

Life of LED-based white light sources

Nadarajah Narendran and Yimin Gu

Lighting Research Center
Rensselaer Polytechnic Institute, Troy, NY 12180
www.lrc.rpi.edu

Narendran, N. and Y. Gu. 2005. Life of LED-based white light sources. *IEEE/OSA Journal of Display Technology* 1(1): 167-171.

Copyright 2005 IEEE.

This paper is being distributed electronically under the "Fair Use Copyright Act." One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited under United States and international laws.

Life of LED-Based White Light Sources

Nadarajah Narendran and Yimin Gu

Abstract—Even though light-emitting diodes (LEDs) may have a very long life, poorly designed LED lighting systems can experience a short life. Because heat at the p-n-junction is one of the main factors that affect the life of the LED, by knowing the relationship between life and heat, LED system manufacturers can design and build long-lasting systems. In this study, several white LEDs from the same manufacturer were subjected to life tests at different ambient temperatures. The exponential decay of light output as a function of time provided a convenient method to rapidly estimate life by data extrapolation. The life of these LEDs decreases in an exponential manner with increasing temperature. In a second experiment, several high-power white LEDs from different manufacturers were life-tested under similar conditions. Results show that the different products have significantly different life values.

Index Terms—Degradation, life, light source, white light-emitting diode (LED).

I. INTRODUCTION

THE interest for using light-emitting diodes (LEDs) for display and illumination applications has been growing steadily over the past few years. The potential for long life and reduced energy use are two key attributes of this rapidly evolving technology that have generated so much interest for its use in the above mentioned applications. Traditionally, the lamp life of light sources commonly used in illumination applications is determined by subjecting them to a predetermined on/off cycle until half the number of light sources cease to produce light [1]. Unlike these sources, LEDs rarely fail catastrophically; instead, their light output slowly degrades over time. Even if an LED is technically operating and producing light, at some point the amount of light produced by the LED will be insufficient for the intended application. Therefore, the life of an LED should be based on the amount of time that the device can produce sufficient light for the intended application, rather than complete failure. Based on this argument, a recent publication from an industry group defines the life of an LED device or system for use in general lighting applications as the operating time, in hours, for the light output to reach 70% of its initial value [2].

The most widely used white LEDs incorporate a layer of phosphor over a GaN-based, short-wavelength light emitter [3]. Usually, the phosphor is embedded inside an epoxy resin that surrounds the LED die. Some portion of the short-wavelength radiation emitted by the LED is down-converted by the phosphor, and the combined radiation creates white light.

Manuscript received January 26, 2005; revised April 20, 2005. This work was supported in part by the U.S. Department of Energy under Cooperative Agreement DE-FC26-01NT41203 and by the University of California, Santa Barbara.

The authors are with the Lighting Research Center at Rensselaer Polytechnic Institute, Troy, NY 12180 USA (e-mail: narenn2@rpi.edu; guyim@rpi.edu).

Digital Object Identifier 10.1109/JDT.2005.852510

Early white LEDs were packaged similar to the indicator-style colored LEDs, specifically 5 mm and SMD (surface mount devices). Although these products demonstrated the concept of a white light source, they did not produce sufficient light for display and illumination applications. Furthermore, these indicator-style white LEDs had a relatively short life, 5000–10 000 h to reach 70% light level under normal operating conditions [4]. To address the higher luminous flux requirements, manufacturers have started to commercialize high-power illuminator LEDs that are presently producing over one hundred times the flux compared to indicator-style white LEDs. The higher light output is achieved by using larger dies, higher drive currents, and improved heat extraction methods [5], [6]. In addition, some manufacturers are using better encapsulants to improve the life of white LEDs [6].

There are several studies that have investigated the aging mechanisms of GaN-based LEDs [7]–[10]. During the 1990s, Barton *et al.* investigated the degradation of GaN-based blue LEDs and showed that light output reduction over time occurred primarily due to the yellowing of the epoxy surrounding the die [7]. In 2001, Narendran *et al.* observed that indicator-style white LED packages degraded very rapidly, with the LEDs reaching the 50% light output level within 6000 h [4]. In that same study, it was shown that the chromaticity values of the white LEDs shifted toward yellow over time, and it was speculated that the yellowing of the epoxy was the main cause for light output degradation [4]. Therefore, based on past studies, the primary reason for the degradation of indicator-style white LED packages is the yellowing of the epoxy that is caused by excessive heat at the p-n-junction of the LED [10]. Some of the newer illuminator-style white LEDs use encapsulant materials that have lower photodegradation characteristics [5], and therefore have a lower degradation rate. However, there are factors such as the degradation of the die attaché epoxy, discoloration of the metal reflectors and the lead wires, and degradation of the semiconducting element that are influenced by heat, and these all contribute to the overall degradation of the white LED. Although the newer high-power white LEDs would have a lower degradation rate compared to the early indicator-style devices, it is the heat at the p-n-junction that most influences the degradation. The heat at the p-n-junction is caused by the ambient temperature and the ohmic heating at the bandgap.

As stated earlier, long life is one key feature of LED technology that has attracted so many end-use communities. To benefit from the long-life feature, it is the final system that has to operate for a long time, not just the individual LED. As noted in past studies, heat at the p-n-junction is one of the key factors that determine the life of the white LED. Therefore, if systems are not properly designed with good thermal management

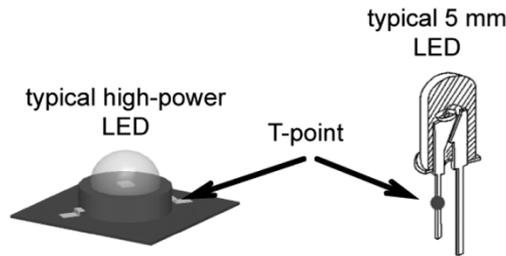


Fig. 1. Examples of T-points for two different types of LEDs.

techniques, even if they use long-life white LEDs the life of the final system would be short. Developing the relationship between junction temperature and life would be very useful for producing long-life systems.

Although there are different methods available for estimating the junction temperature of LEDs, they are not very convenient, especially once the LEDs are integrated into a system [11]. Furthermore, these methods are not direct; consequently, they are prone to erroneous results. Alternatively, it is much more convenient and direct to measure the heat at a location external to the LED package that is sufficiently close to the junction and where a temperature sensor can be directly attached. The temperature of this point should have a good relationship to the junction temperature. The point where a temperature sensor can be attached for this measurement could be the lead wire (cathode side) for the indicator-style LEDs and the board for high-power LEDs (see Fig. 1). Most manufacturers can recommend such a point, and we refer to this as the T-point in this manuscript.

Since white LEDs in the marketplace are packaged differently, their ability to transfer heat from the die to the surrounding environment is different from product to product. Therefore, it is reasonable to assume that different products have different degradation rates as a function of heat. A graph that shows the life of the LED as a function of T-point temperature is extremely useful for system manufacturers to build reliable, long-lasting systems. By knowing how much impact heat has on the degradation rate or life of the LED, the system manufacturer can select components and drive parameters, including the amount of heat sink and drive current, for a product being designed for a given application.

Therefore, the objective of the study presented in this manuscript was to investigate the relationship between the T-point temperature and life of a white LED. A second objective was to understand the degradation rate of different high-power white LED products presently available in the marketplace.

II. EXPERIMENT

To understand the relationship between the T-point temperature and life, one type of high-power white LED that is commonly available in the marketplace was selected. Several of these LEDs were subjected to a life test under different ambient temperatures. The details of the experimental setup are described in the following paragraphs.

Because the different LED arrays have to operate at a particular ambient temperature, the arrays were placed inside specially designed, individual life-test chambers, shown in Fig. 2 [5]. The test chambers had two different functions: 1) to keep

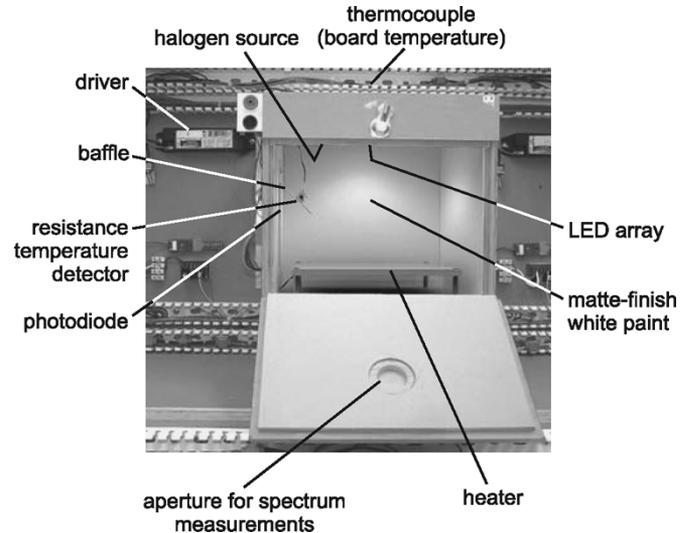


Fig. 2. LED life-test chamber.

the ambient temperature constant for the LED arrays and 2) to act as light-integrating boxes for measuring light output. Each individual LED array was mounted at the center of the inside top surface of a life-test chamber. A photodiode attached to the center of the left panel continuously measured the light output. A small white baffle placed over the photodiode shielded it from the direct light, allowing only the reflected light to reach the photodiode. A resistance temperature detector placed on top of the baffle measured the chamber's ambient temperature and controlled the heater that provided the necessary heat to the chamber through a temperature controller. The temperature inside the box remained within ± 1 °C. The heater was attached to a raised aluminum plate with a matte-white cover that sat on the chamber floor. The temperature was estimated using a J-type thin wire thermocouple soldered to the T-point of one white LED. For each chamber, an external LED driver controlled the current flow through the LEDs. All life-test chambers were placed inside a temperature-controlled room, as shown in Fig. 3. The life-test chambers were staggered vertically and horizontally to ensure that heat rising from the bottom chambers did not affect the chambers above them.

A. Experiment 1

The goal of the first experiment was to determine the effect of heat on the life of high-power white LEDs. Ten similar high-power white LEDs from the same manufacturing batch were acquired in early 2004. Five arrays were created by connecting two high-power LEDs in series per array, and these arrays were life-tested. The LEDs were operated at their rated current of 350 mA but at different ambient temperatures.

After the initial batch of LEDs, arrays 1–5, were tested for several thousand hours, additional high-power white LEDs from the same manufacturer were acquired during the latter part of 2004 and were subjected to similar life-testing (arrays 6–7). The operating conditions of the arrays are summarized in Table I. Two additional life test data (arrays 8–9), obtained using similar high-power white LEDs purchased in 2002 and operated under similar conditions, are also included. The only difference is that



Fig. 3. LED life-test laboratory.

TABLE I
TESTING CONDITIONS FOR THE HIGH-FLUX WHITE LED ARRAYS IN
EXPERIMENT I

Array #	Ambient Temperature (°C)	Drive Current (mA)	T-Point Temperature (°C)
Array 1	35	350	38
Array 2	45	350	42
Array 3	50	350	47
Array 4	55	350	51
Array 5	65	350	58
Array 6	50	350	49
Array 7	55	350	52
Array 8	35	350	43
Array 9	50	350	53

arrays 8 and 9 had six white LEDs instead of two, as used in the other arrays.

Usually during the initial period, the light output of the LEDs increases and then decreases. This is most likely due to annealing effects. The time it takes for the light output to reach the maximum varies depending on the operating conditions. As the operating temperature increases, the time it takes for the LEDs to reach the maximum decreases.

Fig. 4 shows the relative light output as a function of time for the high-power white LEDs. The lines in this figure are the regression fits for the data collected at the different temperatures. Because most of the LED arrays could take several years to reach the 70% light level, it is necessary to use a mathematical fit to extrapolate the data and estimate life. For white LEDs of this type, the light output decrease follows an exponential decay curve. It is worth noting here that with other package types, the light output decrease may not follow the same exponential decay. It is our experience that the estimated lifetime using an exponential fit is reliable when the initial 1000 h of

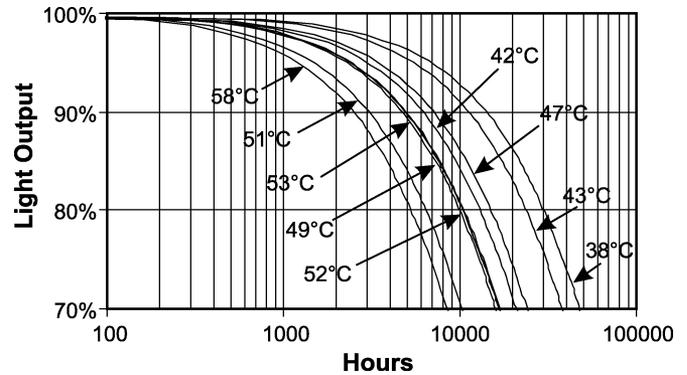


Fig. 4. Light output as a function of time for high-power white LEDs operated at various ambient temperatures. The lines are the regression fits for the data collected. T-point temperatures for each array are shown.

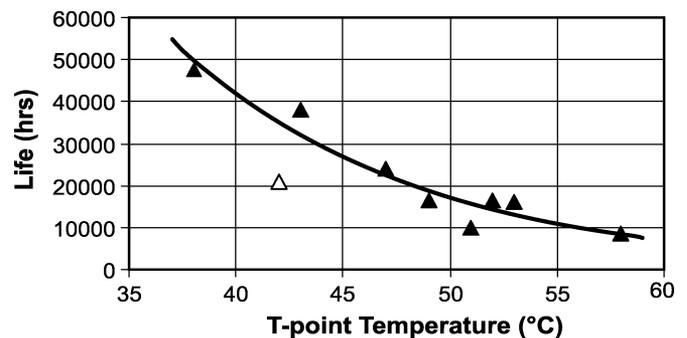


Fig. 5. Life as a function of T-point temperature.

data is omitted and a minimum of 5000 h of data beyond the initial 1000 h is used. (We would like to point out that with improvements in product performance, more data may be needed to reliably project LED life.) In Fig. 4, all light output values are normalized to their value at 1000 h, and an exponential fit to the respective data points produced the light output decay curves, which were plotted on a logarithmic scale. Life values were estimated using these curves.

Fig. 5 illustrates the estimated life of the white LEDs as a function of T-point temperature for the nine arrays. The life decreased as the T-point temperature increased. The life as a function of T-point temperature also followed an exponential curve. However, one data point, denoted by an open triangle in Fig. 5, did not fall on this trend line and deviated significantly. To identify possible reasons for this deviation, the T-point temperature data over the period of the life test were carefully analyzed. However, nothing looked abnormal, and the average value was maintained throughout.

One possible explanation for the deviation could be that the performance variation between similar LEDs is large, due to manufacturing issues. It is not possible to verify this explanation in this life study, since the sample size is too small and the light output of each individual LED in the array was not monitored. A large sample size with LEDs from different manufacturing batches would yield the average degradation rate and the variance between similar LEDs if their individual light output were measured. We are not aware of any published data that show this information for these types of LEDs.

From Figs. 4 and 5, it appears that the life of white LEDs of this type is over 50 000 h at room temperature, 25 °C.

TABLE II
TESTING CONDITIONS FOR THE HIGH-FLUX LED ARRAYS IN EXPERIMENT 2

High-Power White LED	Ambient Temperature (°C)	Drive Current (mA)	T-point Temperature (°C)
A	35	350	52
B	35	350	38
C	35	350	40
D	35	350	38
E	35	350	44
F	35	350	59

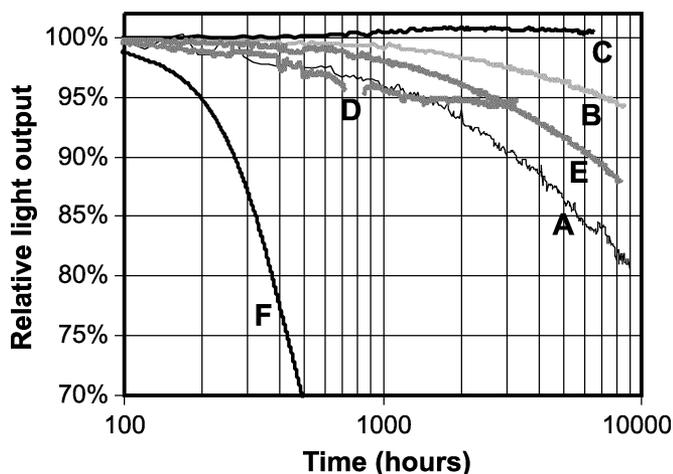


Fig. 6. Relative light output over time for several commercial high-power white LEDs operated under the same conditions.

B. Experiment 2

As mentioned earlier, there are many high-power white LEDs presently available in the marketplace. The goal of the second experiment was to study how the different commercial high-power white LEDs performed when operated under similar conditions. This experiment was very similar to Experiment 1. Altogether, six arrays of white LED packages were life-tested; two arrays consisted of multi-die packages and the remaining were single-die packages. All LEDs were operated at their rated current (350 mA) and at an ambient temperature of 35 °C. The operating conditions of the arrays and the measured T-point temperatures are summarized in Table II.

Fig. 6 shows the relative light output as a function of time for the LED arrays. Here, the data is normalized to the value at zero hours. As seen in Fig. 6, the different commercial white LEDs degrade at different rates. From these initial data it appears that for the same operating conditions, the different LEDs have different T-point temperatures and would result in much different life values. These results indicate that the different LEDs would require different amounts of heat sink when being packaged into fixtures in order to have similar life.

III. SUMMARY

The results of this study underscore the importance of packaging white LEDs using proper thermal management to maintain light output, and thereby extend system life. Heat at

the p-n-junction is one of the main factors that affect the life of white LEDs. Therefore, knowing the relationship between life and heat would be very useful for manufacturers who are interested in developing reliable, long-lasting systems. Results from the first experiment—conducted under various ambient temperatures to understand the relationship between T-point temperature and life—indicate that life decreases with increasing temperature in an exponential manner. Results from the second experiment—conducted to understand how different commercial white LEDs perform under identical operating conditions—show a large variation in life among the different packages, indicating that the packages used different heat extraction techniques and materials.

As part of ongoing research, we hope to further investigate how the different commercial LEDs are affected by heat and finally develop a family of curves that illustrate the relationship between life and T-point temperature for the different products.

ACKNOWLEDGMENT

The authors would like to thank R. Pysar of the Lighting Research Center (LRC), Rensselaer Polytechnic Institute, Troy, NY, for designing and implementing the LED life-test apparatus. They would also like to thank Ms. J. Taylor of the LRC for helping to prepare this manuscript.

REFERENCES

- [1] M. S. Rea, *The IESNA Lighting Handbook*, ninth ed. New York: Illum. Eng. Soc. of North America, 2000.
- [2] Alliance for Solid-State Illumination Systems and Technologies (AS-SIST). (2005) *ASSIST Recommends: LED Life for General Lighting* [Online]. Available: <http://www.lrc.rpi.edu/programs/solidstate/assist/recommends.asp>
- [3] S. Nakamura, T. Mukai, and M. Senoh, "Candela-class high brightness InGaN/AlGaIn double-heterostructure blue-light-emitting-diodes," *Appl. Phys. Lett.*, vol. 64, pp. 1687–1689, Mar. 1994.
- [4] N. Narendran, J. Bullough, N. Maliyagoda, and A. Bierman, "What is useful life for white light LEDs?," *J. Illum. Eng. Soc.*, vol. 30, no. 1, pp. 57–67, Winter 2001.
- [5] N. Narendran, L. Deng, R. M. Pysar, Y. Gu, and H. Yu, "Performance characteristics of high-power light-emitting diodes," in *Proc. SPIE Third Int. Conf. on Solid State Lighting*, vol. 5187, San Diego, CA, 2003, pp. 267–275.
- [6] D. A. Steigerwald, J. C. Bhat, D. Collins, R. M. Fletcher, M. O. Holcomb, M. J. Ludowise, P. S. Martin, and S. Rudaz, "Illumination with solid state lighting technology," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 2, pp. 310–320, Mar./Apr. 2002.
- [7] D. L. Barton, M. Osinski, P. Perlin, C. J. Helms, and N. H. Berg, "Life tests and failure mechanisms of GaN/AlGaIn/InGaIn light emitting diodes," in *Proc. SPIE*, vol. 3279, San Jose, CA, 1998, pp. 17–27.
- [8] G. Meneghesso, S. Levada, E. Zanini, S. Podda, G. Mura, M. Vanzi, A. Cavallini, A. Castaldini, S. Du, and I. Eliashevich, "Failure modes and mechanisms of DC-aged GaN LEDs," *Phys. Stat. Sol. (a)*, vol. 194, no. 2, pp. 389–392, 2002.
- [9] F. Manyakhin, A. Kovalev, and A. E. Yunovich, "Aging mechanisms of InGaN/AlGaIn/GaN light emitting diodes operating at high currents," *MRS Internet J. Nitride Semicond. Res.*, vol. 3, p. 53, 1998.
- [10] N. Narendran, Y. Gu, J. P. Freyssinier, H. Yu, and L. Deng, "Solid-state lighting: failure analysis of white LEDs," *J. Cryst. Growth*, vol. 268, no. 3–4, pp. 449–456, Aug. 2004.
- [11] Y. Gu and N. Narendran, "A noncontact method for determining junction temperature of phosphor-converted white LEDs," in *Proc. SPIE Third Int. Conf. on Solid State Lighting*, vol. 5187, San Diego, CA, 2003, pp. 107–114.

Nadarajah Narendran received the Ph.D. degree in physics from the University of Rhode Island, Kingston, in 1991.

He joined the Lighting Research Center at Rensselaer Polytechnic Institute, Troy, NY, as a Research Associate Professor in 1996. Since 1998, he has been the Lighting Research Center's Director of Research, and since 2003, he is also an Associate Professor for Rensselaer's School of Architecture. His research interests include LED technology for lighting applications. He has authored or coauthored more than 50 articles in archival journals and proceedings.

Dr. Narendran is a Fellow of the Illuminating Engineering Society of North America and a member of the International Society for Optical Engineering.

Yimin Gu received the B.S. degree in electrical engineering from Shenyang Architecture and Civil Engineering Institute, Shenyang, China, in 1997, and the M.S. degree in lighting technique from Tongji University, Shanghai, China, in 2000. She also received the M.S. degree in lighting from the Lighting Research Center at Rensselaer Polytechnic Institute, Troy, NY, in 2003.

Following her M.S. degree in 2000, she joined the GE Asia Lighting Center, Shanghai, China, as a fixture designer. After graduation in 2003, she joined the Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY, as a research specialist. Her research focuses upon the degradation of LEDs and solid-state lighting applications.

Ms. Gu is a member of the Illuminating Engineering Society of North America and a member of the International Society for Optical Engineering.