Predicting LED System Life: A Long-term Study of the Factors that Determine Performance and Failure

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Abstract

Present industry practice allows reporting of LED system life as the time for the light output to reach the 70% value, estimated according to LM-80 and TM-21. In these procedures, only one component of the system, the LED, is tested under a continuous-on condition without switching on and off, and only one failure type, lumen depreciation, is considered. However, because LED systems have multiple components and generally experience different thermal environments and switching patterns when used in lighting applications, the current industry test methods often do not produce accurate lifetime estimates and also do not consider the possibility of catastrophic failure. In this manuscript, we present a study that was conducted to develop a short duration, predictive test method for LED system life that can estimate product lifetime in any lighting application, if the temperature and use pattern are known. The method tests the whole system, includes on-off power cycling with sufficient dwell time, and considers both catastrophic and parametric failures (L70). A total of 90 commercially available LED A-lamps (75W incandescent equivalent) were subjected to different test conditions of delta temperature and dwell time. The results showed that both catastrophic and parametric failure types exist. Power cycling encourages catastrophic failure, making it clear that LED system life is negatively affected by on-off switching — contrary to common belief. Maximum operating temperature influences the lumen depreciation rate. Additionally, we propose an alternative, lower cost experiment setup and procedure for testing LED A-lamps that can provide an accurate system life estimate within 1500 hours.

Introduction

During the past few years, light-emitting diode (LED) lighting systems, including replacement lamps, have been displacing their traditional counterparts and have been gaining market share very rapidly. Energy savings and long service life are two of the claimed benefits for LED lighting systems. For example, LED A-lamps can save more than 85% of the energy used by their incandescent counterparts. Likewise, LED A-lamps are claimed to have lifetime values in the 25,000-hour range, which is much greater than incandescent A-lamps. Since LED A-lamps are used in many types of lighting fixtures, including table lamps, ceiling-mounted fixtures, wall sconces, recessed downlights, and others, consumers expect them to last the claimed number of hours in these applications. However, LED lamps can experience different thermal environments and on-off switching patterns in these different applications. Therefore, it is possible for LED system life to vary from one application environment to the next.

The question is how should manufacturers test and report lifetime values for LED systems. Today, LED product lifetime is estimated based on the time for the LED light output to depreciate to 70% of its original value (L70). The Illuminating Engineering Society's IES LM-80 and IES TM-21 standards describe the process for testing and extrapolating data to estimate the L70 value experienced by the LED in the application.^{1,2} The resulting value for the LED is reported as the whole system life. Because an LED lighting system has many components, not just the LED or LED array, the failure of any one of these components can lead to the failure of the entire system. Defining the whole system life based on the failure time of the LED (which has a very long life compared to other components in the system) can lead to inaccurate life estimates and ultimately result in consumer disappointment. Generally, the LED system can fail catastrophically, in which the LEDs do not produce any light, or parametrically, in which the LEDs produce light but the luminous flux is diminished from their initial values. The LM-80 test method considers only the parametric failure of the system.

Because the global lighting industry is seeking shorter testing times to help speed the introduction of new LED products into the market, several earlier studies have investigated highly accelerated life-test methods for LED luminaries.³⁻⁸ Most of these methods consider lumen depreciation as the only failure mode. Published literature shows that researchers have studied fatigue failure of semiconductor components by power cycling other types of electronic products.⁹ These studies emphasize that failure can be parametric or catastrophic, and therefore it is important to consider both types of failure.

During the past several years, we have been conducting LED system failure studies to understand what factors contribute to LED product failure. Furthermore, we have been investigating methods for testing LED systems and estimating lifetimes. These studies revealed that for an accurate estimate of LED system life, the whole lighting system must be tested. Furthermore, it is necessary to include on-off switching, and both failure types, namely catastrophic and parametric, must be considered.¹⁰⁻¹² Industry groups studying the same issue have recognized these key points.¹³ In 2014, the IES published LM-84 for testing LED systems.¹⁴ This standard, similar to LM-80, recommends continuous-on operation and considers only lumen depreciation (parametric).¹⁴

In this manuscript, we describe the long-term study¹² conducted to develop a short-duration test method that allows for accurate prediction of LED system life in any lighting application if the LED junction temperature and the on-off switching pattern are known. In addition, we explored a low cost experimental setup that can be used for life-testing LED lamps based on the procedure used in this study and its potential for producing accurate results.

Long-term LED A-Lamp Life-test Study

Experiment

Earlier studies¹⁰⁻¹² by our research group concluded that delta temperature (Δ T) (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.¹¹ Therefore, our follow-up published study¹² investigated a commercially available LED A-lamp product, rated as a 75W incandescent replacement, which was tested to validate the findings and develop the test methodology. The first step of this study was to determine the appropriate Δ T to be used in the life test. Three LED A-lamps were placed inside a three-lamp surface-mount fixture like those commonly used in residential applications. To obtain a

relationship between the LED housing temperature and the LED junction temperature, two thermal sensors were attached to a predetermined location on the lamp housing and the LED pin. Using the pin temperature value after the fixture reached thermal stability and the thermal resistance coefficient of the LED package, the LED junction temperature, Tj, was estimated and the relationship between the LED housing temperature and the LED junction temperature was inferred. Additionally, the LED A-lamp was tested in open-air, at room temperature, and the corresponding LED junction temperature, Tj, was determined. These two tests provided estimates for the two ends, lower and upper, for Tj values that can be found in most applications using this LED A-lamp. For the lamp tested, the LED junction temperatures were in the range of 115° C to 146° C.¹² The Δ T values were in the range of 85° C to 116° C when the lamp was switched on and off. A sample temperature profile experienced by the LED junction during power on and off is shown Figure 1.



Fig. 1 Temperature cycle profile (temperature measured on the housing of the LED A-lamp).¹²

Figure 2 shows the schematic and two photographs of the experiment setup. A total of 90 16W rated LED A-lamp samples (75W incandescent lamp equivalent) were used in the experiment. The LED A-lamps were placed inside a downlight fixture. A heater pad attached to the downlight housing controlled the temperature of the test lamp (Tj) placed inside the downlight housing. A light sensor at the opening of the downlight monitored the light output and detected catastrophic failure or lumen depreciation for each lamp. A temperature sensor attached to the LED A-lamp housing allowed for the estimation of the LED junction temperature. Control circuits switched the lamps and the heater pad on and off to maintain the designed dwell time and ΔT . The tested independent variables included three ΔTs of 80°C, 90°C, and 100°C, and three dwell times of 2 hours on with 50 minutes off, 4 hours on with 50 minutes off, and continuous-on. The ΔT values selected here for the life test were based on the results obtained from the first part of this study. Each test condition had 10 lamp samples and altogether 90 lamp samples were used at the three ΔT with three dwell time conditions For each ΔT , lamps were switched on and off to achieve 2-hour and 4-hour dwell times and in the third case kept the lamp powered on continuously. 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, input power, input current, and lamp housing temperature.



Fig. 2 Experiment setup for the long-term life-test study of LED A-lamps.¹²

Results: LED A-lamp catastrophic failure

Table 1 shows the summary of the results for the catastrophic failure of LED A-lamps for the different test conditions.¹² The average time between the 5th and the 6th lamp failures denotes the median life. The results clearly show that the lamp life depends on the test conditions, namely ΔT and the dwell time. Further analysis of the failed lamps 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 for the lamps tested in this study.

	Delta time-averaged temperature (°C)		Time to failure (median life) (hours)	
ΔT/Dwell Condition	2 hours	4 hours	2 hours	4 hours
80°C	48	60	7,516	8,801
90°C	61	69	3,411	7,091
100°C	69	82	3,225	521

Table 1 LED A-lamp failure times due to catastrophic failure for each test condition (ΔT and dwell time).¹²

Table 1 shows the delta time-averaged temperature and median life in hours for the tested conditions. As seen in Table 1, higher ΔT conditions result in shorter time to failure for both dwell time conditions. Also, shorter dwell times result in shorter time to failure for 80°C and 90°C. However, for the median time to failure for ΔT at 100°C, the 4-hour dwell time was shorter than the 2-hour dwell time. This is because the failure takes place due to cumulative damages caused at each transition that are also dependent on the temperature change during the transition. Temperature change during transition stresses the interface between the LED and the electronic board, namely the solder interface layer that ultimately fails due to fatigue. Therefore, with increasing delta temperature, the number of transitions per unit time, the time-averaged temperature experienced by the component will increase. In the case of ΔT at 100°C and 4-hour dwell time, the time-averaged temperature is relatively higher compared with others and results in a fewer number of transitions before failure.

Figure 3 shows that for the product tested, the cycles to failure (median life) and delta timeaveraged temperature have an inverse linear relationship with goodness-of-fit, $R^2 > 0.9$. It is worth noting that the results from this study clearly show that the life of an LED system is affected by switching it on and off, contrary to common belief. 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.



Fig. 3 Cycles to failure as a function delta time-averaged temperature (ΔT_{avg}) .¹²

To illustrate that frequent on-off switching of LED systems shortens lamp life, the time to catastrophic failure data obtained for ΔT at 80°C and ΔT at 90°C were interpolated and extrapolated and the delta time-averaged temperature values for 1-hour and 3-hour dwell times were estimated. From Figure 3, the cycles to failure at each of those delta time-averaged temperatures were inferred. Knowing the total cycle time for each dwell time, the cycles to failure were converted to time to failure. Figure 4 illustrates the time to failure as a function of dwell time. This graph clearly shows that with shorter dwell time, more frequent on-off switching will cause LED systems to fail faster.



Fig. 4 Time to failure as a function of dwell time for the different delta temperature values.

Results: LED A-lamp parametric failure (lumen depreciation)

Analyzing the lumen depreciation values just prior to lamps failing catastrophically showed that most of the samples failed catastrophically before the light output reached L70. In this case the catastrophic failure times were shorter than the parametric failure time, L70. This finding emphasizes the point that a power cycling test is essential to accurately determine the life of LED systems. By extrapolating lumen depreciation data, L70 values for each condition were determined. The median lamp life, L70 in hours, is shown in Table 2. Figure 5 shows that for the product tested, L70 time to failure (median life) as a function of maximum operating temperature shows an inverse linear relationship with goodness-of-fit, $R^2 > 0.9$. The estimated L70 values decreased when the maximum operating temperature increased. The projected L70 values for the different dwell times for each ΔT are similar, indicating that the cycling has minimum effect on lumen depreciation. Parametric failure such as lumen depreciation is 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.

Table 2 Maximum operating temperature (ΔT_{avg}) values and time to failure values for the different ΔT and dwell time conditions.¹²

	Maximum operating temperature (°C)		Time to L70 (hrs)			
ΔT/Dwell Condition	2 hours	4 hours	Continuous-on	2 hours	4 hours	Continuous-on
80°C	106	108	108	25,528	20,998	23,979
90°C	125	124	124	11,019	12,185	11,657
100°C	131	136	131	7,289	5,308	5,171



Fig. 5 Time to failure due to lumen depreciation, L70, as a function of maximum operating temperature.¹²

An Alternative, Lower Cost Experiment Setup for Life Testing LED A-lamps

Just as shorter time life testing of LED systems is an important consideration for manufacturers, a lower cost, easy to implement experiment setup is also important. Therefore, we created a setup using surface mount fixtures. The objective of this study was to develop and verify a lower cost life-test setup to test LED A-lamps and to determine the time required to complete the test for a given product. The setup is shown in Figure 6.



Fig. 6 Lower cost experiment setup for life testing LED A-lamps.

The idea is to use three-lamp surface mount light fixtures that can house an LED A-lamp (60W incandescent equivalent) and two incandescent A-lamps of different wattages (25W/40W/60W) to create the necessary delta temperatures to stress the LED lamp. A power on-off controller was used to achieve the necessary dwell time, which in this case was set to 3 hours on and 1 hour off. The LED junction temperature, Tj, was estimated by measuring the LED A-lamp housing temperature using a thermistor attached to the lamp body. A photo cell with a black tube aimed at the LED A-lamp was placed inside the surface mount fixture to measure the light output of the lamp. The black tube ensured the measured light was from the LED lamp only. Table 3 lists the estimated LED Tj maximum operating temperature and the delta time-averaged temperature for each experiment condition.

Table 3 Estimated LED Tj values and the corresponding ΔT values for the different experiment conditions; two 25W, two 40W, and two 60W incandescent lamps are shown. The maximum Tj and the delta time-averaged temperatures for each condition are also shown.

Heater lamps	2*25W	2*40W	2*60W
On-Off Cycle	3 hr/1 hr	3 hr/1 hr	3 hr/1 hr
T ref max	100 C	110 C	116 C
Tj max operating	125 C	135 C	141 C
T ref min	26 C	30 C	30 C
Delta TAT	81 C	87 C	91 C
Delta T	99 C	105 C	111C

The measured light output data as a function of time are shown in Figure 7. The time to L70 and catastrophic failures are also shown in Figure 7.



Fig.7 Relative light output as a function of time for the three test conditions (Tj max= 125°C, 135°C, 140°C) for the tested LED A-lamps.

Time to catastrophic and parametric (L70) failures is shown in Figure 8.



Fig. 8 Left: Cycles to failure as a function of delta time-averaged temperature; Right: Time to L70 as a function of maximum operating (Tj) temperature.

Results from this lower cost experiment setup are similar to previous studies, where cycles to failure (median life) and delta time-averaged temperature have an inverse linear relationship with goodness-of-fit, $R^2 = 0.99$. Also, L70, time to parametric failure (median life), as a function of maximum operating temperature also shows an inverse linear relationship with goodness-of-fit, $R^2 = 0.99$. With 4 hours (3 hours on and 1 hour off) per cycle, the total test time required is less than 1500 hours.

Discussion

The study explained in this manuscript describes a short-duration test method that allows for accurate prediction of LED system life in any lighting application if the LED junction temperature and the on-off switching pattern are known.

The results from this study showed that LED systems will encounter both catastrophic and parametric types of failure. Therefore, a test procedure must be designed to influence both failure types and the shorter of the two times to failure should be considered as the lifetime of the product. The current industry test standards and practices determine parametric failure only. Therefore, life testing must include on-off switching to induce catastrophic failure as well.

It is also shown here that the test method can be implemented without incurring much cost by using commonly available surface mount light fixtures. Furthermore, with the test method explained in this study, the test time can be of the order of 1500 hours for LED replacement lamps.

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