Long-term lumen depreciation behavior and failure modes of multi-die array LEDs

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ABSTRACT

One of the main advantages of multi-die array light-emitting diodes (LEDs) is their high flux density. However, a challenge for using such a product in lighting fixture applications is the heat density and the need for thermal management to keep the junction temperatures of all the dies low for long-term reliable performance. Ten multi-die LED array samples for each product from four different manufacturers were subjected to lumen maintenance testing (as described in IES-LM-80-08), and their resulting lumen depreciation and failure modes were studied. The products were tested at the maximum case (or pin) temperature reported by the respective manufacturer by appropriately powering the LEDs. In addition, three samples for each product from two different manufacturers were subjected to rapid thermal cycling, and the resulting lumen depreciation and failure modes were studied. The results showed that the exponential lumen decay model using long-term lumen maintenance data as recommended in IES TM-21 does not fit for all package types. The failure of a string of dies and single die failure in a string were observed in some of the packages.

Keywords: LED, array, failure, lumen, depreciation, multi-die, short circuit, open circuit

1. INTRODUCTION

Multi-die array light-emitting diodes (LEDs) are becoming more common in the marketplace for use in illumination applications. The multi-die array LED package is a high density package type where multiple dies are connected in series-parallel configuration. One of the main advantages of such packages is that the overall footprint of the LED package is small for the amount of flux produced. However, a challenge for using such a product in lighting fixture applications is the heat density and the thermal management strategy needed to keep the LED junctions at low temperatures for reliable performance.[1-3] The current flow through each LED can be affected by the electrical circuit configurations, such as series or parallel arrangements for stringing the LED dies. Even though LED dies of similar forward voltage may have been selected when manufacturing high density packages, over time and with temperature variation these forward voltages can deviate and result in different current through each individual LED die. This affects the junction temperature of the LEDs and thus the long-term reliability of the LED array. LED array circuit failure is another possibility when the device is powered on and off. Such failures can be caused by high stresses introduced on the interconnects by thermal expansion mismatch between the different materials. As a result, during long-term operation of luminaires using array LEDs, it is possible to experience lumen depreciation and catastrophic failure (no light from the individual dies or a string of dies). A weak component within the array can affect the reliability of the entire package. Although several past studies on the thermal management of multi-die arrays have raised reliability concerns, we were not able to find literature showing long-term lumen depreciation data on such LED packages. Therefore, the objective of this study was to understand the possible failure modes seen in commercially available multi-die array LEDs during usage, continuous power on and rapid thermal cycling.

2. EXPERIMENT

2.1 Long Term Lumen Maintenance Study

Commercial multi-die array LED packages from four different manufacturers were purchased for the study during the early part of 2012. Descriptions and the basic parameters of the LED packages tested are given in Table 1. LED arrays 1 and 2 had metal substrates; arrays 3 and 4 had ceramic substrates. Ten samples from each package type were used for the

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long-term lumen maintenance study. The experiment was implemented in two groups. Five samples from each product were mounted on the test rack as the first group, and the remaining five samples from each product were mounted as the second group. The test conditions were similar for both groups; the only difference was that the second group test started 1300 hours after the start of the first group.

Table 1. Parameters of the tested LED packages

LED	Array	Package Voltage (V)	Package Current (A)	T_{case} max (per manufacturer) °C	T_{case} max (measured) °C
Array 1	6 x 4	36.4	0.7	100	100
Array 2	14 x 8	48.4	0.7	105*	104
Array 3	14 x 12	35.6	0.7	90	91
Array 4	12 x 12	37.6	0.7	100	100

* The case temperature was computed based on the maximum junction temperature and thermal resistance value reported in the data sheet.

Each LED package was attached to a temperature-controlled heat sink using mechanical screws and thermal grease (Fig. 1). A thermistor was attached to the LED case at the temperature measurement point, recommended by the manufacturer, using thermal epoxy. A temperature controller was used to regulate the heat sink temperature, to maintain the case temperature of the LED at a fixed value within ± 2°C. A constant direct current (DC) current regulator supplied 700 mA of current to the LED during the test period. The case temperature, voltage, and current were measured and recorded at every 4-hour interval for each LED package.

Each LED package was placed inside a light integrating box to monitor the light output data continuously. The inside walls of the light integrating box were painted with matte white paint. A V(λ) corrected photocell was mounted behind a baffle that blocked the direct light to monitor the light output of the LED. During the 4-hour measurement cycle, along with other parameters, the photocell reading was also recorded.

2.1.1 Light Output Data

Each LED sample was tested in an integrating sphere periodically to obtain total luminous flux and chromaticity values. Prior to every photometry measurement cycle, the integrating sphere and spectrometer setup were calibrated. Photometry measurements were made for the LED under pulsed current conditions to minimize the temperature rise of junction temperature above the nominal test environment temperature. The total data gathering time for the LEDs in each group was about 6000 hours.

2.2 Rapid Thermal Cycle Lumen Maintenance Study

LED packages from array 2 and array 3 were purchased for the rapid thermal cycle lumen maintenance study during the early part of 2013. Array 2 had a metal substrate and array 3 had a ceramic substrate. Three samples from each package type were used for the study. Samples were mounted on variously sized heat sinks, with size dependent on the array's substrate material (metal or ceramic) and the ability of the array package to reach the maximum test temperature (>100°C) within a 5-minute period. Heat sinks were mounted via posts to a stable Teflon base, allowing airflow around the entire array/heat sink package.

Samples were placed in the thermal chamber kept at a constant -40°C for 5 minutes prior to the first shock cycle. Samples were then powered on at 700 mA constant current using constant current LED drivers. Samples were powered for 5 minutes, and the pin temperature (T_p) monitored. After the 5-minute on period, samples were powered off and allowed to reach the ambient temperature of the chamber as reported by the T_p. All samples were continuously cycled until failure. The light output was periodically measured in the integrating sphere using the same protocol mentioned in

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section 2.1.1. Furthermore, at each measurement point the LED arrays were inspected under a microscope to see if certain LED dies or strings of dies had completely failed.

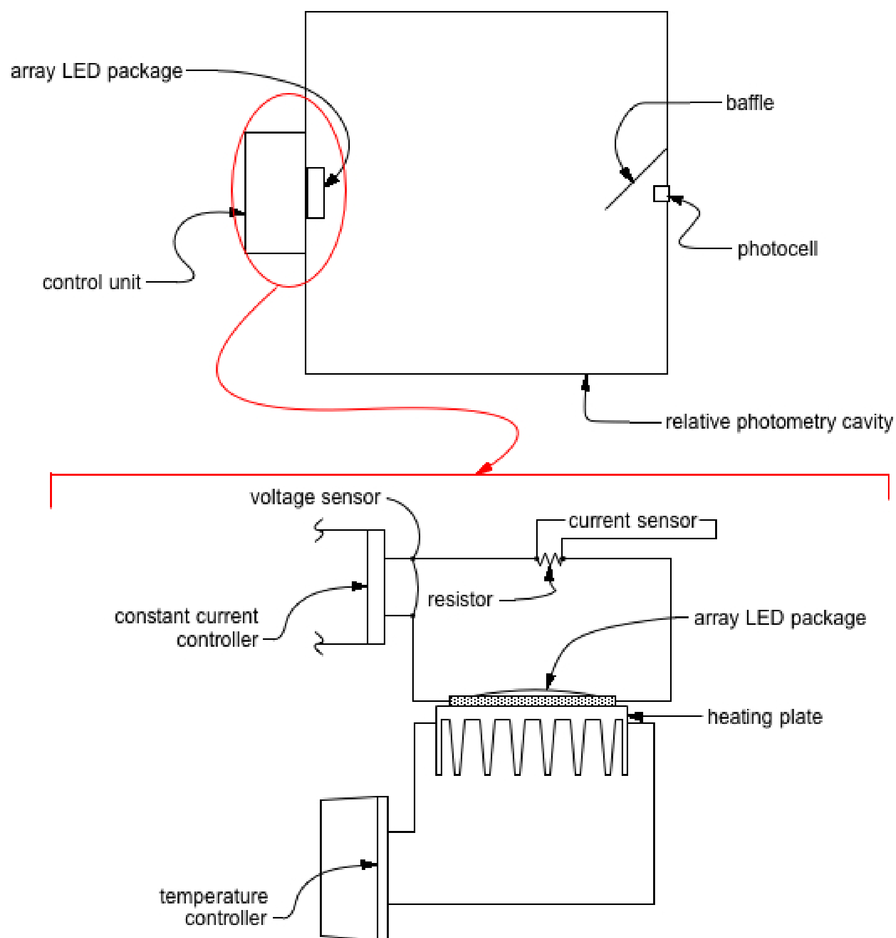

Fig. 1. The temperature-controlled heat sink with the driving unit and the light integrating box.

3. RESULTS

3.1 Long Term Lumen Maintenance Study

IES TM-21 recommendation[4] was used to estimate the parametric lifetime (L_{70}) of the packages based on the collected lumen depreciation data. The first 1000 hours of data were ignored when using the exponential equation for the projection. The exponential decay model was used in the projection and is given in Eq. 1 below:

$$L = a*exp(b*t) \quad (1)$$

where L is relative light output, t is time, a and b are constants. The exponential decay model parameters and L_{70} life projections based on these parameters are shown in Table 2.

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The lumen depreciation data of array 1 shows a strong correlation with the exponential decay model, as shown in Fig. 2 and Table 2. Even though the average value of the ten LED samples projected well to the L_{70} value, the variance of the projected results is very large for array 1 LEDs, as shown in Table 2.

In the case of array 2, the lumen depreciation data show a good fit to the exponential decay model, and the variance of LED life estimation is small. This is due to the fact that the lumen depreciation of the LEDs was rapid during the test period, and all array 2 samples approached the L_{70} value within a few hours beyond the data collection period.

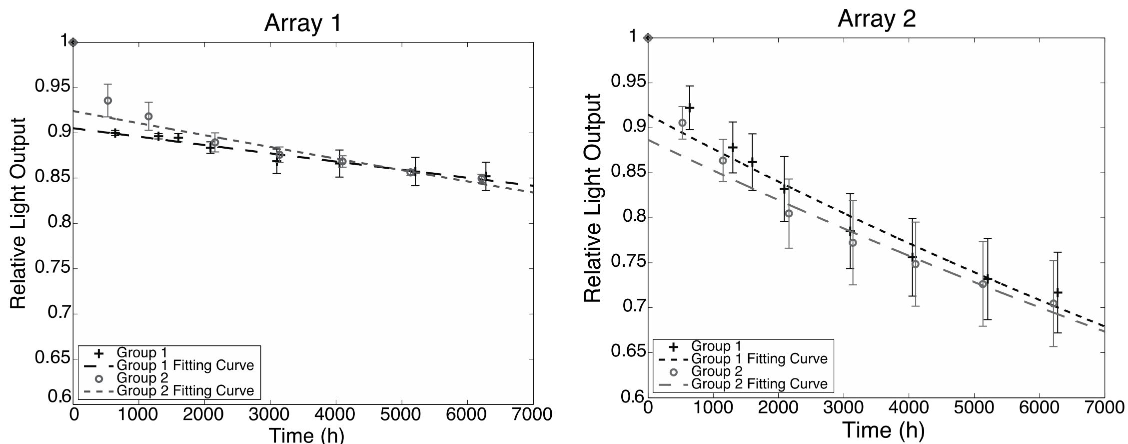

Fig. 2. Relative light output over time for LED arrays 1 and 2. The fitting curve indicates the exponential decay model, and error bars are standard deviation.

Table 2. The exponential decay model parameters and L_{70} life projections for arrays 1 and 2. R^2 indicates the coefficient of determination, or "goodness of fit," the data had with the fitting model used, in this case an exponential decay model.

Array 1	**Group 1**		**Group 2**	
	average	*95% Confidence band*	*average*	*95% Confidence band*
a	0.91	(0.89, 0.92)	0.92	(0.90, 0.94)
b	-1.10E-05	(-1.56e-5 , -6.35e-6)	-1.46E-04	(-2.01e-5, -9.14e-6)
L70 (hours)	23,500	(15,400 - 34,000)	19,000	(12,800 - 32,700)
R^2	0.88		0.93	

Array 2	**Group 1**		**Group 2**	
	average	*95% Confidence band*	*average*	*95% Confidence band*
a	0.91	(0.88, 0.95)	0.89	(0.85, 0.92)
b	-4.25e-05	(-5.27e-05, -3.24e-05)	-3.93e-05	(-5.01e-05, -2.84e-05)
L70 (hours)	6290	(4390, 7130)	6020	(3870, 9740)
R^2	0.96		0.96	

The lumen depreciation data for LED arrays 3 and 4 did not follow the exponential decay model (Fig. 3 and Table 3). The reason could be that the dominant degradation mechanisms for these LEDs are different.

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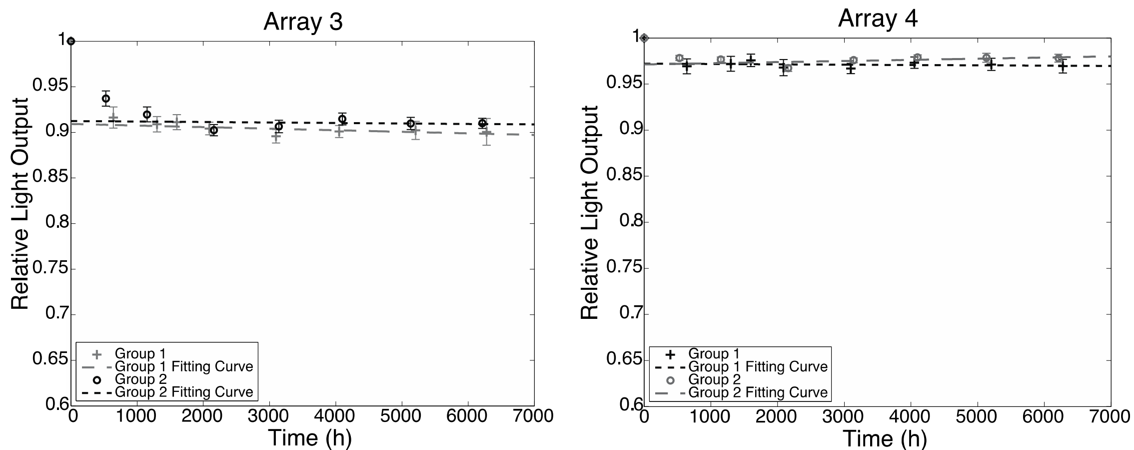

Fig. 3. Relative light output over time for LED arrays 3 and 4. The fitting curve indicates the exponential decay model, and error bars are standard deviation.

Table 3. The exponential decay model parameters for arrays 3 and 4. R^2 indicates the coefficient of determination, or "goodness of fit," the data had with the fitting model used, in this case an exponential decay model.

Array 3	**Group 1**		**Group 2**	
	average	*95% Confidence band*	*average*	*95% Confidence band*
a	0.90	(0.90, 0.92)	0.91	(0.89, 0.93)
b	-1.89e-06	(-4.681e-06, 8.928e-07)	-5.837e-07	(-5.42e-06, 4.25e-06)
R^2	0.38		0.03	

Array 4	**Group 1**		**Group 2**	
	average	*95% Confidence band*	*average*	*95% Confidence band*
a	0.97	(0.97, 0.98)	0.97	(0.96, 0.98)
b	-3.66e-07	(-2.26e-06, 1.53e-06)	1.27e-06	(-1.51e-06, 4.04e-06)
R^2	0.05		0.29	

Evidence of degradation mechanisms such as browning of the package, reduction in phosphor conversion efficiency, and ohmic contact degradation was observed during the study. The relative contribution of these mechanisms differs depending on the package design. These degradation mechanisms also were observed in single-die LED packages in past studies. In some samples there was also evidence of single die or string failures. In array 1, there was a sample with two string failures. Array 2 also had a sample with a string failure. A sample of array 3 had individual die failures in four different strings. A sample of array 4 had five single-die failures in three different strings. Failures were observed under a microscope at a low bias current.

3.2 Rapid Thermal Cycle Lumen Maintenance Study

The luminous flux data (Fig. 4) measured as a function of the number of rapid thermal cycles for a sample of array 2 show depreciation following an exponential fit. From the collected data, the samples fell below L_{70} around approximately 500 cycles. A cycle consists of a ramp up to maximum temperature (approximately 100°C) and a ramp down to minimum temperature (-40°C) over a 10-minute time period.

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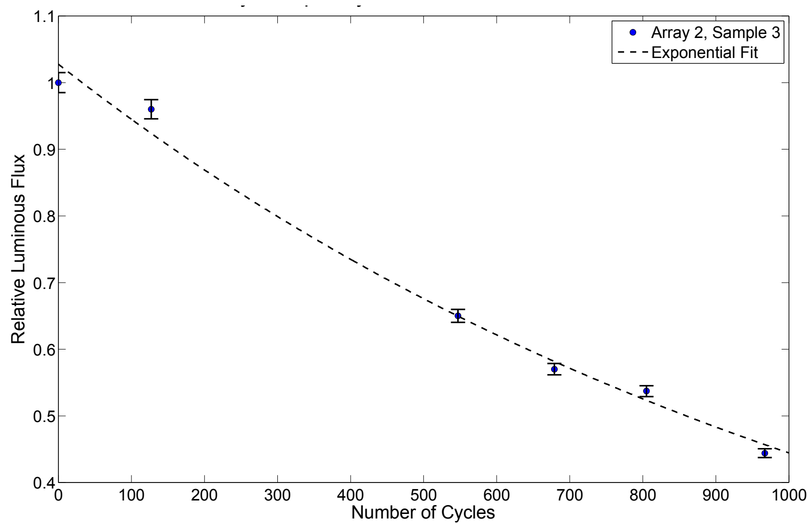

Fig. 4. Relative luminous flux over cycles for one sample from LED array 2.

Lumen depreciation data (Fig. 5) from a sample from array 3 also show rapid depreciation. In this case, the luminous flux of the sample fell below L_{70} just prior to completing the 30th cycle. In both cases, there were die and string failures. As expected, die or string failures cause a sharp reduction in light output. In the case of array 2, the string failures were observed after 500 cycles, and progressive failures of strings were observed at each measurement point thereafter. The string failures led to an increase in forward voltage, which inhibited the driver from supplying the constant current of 700 mA. In the case of array 3, both die failures and string failures were observed. The sudden drop in light output after the 28th cycle was a result of catastrophic failure of almost half of the dies in the LED package. Until that catastrophic failure, lumen depreciation followed an exponential fit (Fig. 5). Cracks in the encapsulant also were observed and were due to a CTE mismatch between the plastic ring and the encapsulant.

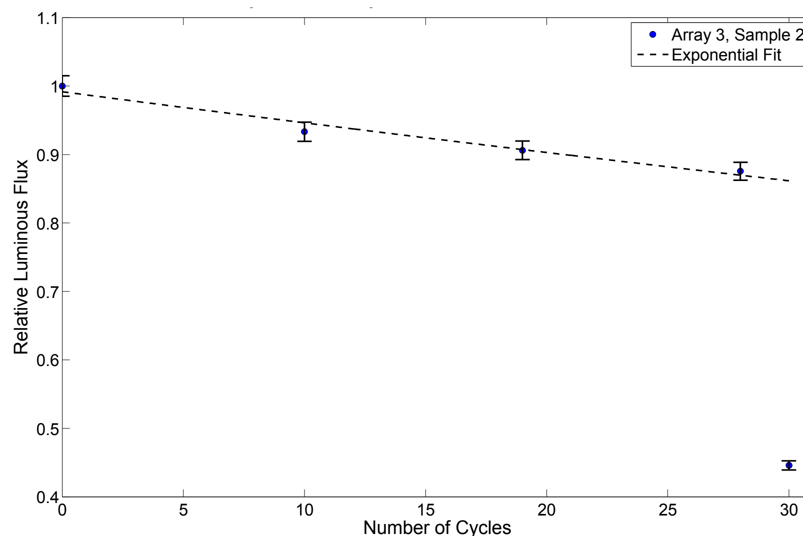

Fig. 5. Relative luminous flux over cycles for one sample from LED array 3.

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4. DISCUSSION AND SUMMARY

The multi-die array LED packages tested share similar degradation and failure mechanisms to those that have been presented in literature for single-die LED packages. However, there is also the possibility of single die or string (in series–parallel configuration) failure that could potentially cause current imbalances in the package and may accelerate the degradation process. Further, failure of a die or a string may not result in a proportionate drop in the light output because the current redistribution inside the package may compensate fully or partially for the lost die(s). However, in the long run, the current redistribution will lead to faster degradation of the functioning dies and, therefore, the package.

The results of this study show that string and die failures occur when multi-die array LED packages are subjected to two different stress conditions, continuous thermal stress and rapid thermal cycling stress. It is hypothesized that single die failure in a string of LEDs is due to a short circuit failure of the die, since the current path in the string is not interrupted by the failed die. A string with a shorted die would have a larger current flow when compared to other strings in the package. String failures could occur due to electrical contact failure at any point in the string. The rapid thermal cycling induces stresses at the material interfaces, due to thermal expansion coefficient mismatch of different materials. Therefore, all samples that were subjected to thermal cycling had catastrophic failures at an electrical contact point. On the other hand, a majority of the samples that were subjected to continuous thermal stress did not show any catastrophic failure of dies or strings in the package.

In applications, LED packages are subjected to both types of stresses. Therefore, it is useful to know the performance of an LED package under both types of stress conditions. For example, array 3 showed contrasting results when subjected to two different stress conditions. The lack of lumen depreciation seen in the long-term lumen maintenance test, in contrast with the rapid thermal cycle data from array 3, indicate that LM-80 and TM-21 are inadequate to predict useful life of array LED packages. The inadequacy of TM-21 in predicting LED package lifetime with a reasonable uncertainty is evident, even under continuous thermal stress conditions. Further research on multi-die array LED packages is required to understand the associated failure mechanisms and to develop a robust life-prediction method.

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