Temperature of LEDs and *MF* coefficients under cycles test.

DT	T(°C)	LED M1	LED M2	LED M3
DT-A	T_{min}	80	80	80
	T_{max}	113.02	103.66	116.69
	ΔT	33.02	23.66	36.69
DT-B	T_{min}	60	60	60
	T_{max}	98.84	85.69	100
	ΔT	38.84	25.69	40
DT-C	T_{min}	27	27	27
	T_{max}	79.25	64.58	85.92
	ΔT	52.25	37.58	58.92
MF coefficients	a	-4021.34	7009.95	2402.83
	n	-4.8883	2.3192	-0.7352

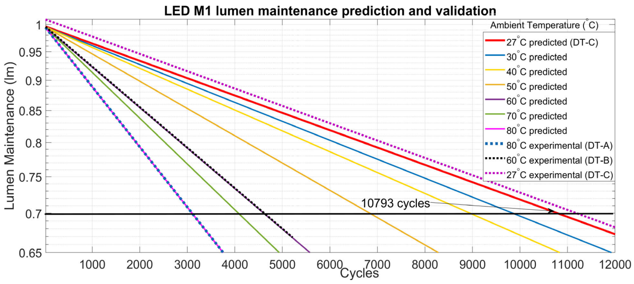

FIGURE 12. Lumen based performance prediction of LED M1 and validation.

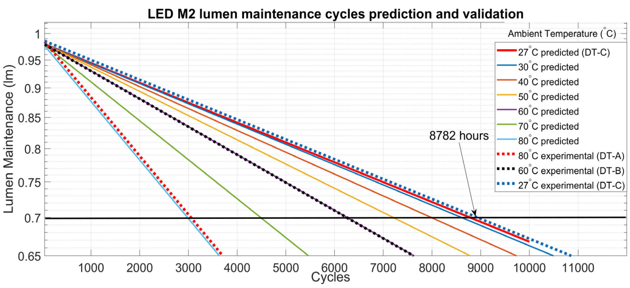

FIGURE 13. Lumen based performance prediction of LED M2 and validation.

The performance of the LED luminaire based on lumen maintenance is predicted for various temperature conditions within the range of practical temperature of 27°C and up to a maximum of 80°C (DT-A) ambient conditions. The values of minimum temperature (ambient) and maximum temperature (junction) with corresponding multiplication factors are presented in Table 4. The computed multiplication factors along with equation (3) is used to predict the degradation coefficient (β_{pred}) considering 60°C(DT-B) as the reference. The initial coefficients(A_{pred}) is same as the coefficient under DT-B condition(A_{acc}) and the values (from Table 2) are 0.99, 0.98 and 0.99 for LED M1, LED M2 and LED M3 respectively. The lumen maintenance L70 prediction based on cycles of operation for all the luminaires under the study is presented in Table 5. The prediction of lumen maintenance performance based on cycles of operation with DT-B as reference condition is shown in Fig. 12, Fig. 13 and Fig. 14 for LED M1, LED M2 and LED M3 respectively. From the figures, the predicted results for practical conditions

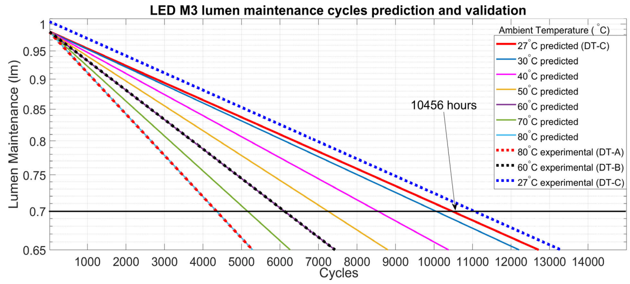

FIGURE 14. Lumen based performance prediction of LED M3 and validation.

TABLE 5. Predicted coefficients of model and lumen maintenance life cycles prediction and validation.

LED	B_{pred}	C_{pred}	A_{exp}	B_{exp}	C_{exp}	% error
M1	3.275x10-5	10793	1.01	3.276x10-5	11191	-3.56
M2	3.850x10-5	8782	0.99	3.850x10-5	8924	-1.6
M3	3.277x10-5	10456	1	3.281x10-5	11033	-5.23

are comparable to those obtained experimentally under practical conditions. However, to validate the predictions, the lumen maintenance model coefficients (A_{pred} and B_{pred}) for practical operating conditions (27°C) predicted using DT-B results and the coefficients from experiments at DT-C conditions(A_{exp} and B_{exp}) are presented in Table 5. The cycle-based L70-life (C_{pred}) is obtained using predicted coefficients and lumen maintenance model as in equation (1), and is compared with experimentally obtained L70-life (C_{exp}) for practical conditions (DT-C). The prediction is validated with the % error of less than 6% as shown in Table 5.

E. LED DRIVER ESR BASED PERFORMANCE PREDICTION AND VALIDATION FOR CYCLES OF OPERATION

An accelerated multiplication factor based performance prediction model is proposed for ESR based performance estimation in terms of cycles of operation. The proposed model for ESR based life prediction is similar to cycles based life prediction of lumen maintenance. The multiplication factor is the same given in equation (5). The method for predicting the MF coefficients uses all DT analysis results and the degradation parameter of the ESR based model, shown in equation (2).The predicted coefficients are derived as shown in equation (3)(using $A'_{use/acc}$ and $B'_{use/acc}$ instead of $A_{use/acc}$ and $B_{use/acc}$ for ESR estimation). For the LED driver under cycles operation, the representation of temperature are maximum capacitor surface temperature assumed as the maximum temperature(T_{max}) and the ambient temperature as the minimum temperature(T_{min}). The difference of these temperature are the temperature change with cycles represented as ΔT. The temperature of LED driver capacitor are shown in Table 6 for DT-A, DT-B and DT-C conditions. The coefficients of the multiplication factor are computed using DT-A - DT-B and DT-A - DT-C experiments and are shown in Table 6.

The performance of the LED driver based on ESR is predicted for various temperature conditions within the range

TABLE 6. Temperature (°*C*) of LED driver capacitor and *MF* coefficients under cycles of operation.

DT	T(°C)	LED M1	LED M2	LED M3
DT-A	T_{min}	80	80	80
	T_{max}	85	88	85
	ΔT	5	8	5
DT-B	T_{min}	60	60	60
	T_{max}	67.5	70.2	66.2
	ΔT	7.5	10.2	6.2
DT-C	T_{min}	27	27	27
	T_{max}	37.2	40.9	36.2
	ΔT	10.2	13.9	9.2
MF coefficients	a	1108.92	-1375.31	10150.95
	n	-1.5147	-3.066	-9.7175

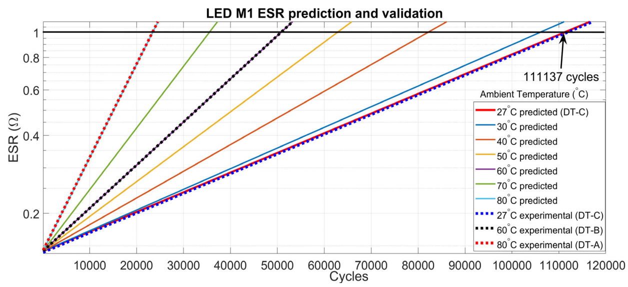

FIGURE 15. ESR based performance prediction of LED M1 and validation.

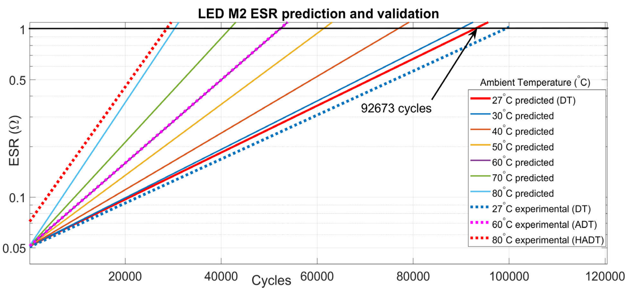

FIGURE 16. ESR based performance prediction of LED M2 and validation.

of practical temperature of 27°C and up to a maximum of 80°C ambient conditions. The values of minimum temperature (ambient) and maximum temperature (capacitor) with corresponding multiplication factors are presented in Table 6. The computed multiplication factors along with equation (3) is used to predict the degradation coefficient (β'_{pred}) considering 60°C(DT-B) as the reference. The initial coefficient(A'_{pred}) is same as that of DT-B conditions (A'_{acc}), and the values are 0.143, 0.051 and 0.133 for LED M1, LED M2 and LED M3 respectively. The prediction of ESR performance based on cycles of operation with ADT as reference condition is shown in Fig. 15, Fig. 16 and Fig. 17 for LED M1, LED M2 and LED M3 respectively. The predicted ESR based life cycles results for practical conditions are compared to those obtained experimentally under practical conditions for validation as seen in the figures. The ESR model coefficients (A'_{pred} and B'_{pred}) for practical operating conditions (27°C) predicted using DT-B results

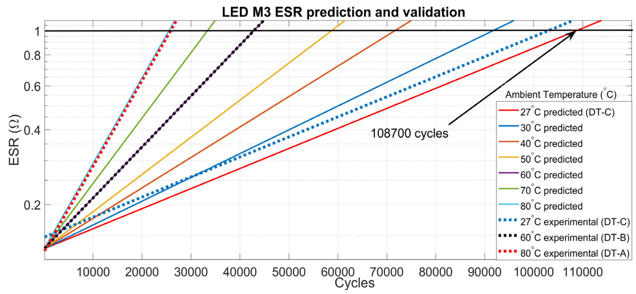

FIGURE 17. ESR based performance prediction of LED M3 and validation.

TABLE 7. Predicted coefficients of model and ESR life cycles prediction and validation.

LED	B'_{pred}	C'_{pred}	A'_{exp}	B'_{exp}	C'_{exp}	% error
M1	1.752x10-5	111137	0.141	1.75x10-5	111734	-0.5
M2	3.209x10-5	92673	0.05	3.02x10-5	99031	-6.4
M3	1.858x10-5	108700	0.148	1.86x10-5	102937	5.6

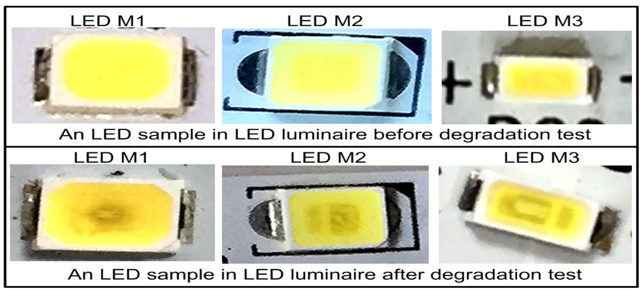

FIGURE 18. The visual of LEDs afresh before and discoloration after the DTs.

and the coefficients from experiments at DT-C conditions (A'_{exp} and B'_{exp}) are presented in Table 7. The cycle-based ESR-life (C'_{pred}) is obtained using predicted coefficients and is compared with experimentally obtained ESR-life (C'_{exp}) for % error computation as shown in Table 7. The life-cycles are predicted and validated with an % error of less than 7%. Thus, the proposed model with help of three experiments, is used to predict the ESR based performance of the LED luminaire for different operating conditions.

F. LED PACKAGE ANALYSIS

The LEDs inside the LED luminaires are exposed and observed to identify the reason for the light output degradation. The discoloration is observed after the degradation testing as shown in Fig. 18. To determine the chemical composition and examine the discoloration, the LEDs are cautiously dismantled to expose the Silver(Ag)-mirror, and it is noticed that because of the build-up of additional elements on the Ag mirror, a layer of brown/black patina is observed at the perimeter and around the LED chip of the LEDs. The SEM-EDS analysis is performed to identify the elements, and the results of a new LED and a degraded LED of LED M1 after the experimentation DT-A is completed are shown in Fig. 19 and similar observations were found in other LED samples at the degradation tests. Similar results are also

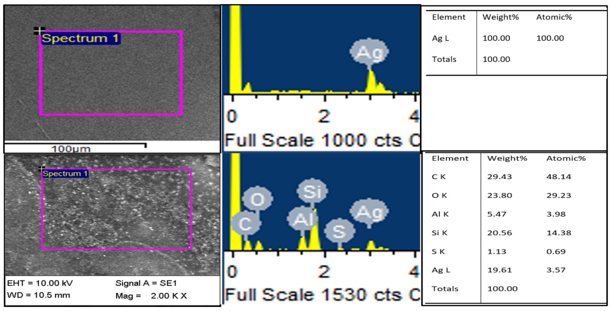

FIGURE 19. SEM-EDS results of fresh and degraded LEDs under DT.

observed in literature under continuous hours of degradation test as one of the reason for LED failure [26]. The EDS analysis also revealed the presence of Sulphur (S), which is highly reactive at higher temperatures with silver, to form silver sulfide (Ag_2S) [30], as shown in the equation (6)

$$4Ag + 2H_2S + O_2 = 2Ag_2S + 2H_2O \tag{6}$$

The resultant of this oxidation leads to the generation of brown-colored deposition, drastically reducing the LED light output. Chemical residues left over from the production process on the lead frame are another potential cause of contamination in LED packages. The use of materials or equipment containing chlorine or sulphur as well as the handling or transportation of lead frames prior to silicone dispensing are other potential reasons. High response rates are caused by higher temperatures and light photons, which shorten the lifetime of LED packages by hastening tarnish and seriously impairing LED lumen output. As a result, improving the performance of LED packages and, therefore, the lifespan of the overall LED luminaire system, necessitates a sturdy design of LED packages.

IV. CONCLUSION

The LED luminaire lifetime performance depends on the combination of the LED light engine performance and the LED driver performance. Accelerated degradation testing should represent the real-world application; therefore, the following selections were made for the degradation analysis of the LED luminaires. Three different models of LED luminaires readily available in the market manufactured by leading companies are chosen for the study. Three degradation test conditions were selected to consider practical room operation conditions to worst-case temperature conditions. Most importantly, LED luminaires (light engine with driver) are subjected to ON/OFF cycles with a delay to stabilize the LED luminaire temperature. The degradation analysis revealed that lumen degradation is primarily the reason for failure, followed by the filter capacitor in the LED driver. SPD analysis also conveys the lumen degradation effect, and SEM-EDS analysis revealed the tarnishing of the Ag-mirror. An empirical multiplication factor-based model is presented to estimate the lifetime for any desired operating temperature conditions with restricted number degradation testing. Thus, the work forms a reference guide for manufacturers and researchers to determine the lifetime of LED luminaires effectively considering real operating scenarios and therefore give a realistic projection of LED lifetime for any operating conditions.

REFERENCES

[1] B. Sun, X. Jiang, K.-C. Yung, J. Fan, and M. G. Pecht, "A review of prognostic techniques for high-power white LEDs," *IEEE Trans. Power Electron.*, vol. 32, no. 8, pp. 6338–6362, Aug. 2017, doi: 10.1109/TPEL.2016.2618422.

[2] I. L. Azevedo, M. G. Morgan, and F. Morgan, "The transition to solid-state lighting," *Proc. IEEE*, vol. 97, no. 3, pp. 481–510, Mar. 2009.

[3] Y. Wang, J. M. Alonso, and X. Ruan, "A review of LED drivers and related technologies," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5754–5765, Jul. 2017, doi: 10.1109/TIE.2017.2677335.

[4] S.-Y.-R. Hui, A. T. L. Lee, J. Wu, and S. C. Tan, "Analysis and practical evaluation of dimmable passive light-emitting diode drivers for smart lampposts," *IEEE Trans. Ind. Electron.*, vol. 71, no. 6, pp. 5704–5713, Jun. 2024, doi: 10.1109/TIE.2023.3296815.

[5] N. Molavi and H. Farzanehfard, "A nonisolated wide-range resonant converter for LED driver applications," *IEEE Trans. Ind. Electron.*, vol. 70, no. 9, pp. 8939–8946, Sep. 2023, doi: 10.1109/TIE.2022.3210546.

[6] *80–15. Approved Method for Lumen Maintenance Testing of LED Light Source*, Illum. Eng. Soc., New York, NY, USA, 2015.

[7] H. Ye, S. W. Koh, C. Yuan, H. van Zeijl, A. W. J. Gielen, S.-W.-R. Lee, and G. Zhang, "Electrical–thermal–luminous–chromatic model of phosphor-converted white light-emitting diodes," *Appl. Thermal Eng.*, vol. 63, no. 2, pp. 588–597, Feb. 2014, doi: 10.1016/j.applthermaleng.2013.11.058.

[8] A. Ikuzwe, X. Ye, and X. Xia, "Energy-maintenance optimization for retrofitted lighting system incorporating luminous flux degradation to enhance visual comfort," *Appl. Energy*, vol. 261, Mar. 2020, Art. no. 114379, doi: 10.1016/j.apenergy.2019.114379.

[9] H. Albu, D. Beu, T. Rus, R. Moldovan, F. Domniţa, and S. Vilceková, "Life cycle assessment of LED luminaire and impact on lighting installation—A case study," *Alexandria Eng. J.*, vol. 80, pp. 282–293, Oct. 2023, doi: 10.1016/j.aej.2023.08.068.

[10] N. Trivellin, M. Meneghini, M. Buffolo, G. Meneghesso, and E. Zanoni, "Failures of LEDs in real-world applications: A review," *IEEE Trans. Device Mater. Rel.*, vol. 18, no. 3, pp. 391–396, Sep. 2018, doi: 10.1109/TDMR.2018.2852000.

[11] L. A. Escobar and W. Q. Meeker, "A review of accelerated test models," *Stat. Sci.*, vol. 21, no. 4, pp. 552–577, Nov. 2006, doi: 10.1214/088342306000000321.

[12] J. Huang, D. S. Golubovic, S. Koh, D. Yang, X. Li, X. Fan, and G. Zhang, "Degradation mechanism decoupling of mid-power white-light LEDs by SPD simulation," *IEEE Trans. Electron Devices*, vol. 63, no. 7, pp. 2807–2814, Jul. 2016, doi: 10.1109/TED.2016.2565709.

[13] J. Hao, Q. Sun, Z. Xu, L. Jing, Y. Wang, and H. L. Ke, "The design of two-step-down aging test for LED lamps under temperature stress," *IEEE Trans. Electron Devices*, vol. 63, no. 3, pp. 1148–1153, Mar. 2016, doi: 10.1109/TED.2016.2520961.

[14] C. Qian, X. J. Fan, J. J. Fan, C. A. Yuan, and G. Q. Zhang, "An accelerated test method of luminous flux depreciation for LED luminaires and lamps," *Rel. Eng. Syst. Saf.*, vol. 147, pp. 84–92, Mar. 2016, doi: 10.1016/j.ress.2015.11.009.

[15] M. Cai, D. Yang, K. Tian, P. Zhang, X. Chen, L. Liu, and G. Zhang, "Step-stress accelerated testing of high-power LED lamps based on subsystem isolation method," *Microelectron. Rel.*, vol. 55, nos. 9–10, pp. 1784–1789, Aug. 2015, doi: 10.1016/j.microrel.2015.06.147.

[16] L. Trevisanello, M. Meneghini, G. Mura, M. Vanzi, M. Pavesi, G. Meneghesso, and E. Zanoni, "Accelerated life test of high brightness light emitting diodes," *IEEE Trans. Device Mater. Rel.*, vol. 8, no. 2, pp. 304–311, Jun. 2008, doi: 10.1109/TDMR.2008.919596.

[17] H.-K. Fu, S.-P. Ying, T.-T. Chen, H.-H. Hsieh, and Y.-C. Yang, "Accelerated life testing and fault analysis of high-power LED," *IEEE Trans. Electron Devices*, vol. 65, no. 3, pp. 1036–1042, Mar. 2018, doi: 10.1109/TED.2018.2790003.

[18] M.-Y. Tsai, C.-Y. Tang, C. H. Wang, Y. Y. Tsai, and C.-H. Chen, "Investigation on some parameters affecting optical degradation of LED packages during high-temperature aging," *IEEE Trans. Device Mater. Rel.*, vol. 15, no. 3, pp. 335–341, Sep. 2015, doi: 10.1109/TDMR.2015.2441751.

[19] Q. Chen, Q. Chen, S. Liu, and X. Luo, "A design for in-situ measurement of optical degradation of high power light-emitting diodes under accelerated life test," *IEEE Trans. Device Mater. Rel.*, vol. 14, no. 2, pp. 645–650, Jun. 2014, doi: 10.1109/TDMR.2014.2309127.

[20] M. Cai, D. Yang, Y. Mo, J. Huang, L. Yin, L. Yang, X. Chen, W. Chen, and G. Zhang, "Determining the thermal stress limit of LED lamps using highly accelerated decay testing," *Appl. Thermal Eng.*, vol. 102, pp. 1451–1461, Jun. 2016, doi: 10.1016/j.applthermaleng.2016.04.012.

[21] M. Cai, D. Yang, J. Zheng, Y. Mo, J. Huang, J. Xu, W. Chen, G. Zhang, and X. Chen, "Thermal degradation kinetics of LED lamps in step-up-stress and step-down-stress accelerated degradation testing," *Appl. Thermal Eng.*, vol. 107, pp. 918–926, Aug. 2016, doi: 10.1016/j.applthermaleng.2016.07.065.

[22] Y.-J. Lu, Z.-Q. Guo, T.-M. Shih, Y.-L. Gao, W.-L. Huang, H.-L. Lu, Y. Lin, and Z. Chen, "Optical degradation mechanisms of indium gallium nitride-based white light emitting diodes by high-temperature aging tests," *IEEE Trans. Rel.*, vol. 65, no. 1, pp. 256–262, Mar. 2016, doi: 10.1109/TR.2015.2444834.

[23] N. Narendran, Y.-W. Liu, X. Mou, D. R. Thotagamuwa, and O. V. M. Eshwarage, "Projecting LED product life based on application," in *Proc. 15th Int. Conf. Solid State Lighting LED-Based Illumination Syst.*, Sep. 2016, p. 99540, doi: 10.1117/12.2240464.

[24] J. Magnien, L. Mitterhuber, J. Rosc, F. Schrank, S. Hörth, M. Hutter, S. Defregger, and E. Kraker, "Parameter driven monitoring for a flip-chip LED module under power cycling condition," *Microelectron. Rel.*, vol. 82, pp. 84–89, Mar. 2018, doi: 10.1016/j.microrel.2018.01.005.

[25] L. Mitterhuber, S. Defregger, J. Magnien, J. Rosc, R. Hammer, L. Goullon, M. Hutter, F. Schrank, S. Hörth, and E. Kraker, "Thermal transient measurement and modelling of a power cycled flip-chip LED module," *Microelectron. Rel.*, vol. 81, pp. 373–380, Feb. 2018, doi: 10.1016/j.microrel.2017.10.032.

[26] A. N. Padmasali and S. G. Kini, "Lifetime color consistency analysis of cool-white LED luminaires for general applications," *IEEE Trans. Electron Devices*, vol. 68, no. 11, pp. 5634–5639, Nov. 2021, doi: 10.1109/TED.2021.3109571.

[27] A. N. Padmasali and S. G. Kini, "Accelerated degradation test investigation for life-time performance analysis of LED luminaires," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 10, no. 4, pp. 551–558, Apr. 2020, doi: 10.1109/TCPMT.2019.2958852.

[28] A. Padmasali, J. E. Noronha, and S. G. Kini, "The effect of capacitance on drive current of general lighting led luminaires," *Lighting Res. Technol.*, vol. 50, no. 8, pp. 1270–1281, 2018.

[29] H. Cui, "Accelerated temperature cycle test and coffin-manson model for electronic packaging," in *Proc. Annu. Rel. Maintainability Symp.*, 2005, pp. 556–560, doi: 10.1109/RAMS.2005.1408421.

[30] W. D. Van Driel, X. Fan, and G. Q. Zhang, *Solid State Lighting Reliability Part 2*. Cham, Switzerland: Springer, 2017.

ANJAN N. PADMASALI is currently an Associate Professor with the Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal. His research interests include solid state lighting, diagnosis and performance analysis and prediction of electronics, LEDs, and BMS in EV.

J. LOKESH is currently an Assistant Professor with the Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal. His research interests include solid state lighting devices, reliability studies analysis, and prediction.

SAVITHA G. KINI is currently a Professor with the Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal. She has over a decade of research experience in the area of illumination technology, solid state lighting reliability studies and lighting controls. Her research is expanding to data analytics application to reliability studies of solid state lighting systems.