

IES Paper #52

What is Useful Life for White Light LEDs?

N. Narendran, J. D. Bullough, N. Maliyagoda, and A. Bierman

Lighting Research Center

Rensselaer Polytechnic Institute, Troy, NY 12180

Tel: (518) 687-7176; Fax (518) 687-7120

ABSTRACT

The goal of this paper is to initiate a discussion within the lighting community regarding standardized measurement procedures and a definition for useful life for light emitting diode (LED) technology. In general, LEDs do not fail catastrophically, but instead their light output slowly decreases over their operating period. Presently, some manufacturers use a 50% light output level as the criterion for LED life. Although 50% light loss might be acceptable for noncritical signage applications using monochromatic LEDs, it might not be acceptable for general lighting applications. It is important to develop a method for rating lamp life and a definition of "useful life" for LEDs so that when reported by manufacturers, the lighting community can compare LEDs to traditional light sources. The "useful life" definition for LEDs should consider light loss and color shift. Therefore, an experimental study was conducted to investigate light loss and color shift patterns of white LEDs as a function of operating time. The 5-mm type white InGaN +YAG LEDs evaluated in this experiment, representing technology commercially available in 1999, exhibited high light output degradation rates and color shifts as a function of operating time. It is further shown that using a simple mathematical fit to the data gathered during a short life-test study, and extrapolating it to predict the life of white LEDs, depends on the initial data collection period. Therefore, an alternate method for projecting LED life is investigated by overdriving the LEDs at different currents. Using their degradation patterns at higher drive currents, the life of these LEDs was predicted at normal drive current values. The results show excellent correlations between predicted light loss and actual measured losses at 20 and 30 mA drive currents for the LEDs tested. The authors believe that this technique is applicable for accurately predicting life of any type of LED and hope to verify this using future configurations. This study adds information to the knowledge needed for the lighting community to develop standardized measurement procedures and a definition for useful life for LED technology.

INTRODUCTION

Light emitting diodes (LEDs) were first developed over three decades ago. Most of the early LEDs were narrow wavelength band emitters with light output predominantly in the red to yellow region. During the 1990s Nakamura and colleagues (1994, 1997, 1998, 1999) demonstrated a blue LED based on gallium nitride (GaN). The development of the blue LED made the creation of the broad band white LED possible. Presently, white light is generated by combining the GaN-based blue LED and $Y_3Al_5O_{12}$ (yttrium aluminum garnet or YAG) phosphor or by grouping red, green and blue LEDs in the correct proportions. *[Refer to Stringfellow and Craford (1997) for an in-depth discussion of LED technology.]*

The potential for significant energy savings and the potential for long life are the two major factors that have attracted this technology to the general lighting community. Over the past few years the technology has advanced significantly and some white LEDs presently available in the marketplace are rated at 10 to 15 lumens per watt (lm/W). White-light LEDs are among the first signs of an evolving solid-state technology for architectural lighting applications. Many industry experts are optimistic that solid-state technology will revolutionize the architectural lighting industry. Although luminous efficacies have been steadily growing for these LEDs, the amount of light generated by a single device is still low, usually under 1 lm. Manufacturers are actively working towards developing larger light output LED devices. Some of the methods presently used for achieving this goal include, grouping several smaller LED devices together, increasing the size of the semiconductor device, enabling the device to be driven at higher drive currents, and improving the light extraction efficiencies by shaping or modifying the emitting surfaces of the semiconductor device to prevent the light from being trapped within the cavity by total internal reflection (Ochiai-Holcomb *et al.*, 2000; Windisch *et al.*, 2000).

The development of LED technology is fueled by the electronics industry, and as a result, the advances of this technology have been much faster than most lighting technologies. In anticipation of its widespread use for architectural lighting applications, many original equipment manufacturers (OEMs) have begun to develop light sources using white LEDs for the marketplace. Developing a new light source for general lighting and achieving high levels of application depends upon industry's success at standardizing product performance and at designing cost-effective products that reliably produce light of acceptable color. Other promising lighting technologies,

including compact fluorescent lamps, fiber optics, and certain types of electrodeless lamps, have not achieved high levels of success because of failures in these areas.

LIGHT SOURCES FOR GENERAL LIGHTING APPLICATIONS

Current trends in the lighting industry for new light sources and luminaires are toward smaller, more energy efficient, and longer life lamps. LEDs have the potential to meet these requirements. Therefore, they are well suited to be developed as a viable light source for the lighting industry. At present there is a fair amount of enthusiasm within the LED industry for developing a light source that could replace incandescent, and perhaps some fluorescent lamps. For LEDs to directly compete with any of these technologies for a given application they have to meet characteristics of the target light sources in all areas. For example, amber LEDs, even with high luminous efficacies of 100 lm/W cannot compete with fluorescent lamps in all applications where fluorescent lamps are used, because luminous efficacy is not the only parameter that makes a fluorescent lamp suitable for an application. Table 1 summarizes key characteristics of some commonly used light sources. The importance of any of the parameters listed in Table 1 varies widely depending on the application. In residential applications, cost, color, and lumen output might be most important, which makes the incandescent lamp a viable choice. In commercial spaces, lumen output, color, and lamp life might be most important, making linear fluorescent lamps a good choice. Usually, lighting specifiers consider all of the requirements of the target application in this way when selecting light sources.

Lamp	Lumens	Lamp efficacy (lm/W)	CCT (K)	CRI	Cost (\$, including ballast if needed)	Lamp life (hr)
Incandescent (100W A-lamp)	1680	17	2800	100	\$1.36	1000
Halogen (100W T4)	2500	25	3200	100	\$9.90	2000
Linear fluorescent (F32T8)	2900	90	3000	73	\$3.10 lamp + \$29.00 ballast	20,000
Compact fluorescent (20W screwbase)	1380	69	2700	82	\$8.40	10,000
Metal halide (400W)	36,000	90	3800	70	\$49.25 lamp + \$109.00 ballast	15,000
Mercury (400W)	23,000	58	3600	49	\$32.75 lamp + \$106.00 ballast	24,000
High pressure sodium (400W)	50,000	125	2100	22	\$76.00 lamp + \$208.00 ballast	24,000

Table 1. Lamp performance data from *IESNA Lighting Handbook: Reference and Application, 9th edition (2000)*. Lamp cost data from *Means Electrical Cost Data, 21st edition (1998)*.

Presently there are standard definitions and established methods for measuring most of the parameters listed in Table 1. However, of all the parameters, rated life for lamps is one of the most difficult to describe. The goal of this paper is to initiate a discussion within the lighting community regarding standardized measurement procedures and definitions for useful life for LED technology.

The glossary section of the *IESNA Lighting Handbook (2000)* does not carry a term called lamp life, but most lamp manufacturers define lamp life as the time at which 50% of the test samples have burned out (GE Lighting, 1999; OSRAM SYLVANIA Inc., 1998; Philips Lighting Company, 1999; Venture Lighting, 1995). Although the rated life definition is same, the measurement method varies depending on the lamp technology. For incandescent technology, lamps are operated continuously at a constant voltage until 50% of the lamps fail. Incandescent lamps may be tested at rated voltage or at overvoltage conditions. Fluorescent lamps are operated under controlled conditions on a continuous 3-hr-on/20-min-off cycle; high intensity discharge lamps are operated on a continuous 11-hr-on/1-hr-off cycle. Shorter operating cycles will shorten lamp life of most discharge lamps (IESNA, 2000). One of the commonly raised questions is, "How does rated lamp life relate to the life of a light source in a particular application?" Ultimately, it is the useful life in application that matters to end-users. However,

at the present time it is the rated life that is commonly used in computing life-cycle cost and in comparing among light sources.

With certain types of metal halide lamps, the application community and manufacturers use a definition called “*econo life*” or “*useful life*,” which is typically used for group relamping. The main reason is that the light output of metal halide lamps decreases, and their color shifts as a function of operating time. Although the term rated life for these metal halide lamps denotes the time at which 50% of the lamps would have ceased to operate (under standard testing conditions), their resulting “useful life” is about 60% to 70% of their rated life owing to high lumen depreciation and to color shifts. For example, a metal halide lamp rated at 10,000 hours (hr) may have about 6000 hr of useful life. At this point, such a lamp produces about 70% of its initial light output. Manufacturers recommend the useful life as the time for group relamping of metal halide lamps in certain applications (Venture Lighting, 1995).

Thus, rated lamp life provides only partial information when comparing light source performance. One has to look at other factors such as lumen depreciation and color shift over the operating period of a light source and define a useful life for the product. Table 2 shows the rated lamp life and lumen maintenance values of various light sources commonly used in architectural lighting applications. For all of these technologies, 35% light loss seems to be the worst case at end of life.

Light source	Rated life	Lumen maintenance @ 50% rated life	Lumen maintenance @ 100% rated life
Incandescent	1000	90%	78%
Tungsten-halogen	2000	97%	93%
Fluorescent (medium loading)	20,000	85%	75%
Mercury	24,000	75%	65%
Metal halide	15,000	80%	65%
High pressure sodium	24,000	90%	72%

Table 2. Life and lumen maintenance data adapted from IESNA Lighting Handbook: Reference and Application, 9th edition (2000).

LEDS FOR GENERAL LIGHTING

A commonly claimed advantage of LED light source technology is its long lamp life: 50,000 to 100,000 hr. These long life numbers first originated from AlGaInP red and yellow LED technology. In general, LEDs do not fail catastrophically, but instead their light output slowly decreases with operating time. It is not practical to monitor light output for the long time periods estimated by manufacturers. Therefore, the current practice by LED manufacturers is to measure the light output for a certain number of hours, such as 5000 hr, and then to use a mathematical fit to extrapolate data to some percentage of its initial value. A 50% light output level might be considered the life of the LED. Manufacturers estimate that AlGaInP LEDs and blue and green InGaN LEDs produce over 70% of their initial light output at 100,000 hr (Evans, 1997). At the present time there is a perceived opinion within the lighting industry that all commercially available LEDs, including white LEDs, have similar light output characteristics as AlGaInP and other InGaN LEDs throughout their life. In an earlier set of measurements, tests of 5-mm type white light LEDs showed high lumen depreciation rates, lasting only about 6000 hr before their light output levels reached 50% of initial values (Narendran et al., 2000).

Although 50% light loss might be acceptable for many noncritical signage applications using monochromatic LEDs, it might not be an acceptable criterion for general lighting applications. As an example, if the lighting in a conference room is designed for 500 lx on the table top, 250 lx might not be considered an acceptable illuminance when the light source is at its end of life. It was mentioned earlier that with certain type of metal halide lamps, at the end of useful life the light loss was around 30%. It was also observed in Table 2 that at 100% of rated life, the light loss was 35% or less for all lamps.

White light LEDs are new to the lighting industry and therefore, at present there is no standard procedure for rating LED life for lighting applications. Since white LEDs have light loss characteristics similar to some metal halide lamps (Narendran et al., 2000), LEDs may too need a “useful life” definition. It is important for the LED light source community to develop a preliminary methodology for rating lamp life and a definition for “useful life” for LEDs. Thus, when life values are reported by manufacturers, the lighting community can compare LEDs to other sources and develop uses of this technology for practical lighting applications. Currently, sufficient information regarding the photometric performance of these LEDs is not available in order to develop a good definition. Therefore, an experimental study was conducted to understand how light output and color of these white light LEDs

change with operating time. This study will add to the knowledge needed for the lighting community to develop standardized measurement procedures and a definition for useful life for LED technology.

In the future, white light LEDs might have much longer rated life and it might not be practical to gather data for long periods of time. Therefore, it is also important to identify ways to predict LED lumen depreciation with some form of rapid life testing. This paper describes an accelerated life test method that can be effectively utilized for predicting lumen depreciation of white LEDs. The details of the experimental setup, data, and the analysis method are presented in this paper.

EXPERIMENT

The experimental study described in this section is a continuation of the experiment presented in an earlier paper (Narendran *et al.*, 2000) using white LEDs. In that earlier study, LED samples tested came from a single manufacturing batch. However, the white LEDs used in this experiment were obtained from two different manufacturers and in one case the LEDs came from two different manufacturing batches, early 1999 and mid-1999. The LEDs investigated in this study were the 5-mm type using InGaN technology with a YAG phosphor, the only type of white LEDs commercially available when the experiment was conducted (in 1999).

The LEDs were mounted on printed circuit boards with current-regulating circuits mounted behind the boards. The current in each LED was individually controlled by a separate circuit. Each board carried ten LEDs. All together, seven boards were used in this study, six containing white LEDs and one containing red LEDs (also 5-mm type). Three of the boards containing the white LEDs were driven at 20 mA dc current and the other three were driven at 50 mA dc current. The red LEDs were driven at 20 mA dc current and were used as controls in this study, since they have well documented light output depreciation curves (Evans, 1997).

Lumen Depreciation Measurement

The experimental setup used for measuring light output as a function of time is shown in Figure 1. The imaging setup used in this study ensured that the surrounding environment of the LEDs was not disturbed while gathering light output information. All circuit boards were mounted on a common mounting plate, and the system was driven by a regulated power supply at 12 V dc. The mounting plate with the LED circuit boards was placed vertically in front of an optically diffuse glass plate, and a CCD camera was placed on the opposite side as shown in Figure 1. Images of the LEDs through the diffuse glass were captured at regular intervals, and the software associated with the camera estimated the relative luminance associated with each individual LED. The diffuse glass served to reduce the luminance of the bare LEDs and to make the luminance more uniform, both spatially and directionally. This arrangement lessened sensitivity to vibration and misalignment. A thermocouple placed near the white LEDs monitored the temperature, which was in the range $25^{\circ}\text{C} \pm 2^{\circ}\text{C}$ throughout the experiment. A second thermocouple monitored the temperature near the red LEDs, which were placed at a higher location; the temperature near these LEDs was in the range $50^{\circ}\text{C} \pm 5^{\circ}\text{C}$ throughout the experiment.

Figure 2 illustrates the mean light output value of the ten LEDs on each board for the seven boards. All light output values are normalized to their values at 100 hr. As observed in the previous study, the light output of the white LEDs depreciated much faster than the red LEDs even though they were driven at the 20-mA value, recommended by the manufacturers. The light output depreciation rate of the red LEDs matches data published in literature (Evans, 1997). The three groups of white LEDs driven at 20 mA dc track each other closely and are between 70% and 85% of their initial light output value at 3000 hr. Similarly, the other white LEDs driven at 50 mA dc are between 30% and 40% of their initial light output value at 3000 hr and they too track each other closely. The light output of the red LED depreciated only 5% at 3000 hr. It should be noted that the temperature environment near the red LEDs was around 50°C , higher than the environment surrounding the white LEDs. Since the red LED data match other published data (taken at 55°C per Evans [1997]), it is inferred that the setup used in this experimental investigation is appropriate for studying the relative light output depreciation of LEDs. *Furthermore, the data confirm the findings of the earlier study (Narendran et al., 2000) which found similarly-configured white LEDs to have high light output degradation rates under the test conditions used.* Using a 50% light output criterion as the definition of life, the white LEDs tested in this experiment would be expected to have life values less than 10,000 hr, much lower than the 100,000 hour figure commonly suggested. One of the reported causes for this rapid decrease in light output is the degradation of the epoxy encapsulant and the phosphor due to excess heat (Wierer *et al.*, 2000). In a recent publication it was mentioned that such light losses would be recoverable by removing the semiconductor die from its original epoxy encapsulant and repackaging it in a new epoxy encapsulant heat (Wierer *et al.*, 2000). Manufacturers are currently working on improving reliability by devising better heat sinking methods to extract the heat from the semiconductor element that seems to cause most of the damage.

Projecting Life Data

Figure 3 illustrates the relative light output degradation curve for a 5-mm type white LED driven at 20 mA. Figure 3a shows the data gathered up to 2000 hr, and the projected life of the LED, defined here as 50% light output. In this plot two different functional forms of best-fit curves, namely logarithmic and linear, are utilized to project the life at 50% light output. As it can be seen in Figure 3a, the projected life values using the two functions are significantly different. The logarithmic fit estimates 100,000 hr whereas the linear fit estimates 4500 hr. Figures 3b and 3c illustrate similar information, except that the initial data gathering periods are extended to 3000 and 5000 hr. Once again similar trends are observed for the two extrapolations. It is interesting to see from these plots that the logarithmic best-fit projections for the LED life at 50% are 100,000, 50,000 and 20,000 hr from the initial data collection periods of 2000, 3000 and 5000 hr, respectively. Likewise, the linear fit projections are 4,500, 5,000 and 6,000 hr for the initial data collection periods 2000, 3000 and 5000 hr, respectively. It appears that the logarithmic fit is not a good fit for extrapolating data for the type of white light LEDs used in this study. In both cases, the projected life depends on the initial data collection period. *It should be noted that mathematical functions other than simple linear and logarithmic fits might be more appropriate for more correctly modeling life performance. Future work to understand the mechanisms of light output degradation should be continued.*

Accelerated Life Test

A valid next question relates to the proper mathematical function to use, and the proper initial data collection period, for extrapolation of life data. A fundamental understanding of all the degradation mechanisms, including, the diode, epoxy, lead wire and phosphor, and development of a mathematical model of these mechanisms would be the best choice. The mathematical model may vary from product to product depending upon packaging. Concerns exist that LED packages with poor heat transferring properties will negatively affect product performance and reliability (DeJule, 1999). *Furthermore, LEDs operated at higher currents will generate more heat. Because of these effects, it seems reasonable to test the hypothesis that the relatively rapid light output degradation at higher operating currents could be used to model, mathematically, the light output degradation at normal operating currents.* Such a method is analogous to testing incandescent lamps at overvoltage conditions.

Figure 4 illustrates light output degradation curves for the white LEDs used in this study, when overdriven at constant currents of 50, 70, 90, and 110 mA. The data shown in Figure 4 are adapted from Narendran *et al.* (2000). Figure 4 illustrates best-fit exponential curves, and their respective correlation coefficients. It should be noted that the data used here are limited to the first 2000 hr; not all LEDs have data for the entire period. The LEDs driven at very high currents depreciated to 20% light output within a short time, and from then on, maintained a small amount of light. For these cases, the data are taken up to the 20% light output value. Table 3 summarizes the equations of the best fit and the corresponding correlation coefficients for each drive current. As seen in Table 3, the correlation coefficients are very high. The light output degradation curves follow an exponential decay with time, given by:

$$y = e^{-\alpha t} \quad (1)$$

where y represents the relative light output, α represents the decay constant, and t represents the time in hr. Figure 5 illustrates a plot of the decay constants, α , for these curves versus drive current. Once again, fitting an exponential curve here results in a very high correlation coefficient of 0.99, indicating an exponential relationship between decay constant, α , and drive current. The equation that relates these two quantities for the LEDs tested in this study is given by:

$$\alpha = 5 \times 10^{-5} e^{(0.0375) I} \quad (2)$$

where I denotes the drive current in mA. Using equation 2, decay constant values, α , for 20 and 30 mA were determined, and these values are summarized in Table 4. Substituting the α values determined for 20 and 30 mA, into equation (1), the relative light output degradation at 20 and 30 mA are predicted. Figure 6 illustrates the predicted data and the actual data gathered at 20 and 30 mA. From Figure 6 it can be seen that the predicted data match fairly well with the actual data gathered at 20 and 30 mA. The actual data for light output degradation at these two drive current values seem to oscillate somewhat about the general trend, perhaps owing to temperature fluctuations in the room. Overall, the accelerated life test method seems to work well for the type of LEDs used in this experiment. The authors believe that this technique should work well for any type of LED or LED system and would provide a better estimate for the life of LEDs than simply using a mathematical fit to extrapolate data taken at

normal drive currents. Further tests should be conducted with other LED packages and configurations to validate this belief.

Drive Current (mA)	Fit Equation	R ²
50	$y = e^{-0.0004 t}$	0.99
70	$y = e^{-0.0008 t}$	0.99
90	$y = e^{-0.0014 t}$	0.99
110	$y = e^{-0.0029 t}$	0.84

Table 3: Summary of the equations of the best-fit and the corresponding correlation coefficients for each drive current.

Drive Current, I, (mA)	α
20	0.000106
30	0.000154

Table 4: Summary of the exponent values for 20 and 30 mA determined from equation 2.

Color Shift Measurement

A spectrum analyzer with an optical fiber probe attached to it was utilized to measure the color variations among individual white LEDs. Figure 7 illustrates the CIE x,y chromaticity values of ten white light LEDs when driven at 20-mA constant current. Figure 8 illustrates the chromaticity shift as a function of time for these LEDs. The four data points corresponding to each LED in Figure 8 represent time, which increase from left to right. The time values are 0, 32, 768, and 1128 hours. Data is shown only for five LEDs to make the graph more legible in Figure 8. The other five LEDs behaved very similarly. A 3-step MacAdam ellipse (*MacAdam, 1942*) (thought to represent color differences visible by 99% of observers) is drawn on the same figure for comparison. From Figure 7 it can be seen that the color variations among similar LEDs are significant, on the order of 10 to 12 MacAdam ellipses. Likewise, from Figure 8 it can be seen that there is color shift as a function of time. These *preliminary* data are currently not sufficient to conclude precisely how much color shift there would be as a function of time, but they indicate the degree of differences that can be found among white light LEDs from the same manufacturing batch and at different points during their lives. Further research is needed to quantify the overall color shift over the life of the LED. In any event, color variations among similar LEDs can be high at the present time and would most likely need to be tighter if they are to be used in indoor lighting applications where the light source or reflections of it will be directly visible to the observer. The degree of color variation that is acceptable among light sources depends very much on the target application. Previous research by Narendran *et al.* (1999) shows a systematic study that evaluates the perceivable color difference between similar light sources in certain applications.

SUMMARY

This paper lays out a framework for discussing a useful definition of life for LED lighting technology. Both lumen depreciation and color shift are important parameters needed for defining the “useful life” of LEDs for general lighting applications. The results of our experimental study confirm the findings of an earlier study that 5-mm type of white LEDs have high degradation rates and would be expected to have life values less than 10,000 hr, much lower than the 100,000-hr figure popularly suggested. It is further shown that using a simple mathematical fit to data gathered during a short life test study, and extrapolating it to project the life of white LEDs, depends upon the initial data collection period. Therefore, an alternate method for projecting LED life is investigated by overdriving the LEDs at different rates. Using their degradation patterns at higher drive currents, the life of these LEDs is closely predicted at normal drive current values. The results show excellent correlations between predicted light losses and actual data at 20 and 30 mA drive currents for the white LEDs that were tested. The authors believe that this technique is applicable for accurately predicting life of any type of LED and hope to verify this using future LED configurations. The color variations among similar white LEDs are significant, and further research is needed to quantify the overall color shift over the life of the LED.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Lighting Research Center (LRC). Richard Pysar and Martin Overington of the LRC developed the experimental apparatus. Review of the manuscript by Victor Roberts of the LRC is also gratefully acknowledged.

REFERENCES

- DeJule, B. "White LEDs: A better light bulb?" *Semiconductor International*, May, 1999.
- Evans, D., "High luminance LEDs replace incandescent lamps in new applications," *SPIE*, Vol. 3002, 1997.
- General Electric Lighting, *Lamp Products Catalog*, 1999.
- Illuminating Engineering Society of North America, *Lighting Handbook: Reference and application*, 9th Edition (M. S. Rea, editor), New York: Illumination Society of North America, 2000.
- MacAdam, D. L. "Visual sensitivities to color difference in daylight." *Journal of the Optical Society* 32, 247-274, 1942.
- Means, R. S., Inc., *Means Electrical Cost Data*, Kingston, R. S. Means, Inc., 1998.
- Nakamura, S. "Progress with GaN-based blue/green LEDs and bluish-purple semiconductor LEDs," *Photonics and Communications in Japan*, Part 2, Vol. 81, No. 5, 1998.
- Nakamura, S. and G. Fasol, *The Blue Laser Diode*, Springer-Verlag Berlin, Heidelberg New York, 1997.
- Nakamura, S., "InGaN-based blue light-emitting diodes and laser diodes," *Journal of Crystal Growth*, 201/202: 1999.
- Nakamura, S., T. Mukai, M. Senoh, "Candela-class high brightness InGaN/AlGaIn double-heterostructure blue-light-emitting-diodes," *Appl. Phys. Lett.* 64, 1994.
- Narendran, N., Maliyagoda, N., Bierman, A., Pysar, R., and Overington, M., "Characterizing White LEDs for General Illumination Applications", *SPIE Proceedings*, Vol. 3950, 2000.
- Narendran, N., Vasconez, S., Boyce, P., and Eklund, N., "Just-Perceivable Color Differences between Similar Light Sources in Display Lighting Applications," *IESNA Annual Conference Proceedings*, August 1999.
- Ochiai-Holcomb, M. *et al.*, "High-power truncated-inverted-pyramid (Al_xGa_{1-x})_{0.5}n_{0.5}P light emitting diodes," *SPIE Proceedings*, Vol. 3950, 2000.
- OSRAM SYLVANIA INC., *Lamp and Ballast Catalog*, 1998.
- Philips Lighting Company, *Lamp Specification and Application Guide*, 1999.
- Stringfellow, G. B. and M. G. Craford (eds.), *High-Brightness Light Emitting Diodes*, San Diego, Academic Press, 1997.
- Venture Lighting, *The Metal Halide Specification Book*, Venture Lighting, 1995.
- Wierer, J. J. *et al.*, "High-brightness AlGaInN light-emitting diodes," *SPIE Proceedings*, Vol. 3950, 2000.
- Windisch, R. *et al.*, "Non-resonant cavity light emitting diodes," *SPIE Proceedings*, Vol. 3950, 2000.

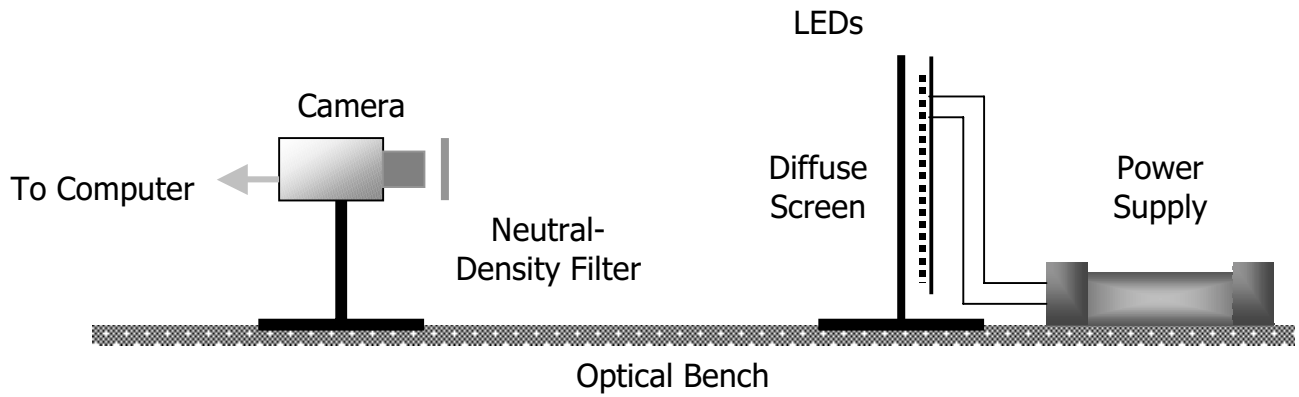


Figure 1. Life test experimental setup.

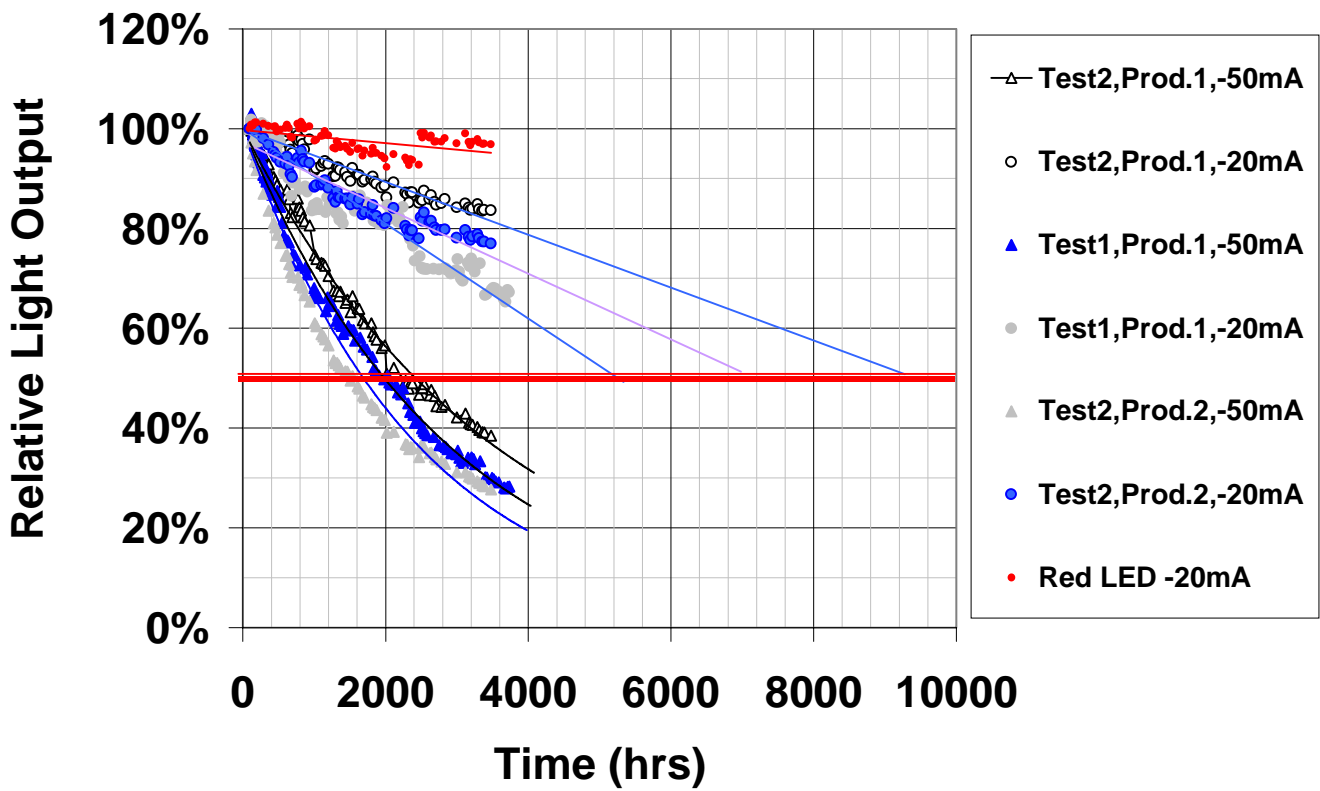


Figure 2: Relative light output variation as a function of operating time

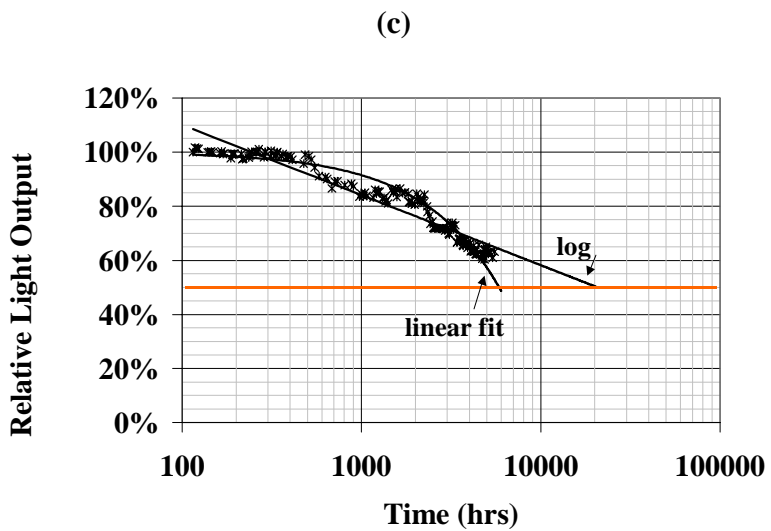
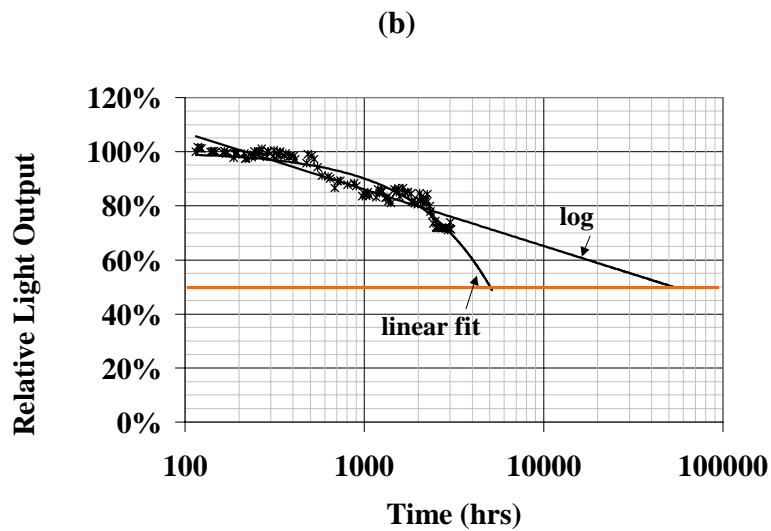
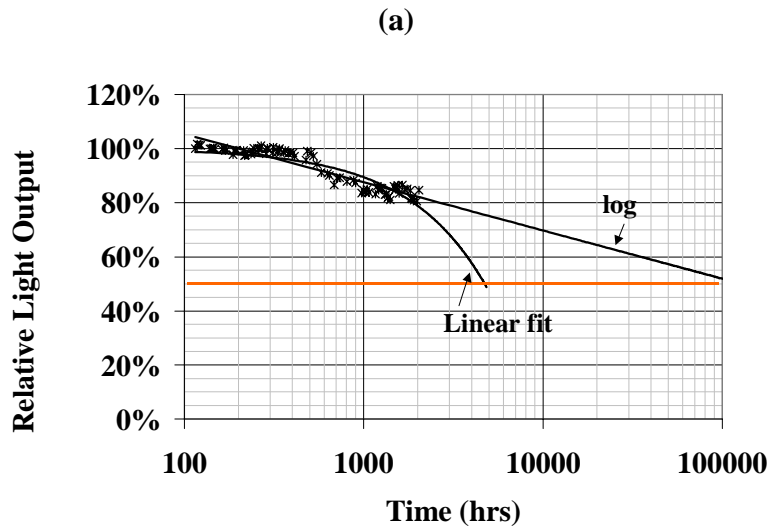


Figure 3: Extrapolating data to obtain life at 50% light output using two different mathematics fits, logarithmic and linear after collecting data for a) 2000 hours; b) 3000 hours; c) 5000 hours

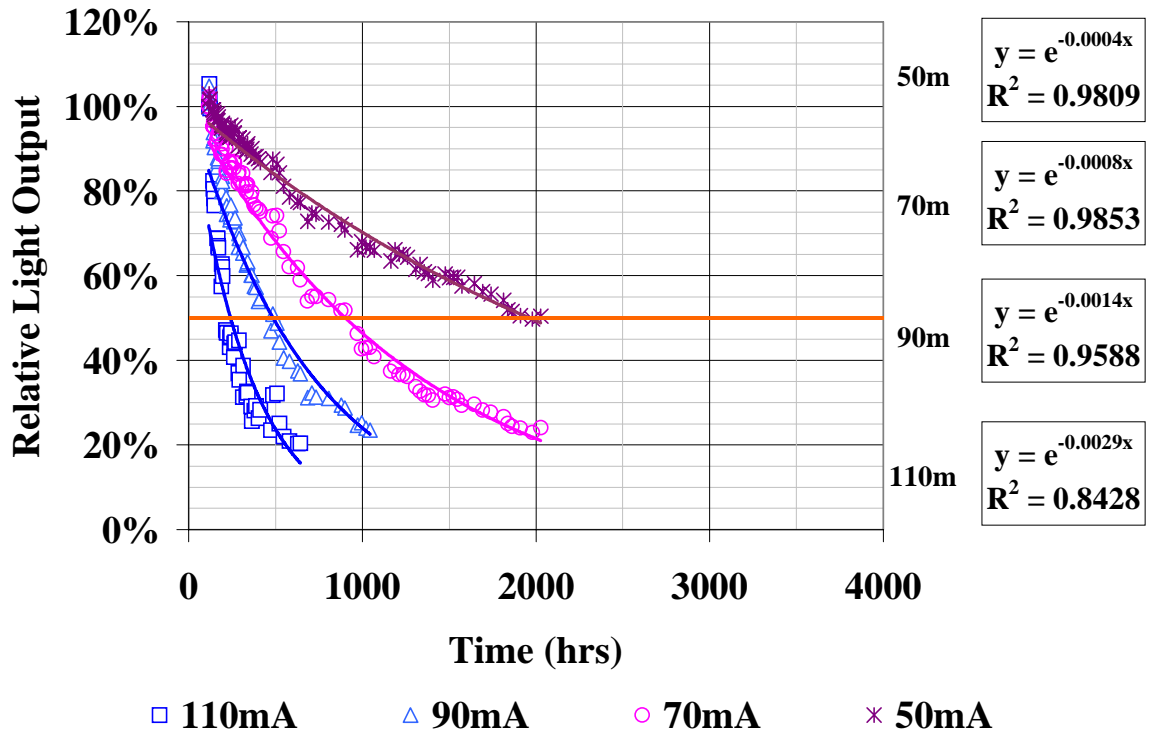


Figure 4: Relative light output variation as a function of time for different drive currents

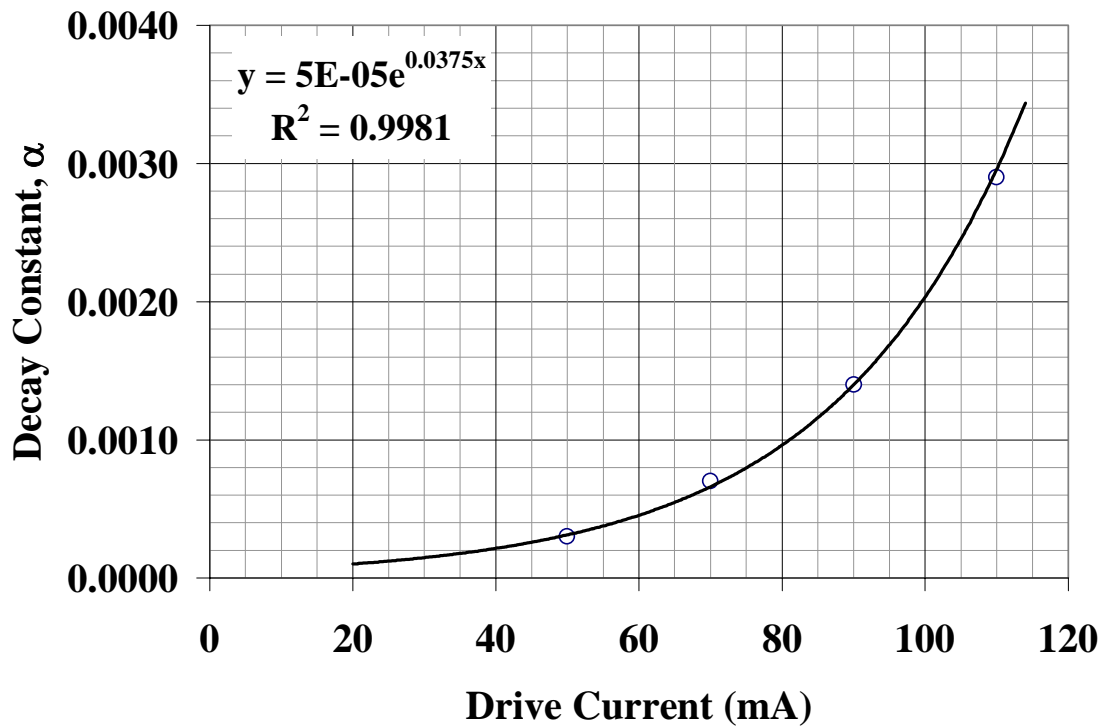


Figure 5: Plot of decay constant versus drive current

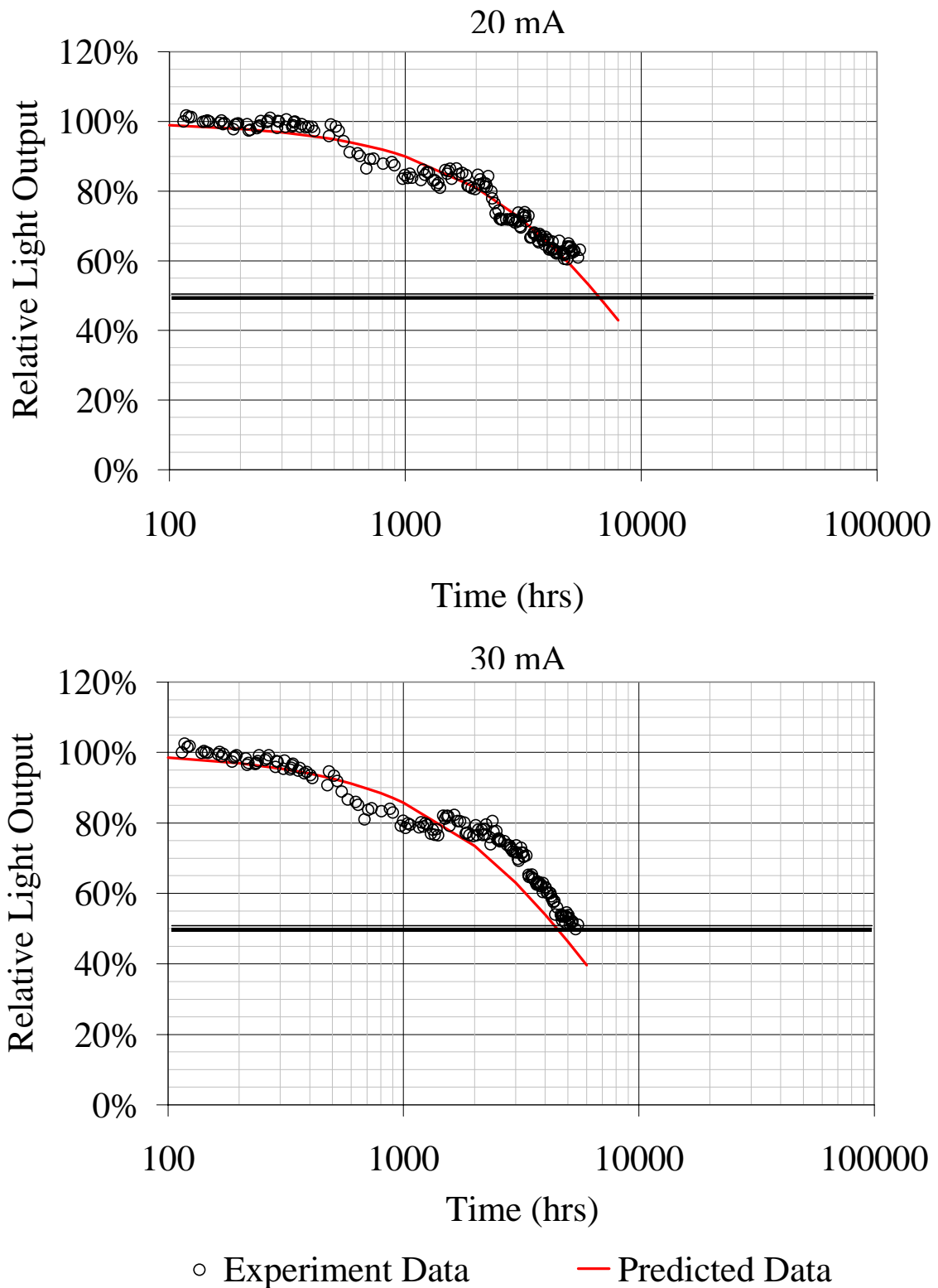


Figure 6: Comparison of predicted light output and experimental data at 20 mA and 30mA drive currents.

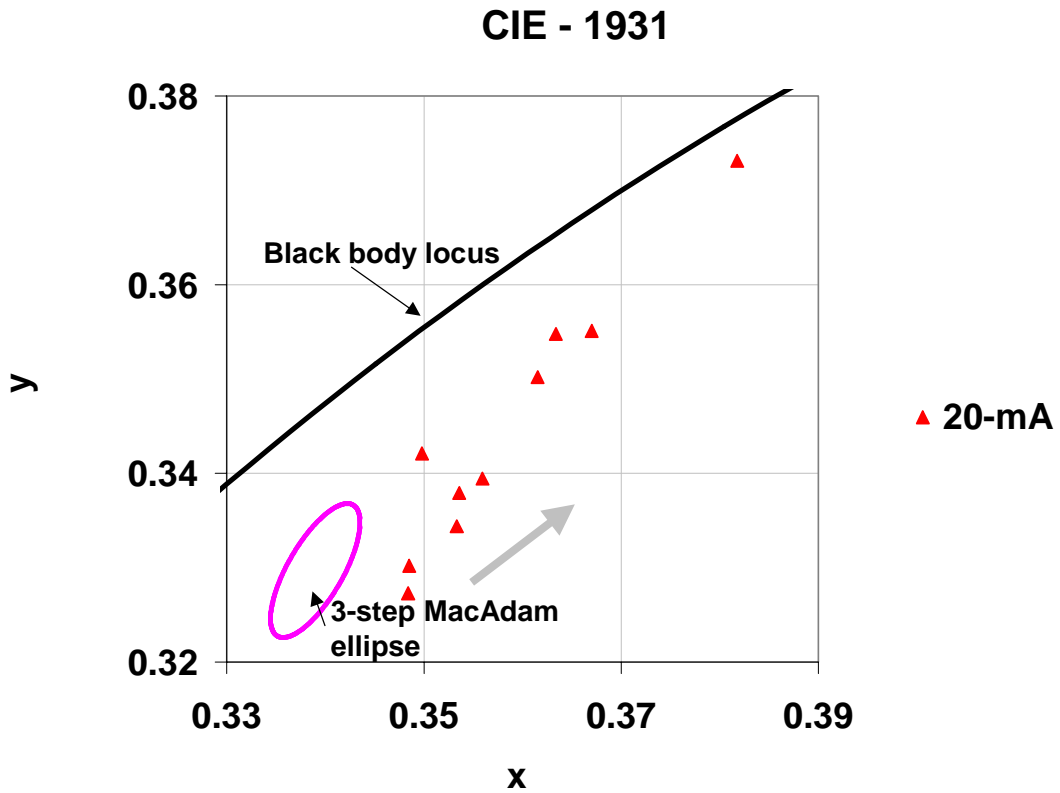


Figure 7: Color variation between ten similar white LEDs at 20 mA drive

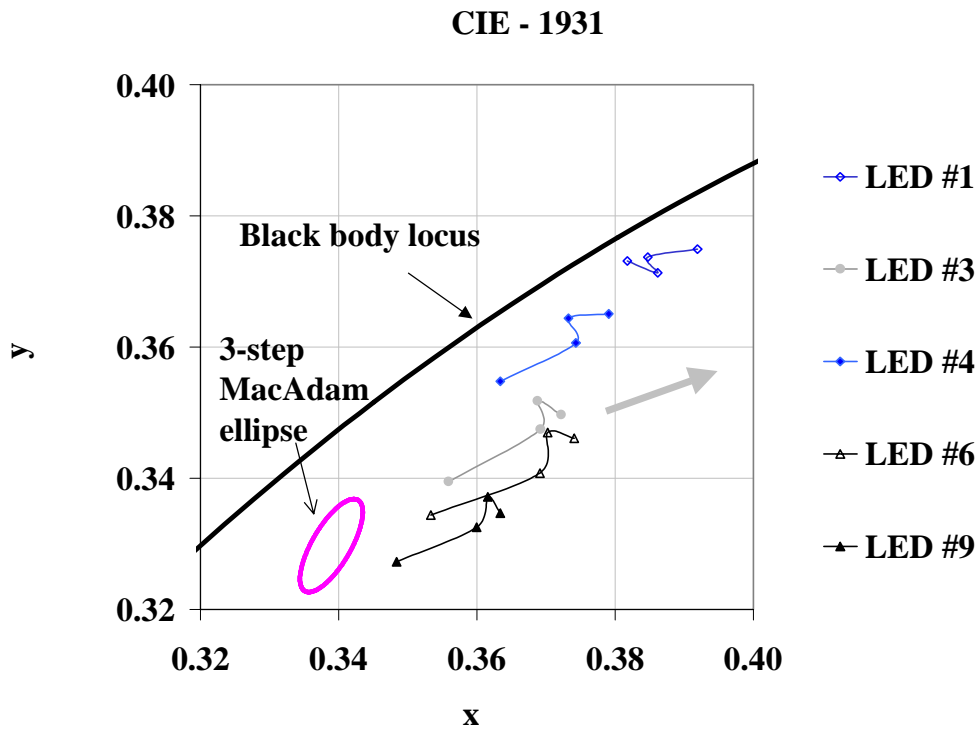


Figure 8: Color shift as a function of time, for $t=0, 432, 768,$ and 1128 hours of operation, for five LEDs