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N. Narendran, L. Deng, R.M. Pysar, Y. Gu and H. Yu

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

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Performance Characteristics of High-Power Light-Emitting Diodes

N. Narendran, L. Deng, R.M. Pysar, Y. Gu, and H. Yu
Lighting Research Center
Rensselaer Polytechnic Institute, Troy, NY 12180

ABSTRACT

A laboratory experiment was conducted to investigate the performance characteristics of the currently available high-power LEDs under various drive conditions and ambient temperatures. Light output degradation and color shift properties as a function of time were measured for five types of commercial high-flux LEDs, namely, red, green, blue, and white from one manufacturer, and a different high-flux white LED package from a second manufacturer. The major difference between the two manufacturers' products is that the first uses a single LED die per package, and the second uses multiple dies within its package. LED arrays were tested under normal drive current and ambient temperature, normal drive current and higher ambient temperature, and higher drive current and normal ambient temperature. Because each LED type has to operate at a particular ambient temperature, all were tested in specially designed individual life-test chambers. These test chambers had two functions: one, to keep the ambient temperature constant, and two, to act as light-integrating boxes for measuring light output parameters. Overall, the single-die green and white LED arrays showed very little light loss after 2,000 hours, even though the current and the ambient temperature were increased. However, the red LED array seemed to have a high degradation rate. The white LEDs had a significant color variation (of the order of a 12-step MacAdam ellipse) between them. However, the color shift over time was very small during the initial 2,000-hour period. For white LEDs to be accepted broadly for general illumination applications, the color variation between similar products must become much smaller, of the order of a 2-step MacAdam ellipse.

Keywords: High-flux LED, white LED, degradation, lumen maintenance, color shift, junction temperature

1. INTRODUCTION

The light-emitting diode (LED) was first demonstrated in 1962.¹ Early LEDs produced radiation only in certain parts of the visible spectrum, and they were used primarily in indicator-lighting applications. Improvements in materials and crystal-growth techniques enabled the production of high-brightness LEDs, which were introduced in the early 1990s.² High-brightness LEDs produce almost 1,000 times more light output per package compared with the initial devices; however, this increased light output is only in the yellow to red part of the visible spectrum. Energy savings and the promise of reduced maintenance costs were the two main drivers that encouraged the use of high-brightness LEDs in applications such as EXIT signs, traffic signals, and other forms of displays. The thought of using LEDs for general illumination became a reality during the mid-1990s, when high-brightness blue LEDs were introduced into the marketplace.³ Since then, several manufacturers have introduced white-light LEDs. Early white LEDs were similar to other indicator LEDs, 5 mm, and surface mount device (SMD) packages. Although some early adopters of this technology demonstrated the use of indicator-type white LEDs in certain niche illumination applications, they were not suitable for general illumination applications mainly because of their small lumen package and high lumen depreciation.^{4,5} During the latter part of the 1990s, manufacturers began to produce high-power LED packages.^{6,7,8} High-power white LEDs are particularly of interest because of their larger lumen packages and greater luminous efficacy, making them better equipped to meet a variety of illumination needs. Compared with the early indicator-type white LEDs that produced one to two lumens per device, the newer high-power white LED packages produce ten to 100-plus lumens per device.⁹ Furthermore, some of these high-power white LEDs have luminous efficacy values greater than 20 lumens per watt. General illumination using LEDs looks more promising now than ever before because of the improvements made in high-power LED technology.

The two most common approaches for creating white light with LEDs are to 1) combine a short-wavelength LED with a single phosphor or multiple down-conversion phosphors, and 2) to mix monochromatic LEDs in appropriate proportions. Both techniques have advantages and disadvantages. The phosphor method produces a convenient,

integrated single-LED package. The mixing of colored LEDs has the potential to be much more efficient at creating white light because the down conversion process in the phosphor white LED causes light loss. However, creating a stable white light source using the mixed-color approach is complicated, since the light outputs of the different colored LEDs change as a function of time and temperature, and the peak wavelength shifts as a function of temperature.^{10, 11}

Original equipment manufacturers (OEMs) have started to produce light fixtures that use high-power LEDs. Although the high-power LEDs have an improved performance over previous types of LEDs, if the light fixtures are not properly designed, the overall performance can be poor. One major issue with high-power LEDs is that with increased light output, the amount of heat generated by the individual LEDs also increases. Therefore, when creating good light fixtures, it is extremely important to transfer the heat away from the LEDs in order to keep the LED junction temperature low. With increased junction temperature, the performance of LEDs can suffer.

Because of significant differences in performance among the various LED packages and different colored LEDs, a better understanding of how different LEDs perform under different circumstances is important. With this knowledge, LED fixture manufacturers can design more efficient and reliable systems. Therefore, the goal of this study was to investigate the performance characteristics of the currently available high-power LED devices under various drive conditions and ambient temperatures. The details of the experiment and the results are presented in this paper.

2. EXPERIMENT

This LED life-test study explored light output depreciation and color shift properties as a function of time for high-power LEDs. To start, five types of high-power LEDs—red, green, blue, and white from one manufacturer (Product 1), and a different high-power white LED package from a second manufacturer (Product 2)—were used in this study. The major difference between the two manufacturers' products is that the first uses a single LED die per package, and the second uses multiple dies within its package. LED arrays for each type were tested under three different operating conditions, for a total of 15 LED arrays. The single-die LED array consisted of six LEDs, and the multiple-die LED array consisted of two LEDs.

Typically, LED performance is affected by the drive current and by the ambient temperature surrounding the LED. Both of these parameters contribute to the junction temperature of the LED, which affects the performance. To understand how the different LED packages are affected by these parameters, the LED arrays were tested at three different operating conditions, namely, 350 mA drive current and 35°C ambient temperature, 350 mA drive current and 50°C ambient temperature, and 450 mA drive current and 35°C ambient temperature. The manufacturers' ratings for drive current are 350 mA and 300 mA for Product 1 and Product 2, respectively. These two ambient temperatures were chosen because the temperature within an enclosed high-flux LED fixture can be in the range of 35°C to 50°C, even if the room temperature is 25°C. Because each LED type has to operate at a particular ambient temperature, all were tested in specially designed individual life-test chambers. These test chambers had two functions: one, to keep the ambient temperature constant, and two, to act as light-integrating boxes for measuring light output parameters.

Figure 1a and Figure 1b illustrate the experimental setup. Fifteen life-test chambers, 9 in. by 9 in. (22.86 cm by 22.86 cm) square wood laminate, were assembled. All life-test chambers were placed inside a temperature-controlled room, as shown in Figure 2. The life-test chambers were staggered in both directions (vertically and horizontally) such that the heat rise from the bottom chambers did not affect the chambers above them.

The inside of each chamber was painted white with a matte finish. A 1 in. (2.54 cm) round aperture was cut into the front panel of each chamber and was fitted with a transparent glass so that spectral measurements could be recorded through this aperture. The aperture was covered with black fabric during the life-test experiment to keep external light from entering the box. Each chamber contained one LED array mounted inside at the center of the top surface. Although each LED package included a heat-sinking device, the top panel of the chamber was constructed from aluminum, 0.0625 in. (0.15875 cm) thick, to allow heat to be transferred off to the surrounding ambient external to the chamber. An integrated photodiode-amplifier, which continuously measured the light output (LO), was attached to the center of the left panel. A small baffle, painted white, buffered the direct light so that only the reflected light reached the photodiode. A resistance temperature detector (RTD) placed on top of the baffle, which is also located at the midpoint in the vertical

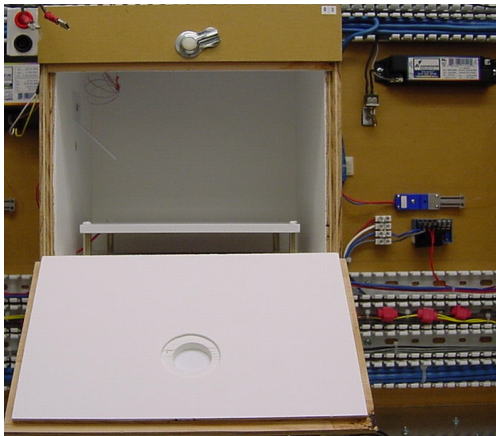


Figure 1a: Life-test setup.

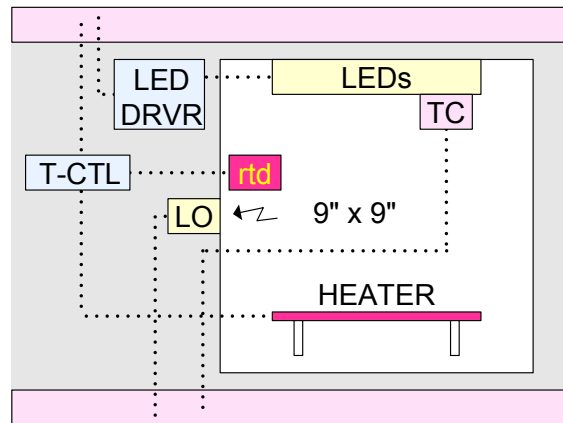


Figure 1b: Schematic of the experimental setup.

direction, measured the ambient temperature within the chamber and controlled the heater through the temperature controller (T-CTL). This ensured that the temperature inside the box remained constant (within $\pm 1^\circ\text{C}$). A small wooden shield blocked direct light from the RTD. The heater was attached to a raised aluminum plate with a matte-white cover that sat on the bottom of the chamber. To measure the LED board temperature, a 40-gauge wire thermocouple (TC, Type T) was soldered to the lead pin of one individual LED in the array. Previous tests showed that the board temperature was even for all LEDs in the array; therefore, the board temperature measurement of one LED could be used as the temperature for the entire array. Outside each chamber, an LED driver (a commercial product), controlled the current sent to the LEDs.

Additionally, when the life-test chambers were built, a small socket to hold a halogen light source was placed inside the top left of each chamber. The halogen light source was not used during the experiment, but it was used to calibrate the chamber, which also acts as a small integrating box for measuring spectrum and luminous flux. The integrating box was calibrated at regular intervals throughout the life test to ensure that the light output degradation was only from the LEDs



Figure 2: LED life-test laboratory.

and not due to degrading paint inside the box. Outside the chambers, two sensors measured the ambient temperature of the laboratory. A power meter measured the AC input power consumption (power, current, voltage, and power factor) of each LED driver. A computer-controlled data acquisition system (Agilent 34970A Data Acquisition/Switch Unit and LabView software) gathered six channels of information (light output, board temperature, voltage, current, power, and power factor) for each box. Data was acquired once every hour.

Initially, the LEDs were operated in their individual chambers for 500 hours. This initial seasoning was done because prior experiments in the laboratory showed that LEDs undergo rapid changes initially, probably due to annealing factors, and then undergo a steadier decline over time. After the 500-hour seasoning, each array was removed from its respective

chamber and tested in a 6 ft. (2 m) integrating sphere. There, the LEDs were powered by a standard power supply (Hewlett Packard 6675A). The system used for this initial light output measurement is accredited by the U.S. Department of Commerce National Institute of Standards and Technology [National Voluntary Laboratory Accreditation Program (NVLAP)]. The light output and electrical power measurements taken initially yielded the average luminous

flux per LED, the average luminous efficacy, and the chromaticity coordinates (CIE x,y values). These values benchmarked the initial performance of the LEDs and the LED arrays. The LED arrays then were returned to their respective life-test chambers for continuous measurement.

Prior to starting the life test and afterwards at regular time intervals (every 1,000 hours), spectral measurements of each individual LED on the array were taken within the box to measure the color shift of each individual LED over time. Measurements of individual LEDs were taken by covering the other LEDs in the array with black caps. A spectrometer aimed through the front aperture of the life-test chamber measured the SPD of the individual LEDs. As mentioned earlier, prior to taking the spectral measurements of the LEDs, the test chambers were calibrated using the halogen source.

3. RESULTS

Figure 3 illustrates the data from a previous life test started during the latter part of 2001 and which is still ongoing.¹⁰ Twelve high-power white LEDs have been operating continuously at the manufacturer-rated current and at room temperature for more than 18,000 hours. Figure 3 also shows the light output degradation of 5 mm-type white LEDs that were tested in the laboratory in 2001. As seen in Figure 3, the light output of the high-power white LEDs have degraded to 80% of their initial value in 18,000 hours. This is a significant improvement over the conventional 5 mm-type white LEDs, which reached the 80% value in approximately 1,000 hours.

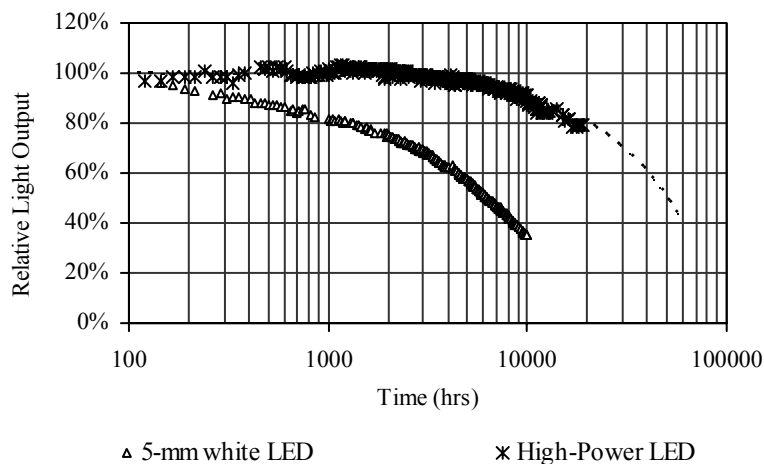


Figure 3: Light output change over time for high-power and 5mm white LEDs, measured from a previous life test.

Figure 4 illustrates the CIE x,y values of the twelve white LEDs measured at different points throughout their life tests. As seen in Figure 4, there is significant color variation between the LEDs, greater than the 12-step MacAdam ellipse. Usually, if the color variation exceeds the 4-step MacAdam ellipse, almost all people with normal color vision will perceive the color difference. As a comparison point, the color variation between similar linear fluorescent lamps that are presently available for general illumination (F32T8) is less than the 2-step MacAdam ellipse. Therefore, the color variation between similar white LEDs must become much smaller if they are to be accepted broadly for general illumination applications.

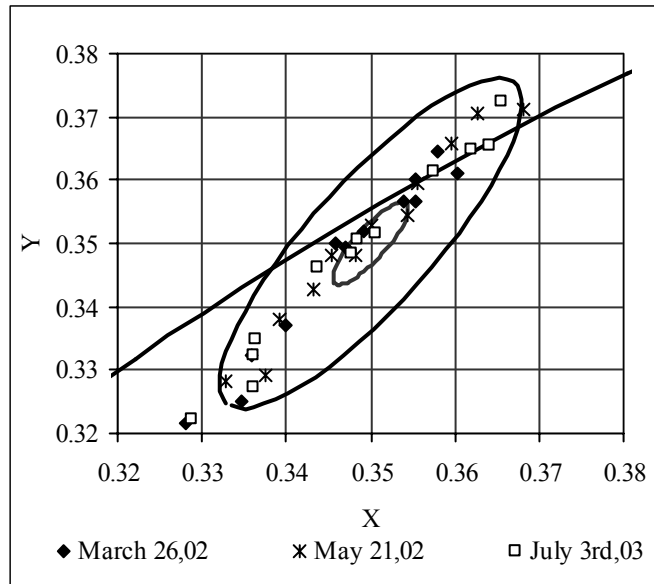


Figure 4: CIE x,y values of high-power white LEDs, measured at different times. The results are from an earlier life test that is still ongoing.

3.1 Present life-test results

Figure 5 illustrates the SPDs of the different high-flux colored LEDs and the white LEDs tested in this study. All three arrays of red and green LEDs had similar spectrums, with the peak wavelengths nominally at the same value. However, in the case of the blue LEDs, two of the arrays had similar spectrums, but one had a significantly different peak wavelength. The white LEDs, too, had dissimilar SPDs.

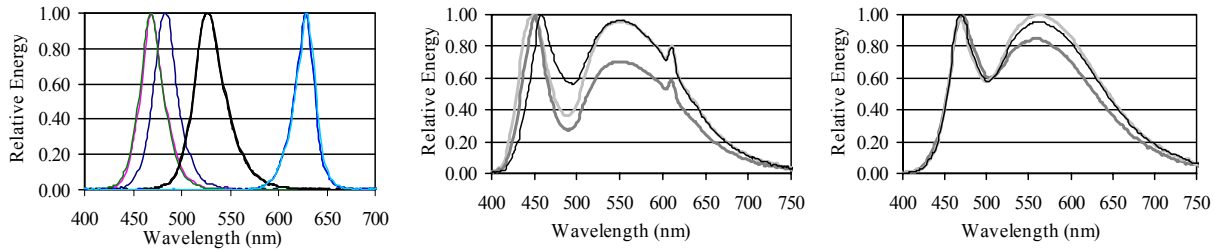


Figure 5: SPDs of the different colored LEDs and the two types of white LEDs tested in this study.

3.1.1 Lumen depreciation

Figure 6 illustrates the light output change as a function of time for the different LEDs at the three different operating conditions. At the first operating condition—350 mA and 35°C—one of the white LED arrays (white-2) and the red LED array had the highest light output loss, approximately 5% during the initial 2,000-hour period. The green and the other white LED (white-1) arrays had similar degradations, approximately 2%. However, the blue LED array showed increased light output during the first 1,000 hours before starting to reduce, and at 2,000 hours was still at the 100% level. Table 1 shows the average board temperatures and the corresponding junction temperatures of the different LEDs at the three operating conditions.

At the second operating condition—350 mA and 50°C—where the drive current was similar to the first condition but the ambient temperature was higher, the white-2, red, and blue LED arrays experienced approximately 16%, 10%, and 7% light loss, respectively, at the 2,000-hour point. However, the green and white-1 LED arrays experienced very little light

loss, less than 2%. As seen in Table 1, all of the LED arrays at this operating condition had the highest board temperatures, approximately 53°C, except for the white-2 LED array.

At the third operating condition—450 mA and 35°C—where the ambient temperature was similar to the first condition but the drive current was higher, the red and the white-2 LED arrays experienced light loss of approximately 15% and 8%, respectively. Once again, the green and white-1 LED arrays experienced very little light loss, less than 2%. The blue LED array showed increased light output during this initial 2,000-hour period. This particular blue LED array had a higher peak wavelength than the other two. Furthermore, this array had the highest junction temperature compared with the other two blue LED arrays, and yet showed better lumen maintenance up to this point.

Overall, the green and white-1 LED arrays showed very little light loss after 2,000 hours, even though the current and the ambient temperature were increased. The red LED arrays seem to have the highest overall degradation.

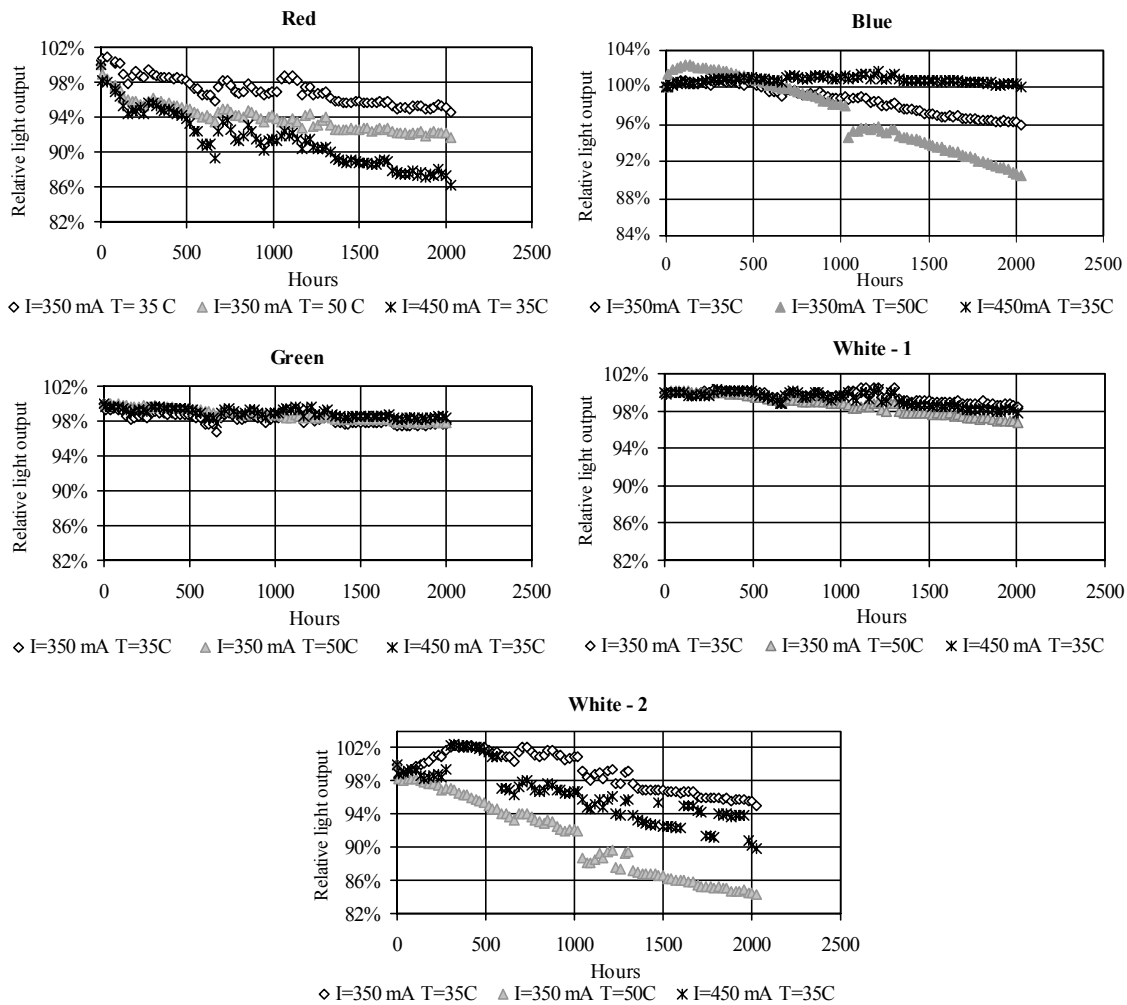


Figure 6: Relative light output change as a function of time for each LED type tested.

Table 1: Average board temperature and estimated junction temperature of each LED array tested.

| LED Type | Operating Condition | Measured Board Temperature °C | Estimated Junction Temperature °C |
|----------|---------------------|-------------------------------|-----------------------------------|
| Red | 350 mA, 35°C | 41.3 | 62.1 |
| Red | 350 mA, 50°C | 52.1 | 73.6 |
| Red | 450 mA, 35°C | 48.0 | 79.7 |
| Green | 350 mA, 35°C | 42.4 | 61.8 |
| Green | 350 mA, 50°C | 52.4 | 71.5 |
| Green | 450 mA, 35°C | 46.4 | 72.6 |
| Blue | 350 mA, 35°C | 43.8 | 64.6 |
| Blue | 350 mA, 50°C | 52.7 | 72.9 |
| Blue | 450 mA, 35°C | 49.8 | 75.3 |
| White 1 | 350 mA, 35°C | 42.9 | 62.8 |
| White 1 | 350 mA, 50°C | 53.2 | 73.9 |
| White 1 | 450 mA, 35°C | 48.2 | 76.5 |
| White 2 | 350 mA, 35°C | 52.2 | 76.6 |
| White 2 | 350 mA, 50°C | 58.3 | 82.4 |
| White 2 | 450 mA, 35°C | 72.8 | 107.6 |

3.1.2 Color Shift

Figure 7 illustrates the CIE x,y values of the individual white LEDs after 0, 1,000, and 2,000 hours. Similar to the previous life test, the white LEDs still had significant color variations (of the order of a 12-step MacAdam ellipse) between them. LEDs in the white-1 array showed more color variation between products compared with the LEDs in the white-2 array. However, as in the earlier study, the color shift over time was minimal during this initial 2,000-hour period.

4. DISCUSSION

A laboratory experiment was conducted to investigate the performance characteristics of the currently available high-power LEDs under various drive conditions and ambient temperatures. Light output degradation and color shift properties as a function of time were measured for five types of commercial high-flux LEDs, namely, red, green, blue, and white from one manufacturer, and a different high-flux white-LED package from a second manufacturer. The major difference between the two manufacturers' products is that the first uses a single LED die per package, and the second uses multiple dies within its package. LED arrays for each type were tested under three different operating conditions, for a total of 15 LED arrays. Because each LED type has to operate at a particular ambient temperature, all were tested in specially designed individual life-test chambers. These test chambers had two functions: one, to keep the ambient temperature constant, and two, to act as light-integrating boxes for measuring light output parameters. Overall, the single-die green and white LED arrays showed very little light loss after 2,000 hours, even when the current and the ambient temperature were increased much above normal operating conditions. However, the red LED array seemed to have a high degradation rate. Although the degradation rate appeared to increase with increasing junction temperature for most LEDs within each LED type, it is too early to generalize. Many previously published studies indicate that junction heat is one of the primary causes of LED degradation. It is worth noting here that for a given junction temperature, the degradation rate will be different for the different types of LEDs. As an example, the results from this study show that at a junction temperature around 70°C, the degradation rates for the white-1 and the green LEDs are similar and low; however, for the red and the blue LEDs, they are much higher.

The white LEDs had significant color variations (of the order of a 12-step MacAdam ellipse) between each individual LED. However, the color shift over time was very small. For white LEDs to be accepted broadly for general illumination applications, the color variation between similar products must become much smaller, of the order of a 2-step MacAdam ellipse, in order to match the performance of linear fluorescent lamps available at the present time. Until

manufacturing processes improve to provide consistent color between similar LEDs, color binning is one option for creating arrays with unnoticeable color variation.

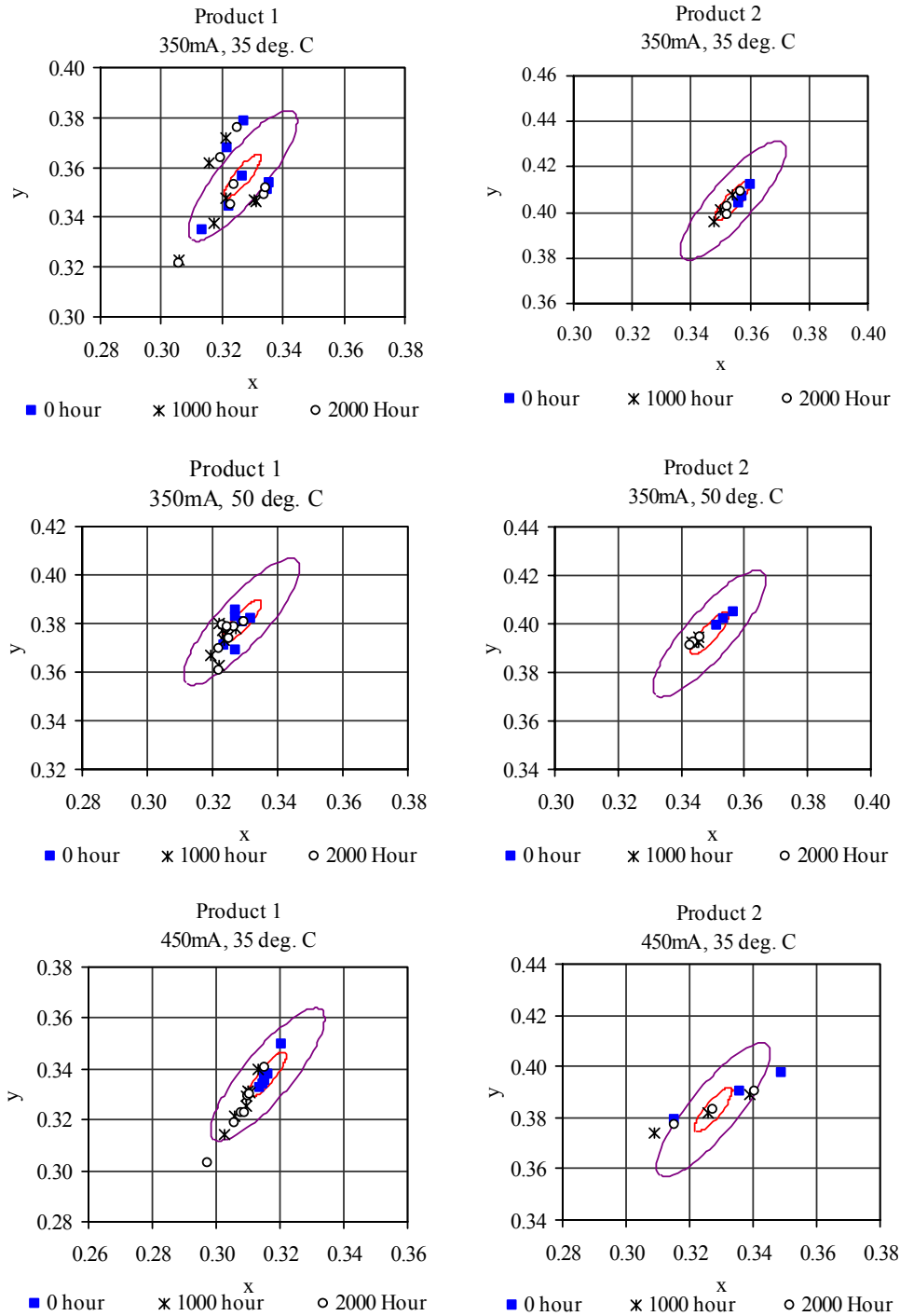


Figure 7: The CIE x,y values of the individual white LEDs after 0, 1,000, and 2,000 hours.

The drivers used in this experiment exhibited efficiencies in the range of 78% to 89%. During this initial 2,000-hour period, the power characteristics of the drivers did not change.

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