A Lifetime Prediction Method for LEDs Considering Mission Profiles

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***Abstract*—Light-Emitting Diodes (LEDs) has become a very promising alternative lighting source with the advantages of longer lifetime and higher efficiency than traditional ones. The lifetime prediction of LEDs is important to guide the LED system designers to fulfill the design specifications and to benchmark the cost-competitiveness of different lighting technologies. The existing lifetime data released by LED manufacturers or standard organizations are usually applicable only for specific temperature and current levels. Significant lifetime discrepancies may be observed in field operations due to the varying operational and environmental conditions during the entire service time (i.e., mission profiles). To overcome the challenge, this paper proposes an advanced lifetime prediction method, which takes into account the field operation mission profiles and the statistical properties of the life data available from accelerated degradation testing. It identifies also the key variables (e.g., heat sink parameters and lifetime-matching of LED drivers) that can be designed to achieve a specified lifetime and reliability level. Two case studies of an indoor residential lighting and an outdoor street lighting application are presented to demonstrate the prediction procedures and the impact of different mission profiles on the lifetime of LEDs.**

***Index Terms*—LED lighting, lifetime prediction, reliability, mission profile.**

I. Introduction

Power Light-Emitting Diodes (LEDs) are increasingly applied for indoor and outdoor lighting applications due to their higher efficiency and longer lifetime compared to the traditional lighting sources. The lifetime of LED lamps involving LED drivers and source packages is routinely quoted as 25,000 to 50,000 hours in the market [1], [2]. However, the customer experiences may be different and some of the LED lamps can fail in a considerable time ahead of the claimed life [3]. The failure could be induced either by the LED drivers or by the LED packages. The discrepancies between the claimed lifetime and the field operation experiences are mainly due to the following reasons:

1) The definition of the specified lifetime of LED lamps is vague. A necessary lifetime definition should include at least four aspects: a) operation conditions; b) end-of-life criteria; c) required minimum reliability at the end of the specified lifetime; d) confidence level of the specified lifetime.
2) The field environmental and operational conditions may vary within the specifications of the LED lamps, or even exceeding the specifications for severe users.
3) The lifetime mismatch between the LED drivers and the LED packages may occur. Sometimes, the lifetime of LED packages is misused as the claimed lifetime of LED lamps.
4) The thermal design of LED lamps is one of critical aspects that affect the lifetime of both drivers and sources.

Besides of the catastrophic failure due to the sudden breakdown of LED drivers, the two main concerns of LED failures are of source packages with the lumen depreciation and color shift due to degradation. The level of lumen depreciation is usually used as an end-of-life criteria. For color quality critical applications, the color shift level is also used as an additional criteria. Fig. 1 illustrates the definition of the lifetime L_p of LED individuals. For example, L_{70} is the time when the lumen is maintained at 70% of its initial value. With a more stringent requirement on lumen maintenance, the lifetime is shortened (e.g., L_{90} is less than L_{70} for a specific application). Currently, the L_{70} or L_{85} criteria are usually used for commercial and residential outdoor application and L_{90} is for residential indoor application. In some applications without the stringent lumen requirement, L_{50} is also taken into account and used as a design criteria.

It is well known that the L_p lifetime varies among LED samples with the same part number from the same manufacturer due to the variances in materials, process control, etc. Therefore, the percentile lifetime B_X for a population of LEDs is of more interest. Fig. 2 shows the definition of B_X lifetime based on the required minimum reliability at the end of life. For example, B_{10} lifetime means the time when 10% of the LEDs fail (i.e., with a reliability R = 0.9), and B_1 lifetime means the time when 1% of the LEDs fail. Accordingly, L_p/B_X lifetime refers to the time when $X\%$ of the LEDs have the lumen output below $p\%$ with respect to its initial values. The choices of p and X are application-dependent. Moreover, for the data not to be normally distributed, the

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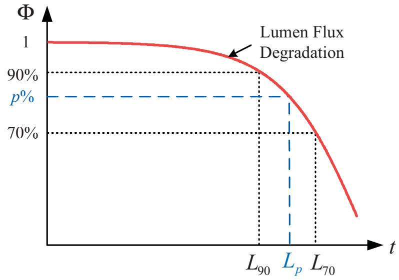


Fig. 1. L_p lifetime for LED individuals. L_p is defined as the time when $p\%$ of the initial output lumen of an LED is maintained.

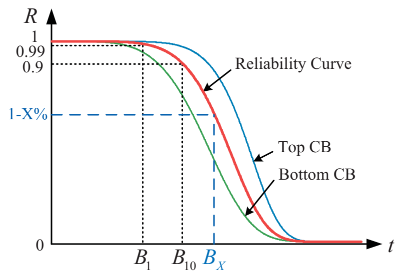


Fig. 2. B_X lifetime for a population of LEDs. B_X is defined as the time when $X\%$ of the LEDs have the lumen output below $p\%$ of their initial values.

median rank method is usually used in the reliability curve plotting to define the cumulative percentage of the population with a 50% confidence level. It is also possible to obtain the reliability range with a certain Confidence Bounds (CBs) as shown in Fig. 2. For example, the 2-sided 90% CBs have the top CB and the bottom CB curve to provide 5% and 95% confidence respectively.

The claimed long lifetime L_p is usually not measured all the time. The Illuminating Engineering Society (IES) [4] specifies the measurement procedures of lumen maintenance in the industry standard IES LM-80 [5] only for LED light sources, where a minimum 6,000 hours testing is carried out with enough sample populations and data. Most tests are provided by the LED manufacturers and last below 10,000 hours. Then longer lifetime is predicted by projecting the average data measured in IES LM-80 via an exponential curve-fitting extrapolation described in standard IES TM-21 [6]. Currently, the IES LM-80 test report is widely required for all LED products in the market to facilitate the assessment of LED performance and to determine the life expectancy of their products. However, the testing in this report is usually performed under several specific conditions, that are typical constant driving currents and at least three cases of ambient temperatures (55°C, 85°C and one selected by the manufacturers). In practise, the driving current depends on the user profiles and driving schemes. The ambient temperature may vary with time daily, monthly or even yearly and also depends on the place location in the world. Therefore, there are still gaps between the degradation testing data and the practical applications as follows:

1) The specific reliability information (with a certain confidence level or confidence bounds) and the corresponding lifetime model are not readily available. A comprehensive analysis on those testing data is needed.
2) The mapping of the reliability under the specific accelerated testing conditions to the lifetime under field conditions (i.e., long-term mission profiles) is missing.

To overcome the above issues, this paper proposes an advanced lifetime prediction method concerning the long-term field operation mission profiles and the statistical properties of the life data available from accelerated degradation testing. With this method, some key variables for thermal design and lifetime-matching of LED drivers in the different field condition can easily be identified to achieve a specified lifetime and reliability level. Two case studies of an indoor residential lighting application and an outdoor street lighting application are presented to demonstrate the prediction procedures and the impact of different mission profiles on the lifetime of LEDs. The proposed method can also be extended to the prediction of the LED drivers and the entire LED lighting systems.

In this paper, Section II introduces a comprehensive lifetime model involving the statistical properties of life data and operational mission profiles. Based on this model, an advanced lifetime prediction method is then detailed in Section III. Two study cases are demonstrated and evaluated the performance of the proposed method in Section IV. Section V concludes the paper.

II. Lifetime Models

Since LEDs are basically p-n junctions, the emitted lumen flux and intensity are proportional to the carriers' concentration [7]. The carrier's concentration depends on current density and junction temperature, which results in LED output lumen, color chromaticity and the forward voltage characteristics also varying with these two stresses. Hence, a generally accepted Black model in (1) can be used to describe the time to failure under different stresses [8], [9].

$$\text{Time to failure} = A_0 J^{-n} e^{\frac{E_a}{k_B T}}, \tag{1}$$

where A_0 is a constant, J is the current density, n is a scaling factor, E_a is the activation energy in unit of eV, k_B is the Boltzmann constant, and T is the absolute temperature in Kelvin.

The model shown in (1) describes the impact of current and temperature on the lifetime of LEDs. Therefore, L_p lifetime, defined as time-to-failure for LED individuals, can use this model. B_X lifetime based on a population of L_p lifetime data can also follow this equation to specify the reliability of an LED population. The parameters of A_0, n and E_a are usually obtained according to accelerated testing data. For an LED population with the same product series and number, the identical physical materials and degradation mechanism make the factors n and E_a constant under different stresses and end-of-life criteria. Hence, (1) can be rearranged as (2) and (3).

$$L_p(I_F, T_J) = A_p I_F^{-n} e^{\frac{E_a}{k_B T_J}}, \text{ and} \tag{2}$$

$$B_X(I_F, T_J) = A_X I_F^{-n} e^{\frac{E_a}{k_B T_J}}, \tag{3}$$

where I_F is the LED driving current proportional to current density, and T_J is the junction temperature of LEDs. Although A_p and A_X are dependent of the different L_p and B_X criteria, (2) and (3) have the same Acceleration Factors (AF).

$$AF(n, E_a) = \left(\frac{I_F}{I_{F0}}\right)^{-n} \cdot e^{\frac{E_a}{k_B}\left(\frac{1}{T_J} - \frac{1}{T_{J0}}\right)}, \tag{4}$$

and (I_{F0}, T_{J0}) is the initial stress level, whilst (I_F, T_J) is the accelerated stress level. To solve factors of n and E_a in (4), at least three different stress levels are required.

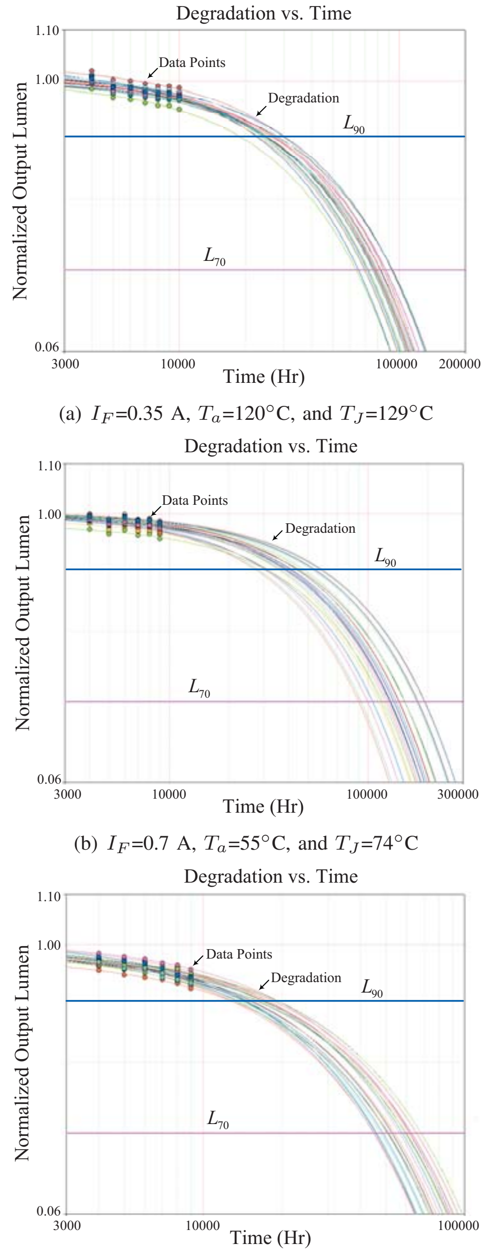
With this information, a study case based on an LM-80 test report [10] for Lumileds Luxeon Rebel LEDs [11] will show how to estimate the models in (2) and (3). Advanced Weibull distribution is the most widely used technique to process the lifetime data and then adopted here to analyze the reliability information. The report [10] provides multiple test conditions with stress levels of I_F from 0.35 A, 0.5 A, 0.7 A, to 1 A and air temperature T_a from 55°C, 85°C, 105°C, to 120°C. Each test condition has 25 samples with at least 9,000 hours testing. To solve n and E_a, three test conditions are randomly selected as shown in Fig. 3 and process the data using software tool *ReliaSoft*. With the exponential extrapolation curves, the L_{70} and L_{90} criteria can be applied to generate two groups of L_p lifetimes easily for each stress level using *Weibull++* degradation. These L_p lifetime data can be arranged in sequence and then ranked by the algebraic approximation of the Median rank in (5) [12].

$$\text{Median rank } r_j = \frac{j - 0.3}{N + 0.4}, \tag{5}$$

where j is the order number of the sequenced L_p data, $j \in [1, N]$ and N is the number of failure (i.e., the size of L_p data). The rank r_j is actually the probability to failure for the j^{th} LED. With these ranks and corresponding L_p group at one stress level, the probability line for this stress level can be generated via *ALTA* (Accelerated Life Testing Analysis) degradation. Figs. 4 (a) and (b) illustrate the unreliability function $F(t)$ (i.e., probability to failure) at each operating stress level by median rank with 50% confidence level. Therefore, B_X satisfying $F(B_X) = X\%$ can easily be obtained in these lines. The probability lines follow the two parameter Weibull distribution and the cumulative failure $F(t)$ is described as

$$F(t) = 1 - R(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}, \tag{6}$$

where t is time, β is the shape parameter, and η is the scale parameter of characteristic life $B_{63.2}$ (i.e., the life at which 63.2% of the tested samples fail) at each stress condition. For wear-out failure, $\beta > 1$. With the same failure mechanism, β is assumed constant under different stress levels within the physical limits [12]. In Figs. 4 (a) and (b), six well fitted curves



(a) I_F=0.35 A, T_a=120°C, and T_J=129°C

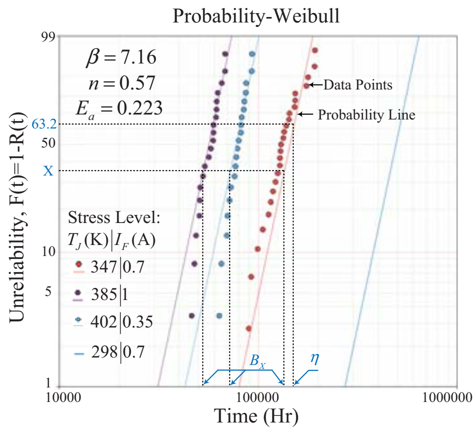
(b) I_F=0.7 A, T_a=55°C, and T_J=74°C

(c) I_F=1 A, T_a=85°C, and T_J=112°C

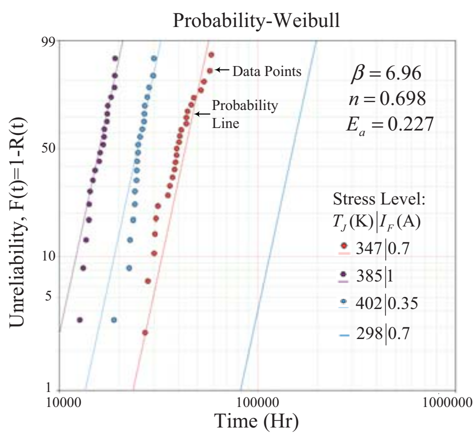
Fig. 3. Lumen degradation curves with L_{70} and L_{90} lifetime criteria under different LED operating conditions of (a), (b) and (c). X-axis is time in hour and Y-axis is the normalized output lumen to the initial lumen at t=0.

show good consistence on β, n and E_a, where small errors are caused by the distribution variation.

With known n and E_a in each figure, substitute any B_X value at one stress (I_F, T_J) into (3), A_X can be solved. Here, B_{10} and B_1 distributions based on L_{70} and L_{90} criteria are given in (7) and Fig. 5 as examples, which are valuable for further mapping the reliability information under field



(a) With L_{70} criteria



(b) With L_{90} criteria

Fig. 4. Unreliability curves under different stress levels based on the L_p data given in Fig. 3. Y-axis is in %.

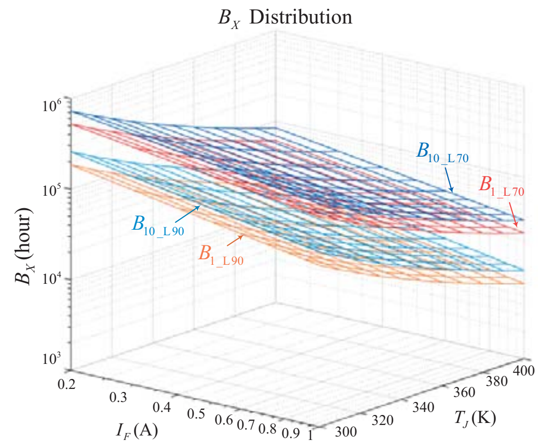


Fig. 5. B_X distributions versus forward current I_F and junction temperature T_J.

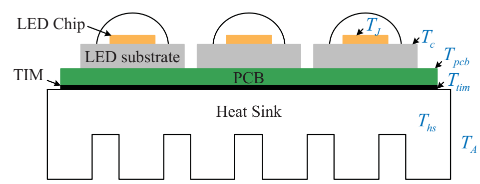


Fig. 6. The typical LED package structure.

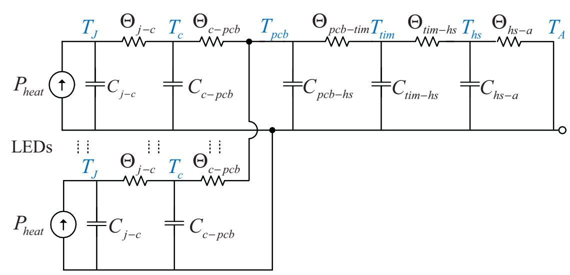


Fig. 7. The equivalent LED thermal circuit using Cauer model.

operational mission profiles, and discussed in the next section.

$$\begin{cases} \ln B_{10\_L70}(I_F, T_J) = 3.956 - 0.57 \ln I_F + \dfrac{2588}{T_J} \\ \ln B_{1\_L70}(I_F, T_J) = 3.628 - 0.57 \ln I_F + \dfrac{2588}{T_J} \\ \ln B_{10\_L90}(I_F, T_J) = 2.558 - 0.698 \ln I_F + \dfrac{2636}{T_J} \\ \ln B_{1\_L90}(I_F, T_J) = 2.221 - 0.698 \ln I_F + \dfrac{2636}{T_J} \end{cases} \tag{7}$$

III. Proposed Mission-Profile Based Lifetime Prediction Method

From Fig. 5, I_F and T_J are the key factors to affect the lifetime and reliability in the LED lighting applications. In the field operation, LED driving current I_F depends on the user profiles (e.g., indoors or outdoors occasion for different lumen requirements, periodical operational hours per day, month or year, etc.) The control schemes including short-term dimming with a period of several milliseconds also affect I_F and then the lifetime and reliability. The junction temperature T_J, which is easily affected by the ambient temperature T_A, power loss in chip and thermal distribution of materials, cannot be measured directly due to the manufacture process. Although there are some methods to reflect T_J using easy-measured electrical variables, the online signal sensing, feedback, translation and calibration are costly and complicated in the long-term LED lifetime prediction [13]. Here, an accurate LED thermal model is more suitable to estimate T_J incorporating the complicated mission profiles.

A. LED Thermal Model

It is known that most energy of LEDs is converted to heat and the left energy is converted into visible radiant light energy. The heat in the LED die can be diffused only by heat sink or external cooling whereas the conventional light sources can emit most heat by radiation. Fig. 6 shows a typical LED package structure, where multiple LED dies are soldered on the same PCB substrate for electrical connection,

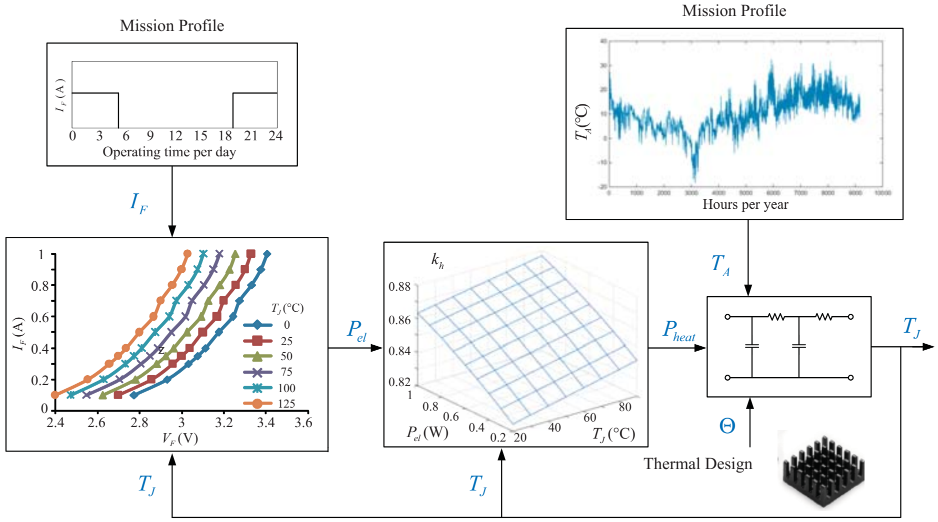


Fig. 8. The real-time thermal feedback model system of the LEDs. The mission profiles are for an outside street LED lamp located at Aalborg, Denmark. The VI relation and k_h are measured for Lumiled Rebel White LEDs as an example [11].

and the PCB is then usually attached to a heat sink for further heat conduction. To maximize the heat transfer between the heatsink and PCB, a good Thermal Interface Material (TIM) is needed to fill the air voids. Heat contributed to the PN junction, die case, cladding layer and heatsink can be described in Fig. 7 using Cauer thermal model, where P_{heat} is the dissipated heat power by each LED die, Θ is the thermal resistor of each layer in $\frac{°C}{W}$ and C is the thermal capacitor in $\frac{J}{°C}$. Both Θ and C are determined by the material and geometry of this layer.

Assuming there are m LEDs series connected in one package and having uniform heat dissipation performance, it follows (8) in the steady state.

$$\begin{aligned} T_J(T_A, P_{\text{heat}}, \Theta_{\text{j−a}}) &= T_A + P_{\text{heat}} \cdot \Theta_{\text{j−a}} \\ &= T_A + P_{\text{heat}} \cdot (\Theta_{\text{j−c}} + \Theta_{\text{c−pcb}} \\ &+ m\Theta_{\text{pcb−tim}} + m\Theta_{\text{tim−hs}} + m\Theta_{\text{hs−a}}), \end{aligned} \tag{8}$$

where $\Theta_{\text{j−c}}$ comes from the LED instinct characteristics, $\Theta_{\text{c−hs}}$ and $\Theta_{\text{hs−a}}$ are decided by designers. P_{heat} is caused by non-radiative electron-hole recombination and counts for a large proportion k_h of the input electrical power P_{el}. P_{el} is the product of driving current I_F and diode forward voltage V_F. Thus,

$$P_{\text{heat}} = k_h P_{\text{el}} = k_h I_F V_F. \tag{9}$$

As a semiconductor p-n junction, the VI-characteristic follows

$$I_F = I_S \left(e^{\frac{eV_F}{Nk_B T_J}} - 1 \right). \tag{10}$$

k_h is not constant for a single LED, varying slighting with T_J and P_{el} [14]. As P_{el} is also the function of I_F and T_J, P_{heat} can be calculated as

$$P_{\text{heat}}(I_F, T_J) = k_h(I_F, T_J) \cdot I_F \cdot V_F(I_F, T_J). \tag{11}$$

B. Acquisition of Operation Points

Comparing (11) and (8), a real-time feedback system is readily generated incorporating the thermal design and mission profiles of T_A and I_F to acquire the accurate operation point as shown in Fig. 8. The mission profiles of I_F and T_A describe the field operation condition of LEDs. Here, it is a typical example of an outside street lamp, whose ambient temperature profile is collected from yearly recorded data (1 hour per sampling data) located at the Aalborg University, Denmark. The street lamp is working at a constant driving current every day from 19:00 pm to the next day 5:00 am continuously. Dimming is not considered here. The relations of LED VI-curve, the dissipated heat coefficient k_h to I_F and T_J, and the thermal resistance of each layer can be obtained from the manufacture datasheets. For accuracy, it is better to measure them experimentally. $k_h = \frac{P_{\text{heat}}}{P_{\text{el}}} = \frac{1-P_{\text{opt}}}{P_{\text{el}}}$, where P_{opt} is the radiated optical power and can be measured by Thermal Transient Tester (T3Ster). The thermal resistance $\Theta_{\text{j−c}}$ of LED chip, $\Theta_{\text{c−pcb}}$, $\Theta_{\text{pcb−tim}}$, $\Theta_{\text{tim−hs}}$ and $\Theta_{\text{hs−a}}$ of each layer can be calculated from FEM simulation or experimental measurement from T3Ster as shown in Section IV. So far, the real-time T_J in one period of the mission profiles can be acquired by the system shown in Fig. 8.

C. Mapping and Evaluation of Reliability

With a designated reliability $(1 - X\%)$, the B_X lifetime at a certain operating point of (I_F, T_J) can be calculated in (3). Mapping all the operating points in one mission profile period will produce a considerable amount of B_X data. How to evaluate the reliability of such products with different B_X in one period? Here, the consumed B_X lifetime in one period is defined in (12), based on the Palmgren-Miner linear

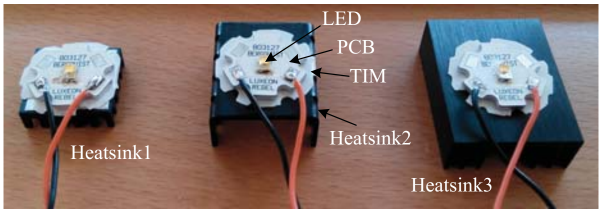


Fig. 9. The experimental LED setups for validating model.

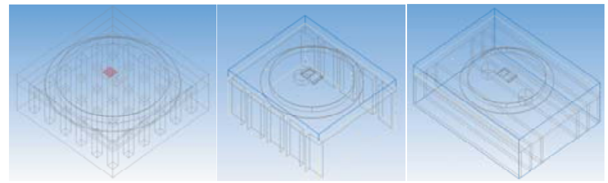


Fig. 10. The FEM simulation models with heatsinks 1, 2, 3 in Fig. 9.

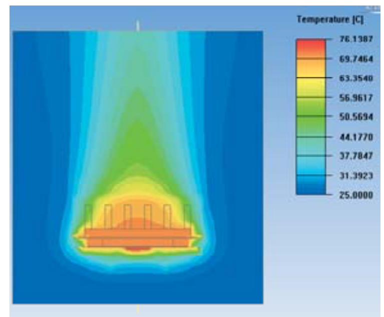


Fig. 11. Example temperature distribution in LED package with heatsink 1.

cumulative damage model [15].

$$CL = \sum_{i=1}^{k} \frac{t_i}{B_{Xi}}, \tag{12}$$

where k is the size of different stress levels, t_i is the duration of the accumulated at stress $(I_F, T_J)_i$ and B_{Xi} is the B_X lifetime at stress $(I_F, T_J)_i$ (e.g., for the case of Fig. 8, k=24×365=8760 hours, t_i=1 hour, and B_{Xi} is calculated by (3)). A larger *CL* means the LED is more close to failure. When *CL* reaches 1, failure will occur. On the contrast, assuming the stress levels in the whole period are uniform, then the average B_X lifetime considering these periodic mission profiles can be defined as

$$B_{X\_\text{avg}}(\text{hour}) = \frac{\text{Period(hour)}}{CL}. \tag{13}$$

Thus, the B_{X_avg} is the lifetime when $X\%$ of LEDs fail under the specified mission profiles.

D. Instruction to Thermal Design

With a given thermal design, B_{X_avg} can be calculated in (12) and (13) for LED quality assessment and lifetime-matchable driver design. With enough thermal data, a B_{X_avg} versus $\Theta_{\text{hs}-\text{a}}$ lookup table can be built. Consequently, for a designated reliability requirement, the maximum thermal resistor of the heat sink can be determined. A design example will be demonstrated in the Section. IV.

IV. Design and Validation

To demonstrate the prediction procedures and the impact of different heat sinks and mission profiles on the lifetime of LEDs, two study cases for an indoor residential lighting application and an outdoor street lighting application at the two cities Aalborg in Denmark and Singapore with very different ambient temperatures are discussed here. The same Lumiled Rebel white LED [11] mounted on the three different heat sinks is used as shown in Fig. 9. The PCB substrate uses thermally conductive insulated metal substrate from Berquistand [16] and TIM uses very thin thermal pad from t-Global Technology [17]. The VI-curve and k_h are measured and given in Fig. 8.

A. Determination of Thermal Resistance

With the material characteristics and geometry of the LED package and heat sink, the model using Finite Element Method (FEM) simulation can be constructed in Fig. 10. The temperature distribution in the LED package with heatsink 1 can be seen as example in Fig. 11. The other two models have the similar distribution. Because $\Theta = \frac{\Delta T}{P_{\text{heat}}}$, Θ of each layer can be calculated. Here, $\Theta_{\text{j}-\text{hs}}$ and $\Theta_{\text{hs}-\text{a}}$ for three cases are listed in Tab. I. With the same LED package, the calculated $\Theta_{\text{j}-\text{hs1}}$, $\Theta_{\text{j}-\text{hs2}}$ and $\Theta_{\text{j}-\text{hs3}}$ are close and verify the simulation results. These thermal resistances can be used to predict junction temperature of LEDs.

B. Indoor Residential Lighting Case

The indoor residential lighting works in nearly constant room temperature, 22°C in the cold half year and 26°C in the warm half year from 19:00 pm to 24:00 pm every day. L_{90} critria runs here. For the lumen requirement, I_F is designed as 0.35 A and 18 LEDs work together. To simplify the simulation model, 18 LEDs are assumed to mount on a single heatsink. Then the equivalent $\Theta_{\text{hs}-\text{a}}$ should be $\Theta_{\text{hs}-\text{a}1,2,3}$/18 for heatsink 1,2,3. With three different $\Theta_{\text{hs}-\text{a}}$, the average lifetime B_{10_avg} can be predicted following the flow-chart in Fig. 8 and Eq. (12),(13). With more $\Theta_{\text{hs}-\text{a}}$, the B_{X_avg} versus $\Theta_{\text{hs}-\text{a}}$ can be drawn in Fig. 12. Obviously, the better heat radiation performance will make the LED to work longer If a minimum 50,000 hours lifetime with 90% reliability is required, the heat sink with a maximum $\Theta_{\text{hs}-\text{a}}$ of 2.96 °C/W is required and heatsinks 1,2,3 can satisfy the requirement.

C. Outdoor Street Lighting Case

Unlike the indoor application, the street lighting endures the variable outdoor temperatures at different locations. The mission profile in Fig. 8 shows the yearly ambient temperature in Aalborg, Denmark, whilst Singapore has a relatively high temperature all the year in Fig. 13. With the same LED street lamp working at I_F=0.7 A from 19:00 pm to the next day 5:00 am per day, Fig. 14 gives comparison of B_{10_avg} based

TABLE I
CALCULATED THERMAL RESISTANCES (°C/W) FROM THE FEM SIMULATION.

Θ_{j-hs1}	Θ_{hs-a1}	Θ_{j-hs2}	Θ_{hs-a2}	Θ_{j-hs3}	Θ_{hs-a3}
5.2591	45.8615	5.6043	31.583	5.3423	23.4623

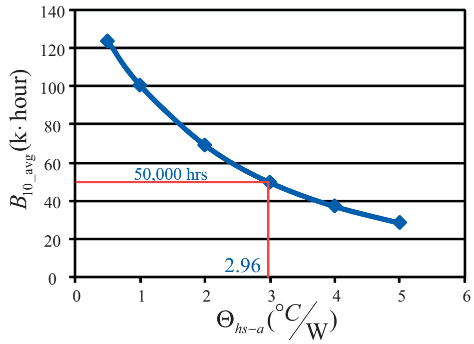


Fig. 12. Average lifetime B_{10_avg} versus Θ_{hs-a} of heat sink for indoor residential LED lighting with L_{90} model.

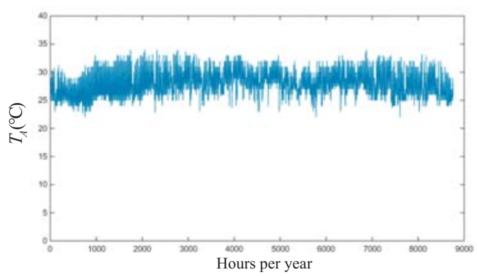


Fig. 13. The yearly ambient temperature distribution of Changi Airport in Singapore. The data is recorded per hour.

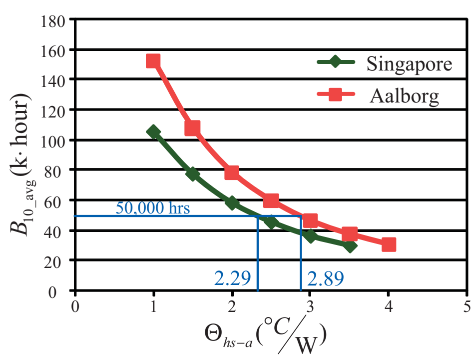


Fig. 14. Average lifetime B_{10_avg} versus Θ_{hs-a} of heat sink for Outdoor street lighting with L_{70} model.

on L_{70} model versus Θ_{hs-a} at these two cities. To have the same 50,000 hours lifetime, a better heat sink in Singapore with Θ_{hs-a} not exceeding 2.29 °C/W is required, which is reduced from the maximum Θ_{hs-a} of 2.89 °C/W in Aalborg. In this case, heatsink 1 with the equivalent Θ_{hs-a} of 2.548 can only be used in Aalborg.

V. CONCLUSION

A mission profile based lifetime prediction method is proposed to estimate the lifetime and reliability performance of LEDs in field operations. It is capable to take into account the impact of long-term electro-thermal loading stresses. Moreover, the statistic properties of life data from accelerated degradation testing are considered through Weibull analysis. The study case of an indoor residential lighting application reveals that the LED B_{10} lifetime could vary with different heat sink thermal resistances. Another specific case of an outdoor street lighting application shows the different predicted lifetime curves under mission profiles in Aalborg and Singapore. The outcomes of the study provide a guideline on the thermal design of LED lighting systems and a procedure to benchmark different design solutions. The experimental study on the junction temperature measurements under different thermal design solutions demonstrates the estimation method of key parameters in the thermal model.

REFERENCES

[1] Cree LED lamps,[Online] Available: http://creebulb.com/products.
[2] GE LED lamps,[Online] Available: http://catalog.gelighting.com/lamp/led-lamps/.
[3] Daily Mail Reporter, "The great LED lightbulb rip-off: One in four expensive 'long-life' bulbs doesn't last anything like as long as the makers claim," 2014. [Online] Available: http://www.dailymail.co.uk/news/article-2546363/.
[4] Illuminating Engineering Sciety, [Online] Available: http://www.ies.org/.
[5] Illuminating Engineering Sciety, "Approved Method: Measuring Lumen Maintenance of LED Light Sources," 2008. [Online] Available: https://www.ies.org/store/product/approved-method-measuring-lumen-maintenance-of-led-light-sources-1096.cfm.
[6] Illuminating Engineering Sciety, "Projecting Long Term Lumen Maintenance of LED Light Sources," 2011. [Online] Available: https://www.ies.org/store/product/projecting-long-term-lumen-maintenance-of-led-light-sources-1253.cfm.
[7] S. Koh, W. V. Driel, and G. Q. Zhang, "Degradation of light emitting diodes: a proposed methodology," *Journal of Semiconductors,* vol. 32, no. 1, pp. 014004-1–4, Jan. 2011.
[8] International Sematech Inc., "semiconductor device reliability failure models," 2000. [Online] Available: http://www.sematech.org/docubase/document/3955axfr.pdf.
[9] C. J. Foo, "White Paper: Calculate the LED lifetime performance in optocouplers to predict reliability," 2014. [Online] Available: http://www.avagotech.com/docs/AV02-3401EN.
[10] Lumileds Inc., "IESNA LM-80 test report," 2012. [Online] Available: http://www.philipslumileds.com/uploads/362/DR05-1-pdf.
[11] Lumileds Inc., "Luxeon Rebel Gerneral purpose white," 2015. [Online] Available: http://www.lumileds.com/uploads/28/DS64-pdf.
[12] P. O'Conneor and A. Kleyner, "Practical reliability engineerign, 5th Ed.," *John Wiley & Sons,* 2012.
[13] X. Qu, S. C. Wong, and C. K. Tse, "Temperature measurement technique for stabilizing the light output of RGB LED lamps," *IEEE Transactions on Instrumentation and Measurement,* vol. 59, no. 3, pp. 661–670, Mar. 2010.
[14] X. Tao, H. Chen, S. Li, and S. Y. R. Hui, "A new noncontact method for the prediction of both internal themal resisitance and junction temperature of white light-emitting diodes," *IEEE Transactions on Power Electronics,* vol. 27, no. 4, pp. 2184–2192, Apr. 2012.
[15] M. Miner, "Cumulative damage in fatigue," *Journal of Applied Mechanics,* vol. 12, pp. A159–A164, 1945.
[16] Bergquist Inc., "Power LED IMS substrates," 2015. [Online] Available: http://www.bergquistcompany.com/pdfs/LEDConfig20Sht_Re204.pdf.
[17] T-Global Technology, "Lumi-Pad for LED configuration," 2015. [Online] Available: http://www.tglobaltechnology.com/LED-die-cuts/LP0005v01-Li98-0.25.PDF.