Projecting LED product life based on application

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ABSTRACT

LED products have started to displace traditional light sources in many lighting applications. One of the commonly claimed benefits for LED lighting products is their long useful lifetime in applications. Today there are many replacement lamp products using LEDs in the marketplace. Typically, lifetime claims of these replacement lamps are in the 25,000-hour range. According to current industry practice, the time for the LED light output to reach the 70% value is estimated according to IESNA LM-80 and TM-21 procedures and the resulting value is reported as the whole system life. LED products generally experience different thermal environments and switching (on-off cycling) patterns when used in applications. Current industry test methods often do not produce accurate lifetime estimates for LED systems because only one component of the system, namely the LED, is tested under a continuous-on burning condition without switching on and off, and because they estimate for only one failure type, lumen depreciation. The objective of the study presented in this manuscript was to develop a test method that could help predict LED system life in any application by testing the whole LED system, including on-off power cycling with sufficient dwell time, and considering both failure types, catastrophic and parametric.

The study results showed for the LED A-lamps tested in this study, both failure types, catastrophic and parametric, exist. The on-off cycling encourages catastrophic failure, and maximum operating temperature influences the lumen depreciation rate and parametric failure time. It was also clear that LED system life is negatively affected by on-off switching, contrary to commonly held belief. In addition, the study results showed that most of the LED systems failed catastrophically much ahead of the LED light output reaching the 70% value. This emphasizes the fact that life testing of LED systems must consider catastrophic failure in addition to lumen depreciation, and the shorter of the two failure modes must be selected as the system life. The results of this study show a shorter time test procedure can be developed to accurately predict LED system life in any application by knowing the LED temperature and the switching cycle.

Keywords: LED, system life, SSL, life test, catastrophic failure, parametric failure, lumen depreciation

1. INTRODUCTION

Light-emitting diode (LED) technology has evolved rapidly, and today it is considered the preferred light source for many lighting applications. One of the claimed benefits for LED lighting systems (lamps and luminaires) is long life. Today there are many replacement lamp products in the marketplace. Typically, lifetime claims of these replacement lamps are in the 25,000-hour range. When customers purchase these products, they expect these lamps to last the advertised lifetime hours in all applications where they would use them. For example, LED A-lamps are used in many lighting fixtures in homes and offices, including table lamps, ceiling-mounted fixtures, wall sconces, recessed downlights, and many others. The LED lamps experience different thermal environments and switching (on-off cycling) patterns in these different applications. Even though it is known that LED system life varies depending on the application environment, presently no studies have shown how to estimate LED system life accurately when used in an application. Therefore, the objective of this study was to develop an accelerated test method for LED lighting systems that allows for accurate determination of system life if the LED junction temperature in the application environment and the on-off switching pattern are known.

According to current industry practice, LED system (lamp or luminaire) lifetime is defined as the time it takes for the LED light output to reach 70% of its initial value (L70) in hours, as defined by the IESNA LM80 standard.[1] The LED used in the luminaire is tested according to IESNA LM-80 and the time to reach the 70% value is projected according to IESNA TM-21[2]; the resulting value is reported as the whole system life. An LED system has many components, including the LED or LED array, printed circuit board (PCB), heat sink, mechanical housing, electronic driver, electrical...
connectors, optics, and others. Failure of any one of these components can lead to the failure of the entire LED lighting system. Defining the entire system life based on the failure time of an LED, which has a very long lifetime compared to other components in the system, is incorrect. Furthermore, an LED system failure can be catastrophic, in which the LEDs do not produce any light, or parametric, in which the LEDs produce light but the luminous flux is reduced or the color of the light has shifted from the initial value.

During the past few years, the lighting industry has been requesting shorter testing times to help speed up the introduction of new lighting products using the latest LED packages with higher lumen and luminous efficacy values. In response to this request, several studies have addressed the issue of shorter life testing by investigating highly accelerated life-test methods for LED luminaries. Most of these methods consider lumen depreciation as the failure mode. However, there are studies that have considered the fatigue failure of other power semiconductors by power cycling. These studies emphasize that failure can be parametric and catastrophic, and therefore it is important to consider both types of failure.

Starting in 2009, we have been investigating LED system life testing. The objective of these studies was to develop an accelerated test method that can help predict LED system life in any application. The conclusions from these studies were that to accurately estimate LED system life, the whole lighting system must be tested, the test procedure must include on-off power cycling with sufficient dwell time, and both failure types, catastrophic and parametric, must be considered. Some of these key points have been recognized and documented by industry groups studying the same issue. In 2014, IESNA published a standard, LM84-14, for testing LED systems. Even though this is an improvement over the use of the LM-80 test method to rate LED system life because it tests the whole system rather than just the LED, the drawbacks are that LM-84 recommends continuous-on operation and considers only lumen depreciation failure.

Therefore, the objective of the study presented in this manuscript was to develop a test method that could help predict LED system life in any application by testing the whole LED system, including on-off power cycling with sufficient dwell time, and considering both failure types, catastrophic and parametric.

2. EXPERIMENT

Some of the preliminary studies conducted in our laboratory using integral LED lamps indicated that delta temperature (ΔT) (defined as the difference between the maximum junction temperature and the room temperature/minimum junction temperature) and dwell time (on time) showed the strongest correlation for catastrophic failure. Therefore, in this study a commercially available LED A-lamp product, rated as a 75W incandescent replacement, was selected as the system to be tested to develop the test methodology. The first step of this study was to determine the appropriate ΔT. Three LED A-lamps, one 75W and two 60W incandescent equivalent lamps, were placed inside a three-lamp surface-mount fixture like those commonly used in residential applications. Temperature measurements were made using thermocouples at two different locations on the lamp, namely the lamp housing temperature and the LED pin temperature, once the fixture reached thermal stability. The pin temperature and the thermal resistance coefficient of the LED package used in the lamp enabled the estimation of the LED junction temperature, Tj, and also provided the relationship between the LED housing temperature and the LED junction temperature. The LED junction temperatures were in the range of 115°C to 146°C. When switched on and off, the resulting ΔTs were in the range of 85°C to 116°C. Figure 1 illustrates a sample temperature profile experienced by the LED junction as a function of time. This figure illustrates the parameters used in this study for setting up the experiment and analysis.
2.1 Experiment variables and sample size

Sample size: A total of 90 LED A-lamp samples, 75W incandescent lamp equivalent, were used in the experiment.

Independent variables: delta temperature (ΔT): 80/90/100°C; dwell time (t): 2-hrs ON with 50 mins OFF/4-hrs ON with 50 mins OFF/continuous-on

Dependent variables: light output, spectral power distribution (chromaticity coordinates), input power, input current, lamp housing temperature

2.2 Experiment setup

Figure 2 shows the schematic and two pictures of the experiment setup. LED A-lamps were placed inside a downlight fixture. A heater pad was wrapped around the downlight housing to control the temperature of the test lamp (Tj). Five of these downlight cans were placed inside a wooden box. A light sensor box was attached to the opening of the downlight to monitor the light output and detect catastrophic failure or lumen depreciation for each lamp. A thermocouple was attached to the housing of the LED A-lamp to estimate the LED junction temperature. In an initial study, the relationship between the LED A-lamp housing temperature and the LED pin temperature was determined by attaching a thermocouple to each location, namely the LED A-lamp housing and the LED case. Using the published thermal resistance value of the LED used in the A-lamp, the junction temperature was estimated. Control circuits switched the lamps and the heater pad on and off at the designed dwell time and ΔT. As described earlier, for each ΔT, lamps were switched on and off to achieve 2- and 4-hour dwell times and in the third case kept the lamp powered on continuously. Each test condition had 10 lamp samples and altogether 90 lamp samples were used at the three ΔT with three dwell time conditions. All test boxes were placed on a rack, and each lamp test assembly was connected to a data acquisition system for continuous monitoring and recording of the dependent variables: light output, spectral power distribution, input power, input current, and lamp housing temperature.
3. RESULTS

3.1. LED A-lamp failure - Catastrophic
Figure 3 shows catastrophic failure of LED A-lamps as a function of time for each test condition, $\Delta T$ and dwell time. The average time between the 5th and the 6th lamp failures denotes the median life, indicated by the solid line in Figure 3. As seen in this figure, the median lamp life due to catastrophic failure depends on $\Delta T$ and the dwell time. A post-failure analysis showed that 84% of the failures were due to failure of the solder between the LED and the PCB, and the remaining 16% were due to driver failure.

![Figure 3. LED A-lamp catastrophic failure as a function of time for each test condition ($\Delta T$ and dwell time).](image-url)
Table 1. Delta time-averaged temperature ($\Delta T_{avg}$) and time to failure for the different $\Delta T$ and dwell time conditions.

<table>
<thead>
<tr>
<th>$\Delta T$ \ Dwell Condition</th>
<th>Delta time-averaged temperature (°C)</th>
<th>Time to failure (median life in hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 hrs</td>
<td>4 hrs</td>
</tr>
<tr>
<td>80°C</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td>90°C</td>
<td>61</td>
<td>69</td>
</tr>
<tr>
<td>100°C</td>
<td>69</td>
<td>82</td>
</tr>
</tbody>
</table>

As seen in Table 1, higher $\Delta T$ results in shorter time to failure for both dwell conditions. Also, shorter dwell time results in shorter time to failure for 80°C and 90°C but not for 100°C. The median time to failure for $\Delta T$ at 100°C and 4-hr dwell time was shorter than for the 2-hr dwell time. This could be because the time-averaged temperature for the 4-hr dwell time compared to other cases was much higher and could have introduced other failure mechanisms. As seen in Figure 4, cycles to failure (median life) as a function of delta time-averaged temperature shows an inverse linear relationship with high goodness-of-fit ($R^2 > 0.9$).

![Figure 4. Cycles to failure as a function delta time-averaged temperature ($\Delta T_{avg}$) (°C).](image)

**Note:** It is worth noting here that the results from this study clearly show that the life of an LED system is affected by switching it on and off. The ability to switch LED lights frequently without affecting life has been a commonly touted benefit over other light sources like compact fluorescent (CFL), but this is clearly not the case.

3.2. LED A-lamp failure – Lumen depreciation

In Figure 5, the data show lumen depreciation values measured just prior to catastrophic failure. The results indicate that lumen depreciation was not affected by on-off cycling. Also, in the lamp selected for test, most lamps underwent catastrophic failure before reaching L70. Lumen depreciation data was extrapolated to determine L70 values for each condition. This finding emphasizes the point that a power cycling test is essential to determine the life of LED systems accurately. To ensure the accuracy of projected values are similar for 80°C, 90°C, and 100°C at each $\Delta T$, the considered data for extrapolation had similar depreciation values, 10%. The median lamp life, L70 in hours, is shown in Table 2. Figure 6 shows that for the product tested, time to failure L70 (median life) as a function of maximum operating temperature shows an inverse linear relationship with goodness-of-fit $R^2 > 0.9$. The projected L70 values decrease as a function of increasing $\Delta T$ condition. However, the cycling seems to have minimum effect. As a result, the projected L70 values for 2- and 4-hr dwell times and continuous-on condition for each $\Delta T$ are similar.
Table 2: Maximum operating temperature and time to L70 failure for the different ΔT and dwell conditions.

<table>
<thead>
<tr>
<th>ΔT\Dwell Conditions</th>
<th>Maximum operating temperature (°C)</th>
<th>Time to L70 (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 hrs</td>
<td>4 hrs</td>
</tr>
<tr>
<td>80°C</td>
<td>106</td>
<td>108</td>
</tr>
<tr>
<td>90°C</td>
<td>125</td>
<td>124</td>
</tr>
<tr>
<td>100°C</td>
<td>131</td>
<td>136</td>
</tr>
</tbody>
</table>

Figure 5. Lumen depreciation values just prior to catastrophic failure.

Figure 6. Time to failure due to lumen depreciation, L70, as a function of maximum operating temperature.
4. DISCUSSION

The study results show for the LED A-lamps tested, both failure types, catastrophic and parametric, exist. The on-off cycling encourages catastrophic failure and maximum operating temperature influences the lumen depreciation rate and parametric failure time. The reason why on-off switching results in catastrophic failure is because of the stresses experienced by the interface material due to thermal expansion mismatch between the different layers in the system that lead to fatigue failure. Parametric failures such as lumen depreciation and color shift are caused by the yellowing of the binding materials used in the LED packages to hold the phosphor particles. Such failures become rapid at higher temperatures. Therefore, transitions taking place during on-off cycling encourage catastrophic failure, and LED device operation at maximum temperature accelerates parametric failure.

Therefore, the shorter of the two times to failure should be considered as the lifetime of the product because in applications, LED systems will experience both types of failure and depending on the conditions, one failure type could dominate. For the lamps tested, catastrophic failure times were shorter than lumen depreciation, L70, failure times. The results from this study show that to obtain more accurate life estimates of LED systems, unlike current industry test standards and practices, life testing must include on-off switching.

Estimating lifetime in different applications: To illustrate the usefulness of this test method and the results, two applications where LED A-lamps are commonly used were selected and the lamp life in each application was estimated.

The first application example considered is a table lamp with the LED A-lamp tested in this study. It is assumed that the table lamp is switched on for 3 hours per day and off during the rest of the day. The maximum operating junction temperature experienced by the LED within the A-lamp, Tj, is 95°C, and the room temperature, Troom, is 30°C. The estimated time-averaged temperature, Tavg, is 80°C, and therefore ∆Tavg = (Tavg – Troom) is 50°C. From Figure 4, the cycles to failure at 50°C is estimated as 3250 cycles, corresponding to 3250 days or 8.9 years. Likewise, from Figure 6 at 95°C maximum operating temperature, the time to L70 can be estimated as 32,000 hrs by extrapolating the linear fit to 95°C. This corresponds to 29 years. Therefore, in the table lamp application the estimated lifetime of the lamp is 8.9 years.

Following the same approach, a second application considered is a recessed downlight (non-IC type) switched on for 2 hours per day. The maximum Tj is 129°C at room temperature, Troom, which is 30°C, and the corresponding ∆Tavg is 77°C. The estimated lamp life values for catastrophic failure and lumen depreciation failure, from Figures 4 and 6, are 1.9 years (700 cycles to failure) and 12.3 years (9000 hours to L70), respectively. Therefore, in this application the same LED A-lamp life is only 1.9 years.

These examples show that the lifetime of LED systems depends on the application environment and the use pattern.

Life testing time: The time required for life-testing LED systems is an important consideration for manufacturers, who prefer a shorter time. The question is what will be a reasonable time needed to implement a test similar to the one described here for other systems. The approach is to identify a suitable ∆T and dwell time so that the lamps fail due to failure modes usually present during applications. Overstressing will introduce additional failure modes that may not be present in typical applications and could lead to underestimating system lifetimes. Therefore, by looking at Figure 4, designing a test procedure such that the time-averaged temperature is in the range of 75°C to 85°C, the total time for testing can be within 3000 hours. However, this hypothesis needs verification by testing several lamps in the marketplace.

From the results of this study and from earlier studies, we are encouraged that a test procedure can be developed to accurately predict LED system life in any application by testing the whole LED system, including on-off power cycling with sufficient dwell time, and considering both failure types, catastrophic and parametric.

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REFERENCES


