Remote monitoring of LED lighting system performance

Dinusha R. Thotagamuwa, Indika U. Perera, Nadarajah Narendran*
Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY 12180

ABSTRACT

The concept of connected lighting systems using LED lighting for the creation of intelligent buildings is becoming attractive to building owners and managers. In this application, the two most important parameters include power demand and the remaining useful life of the LED fixtures. The first enables energy-efficient buildings and the second helps building managers schedule maintenance services. The failure of an LED lighting system can be parametric (such as lumen depreciation) or catastrophic (such as complete cessation of light). Catastrophic failures in LED lighting systems can create serious consequences in safety critical and emergency applications. Therefore, both failure mechanisms must be considered and the shorter of the two must be used as the failure time. Furthermore, because of significant variation between the useful lives of similar products, it is difficult to accurately predict the life of LED systems. Real-time data gathering and analysis of key operating parameters of LED systems can enable the accurate estimation of the useful life of a lighting system. This paper demonstrates the use of a data-driven method (Euclidean distance) to monitor the performance of an LED lighting system and predict its time to failure.

Keywords: remote monitoring, predictive useful life, LED systems

1. INTRODUCTION

Today, light-emitting diode (LED) technology is the preferred light source for many illumination applications. The claimed benefits of LED technology are low power demand and reduced maintenance. Nowadays, energy savings with LED technology is a given; therefore, users are looking for additional benefits beyond energy savings for transforming their lighting to LED technology. The concept of connected lighting systems using LED lighting for the creation of intelligent buildings is becoming attractive to building owners and managers. Remote monitoring of the performance of lighting systems is a welcoming feature for building managers who are looking to optimize energy usage by controlling lights and enabling scheduled maintenance and timely replacement of fixtures ahead of failure.

Prognostics, which is projecting the time to failure of LED lighting systems and estimating the remaining useful life (RUL), is an important aspect of the intelligent building concept.[1] The prognostic algorithms employ current and historical data on operational and environmental loading conditions.[1] Remote monitoring facilitates the continuous measurement of key operational parameters in LED lighting systems and allow users to make decisions based on the behavior of the monitored parameters. The goal of this study was to identify parameters that can signal failure of an LED lighting system and predict failure time, thus the RUL. The earliest time when the failure can be predicted with high accuracy was assessed for the different parameters considered.

The study began with a literature review. Several past studies have shown that when LEDs age, the forward voltage of an LED package increases.[2,3] In 2013, Jayawardena showed increases in series electrical resistance and thermal resistance in high-power LED packages under high temperature and high current aging conditions.[4] Therefore, forward voltage, series resistance, and thermal resistance are some parameters that can be used for assessing the health and estimating the RUL of an LED systems.

Sutharssan et.al.,[5] proposed distance-based, data-driven methods (Euclidean distance [ED]) to detect the health of high-power LEDs with in-situ monitoring of operating parameters such as lead wire temperature, forward voltage, and forward current. In their study, they were able to predict the time to failure within a 10% error at around 60% of the operating life of the LED package. ED is a measure of deviation of the operating parameters from their initial operating conditions. ED converts multi-dimensional data to a single parameter, and it requires failure thresholds and the operational data under normal operating condition in order to work properly.[5] The general form of the ED method is shown below (Eq. 1).

*Corresponding author: narenn2@rpi.edu; +1 (518) 687-7100; www.lrc.rpi.edu/programs/solidstate

Fifteenth International Conference on Solid State Lighting and LED-based Illumination Systems,
edited by Matthew H. Kane, Nikolaus Dietz, Ian T. Ferguson, Proc. of SPIE Vol. 9954,
99540I · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2240463

$$ED_i = \sqrt{(X_i - \overline{X})^2 + (Y_i - \overline{Y})^2} \quad \text{(Eq. 1)}$$

X_i, Y_i = instantaneous *value of the operating parameters*

$\overline{X}, \overline{Y}$ = *mean values of operating parameters under normal operating condition*

Most of the previous reliability and RUL studies have been performed on single LED packages and not on LED lighting systems. An LED system has many components including the LED array, printed circuit board (PCB), heat sink, and driver. As a first step towards developing a suitable method for predicting the RUL of LED lighting systems, we focused our investigation on whether the methods used in past studies for LED packages could be used for LED systems as well, namely the LED array. Forward voltage and LED temperature were used as the monitoring parameters, and the Euclidean distance method was used for predicting time to failure.

2. EXPERIMENT

Four samples of the same commercial downlight were chosen for the experiment. The selected samples consisted of LED arrays with eight mid-power LED packages connected in series. The test samples were prepared by detaching the LED arrays from the fixture driver and readying the LED arrays to be used with direct current (DC) power supplies. The LED array was placed in a laboratory oven and was driven with a constant forward current of 240 mA using a DC power supply. The aging test was conducted at four different LED pin temperature conditions of 150°C, 180°C, 195°C, and 200°C using four similar setups. One sample per temperature condition was used in the study. The experimental variables used in the experiment are given in Table 1.

Table 1. Experimental variables

Independent variables	**Dependent variables**
○ Ambient temperature (LED pin temperature at the beginning 150°C, 180°C, 195°C, 200°C) ○ Forward current (240 mA)	• Forward voltage (V) • Failure time (h) • LED pin temperature (°C)

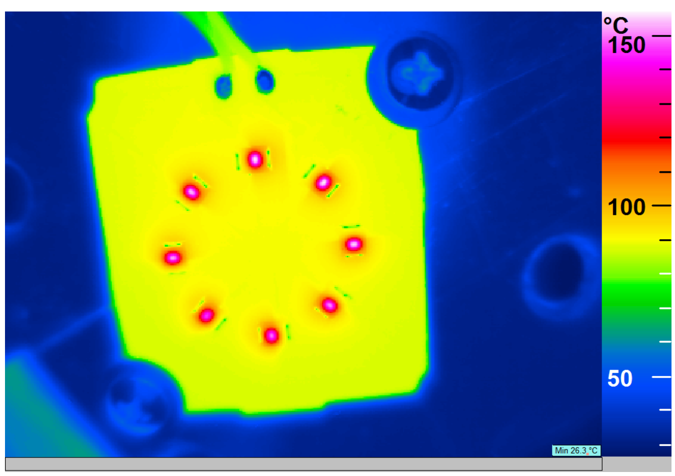

Figure 1. Temperature distribution on the LED board at 240 mA.

A suitable location for the temperature sensor attachment was determined using an IR thermal imager. In this process, the LED array was driven at a current of 240 mA and the sample was allowed to reach steady state. Once thermal steady state was reached, the sample was placed under an IR thermal imager and the temperature distribution was captured, as depicted in Figure 1. It clearly showed that the temperature distribution was uniform across the LED board, and therefore the thermistor was attached to the cathode lead of one of the LED packages, which represents the average temperature of the LED array.

The forward current of the LED array was measured using a shunt resistor. The forward voltage (across the LED array and across two individual LEDs), forward current, and the LED pin temperature data were sampled and acquired using a DAQ and a PC running a LabVieW program. The forward voltage measurement locations on the LED array are illustrated in Figure 2. The experimental setup is shown in Figure 3.

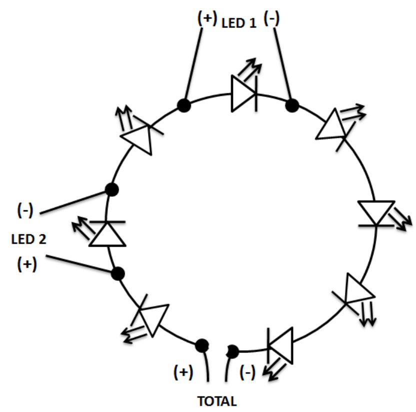

Figure 2. Forward voltage measurement locations on the LED array.

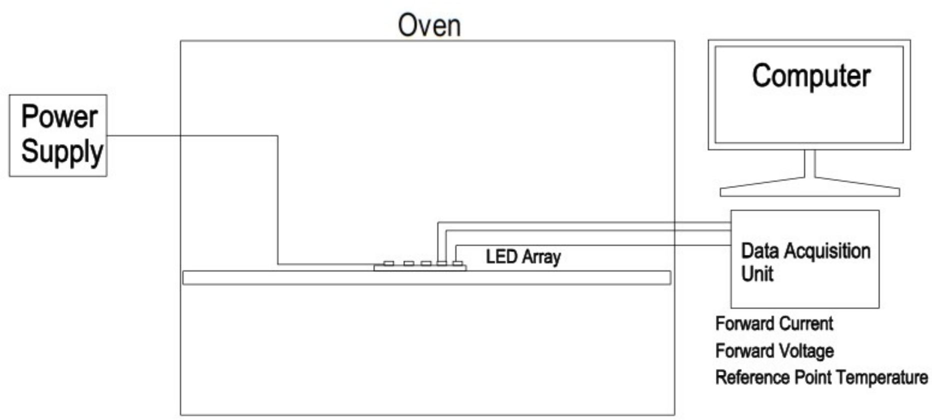

Figure 3. Experimental setup.

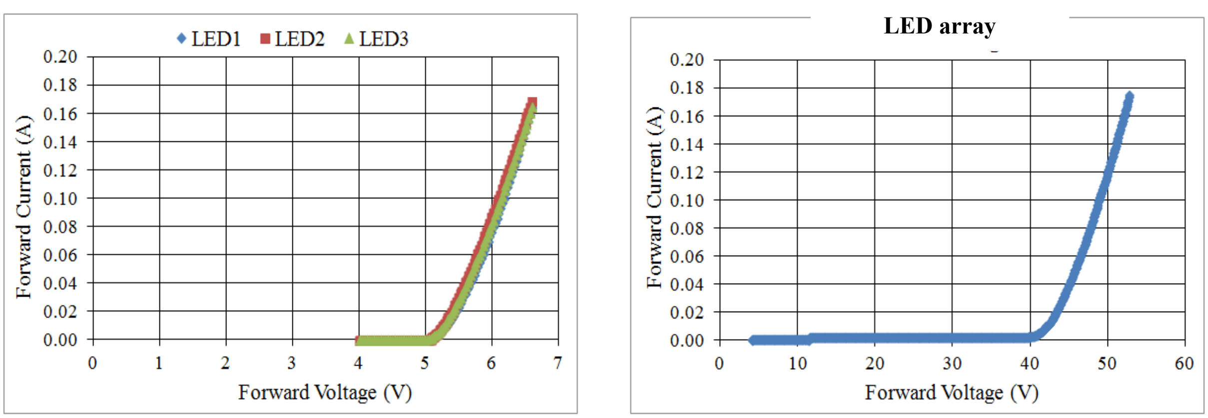

Figure 4. I-V characteristics of individual LEDs and the LED array.

Electrical characterizations were performed on three individual LEDs and the LED array using a source meter, and the I-V curves are shown in Figure 4. It can be seen that the three individual LEDs have similar I-V curves. It is worthwhile noting that the entire LED array only starts conducting after all LED packages get forward biased.

3. RESULTS

Figure 5 shows the forward voltage behaviors of the entire LED string and the two individual LEDs of the test sample aged at 180°C up to the failure point. It can be seen that the rates of forward voltage increase are different for each of the individual LED packages in the array. In the 180°C condition, LED1 showed a forward voltage increase of about 3.5 V while LED2 showed only a 1.0 V increase in forward voltage at the failure point. The LED array failure was observed when the LED array voltage increase reached 8 V.

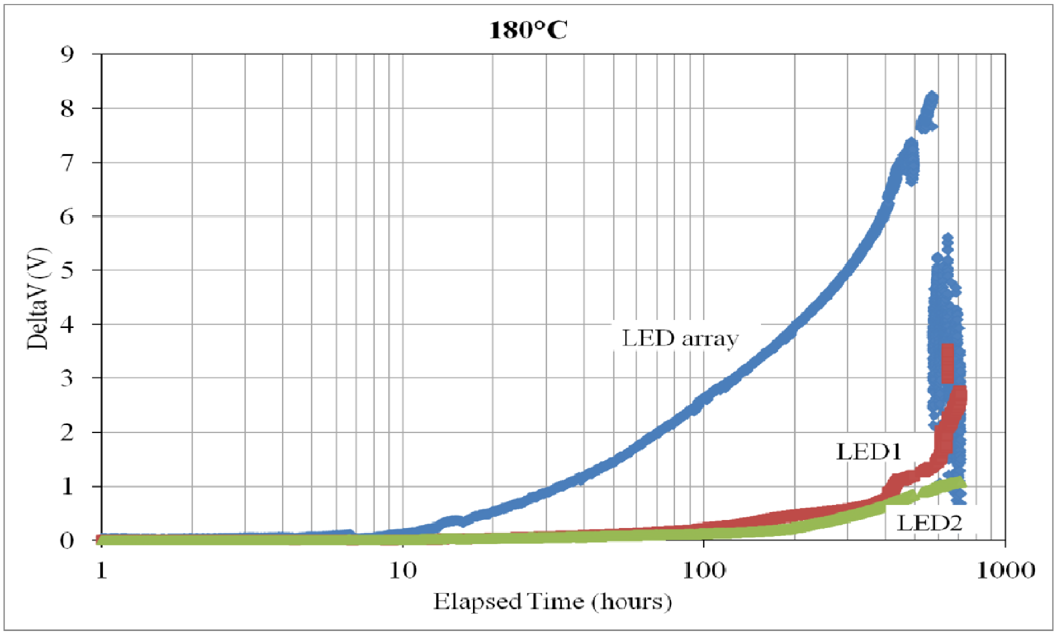

Figure 5. Forward voltage behavior of individual LED packages and the entire LED array during the aging test (T_{ref}=180°C).

Figure 6 shows how the voltage across the LED arrays increased with the stress time under four different temperature conditions. The test samples aged at 180°C, 195°C, and 200° C have failed, and they showed similar forward voltage increases in the range of 7.75V–8.50 V at the failure point. The test sample at 150°C was still operating at 900 hours and the present forward voltage increase was about 2.30 V.

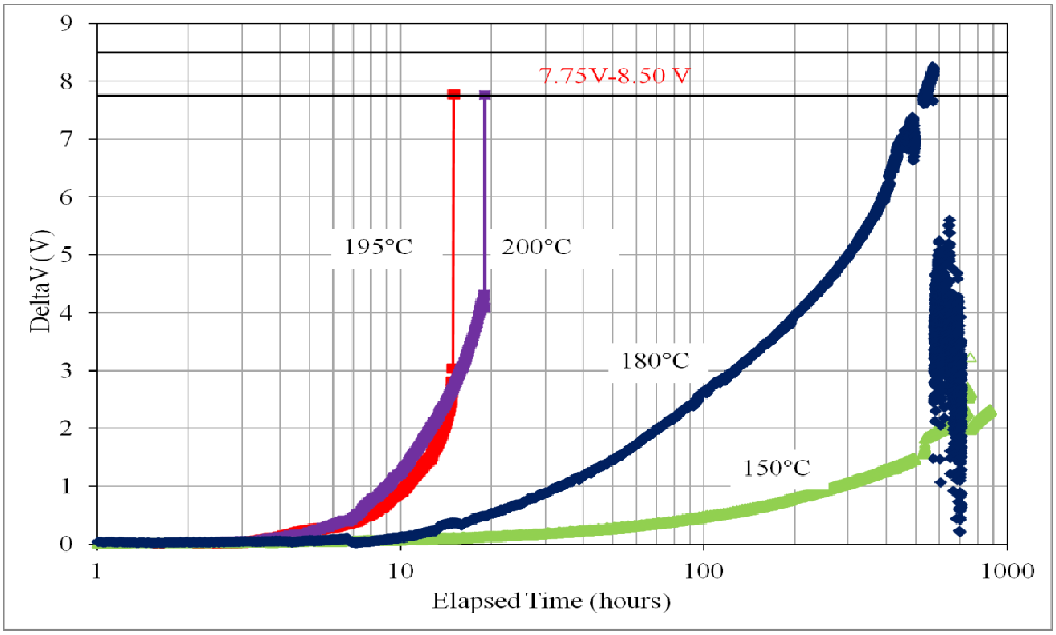

Figure 6. Forward voltage behavior of the LED array under different temperature conditions.

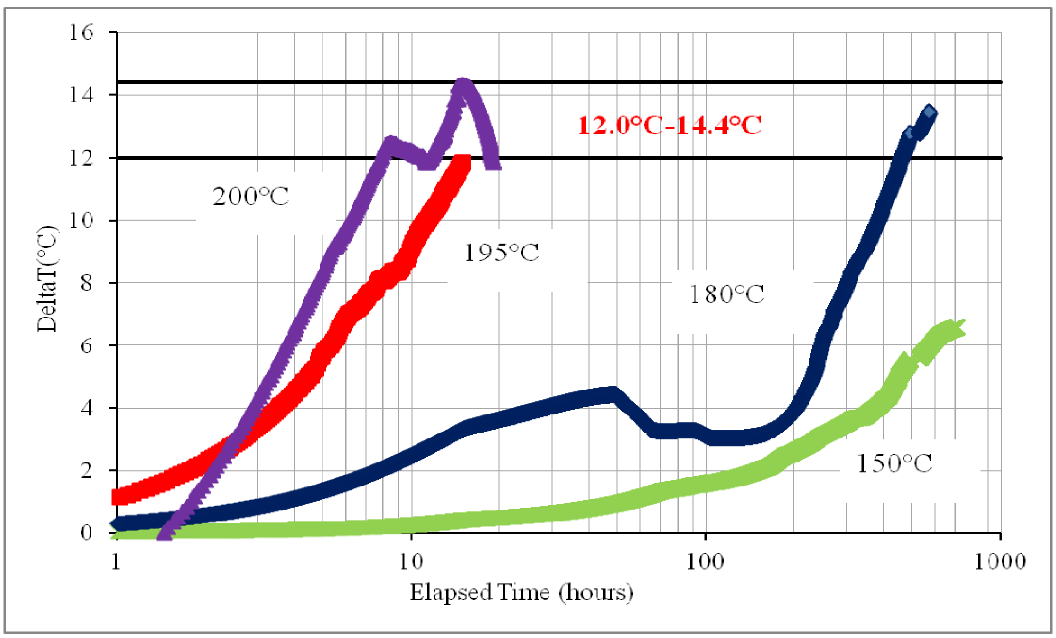

Figure 7. LED pin temperature variation during aging.

The variation of LED pin temperature for the four test conditions during aging is shown in Figure 7. The failed test samples showed LED pin temperature increases between 12.0°C and 14.4°C at the failure point. Failure thresholds were established for voltage and temperature independently by observing the forward voltage and LED pin temperature behaviors of the failed samples. The failure thresholds of 7.75 V and 12.0°C were selected for voltage and temperature, respectively.

The times to reach the corresponding failure thresholds under all test conditions were determined for voltage and temperature independently. The relationship between the time-to-reach-failure criteria and the LED pin temperature is shown in Figure 8. Since the test sample aged at 150°C has not reached the failure threshold as of 900 hours, extrapolated values were used in Figure 8. It is evident from Figure 8 that voltage and temperature independently are capable of predicting failure. In order to investigate whether voltage and temperature combined with Euclidean distance can predict failure with better accuracy at an earlier point in time, the failure threshold for Euclidean distance is determined (Eq. 2)

$$ED_{th} = \sqrt{(\Delta V)^2 + (\Delta Tref)^2} = \sqrt{(7.75)^2 + (12.0)^2} = 14.29 \qquad \text{(Eq. 2)}$$

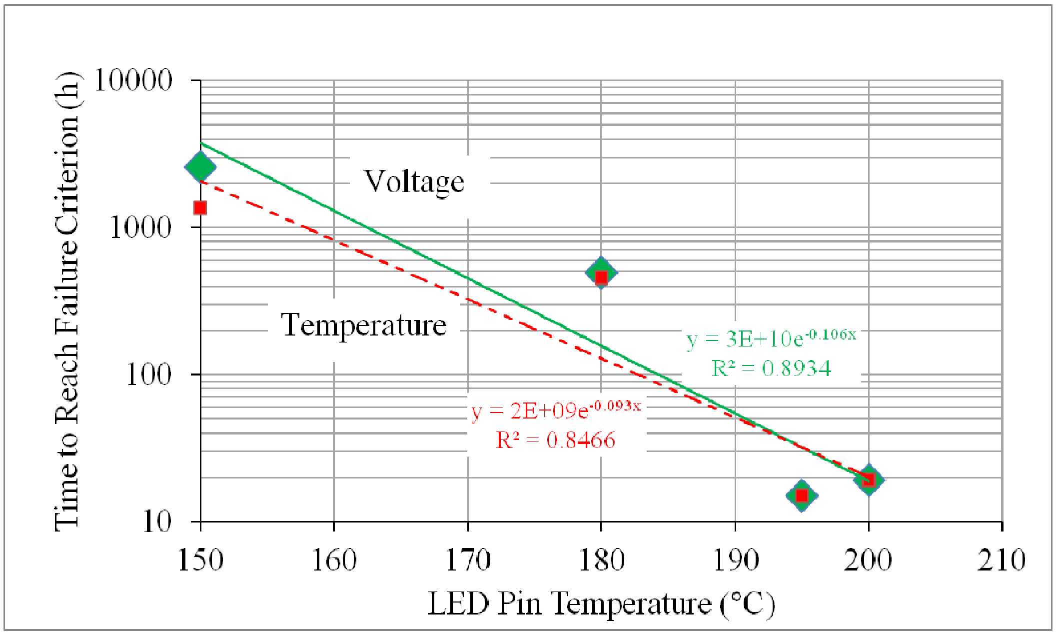

Figure 8. Time to reach failure criteria for voltage and temperature.

Failure time was predicted for the 180°C condition using voltage, temperature, and Euclidean distance methods with the established failure thresholds. A summary of the prediction results is presented in Table 2. All three methods are capable of predicting the failure with an error of 10% prior to 60% of the operating life. Failure prediction using voltage increase reached the least error much before the other two methods. Figure 9 shows the variation of prediction error as a function of percent operating life.

Table 2. Summary of failure time prediction results for the 180°C condition.

Time (h)	Percentage of operating life	Actual TTF (h)	Predicted TTF (h)			Prediction error		
			ED(V)	ED(T)	ED(VT)	ED(V)	ED(T)	ED(VT)
250	47%	531	466	1073	778	-12.3%	102.1%	46.5%
300	56%	531	495	619	588	-6.8%	16.6%	10.7%
350	66%	531	514	569	559	-3.2%	7.2%	5.3%
400	75%	531	520	527	530	-2.1%	-0.8%	-0.2%
450	85%	531	508	511	510	-4.4%	-3.8%	-3.9%
500	94%	531	508	513	530	-4.3%	-3.4%	-0.3%

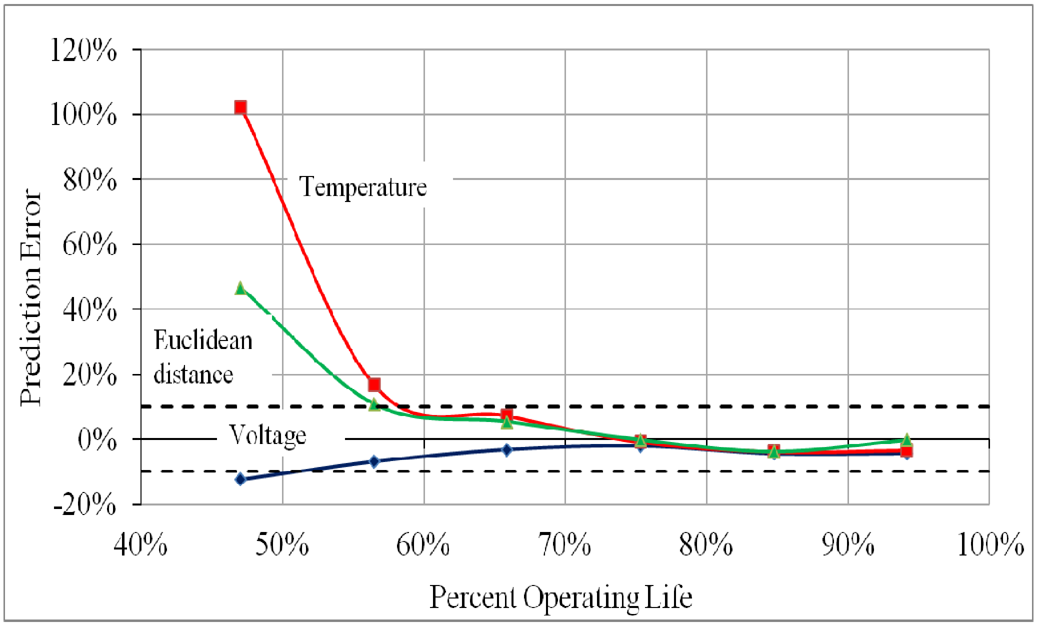

Figure 9. The variation of prediction error of the three methods with percent operating life.

SUMMARY

It was observed that the forward voltage and the LED reference point temperature drifted from their initial healthy conditions when the LED arrays were subjected to high thermal stress. The test samples showed similar forward voltage and LED reference point temperature increase at the failure point during the aging tests. This preliminary study shows that the failure time can be predicted accurately at a sufficiently early time (less than 60% of the operating life). The voltage, temperature, and the combined Euclidean distance can all be used to predict failure time accurately. The I-V characteristics of each LED before and after aging show that the voltage can be very different, resulting in certain LED packages failing faster. Figure 10 shows the I-V characteristics of individual LED packages in a test sample aged at 200°C before and after aging.

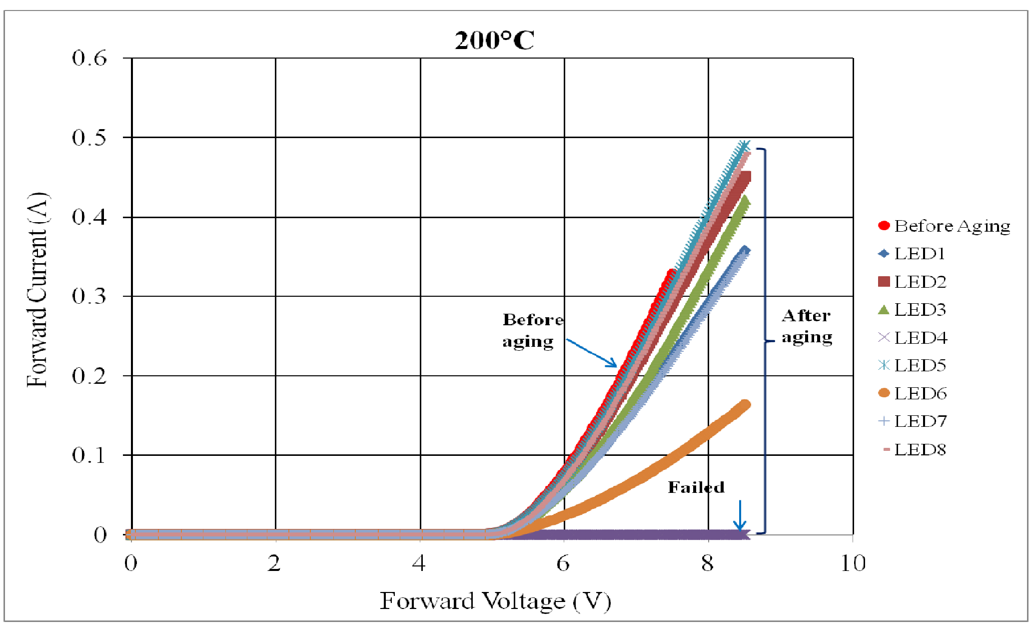

Figure 10. I-V curves of individual LED packages before and after aging.

In predicting the failure time for the 180°C condition, a forward voltage threshold of 7.75 V was used and that resulted in a reasonable prediction accuracy. However, there are many possible failure scenarios where the voltage threshold would be different. As previously stated, the tested LED array had eight mid-power LED packages connected in series, each having an initial forward voltage of 6.60 V.

Out of the many possible scenarios, two extreme scenarios are presented here.

- Scenario 1: When only one LED package's forward voltage increases by 20% and causes open circuit failure: $\Delta V_{threshold}$=6.60*0.2= 1.32 V
- Scenario 2: When all LED packages show an equal forward voltage increase of 20% and cause open circuit failure: $\Delta V_{threshold}$=6.60*0.2= 10.56 V

Based on these two extreme scenarios, the voltage threshold could be any value between 1.3–10.6V depending on how many LED packages contribute to the failure. Therefore, further studies are needed to confirm if accelerated temperature aging will result in accurate forward voltage and LED pin temperature thresholds for estimating time to failure.

ACKNOWLEDGMENTS

We gratefully appreciate Jennifer Taylor from the Lighting Research Center (LRC) for her help in preparing this manuscript. Further, we are thankful to Martin Overington, Jean Paul Freyssinier, Howard Ohlhous, Yi-wei Liu, and Oshadhi Eshwarage of the LRC for their support. We also thank the Office of Graduate Education at Rensselaer Polytechnic Institute for their financial assistance to attend the SPIE conference.

REFERENCES

[1] Pecht, M.G., [Prognostics and Health Management of Electronics], John Wiley & Sons Inc., Hoboken, NJ, Introduction ch. 1, pg. 2 (2008).

[2] Meneghini, M. et al., "High temperature electro-optical degradation of InGaN/GaN HBLEDs," *Microelectronics Reliability* 47(9–11), 1625–1629 (2007); doi: 10.1016/j.microrel.2007.07.081.

[3] Chen, H. et al., "Failure analysis of electrical-thermal-optical characteristics of LEDs based on AlGaInP and InGaN/GaN," *Semiconductor Physics and Technology* 46(10), 1333–1338 (2012); doi: 10.1134/S1063782612100041.

[4] Jayawardena, A., "Changes in electrical and thermal parameters of LED packages under different current and heating stresses," Ph.D. dissertation, School of Architecture, Rensselaer Polytechnic Institute, Troy, NY (2013).

[5] Sutharssan, T. et al., "Prognostics and health monitoring of high power LED," *Micromachines* 3, 78–100 (2012); doi: 10.3390/mi3010078.