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LED Optical Aging Test Instrument

Product No: LEDLM-80PL

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Related Applications

LM-79 and LM-80 Test Solutions

Description Video Download

LEDLM-80PL LED Lumen Maintenance and Aging Life Test System is designed according to IES-LM-80 and TM-21, it used to test & record the optical and electrical Maintenance for single LED or LED module, the software is based on Arrhenius model and TM-21 to calculate the LED life. The LEDLM-80PL needs to work with a GDJW/GW Series High Temperature Chamber and and DC12010 DC Power Source.

LEDLM-84PL LED Lumen Maintenance and Aging Life Test System is designed according to IES LM-84 and TM-28, it used to test & the optical and electrical Maintenance for LED luminaires, the software is based on Arrhenius model and TM-28 to calculate the LED LEDLM-84PL needs to work with a GDJW/GW Series High Temperature Chamber and and LSP-1KVARC AC Power Source.

- Understanding LM-80: Measuring Lumen Maintenance of LED Light Sources
- ANSI/IES LM-80-15 standard update content
- How to choose LISUN products for Saudi Arabia’ s latest standard SASO2902?
- LISUN held a lighting Technology Salon in Egypt
- LISUN held a lighting technology salon in Iran
- LISUN held a lighting technology salon in Saudi Arabia
- LED packaging principle
- How to Use TM-21 and LM-80 to Estimate LED Luminaries Life?
- How to predict and test the life of LED?
- LISUN successfully participate in the Lighting Poland 2018

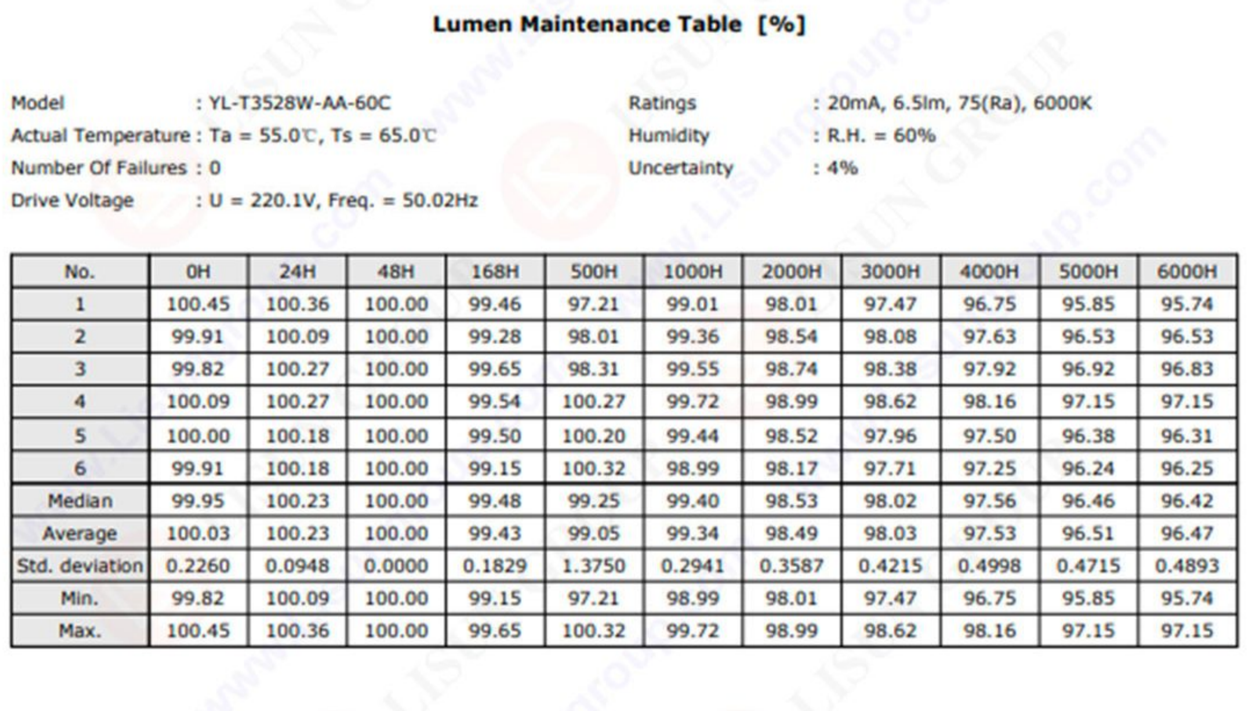
Related Successful Case

- Costa Rica – Installation and training Integrating Sphere Test System, dustproof and waterproof test equipment, EMI/EMC test machine, etc.
- Spain – LISUN engineer Jacky visited new customers

Specifications:

- Record the changing curves of lumen, colorimetric and electrical parameters VS time
- Test and record the light attenuation data within a short time, then software will predict the LED life
- Please click here to see one of the **test report sample of LEDLM-80PL** (The LEDLM-84PL report is similar but only difference is based on TM-28)
- LEDLM-80PL/LEDLM-84PL test system can test 16 DUTs one time. (More DUTs can be special designed according to customers’ requirements)
- LEDLM-80PL/LEDLM-84PL test system already inlcude two sets of testing devices in the temperature chamber.
- The system supply two solutions for LED Lumen Maintenance and Aging Test:

1. Strictly according to LM-80 or LM-84 to test up to 6000hours to get L50 and L70 test report based on TM-21 or TM-28, LISUN LEDLM-80PL/LEDLM-84PL test system will be fully automatic and no need human to operate during 6000hours test.
2. LISUN LEDLM-80PL/LEDLM-84PL test system supply a fast accelerate the DUT, the software was designed based on the Arrhenius Model to simulat 6000hours testing in a “short time” to get the L50 and L70 test report based on TM-21 or TM-28. This solution save a lot of time for the testing company.



Lumen Maintenance Table [%]

Model : YL-T3528W-AA-60C
Actual Temperature : Ta = 55.0℃, Ts = 65.0℃
Number Of Failures : 0
Drive Voltage : U = 220.1V, Freq. = 50.02Hz

Ratings : 20mA, 6.5lm, 75(Ra), 6000K
Humidity : R.H. = 60%
Uncertainty : 4%

No.	0H	24H	48H	168H	500H	1000H	2000H	3000H	4000H	5000H	6000H
1	100.45	100.36	100.00	99.46	97.21	99.01	98.01	97.47	96.75	95.85	95.74
2	99.91	100.09	100.00	99.28	98.01	99.36	98.54	98.08	97.63	96.53	96.53
3	99.82	100.27	100.00	99.65	98.31	99.55	98.74	98.38	97.92	96.92	96.83
4	100.09	100.27	100.00	99.54	100.27	99.72	98.99	98.62	98.16	97.15	97.15
5	100.00	100.18	100.00	99.50	100.20	99.44	98.52	97.96	97.50	96.38	96.31
6	99.91	100.18	100.00	99.15	100.32	98.99	98.17	97.71	97.25	96.24	96.25
Median	99.95	100.23	100.00	99.48	99.25	99.40	98.53	98.02	97.56	96.46	96.42
Average	100.03	100.23	100.00	99.43	99.05	99.34	98.49	98.03	97.53	96.51	96.47
Std. deviation	0.2260	0.0948	0.0000	0.1829	1.3750	0.2941	0.3587	0.4215	0.4998	0.4715	0.4893
Min.	99.82	100.09	100.00	99.15	97.21	98.99	98.01	97.47	96.75	95.85	95.74
Max.	100.45	100.36	100.00	99.65	100.32	99.72	98.99	98.62	98.16	97.15	97.15

LEDLM-80PL LED Optical Aging Test Report (Sample)

Tags : LED Optical Aging Test Instrument , LEDLM-80PL

IES TM-21-11

Projecting Long Term Lumen Maintenance of LED Light Sources

Publication of this Committee report has been approved by IES.

Suggestions for revision should be directed to IES

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Prepared by the Subcommittee on Solid State Lighting of the IESNA Testing Procedures Committee

TM-21 Working Group

Ralph Tuttle, *Technical Coordinator*
Kei Haraguchi
Mark Hodapp
Jianzhong Jiao
Cameron Miller
Yoshi Ohno
Trenton Pulsipher
Emil Radkov
Eric Richman
David Szombatfalvy

Solid-State Lighting Subcommittee

Cameron Miller, *Chair*
Names of subcommittee members
………………

IESNA Testing Procedures Committee

Michael Grather, *Chair*
Names of committee members
………………

· Advisory Member
·· Honorary Member

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Projecting Long Term Lumen Maintenance of LED Packages

Introduction

One of the benefits that LED light sources can provide is very long usable life. Unlike other lighting technologies LEDs typically do not fail catastrophically during use. However over time the light output will gradually depreciate. At some point in time the light emitted from an LED depreciates to a level where it is no longer considered adequate for a specific application. It is important in lighting design to understand when this "useful lifetime" of an LED source is reached.

IES LM-80-08 is the Approved Method for Measuring Lumen Maintenance of LED Light Sources. It defines the setup, conditions, and procedures for performing lumen maintenance testing of LED packages, arrays, and modules. LM-80-08 is the IESNA recommendation that is used widely to characterize the lumen depreciation behavior of LEDs. LED device manufacturers routinely provide LM-80-08 reports for their products with data collected during testing for 6000 hours or more. However, how the data collected from LM-80-08 testing is actually used to best determine the useful lifetime of the tested product is not well defined.

The rated Lumen Maintenance life of an LED is the elapsed operating time over which an LED light source maintains a given percentage of its initial light output. It is defined as Lp, where p is the percentage value. For example, L_{70} is the time (in hours) when the light output from the LED has dropped to 70% of its initial output. The time when the rated lumen maintenance life of an LED light source is reached is dependent upon many variables including the operating temperature, drive current, and the technology and materials used to construct the products. As such, the lumen maintenance of LEDs can vary not only from manufacturer to manufacturer, but also between different LED package types produced by a single manufacturer.

This Technical Memorandum recommends a method of projecting the Lumen Maintenance of LED Light Sources from the data obtained by LM-80-08 testing.

This document was developed by a dedicated TM-21 Working Group of LED industry professionals. The analyses of the LM-80-08 test data provided by major LED manufacturers are used to rationalize and support this document. Much of this LM-80-08 data were from testing that extended to 10000 hours and beyond.

1. Scope

This document provides recommendations for projecting long term lumen maintenance of LED light sources using data obtained when testing them per IES LM-80-08, "IES Approved Method for Measuring Lumen Maintenance of LED Light Sources".

2. Normative References

IES LM-80-08, *Measuring Lumen Maintenance of LED Light Sources*.

3. Definitions

3.1 LED Light Source (IES LM-80-08)

LED package, array, or module that is operated via an auxiliary driver.

3.2 DUT

Device under testing is the LED light source defined in Section 3.2.

3.3 Rated Lumen Maintenance Life, L_p (IES LM-80-08)

The elapsed operating time over which the LED light source will maintain the percentage, p, of its initial light output, e.g.:

L_{70} (hours): Time to 70% lumen maintenance
L_{50} (hours): Time to 50% lumen maintenance

4. Test Data and Sample Size

4.1 Data to be Used

The data to be used in this projection method shall be collected according to the methods described in IES LM-80-08.

4.2 Sample Size Recommendation

All data from the sample set at a given case temperature and drive current from the LM-80-08 test report for a specific product model should be used for lumen maintenance life projection. The recommended number of the sample set is a minimum of 20 units to be able to use a multiplication factor of 6 times the test duration, as specified in Section 5.2.5, for lumen maintenance life projection.

A sample size less than 20 units may be used when specified by the requestor of the application of this estimation method. When a sample size less than 20 units is specified and used, the sample size shall be noted in any reporting of the use of this method. Any change in sample size will lead to a change in uncertainty and the time interval for the projection of the lumen maintenance life. For a sample size of 10 units, a multiplication factor of 5.5 times the test duration, as specified in Section 5.2.5, shall be used for lumen maintenance life projection.

4.3 Luminous Flux Data Collection

Additional measurements after the initial 1000 hours at intervals smaller than 1000 hours (including every 1000 hour points) are encouraged. Additional measurements beyond 6000 hours are encouraged and will provide the basis for more accurate lumen maintenance predictions.

5. Lumen Maintenance Life Projection

5.1 Method

The recommended method of lumen maintenance projection is to use a curve-fit to the collected data to extrapolate the lumen maintenance value to the time point where the luminous flux output decreases to the minimum acceptable level (for example 70% of initial luminous flux). That time point is the lumen maintenance life. The same curve-fit of the collected data can also be used to determine the luminous flux output level at given future time points (i.e., 25000 hours, 35000 hours).

This method is applied separately for each set of DUT test data collected at each operational (e.g., drive current) and environmental (e.g., case temperature) condition as specified in LM-80-08.

5.2 Procedures

5.2.1 Normalization

Normalize all collected data to a value of 1 (100%) at 0 hours for each DUT tested.

5.2.2 Average

Average the normalized measured data of all samples within the same data set defined in 5.1 for each test condition at each measurement point.

5.2.3 Data Used for Curve-fit

For data sets of test duration, *D*, from 6000 hours up to 10000 hours, the data used for the curve-fits shall be the last 5000 hours of data. Data before the 1000 hour reading shall not be used for the curve fit.

For data sets of test duration greater than 10000 hours, the data for the last 50% of the total test duration shall be used for curve-fit. In other words, all data points between *D/2* and *D* shall be used. For example, if the test duration is 13000 hours, use all data points between 6500 hours and 13000 hours. If there is no data point at *D/2*, then the next lower time point shall be included in the data fitting. For example, for *D* of 13000 hours of data taken every 1000 hours, use the data points between 6000 and 13000 hours.

5.2.4 Curve-fit

Perform an exponential least squares curve-fit through the averaged values as specified in Section 5.2.3 for the following equation (see Annex E for calculation examples):

$$\Phi(t) = B\exp(-\alpha t)$$

Where:

t = operating time in hours;

$\Phi(t)$ = averaged normalized luminous flux output at time t;

B = projected initial constant derived by the least squares curve-fit;

α = decay rate constant derived by the least squares curve-fit.

Use the following equations to project the lumen maintenance life.

$$L_{70} = \frac{\ln\left(\frac{B}{0.7}\right)}{\alpha}$$

or

$$L_{50} = \frac{\ln\left(\frac{B}{0.5}\right)}{\alpha}$$

For any levels of lumen maintenance, use the following generic form of the equation:

$$L_p = \frac{\ln\left(100 \times \frac{B}{p}\right)}{\alpha}$$

where:

L_p = lumen maintenance life expressed in hours where p is the percentage of initial lumen output that is maintained.

When $\alpha > 0$, then the exponential curve-fit decays to zero, and L_p is positive. When $\alpha < 0$, then the exponential curve-fit increase over time, and L_p is negative.

Whenever an L_p value is reached experimentally in the course of LM-80-08 testing, the reported value must be obtained by linear interpolation between the two nearest test points and takes precedence over any value projected by the formulas above.

5.2.5 Adjustment of Results

For a sample size of 20 units or more, luminous flux values must not be projected beyond 6 times the total test duration (in hours) of measured data. For a sample size of 10 units, luminous flux values must not be projected beyond 5.5 times the total test duration of measured data.

When the calculated lumen maintenance life (e.g., L_{70}) is positive and less than or equal to 6 (5.5 for a sample size of 10 units) times the total test duration, the calculated lumen maintenance life is the reported lumen maintenance life.

When the calculated lumen maintenance life (e.g., L_{70}) is positive and greater than 6 (5.5 for a sample size of 10 units) times the total test duration, the reported lumen maintenance life value is limited to 6 (5.5 for a sample size of 10 units) times the total test duration.

When the calculated lumen maintenance life (e.g., L_{70}) is negative, the reported lumen maintenance life will be 6 (5.5 for a sample size of 10 units) times the total test duration, and any projections of normalized lumen output at specific operating times beyond the duration of the tests shall be reported to be equal to the normalized lumen output at the last measurement point.

5.2.6 Notation for Projected Lumen Maintenance Life

The lumen maintenance life projected in this method shall be expressed using the following notation:

$L_p\ (D\text{k})$

where p is the percentage of initial lumen output that is maintained, and D is the total duration of the test in hours divided by 1000 and rounded to a nearest integer. For example,

$L_{70}(6\text{k})$ for 6000 hours test data;
$L_{70}(10\text{k})$ for 10000 hours test data.

If the calculated L_p value is reduced by the 6 (5.5 for a sample size of 10 units) times rule (see Section 5.2.5), the lumen maintenance life value shall be expressed with a symbol ">". For example,

$L_{70}(6\text{k}) > 36000$ hours (at $T_s = 55°\text{C}$, $I_F = 350$ mA).

If the L_p value is reached experimentally in the course of LM-80-80 testing then the lumen maintenance life shall be expressed with the D value to be equal to the L_p value in hours divided by 1000 and rounded to a nearest integer. For example,

$L_{70}(4\text{k}) = 4400$ hours (at $T_s = 55°\text{C}$, $I_F = 350$ mA).

6. Temperature Data Interpolation

When in-situ DUT case temperature, $T_{s,i}$, is different from the temperatures used for LM-80-80 tests (e.g., 55°C, 85°C, and a third temperature provided by the DUT manufacturer), the following procedures should be used to predict lumen maintenance life of the DUTs corresponding to the in-situ case temperature with the same operational condition (e.g., drive current).

6.1 Select Tested Case Temperatures

The tested case temperatures used for in-situ case temperature lumen maintenance life interpolation must contain the closest lower temperature, $T_{s,1}$, and the closest higher temperature, $T_{s,2}$, to the in-situ case temperature to be interpolated.

6.2 Convert All Temperatures to Kelvins

The following formula shall be used to convert the temperatures to the unit of Kelvins:

$$T_s[K] = T_s[°C] + 273.15$$

Only values in unit Kelvin shall be used in the subsequent calculations shown in the following sections.

6.3 Use the Arrhenius Equation to Calculate the Interpolated Lumen Maintenance Life

The Arrhenius equation shown below shall be used to calculate in-situ decay rate constant α_i:

$$\alpha_{\mathrm{i}} = A \exp\left(\frac{-E_{\mathrm{a}}}{k_{\mathrm{B}} T_{s,\mathrm{i}}}\right),$$

where:

A = pre-exponential factor;

E_a = activation energy (in eV);

$T_{s,i}$ = in-situ absolute temperature (in K);

k_B = Boltzmann's constant (8.617385x10^{-5} eV/K).

The following intermediate calculation steps need to be carried out in order to find the decay rate constant α_i at an in-situ temperature T_{si} between T_{s1} and T_{s2}.

Step 1: Obtain α_1 and a_2 for the two temperatures $T_{s,1}$ and $T_{s,2}$, which were calculated in the curve-fits performed per Section 5.2.4. Calculate the ratio of E_a/k_B as:

$$\frac{E_{\mathrm{a}}}{k_{\mathrm{B}}} = \frac{\ln\alpha_1 - \ln\alpha_2}{\dfrac{1}{T_{\mathrm{s},2}} - \dfrac{1}{T_{\mathrm{s},1}}}.$$

Step 2: Use the above ratio, plug in $T_{s,1}$ to calculate pre-exponential factor A:

$$A = \alpha_1 \exp\left(\frac{E_{\mathrm{a}}}{k_{\mathrm{B}} T_{\mathrm{s},1}}\right).$$

The above Step 2 can also be used for substituting α_1 and $T_{s,1}$ with α_2 and $T_{s,2}$.

Step 3: Calculate B_0, where:

$B_0 = \sqrt{B_1 B_2}$;

B_1 = projected initial constant for lower temperature case;

B_2 = projected initial constant for higher temperature case.

Step 4: Using the above result of B_0, calculate lumen maintenance life for L_p for in-situ case temperature $T_{s,i}$ as:

$$L_p = \frac{\ln\left(100 \times \frac{B_0}{p}\right)}{\alpha_i}.$$

Results from the above calculation steps as well as the parameters used in the calculations are reported in the Table 2.

Step 5: Calculate the in-situ luminous flux output at time t, $\Phi_i(t)$ for $T_{s,i}$ as:

$$\Phi_i(t) = B_0 \exp(-\alpha_i t).$$

See Annex E for calculation examples.

6.4 Applicability of the Arrhenius Equation

The Arrhenius equation can be used only if both decay rate constants α_1 and α_2 have positive values. In cases where one or both α values are negative (i.e., increasing luminous flux over time), a conservative projection shall be used as specified below.

If only one α value is positive, the corresponding lumen maintenance projections and L_p values (as described in Section 5.2.4 to Section 5.2.5) shall be used for $T_{s,i}$.

If neither α value is positive, the reported lumen maintenance life, L_{70}, at $T_{s,i}$ will be 6 (5.5 for a sample size of 10 units) times the total test duration of measured data, and any projections of normalized lumen output at specific operating times beyond the duration of the tests, shall be reported to be equal to the lower normalized lumen output at the last measurement point between $T_{s,1}$ and $T_{s,2}$.

6.5 Limit for Extrapolation

Extrapolation of any L_p value outside of the operating conditions used in the LM-80-08 test (for example, a higher temperature) is not recommended.

7. Report

The report of lumen maintenance life projection shall include following information shown in Table 1. The calculated and reported L_{70} values shall be rounded to 3 significant digits. α and B values shall be rounded to 4 significant digits.

Table 1 Recommended information to be included in the report at each LM-80-80 test condition

Description of LED light source tested (manufacturer, model, catalog number, etc.)	
Sample size	
DUT drive current used in the test	mA
Test duration	hours
Test duration used for projection	hour to hour
Tested case temperature	°C
α	
B	
Calculated $L_{70}(Dk)$	hours
Reported $L_{70}(Dk)$	hours

When interpolation is used, the additional following information shall be presented, as shown in Table 2.

Table 2 Recommended information to be included in the report for interpolation (refer to Section 6 for definitions)

$T_{s,1}$, (°C)	
$T_{s,1}$, (K)	
α_1	
B_1	
$T_{s,2}$, (°C)	
$T_{s,2}$, (K)	
α_2	

$T_{s,i}$, (°C)	
$T_{s,i}$, (K)	
α_i	
Projected $L_{70}(Dk)$	
Reported $L_{70}(Dk)$	

B_2	
E_a/k_B	
A	
B_0	

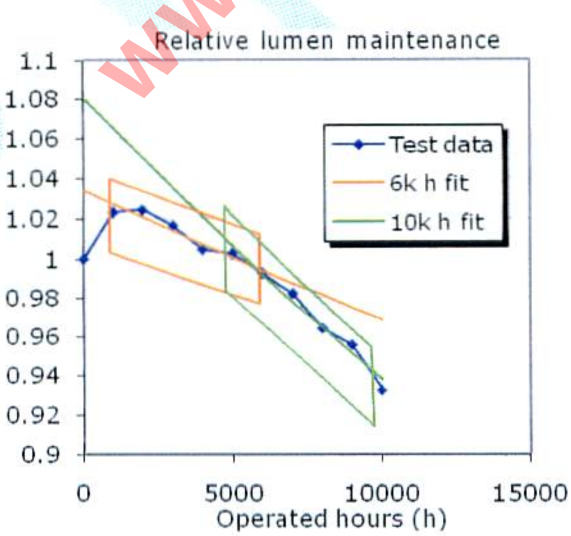
Annex A Rationale for the Recommended Data extrapolation Method

The TM-21 Working Group (WG) conducted statistical analyses for over 40 sets of LM-80-08 test data collected from four major LED manufacturers, in which more than 20 sets data had testing duration greater or equal to 10000 hours. Several mathematical models were proposed to predict lumen maintenance life based on these real LED lumen maintenance data, which exhibited several different trends. The WG conducted thorough investigations in several areas. First, several possible models that express potential LED physical lumen decay behaviors, were identified and proposed and a search made for possible metrics that can be used to evaluate and select the most accurate model for a given set of LM-80 data assuming that the duration is 6000 hours. Second, the WG evaluated the LED lumen maintenance behaviors that are shown in the 40 plus sets of data, and noticed that many LEDs exhibit some rapid changes over the first 1000 or more hours. The WG studied various options including using data only after 1000 hours or only after the first hump of the lumen maintenance curve. This was to verify if a chosen mathematical model can be used more reliably. Thirdly, the WG examined the accuracy of prediction using various proposed models by examining the LM-80 data that extends to longer hours, e.g., 10000 to 15000 hours. These explorations showed that the statistics of model fitting using only 6000 hours of LM-80 data was not conclusive enough to realistically help in identifying the most suitable model to represent lumen output degradation. The explorations also showed that the LED lumen depreciation trends often change after 6000 hours in one way or another and there is no reliable and consistent approach to predict such trends from the 6000 hours data points. Lastly, natural noise in the real data can falsely indicate decay trends in the 6000 hours test, which the test data longer than 6000 hours data shows is not real. Some noisy data points are inevitable due to measurement uncertainties of the luminous flux measurements over a long period of time and the best fit for the given 6000 hour data points would not assure that prediction for much longer time points will be accurate.

The WG further discussed if a possible better model (other than exponential) can be used for test data longer than 6000 hours. Again, some real LED data showed changes in lumen depreciation trend after 10000 hours and the same problems are observed. It is also understood by LED manufacturers that LED lumen maintenance curves tend to change depending on the technologies and materials used in the LED packages. Some of these occur at early times, and some later than 6000 hours or even 10000 hours. The analysis completed on the longer data sets confirmed that selection of a “better” mathematical model is not appropriate even with 10000 hours data.

In many cases the statistical fit data for multiple models showed little difference indicating that more than one model may be as reasonable as another (given the uncertainty of long reaching extrapolation) in determining the expected lumen depreciation of an LED. There is also collective understanding within the LED industry that degradation associated with effects other than the diode itself tends to manifest itself earlier rather than later. Therefore, the more stable lumen depreciation in later time periods is mostly associated with diode degradation and this has been considered reasonable related to classic exponential decay. Therefore, the WG concluded that the most reasonable approach to extrapolation of lumen degradation when removing initial variable data (associated with a hump in the data) was the use of the simple exponential fit. With further analyses of the collected test data, the WG found that for longer test duration, e.g., 10000 hours or longer, using the last 5000 hours of the data (5000 to 10000 hours) showed more consistent and reliable prediction results than using the data for the entire test duration (1000 to 10000 hours). However, there was a concern that the last 5000 hours provides only 6 data points (assuming the test interval is 1000 hours) and the results are susceptible to noisy data points. After further discussions and analyses, the WG determined that the last 50 % of the test data, with a minimum of last 5000 hours duration, would be an appropriate application of the available data for extrapolations. The WG conducted verification extrapolations, and found that this method works well without any serious problems for all the collected LED test data. It is noted that these test data used for verification are still limited to up to approximately 15000 hours.

Some examples of real LED test data and lumen maintenance fitting are shown below. Fig. 1 is an example where the exponential fit for 1000 - 6000 hours appears very good but the trend changes after 6000 hours. In this case, L_{70}(6k) is 60000 hours, but L_{70}(10k) is 30000 hours, which is considered to be more accurate. Fig. 2 is another example where the 1000 – 6000 hours data fits very well in that portion but the trend changes after 6000 hours in the other direction. In this case, L_{70}(6k) is 30000 hours, but L_{70}(10k) is 60000 hours (limited by a value of 6 times the total test duration), which is considered to be more accurate. In both cases it is not possible to predict the change in the trend only from the 6000 hours data points.



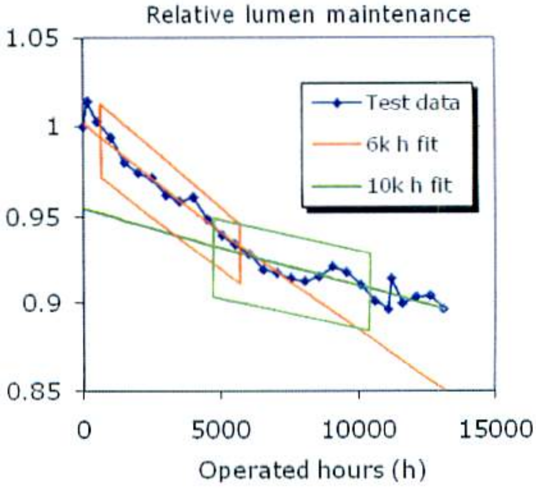


Figure A1 LED data (1)

Figure A2 LED data (2)

As examples shown in the above Figures A1 and A2, the L_{70} prediction by 6000 hours test data is often found unreliable and unsatisfactory. The longer the test duration, more accurate the prediction will be. Thus, it is recommended by the WG that LM-80 tests should be continued after 6000 hours and L_{70} predictions should be updated when test data at longer durations becomes available. To encourage such practice and allow the users to know the length of test data from which L_{70} is determined, the notation, $L_p(D\mathrm{k})$, is introduced so that the duration of test is always reported with the life value. The duration of the test hours helps indicate the degree of reliability of the reported lumen maintenance life.

Annex B Sample Size Selection for Data Extrapolation

As explained in Annex A, the exponentially modeled mean values are used to establish the LED light source decay structure. This fitted exponential model is then used to extrapolate the expected lumen output. When using the simplified structure of fitting to the means at each time period, it is important to identify how many units are tested. Increasing the number of units per time period will provide a stronger foundation for the fitted exponential model. The Figure B1 below shows the percent reduction in uncertainty (y-axis) at each step increase of the number of units used to calculate the mean (sample size). As can be seen, the percent reduction in uncertainty decreases as the number of units increases.

Another concern in model fitting rests on the assumption of the normality of the uncertainty error associated with the fitted model. In this application a similar evaluation of measuring a sufficient number of units at each time period can provide a substantial basis for the normality of the means. Most LED test data collected by the WG have an approximately symmetrical distribution about the mean of the data. This symmetry and, consequently, limited skewness provides rationale that the normality assumptions can be reasonably accepted with as few as 20 units per time period.
Therefore, the WG made recommendation for sample size requirement in Section 4.2.

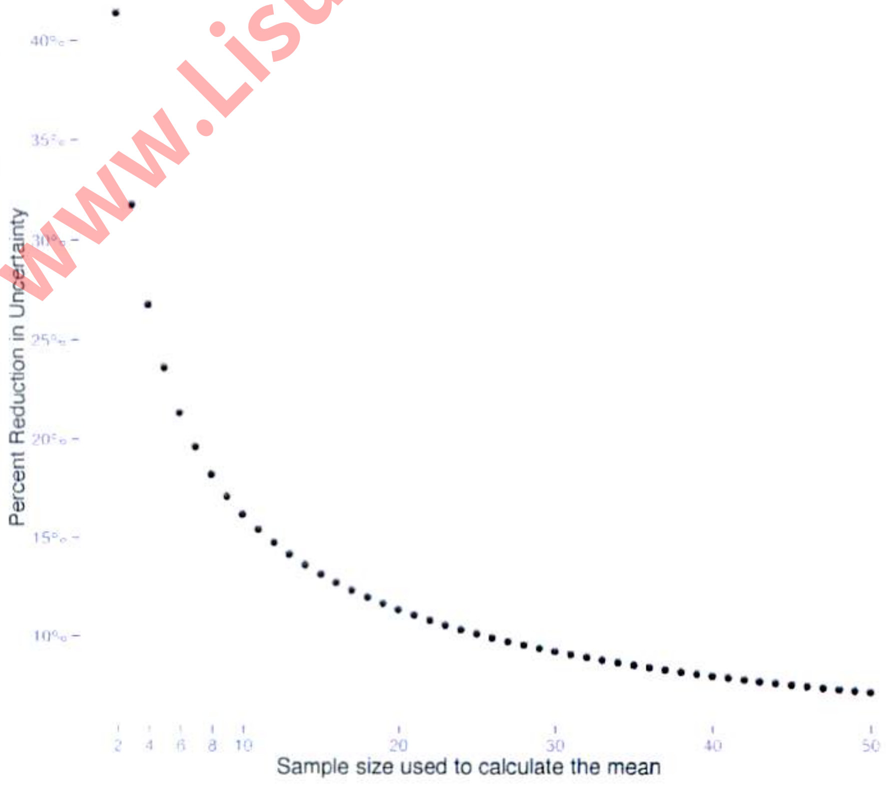


Figure B1 Sample size versus uncertainty

Annex C Least Squares Formula

For a set of *n* experimental data points (x_1, y_1), (x_2, y_2), …, (x_n, y_n), the least squares straight line fit, where *n* is the total number of averaged data points used for curve-fitting according to Section 5.2.4.

$$y = mx + b$$

where m is the slope:

$$m = \frac{n\Sigma xy - \Sigma x \Sigma y}{n\Sigma x^2 - (\Sigma x)^2}$$

b is an intercept:

$$b = \frac{\Sigma y - m\Sigma x}{n}$$

where Σ stands for a sum of n terms as follows:

$$\Sigma xy = x_1 y_1 + x_2 y_2 + \ldots + x_n y_n$$
$$\Sigma x = x_1 + x_2 + \ldots + x_n$$
$$\Sigma y = y_1 + y_2 + \ldots + y_n$$
$$\Sigma x^2 = x_1^2 + x_2^2 + \ldots + x_n^2$$

After the substitutions of:

$x_k = t_k$ $\quad k = 1, 2, \ldots, n$, and
$y_k = \ln \Phi_k$ $\quad k = 1, 2, \ldots, n$.

Then, the above formula can be used to derive:

$$B = \exp(b)$$

and

$$\alpha = -m \,.$$

Annex D Limit for Duration of Prediction

This section describes the analysis used to determine a multiplication factor for the upper limit of L_{70} that is to be reported.

The WG conducted analyses on over 40 sets of LM-80-80 test data collected from several LED manufacturers. To determine the uncertainty of the exponential curve-fit to the datasets, a confidence band was calculated which shows the region within which the model is expected to fall with a certain level of probability. A confidence band is calculated using Student's *t* function, the coefficients of the model, and the estimated uncertainties in the coefficients therefore a covariance matrix of the predictive model is required. Therefore, to calculate a confidence band an estimation of uncertainty is required for each data point. An example of a calculated confidence band is presented in Figure D1.

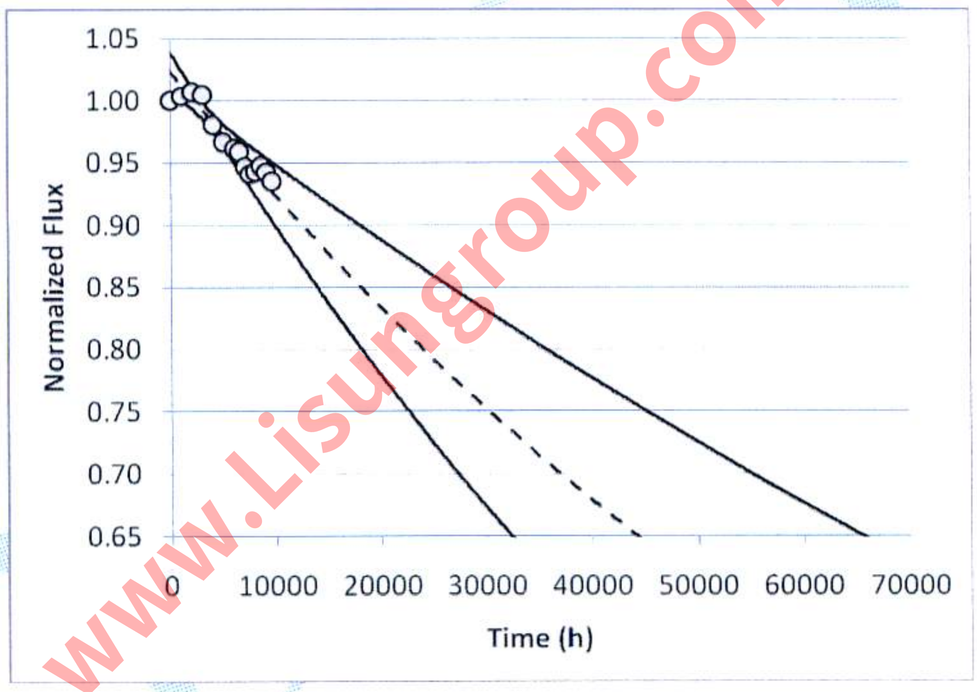


Figure D1 – The grey circles are the normalized data. The dashed line is the optimized curve-fit to the 1000 – 6000 hours data. The solid lines are the confidence bands with respect to the optimized fit.

Two components were combined as a square root of a sum of squares. The first component is the standard deviation of an individual dataset for a given time divided by the square root of the number of points, so the standard deviation of the mean value. The second component is the uncertainty of the measurement system for relative measurements over the time frame of the measurements (test duration). This is a characterization of the reproducibility of the measurement system. A matrix of these two components was analyzed. The number of points used to determine the mean standard deviation was varied from 5, 10, 20, 30, 50, and 100 points. The relative combined uncertainty of the measurement system was varied from 0.10%, 0.25%, 0.40%, 0.50%, 0.75% and 1.0%. The relative combined uncertainty of the measurement system is the uncertainty between measurements for the same device over the duration of the test. It does not include the absolute calibration of the measurement system. It is a measure of the system stability over time. The expanded uncertainty with a coverage factor of *k*=2 which would represent a 95% coverage interval, is 0.2%. 0.5%, 0.8%, 1.0%, 1.5%, and 2.0%. The level of probability for this analysis was set at 90% using a one-sided distribution for the lower confidence band.

To determine a multiplication factor for the upper limit of L_{70} to be reported with a confidence of 90% a hypothesis was created that if the statistic was greater than one the hypothesis is considered true. To calculate the statistic a multiplier to be tested is chosen, for example six. For a given set of data the L_{70} is calculated and the lower confidence band is calculated. The critical time for a multiplier of six is the time interval (6000 hours) times the multiplier plus one, 42000 hours. If the lower confidence band is greater than the cut-off of 36000 hours then the hypothesis is true. To plot this statistic divide the lower confidence band by the L_{70} value, multiply by the multiplier plus one and divide by the multiplier.

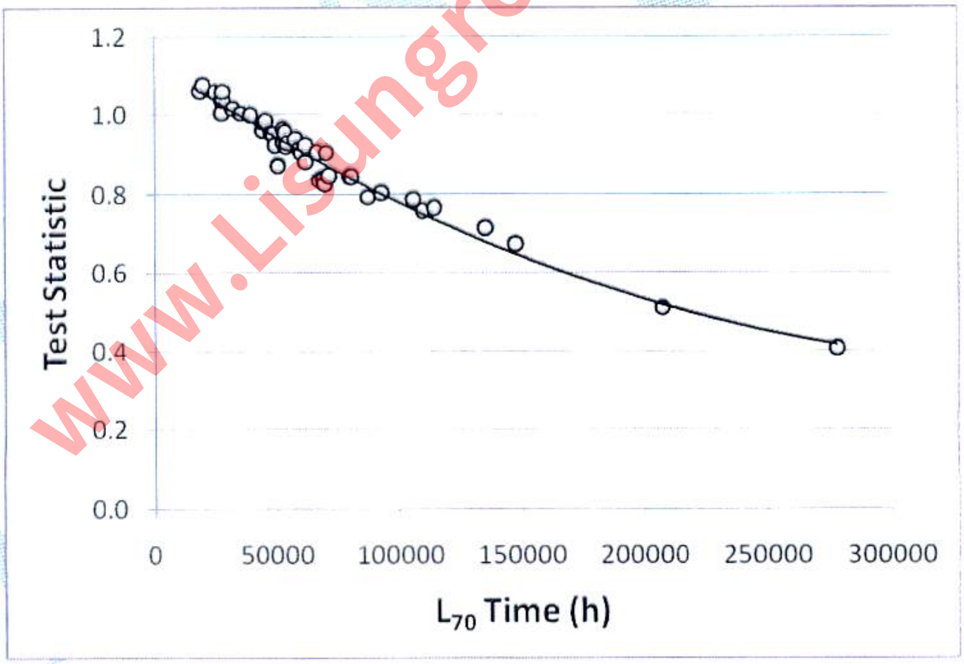


Figure D2 – The test statistic plotted versus the L_{70} calculated for each dataset using 0.40% relative combined uncertainty for the measurement system and 20 data points. A quadratic is fit to the test statistic which is based on a 6 times multiplier.

Figure D2 shows that the statistic has a value of one at the test time of 36000 hours within the uncertainty of the fit. The test statistic decreases with time because at 6000 hours and a L_{70} of 200000 hours the data points provide very little curvature to fit the exponential. The conclusions of the analysis are that for a 0.40 % relative combined uncertainty for the measurement system which is typical for the industry at this time frame, a 6 times multiplier is statistically acceptable for data sets with at least 20 data points (sample units). A 5.5 times multiplier is statistically acceptable for data sets with 10 data points (sample units).

Annex E Data Test Set for Validation of Calculation – Examples

To assist users of this document to carry out the calculations following the procedures listed in Section 5 and Section 6, the examples of the calculations based on the LM-80-08 data are presented in Annex F. The data used in the calculations were selected from the database submitted from LED manufacturers to the WG. It is recommended that users use the data and calculation results presented in Annex E to make comparison in their calculations to ensure the calculation steps programmed by the users are correct.

E1.0 Examples of Normalizing and Fitting 6000 Hours of LM-80-08 Data

Table E1 represents the data sets from 20 units of tested samples for 6000 hours of LM-80-08 test at case temperature 55 °C. Table E2 represents 6000 hours of LM-80-08 test at case temperature 85 °C.

Table E1 6000 hours LM-80-08 test data at case temperature point $T_{s,1}$ = 55 °C

Sample #	0	500	1000	2000	3000	4000	5000	6000
1	1.000	0.970	0.957	0.962	0.957	0.950	0.944	0.947
2	1.000	0.987	0.973	0.976	0.971	0.967	0.960	0.960
3	1.000	0.984	0.966	0.967	0.960	0.954	0.947	0.949
4	1.000	0.990	0.977	0.980	0.976	0.970	0.967	0.965
5	1.000	0.981	0.963	0.969	0.965	0.959	0.953	0.953
6	1.000	0.988	0.975	0.979	0.974	0.968	0.964	0.966
7	1.000	0.990	0.978	0.978	0.974	0.962	0.958	0.954
8	1.000	0.988	0.973	0.974	0.968	0.962	0.957	0.955
9	1.000	0.989	0.975	0.978	0.974	0.968	0.964	0.966
10	1.000	0.982	0.965	0.964	0.957	0.948	0.942	0.936
11	1.000	0.977	0.956	0.960	0.956	0.950	0.946	0.946
12	1.000	0.988	0.975	0.980	0.977	0.970	0.967	0.961
13	1.000	0.985	0.969	0.971	0.965	0.956	0.949	0.945
14	1.000	0.976	0.960	0.966	0.962	0.957	0.953	0.953
15	1.000	0.985	0.971	0.978	0.975	0.969	0.965	0.966
16	1.000	0.977	0.962	0.969	0.964	0.958	0.956	0.952
17	1.000	0.966	0.950	0.954	0.944	0.938	0.935	0.937
18	1.000	0.998	0.983	0.989	0.984	0.977	0.972	0.971
19	1.000	0.985	0.970	0.976	0.969	0.963	0.958	0.957
20	1.000	0.975	0.961	0.967	0.961	0.952	0.948	0.944
Average	1.0000	0.9831	0.9680	0.9719	0.9667	0.9599	0.9553	0.9542
ln(Average)	0.00000	-0.01704	-0.03252	-0.02850	-0.03387	-0.04093	-0.04573	-0.04688

Table E2 6000 hours LM-80-08 test data at case temperature point $T_{s,2}$ = 85 °C

Sample #	0	500	1000	2000	3000	4000	5000	6000
1	1.000	0.995	0.969	0.972	0.957	0.944	0.933	0.929
2	1.000	0.986	0.961	0.968	0.958	0.946	0.938	0.937
3	1.000	0.969	0.951	0.951	0.938	0.923	0.918	0.917
4	1.000	0.988	0.972	0.973	0.959	0.950	0.948	0.947
5	1.000	0.971	0.950	0.950	0.936	0.922	0.911	0.907
6	1.000	0.974	0.956	0.953	0.941	0.927	0.919	0.914
7	1.000	0.988	0.971	0.974	0.966	0.956	0.950	0.950
8	1.000	0.985	0.969	0.976	0.965	0.956	0.951	0.950
9	1.000	0.986	0.967	0.969	0.954	0.938	0.930	0.924
10	1.000	0.949	0.922	0.921	0.907	0.894	0.885	0.885
11	1.000	0.993	0.978	0.982	0.974	0.966	0.961	0.959
12	1.000	0.991	0.976	0.977	0.970	0.959	0.953	0.949
13	1.000	0.981	0.963	0.972	0.966	0.956	0.950	0.952
14	1.000	0.992	0.976	0.982	0.972	0.962	0.958	0.958
15	1.000	0.967	0.947	0.943	0.932	0.920	0.914	0.914
16	1.000	0.984	0.967	0.973	0.965	0.941	0.940	0.940
17	1.000	0.992	0.977	0.982	0.971	0.962	0.956	0.957
18	1.000	0.984	0.967	0.967	0.952	0.939	0.932	0.928
19	1.000	0.981	0.964	0.964	0.953	0.939	0.933	0.929
20	1.000	0.982	0.966	0.970	0.960	0.951	0.948	0.941
Average	1.0000	0.9819	0.9635	0.9660	0.9548	0.9426	0.9364	0.9344
ln(Average)	0.00000	-0.01827	-0.03718	-0.03459	-0.04625	-0.05911	-0.06571	-0.06785

The results of the least squares fit using this dataset is shown in Table E3 for case temperature of 55 °C, and Table E4 for 85 °C. Notice that data from 1000 hours to 6000 hours are used for calculations of projected lumen maintenance life.

Table E3 Least square curve-fit for 6000 hours LM-80-08 test data at temperature point $T_{s,1}$ = 55 °C

Point #	Time [h]	ln(Average)	xy	x	y	x^2
1	1000	-0.03252	-32.5	1000	-0.0325	1.000E+06
2	2000	-0.02850	-57.0	2000	-0.0285	4.000E+06
3	3000	-0.03387	-101.6	3000	-0.0339	9.000E+06
4	4000	-0.04093	-163.7	4000	-0.0409	1.600E+07
5	5000	-0.04573	-228.7	5000	-0.0457	2.500E+07
6	6000	-0.04688	-281.3	6000	-0.0469	3.600E+07
	Sums	-0.2284	-864.8	21000	-0.2284	9.100E+07
	Slope	-3.730E-06				
	Intercept	-2.502E-02				
	α_1	3.730E-06				

B_1	9.753E-01
Calculated L_{70}	88,916
Reported L_{70}	>36,000

Table E4 Least square curve-fit for 6000 hours LM-80-80 test data at temperature point $T_{s,2}$ = 85 °C

Point #	Time [h]	ln(Average)	xy	x	y	x^2
1	1000	-0.03718	-37.2	1000	-0.0372	1.000E+06
2	2000	-0.03459	-69.2	2000	-0.0346	4.000E+06
3	3000	-0.04625	-138.8	3000	-0.0463	9.000E+06
4	4000	-0.05911	-236.4	4000	-0.0591	1.600E+07
5	5000	-0.06571	-328.6	5000	-0.0657	2.500E+07
6	6000	-0.06785	-407.1	6000	-0.0679	3.600E+07
	Sums	-0.31069	-1217.2	21000	-0.3107	9.100E+07
	Slope	-7.416E-06				
	Intercept	-2.582E-02				
	α_1	7.416E-06				
	B_1	9.745E-01				
	Calculated L_{70}	44,611				
	Reported L_{70}	>36,000				

E2.0 Example of Arrhenius interpolation using 6000 hours of LM-80-08 data

As example, if the in-situ case temperature is $T_{s,i}$ = 70 °C, the data in Table E1 ($T_{s,1}$ = 55 °C) and Table E2 ($T_{s,2}$ = 85 °C) are used to interpolate, and to project the lumen maintenance life for $T_{s,i}$ = 70 °C. The parameters are shown as in Table E5.

Table E5 Parameters of interpolation using 6000 hours of LM-80-08 data for in-situ case temperature $T_{s,i}$ = 70 °C

$T_{s,1}$, (°C)	55
$T_{s,1}$, (K)	328
α_1	3.730E-06
B_1	0.9753
$T_{s,2}$, (°C)	85
$T_{s,2}$, (K)	358.15
α_2	7.416E-06
B_2	0.9745

$T_{s,i}$, (°C)	70
$T_{s,i}$, (K)	343
α_i	5.339E-06
Projected $L_{70}(Dk)$	62,043
Reported $L_{70}(Dk)$	>36,000

E_a/k_B	2692
A	1.365E-02
B_0	9.749E-01

The graphic representation of the lumen maintenance life projection results for $T_{s,1}$ = 55 °C, $T_{s,2}$ = 85 °C, and in-situ temperature of $T_{s,i}$ = 70 °C are show in Figure E1.

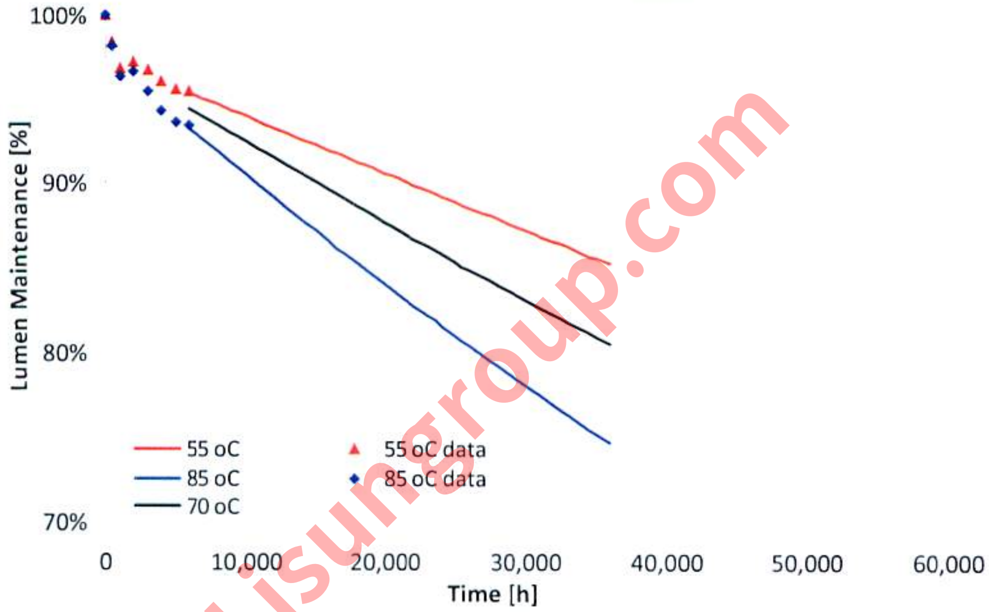


Figure E1 Graphic representation of lumen maintenance life projection using 6000 hours of LM-80 data

The numerical representation of the lumen maintenance life projection results for $T_{s,1}$ = 55 °C, $T_{s,2}$ = 85 °C, and in-situ temperature of $T_{s,i}$ = 70 °C are show in Table F6.

Table F6 Numerical results of lumen maintenance life projection using 6000 hours of LM-80-08 data

Time [h]	**55 °C**	**70 °C**	**85 °C**
6,000	0.954	0.944	0.932
7,000	0.950	0.939	0.925
8,000	0.947	0.934	0.918
9,000	0.943	0.929	0.912
10,000	0.940	0.924	0.905
11,000	0.936	0.919	0.898

12,000	0.933	0.914	0.892
13,000	0.929	0.910	0.885
14,000	0.926	0.905	0.878
15,000	0.922	0.900	0.872
16,000	0.919	0.895	0.865
17,000	0.915	0.890	0.859
18,000	0.912	0.886	0.853
19,000	0.909	0.881	0.846
20,000	0.905	0.876	0.840
21,000	0.902	0.871	0.834
22,000	0.898	0.867	0.828
23,000	0.895	0.862	0.822
24,000	0.892	0.858	0.816
25,000	0.888	0.853	0.810
26,000	0.885	0.849	0.804
27,000	0.882	0.844	0.798
28,000	0.879	0.840	0.792
29,000	0.875	0.835	0.786
30,000	0.872	0.831	0.780
31,000	0.869	0.826	0.774
32,000	0.866	0.822	0.769
33,000	0.862	0.817	0.763
34,000	0.859	0.813	0.757
35,000	0.856	0.809	0.752
36,000	0.853	0.804	0.746

E3.0 Examples of Normalizing and Fitting 10000 Hours of LM-80-08 Data

The examples shown in this section are for the data collected for 10000 hours of LM-80-08 test. Table E7 represents the data sets from 20 units of tested samples for 10000 hours of LM-80-08 test at case temperature 55 °C. Table E8 represents 10000 hours of LM-80-08 test at case temperature 85 °C.

Table E7 10000 hours LM-80-08 test data at case temperature point $T_{s,1}$ = 55 °C

Sample #	0	500	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
1	1.000	0.970	0.957	0.962	0.957	0.950	0.944	0.947	0.947	0.943	0.940	0.943
2	1.000	0.987	0.973	0.976	0.971	0.967	0.960	0.960	0.960	0.956	0.951	0.956
3	1.000	0.984	0.966	0.967	0.960	0.954	0.947	0.949	0.946	0.941	0.936	0.941
4	1.000	0.990	0.977	0.980	0.976	0.970	0.967	0.965	0.967	0.964	0.961	0.964
5	1.000	0.981	0.963	0.969	0.965	0.959	0.953	0.953	0.953	0.948	0.945	0.948
6	1.000	0.988	0.975	0.979	0.974	0.968	0.964	0.966	0.963	0.959	0.954	0.958

7	1.000	0.990	0.978	0.978	0.974	0.962	0.958	0.954	0.961	0.949	0.948	0.951
8	1.000	0.988	0.973	0.974	0.968	0.962	0.957	0.955	0.956	0.952	0.948	0.951
9	1.000	0.989	0.975	0.978	0.974	0.968	0.964	0.966	0.964	0.960	0.957	0.960
10	1.000	0.982	0.965	0.964	0.957	0.948	0.942	0.936	0.939	0.934	0.930	0.930
11	1.000	0.977	0.956	0.960	0.956	0.950	0.946	0.946	0.950	0.946	0.943	0.947
12	1.000	0.988	0.975	0.980	0.977	0.970	0.967	0.961	0.965	0.961	0.959	0.962
13	1.000	0.985	0.969	0.971	0.965	0.956	0.949	0.945	0.946	0.939	0.933	0.933
14	1.000	0.976	0.960	0.966	0.962	0.957	0.953	0.953	0.953	0.950	0.947	0.950
15	1.000	0.985	0.971	0.978	0.975	0.969	0.965	0.966	0.963	0.960	0.957	0.959
16	1.000	0.977	0.962	0.969	0.964	0.958	0.956	0.952	0.956	0.955	0.952	0.953
17	1.000	0.966	0.950	0.954	0.944	0.938	0.935	0.937	0.937	0.932	0.928	0.931
18	1.000	0.998	0.983	0.989	0.984	0.977	0.972	0.971	0.972	0.966	0.960	0.963
19	1.000	0.985	0.970	0.976	0.969	0.963	0.958	0.957	0.956	0.951	0.946	0.949
20	1.000	0.975	0.961	0.967	0.961	0.952	0.948	0.944	0.946	0.942	0.939	0.941
Average	1.0000	0.9831	0.9680	0.9719	0.9667	0.9599	0.9553	0.9542	0.9550	0.9504	0.9467	0.9495
ln(Average)	0.00000	-0.01704	-0.03252	-0.02850	-0.03387	-0.04093	-0.04573	-0.04688	-0.04604	-0.05087	-0.05477	-0.05182

Table E8 10000 hours LM-80-08 test data at case temperature point $T_{s,2}$ = 85 °C

Sample #	0	500	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
1	1.000	0.995	0.969	0.972	0.957	0.944	0.933	0.929	0.924	0.918	0.913	0.914
2	1.000	0.986	0.961	0.968	0.958	0.946	0.938	0.937	0.932	0.924	0.918	0.922
3	1.000	0.969	0.951	0.951	0.938	0.923	0.918	0.917	0.911	0.902	0.898	0.902
4	1.000	0.988	0.972	0.973	0.959	0.950	0.948	0.947	0.949	0.942	0.938	0.941
5	1.000	0.971	0.950	0.950	0.936	0.922	0.911	0.907	0.903	0.894	0.888	0.889
6	1.000	0.974	0.956	0.953	0.941	0.927	0.919	0.914	0.913	0.905	0.900	0.902
7	1.000	0.988	0.971	0.974	0.966	0.956	0.950	0.950	0.950	0.944	0.939	0.942
8	1.000	0.985	0.969	0.976	0.965	0.956	0.951	0.950	0.948	0.942	0.935	0.936
9	1.000	0.986	0.967	0.969	0.954	0.938	0.930	0.924	0.921	0.911	0.905	0.905
10	1.000	0.949	0.922	0.921	0.907	0.894	0.885	0.885	0.880	0.876	0.873	0.878
11	1.000	0.993	0.978	0.982	0.974	0.966	0.961	0.959	0.958	0.952	0.949	0.953
12	1.000	0.991	0.976	0.977	0.970	0.959	0.953	0.949	0.949	0.944	0.939	0.941
13	1.000	0.981	0.963	0.972	0.966	0.956	0.950	0.952	0.951	0.947	0.944	0.950
14	1.000	0.992	0.976	0.982	0.972	0.962	0.958	0.958	0.956	0.949	0.943	0.948
15	1.000	0.967	0.947	0.943	0.932	0.920	0.914	0.914	0.909	0.903	0.900	0.906
16	1.000	0.984	0.967	0.973	0.965	0.941	0.940	0.940	0.938	0.931	0.927	0.931
17	1.000	0.992	0.977	0.982	0.971	0.962	0.956	0.957	0.955	0.947	0.942	0.949
18	1.000	0.984	0.967	0.967	0.952	0.939	0.932	0.928	0.925	0.917	0.913	0.916
19	1.000	0.981	0.964	0.964	0.953	0.939	0.933	0.929	0.928	0.923	0.919	0.923
20	1.000	0.982	0.966	0.970	0.960	0.951	0.948	0.941	0.943	0.937	0.932	0.933
Average	1.0000	0.9819	0.9635	0.9660	0.9548	0.9426	0.9364	0.9344	0.9322	0.9254	0.9208	0.9241
ln(Average)	0.00000	-0.01827	-0.03718	-0.03459	-0.04625	-0.05911	-0.06571	-0.06785	-0.07021	-0.07753	-0.08251	-0.07893

The results of the least squares fit using this dataset is shown in Table E9 for case temperature of 55 °C, and Table E10 for 85 °C. Notice that in this example, following the instruction in section 5.2.3, the data from 6000 hours to 10000 hours are used for calculations of projected lumen maintenance life.

Table E9 Least square curve-fit for 10000 hours LM-80-08 test data at temperature point $T_{s,1}$ = 55 °C

Point #	Time [h]	ln(Average)	xy	x	y	x^2
1	5000	-0.04573	-228.7	5000	-0.0457	2.500E+07
2	6000	-0.04688	-281.3	6000	-0.0469	3.600E+07
3	7000	-0.04604	-322.3	7000	-0.0460	4.900E+07
4	8000	-0.05087	-407.0	8000	-0.0509	6.400E+07
5	9000	-0.05477	-492.9	9000	-0.0548	8.100E+07
6	10000	-0.05182	-518.2	10000	-0.0518	1.000E+08
	Sums	-0.29611	-2250.3	45000	-0.2961	3.550E+08
	Slope	-1.684E-06				
	Intercept	-3.672E-02				
	α_1	1.684E-06				
	B_1	9.639E-01				
	Calculated L_{70}	189,965				
	Reported L_{70}	>60,000				

Table E10 Least square curve-fit for 10000 hours LM-80-08 test data at temperature point $T_{s,1}$ = 85 °C

Point #	Time [h]	ln(Average)	xy	x	y	x^2
1	5000	-0.06571	-328.6	5000	-0.0657	2.500E+07
2	6000	-0.06785	-407.1	6000	-0.0679	3.600E+07
3	7000	-0.07021	-491.5	7000	-0.0702	4.900E+07
4	8000	-0.07753	-620.2	8000	-0.0775	6.400E+07
5	9000	-0.08251	-742.6	9000	-0.0825	8.100E+07
6	10000	-0.07893	-789.3	10000	-0.0789	1.000E+08
	Sums	-0.44274	-3379.3	45000	-0.4427	3.550E+08
	Slope	-3.354E-06				
	Intercept	-4.863E-02				
	α_1	3.354E-06				
	B_1	9.525E-01				
	Calculated L_{70}	91,835				
	Reported L_{70}	>60,000				

E4.0 Example of Arrhenius interpolation using 10000 hours of LM-80-08 data

If the in-situ case temperature is $T_{s,i}$ = 70 °C, the data in Table E9 ($T_{s,1}$ = 55 °C) and Table E10 ($T_{s,2}$ = 85 °C) are used to interpolate, and to project the lumen maintenance life for $T_{s,i}$ = 70 °C. The parameters are shown as in Table E11.

Table E11 Parameters of interpolation using 10000 hours of LM-80-08 data for in-situ case temperature $T_{s,i}$ = 70 °C

$T_{s,1}$, (°C)	55
$T_{s,1}$, (K)	328
α_1	1.684E-06
B_1	0.9639
$T_{s,2}$, (°C)	85
$T_{s,2}$, (K)	358.15
α_2	3.354E-06
B_2	0.9525
E_a/k_B	2699
A	6.283E-03
B_0	9.582E-01

$T_{s,i}$, (°C)	70
$T_{s,i}$, (K)	343
α_i	2.413E-06
Projected L_{70}(Dk)	130,131
Reported L_{70}(Dk)	>60,000

The graphic representation of the lumen maintenance life projection results for $T_{s,1}$ = 55 °C, $T_{s,2}$ = 85 °C, and in-situ temperature of $T_{s,i}$ = 70 °C are show in Figure F2, for 10000 hours of LM-80 data.

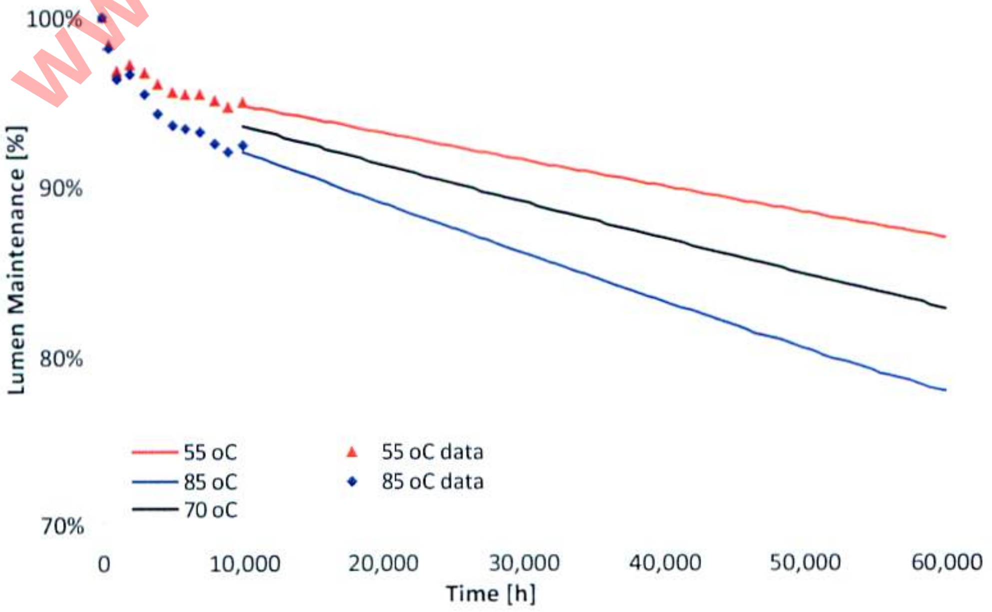


Figure E2 Graphic representation of lumen maintenance life projection using 10000 hours of LM-80-08 data

The numerical representation of the lumen maintenance life projection results for $T_{s,1}$ = 55 °C, $T_{s,2}$ = 85 °C, and in-situ temperature of $T_{s,i}$ = 70 °C are show in Table E12.

Table E12 Numerical results of lumen maintenance life projection using 10000 hours of LM-80-08 data

Time [h]	55 °C	70 °C	85 °C
10,000	0.948	0.935	0.921
11,000	0.946	0.933	0.918
12,000	0.945	0.931	0.915
13,000	0.943	0.929	0.912
14,000	0.941	0.926	0.909
15,000	0.940	0.924	0.906
16,000	0.938	0.922	0.903
17,000	0.937	0.920	0.900
18,000	0.935	0.917	0.897
19,000	0.934	0.915	0.894
20,000	0.932	0.913	0.891
21,000	0.930	0.911	0.888
22,000	0.929	0.909	0.885
23,000	0.927	0.906	0.882
24,000	0.926	0.904	0.879
25,000	0.924	0.902	0.876
26,000	0.923	0.900	0.873
27,000	0.921	0.898	0.870
28,000	0.920	0.896	0.867
29,000	0.918	0.893	0.864
30,000	0.916	0.891	0.861
31,000	0.915	0.889	0.858
32,000	0.913	0.887	0.856
33,000	0.912	0.885	0.853
34,000	0.910	0.883	0.850
35,000	0.909	0.881	0.847
36,000	0.907	0.878	0.844
37,000	0.906	0.876	0.841
38,000	0.904	0.874	0.839
39,000	0.903	0.872	0.836

40,000	0.901	0.870	0.833
41,000	0.900	0.868	0.830
42,000	0.898	0.866	0.827
43,000	0.897	0.864	0.825
44,000	0.895	0.862	0.822
45,000	0.894	0.860	0.819
46,000	0.892	0.858	0.816
47,000	0.891	0.855	0.814
48,000	0.889	0.853	0.811
49,000	0.888	0.851	0.808
50,000	0.886	0.849	0.805
51,000	0.885	0.847	0.803
52,000	0.883	0.845	0.800
53,000	0.882	0.843	0.797
54,000	0.880	0.841	0.795
55,000	0.879	0.839	0.792
56,000	0.877	0.837	0.789
57,000	0.876	0.835	0.787
58,000	0.874	0.833	0.784
59,000	0.873	0.831	0.782
60,000	0.871	0.829	0.779

Annex F Consideration of Manufacturer's Prediction Model

In developing and producing LED packages, the manufacturers have used different technologies for substrates, structures, encapsulation and lens materials, phosphors, etc. The LEDs produced by different manufacturers demonstrated vast differences in the lumen degradation behaviors. The degradations are accelerated with the severity of the operation and environment conditions. In general, the acceleration factors can be: a) temperature induced acceleration; b) current density induced acceleration; c) optical radiation induced acceleration; d) humidity induced acceleration; e) combination of optical radiation and temperature induced acceleration; f) others. Based on the analytical approaches and testing data collections, the LED manufacturers have developed mathematical models to predict their products lumen maintenance lives. The model can be a mathematical equation or a polynomial, and parameters used in the mathematical expression may be chosen based on experimental or engineering judgments.

The WG has considered adopting the prediction models provided by LED manufacturers. The proposed approach was to request manufacturer to provide the mathematical model, the test data, and the lumen maintenance life prediction. Then the document users should be able to verify the validity of the manufacturer's model by comparing to the simple exponential model using the same data provided by the manufacturer, and identifying that the manufacturer's model has higher modeling and projection accuracy. Therefore the Working Group must develop a consistent and reliable method to make the above verification and to approve the validity of the LED manufacturers' prediction. That is important and necessary to ensure the integrity of the document.

During almost three years in developing this document, the WG conducted statistical analyses for over 40 sets of LM-80-08 test data collected from four major LED manufacturers, and more than 20 sets data are collected with testing duration over 10000 hours. To determine if a manufacturer model fits the data statistically better than the model described in the Section 5 (simple exponential model), the RMSE (root mean square error) and other measures were used in the analyses. However, the Working Group did not find a reliable measure to distinguish which model, manufacturer or simple exponential model, appears to be more accurate prediction while using 6000 or up to 10000 hours data. Therefore, the Working Group decided that further studies are needed for finding a method to validate a model provided by LED manufacturer.

Annex G Analysis of Mathematical Modeling as a Method of Projecting Lumen Maintenance Life

G1.0 Analysis Approach

An initial approach to the problem of projecting lumen maintenance life was the consideration of multiple mathematical models. It is known that the various parts of a typical LED product can affect the lumen output over time and if these affects could be mathematically characterized, this might provide a useful method of projection. An initial set of models was suggested that relate to the physics of lumen decay for various parts and/or operating conditions. Additional models and combinations of models were added during the analysis.

All of the early research work in modeling to explain LED degradation was based on semiconductor physics (reactions and motion of various defects). One researcher [5] attributed the degradation to the drift of charged point defects in the quasi-neutral regions of a crystal, leading to a linear dependence with time under certain conditions. Other analysis [2] introduced the simple exponential model for LED light decay with time. Another model [6] was based on quasi-chemical reactions of defects, leading to exponential, faster than exponential, or slower than exponential theoretical decay curves. The work by Ptashchenko [1] defined the degradation rate of LEDs by the expression,

$$S = \frac{\left(\frac{d\Phi}{dt}\right)}{\Phi} \qquad \text{(G.1)}$$

where Φ is LED lumen output. The more recent advent of high brightness white LEDs suitable for general illumination brought up the issues of LED lumen maintenance over time, with related published studies [3, 7-10]. Some of the studies [3, 9] highlight the importance of degradation of subcomponents other than the chip in an LED package. The encapsulant is especially considered important. Thermal degradation of the encapsulant leading to lumen loss has been observed in high temperature storage experiments [10]. An empirical exponential fit of the lumen decay curve over operating time (excluding the first 1000 hours) has been proposed [3]. Results show a large variation in lumen decay rate among different packages, attributable to the use of different heat extraction techniques and materials. The final set of models considered in the analysis is listed in Table G1, which summarizes the decay parameters, mathematical solutions, and degradation mechanism basis for the decay models.

In the decay rate models, the k_1 term is based on the expectation of linear luminous flux dependence over time for some cases. The k_2 term can be obtained by setting $S=k_2$ in Equation (F1) above. The k_3 term is introduced in order to account for possible oxidation or corrosion effects of metals used to make reflectors around or under the chip in LED packages. These effects are believed to follow a logarithmic law in some cases [11. Terms are also combined in the rate equations, to explore mixed decay scenarios (Models 3 and 5).

Table G1 Engineering-based models used in the analysis of model fitting for LED lumen decay life projection

Model	Decay Rate	Closed Form Solution	Comment
1	$\frac{dI_v}{dt} = k_1$	$I_v = I_v^0 + k_1\left(t - t^0\right)$	
2	$\frac{dI_v}{dt} = k_2 I_v$	$I_v = I_v^0 \exp\left[k_2\left(t - t^0\right)\right]$	
3	$\frac{dI_v}{dt} = k_1 I_v + k_2 I_v$	$I_v = \left(I_v^0 + \frac{k_1}{k_2}\right)\exp\left[k_2\left(t - t^0\right)\right] - \frac{k_1}{k_2}$	Model 1 + Model 2
4	$\frac{dI_v}{dt} = \frac{k_3}{t}$	$I_v = I_v^0 + k_3 \ln\left(\frac{t}{t^0}\right)$	
5	$\frac{dI_v}{dt} = k_1 + \frac{k_3}{t}$	$I_v = I_v^0 + k_1\left(t - t^0\right) + k_3 \ln\left(\frac{t}{t^0}\right)$	Model 1 + Model 4
6	$\frac{dI_v}{dt} = -k_4 I_v^2$	$I_v = \frac{I_v^0}{1 + I_v^0 k_4\left(t - t^0\right)}$	
7	$\frac{dI_v}{dt} = k_5 \frac{I_v}{t}$	$I_v = I_v^0\left(t / t^0\right)^{k_5}$	
8	$\frac{dI_v}{dt} = k_2 I_v + \frac{k_5 I_v}{t}$	$I_v = I_v^0 \exp\left[k_2\left(t - t^0\right)\right]\left(t / t^0\right)^{k_5}$	Model 2 + Model 7
9		$I_v = I_v^0 \exp\left[-\frac{\left(t - t^0\right)}{k_6}\right]^{k_7}$	

The approach to considering these models involved looking at the potential fit of the various models to various different types of known and expected LED lumen decay data. By categorizing and comparing the goodness of fit, it was thought that a model or set of models could be identified as most effectively representing expected lumen output decay, given the data, and therefore be used to project lumen maintenance life.

Standard statistical criteria such as coefficient of determination (R^2), the residual sum of squares (SSE) and root mean squared error (RMSE) are generally used to gauge the goodness-of-fit of models. These criteria measure the differences between values predicted by a model and the values actually observed. The individual differences, called residuals, are aggregated together into a single measure of predictive power. The benefit of RMSE over SSE is that RMSE accounts for the relationship of the number of parameters (*p*) in the model to the number of data observations (*n*), as shown in Equation (2). RMSE more accurately accounts for model complexity.

$$\mathrm{RMSE}\ (\theta) = \sqrt{\mathrm{MSE}\ (\theta)} = \sqrt{\frac{\mathrm{SSE}\ (\theta)}{(n - p)}} \qquad \text{(G2)}$$

The preliminary study results indicate that for most LED decay data the differences of R^2, SSE, and RMSE among many models are not significant enough to suggest an absolute best fitting model. Furthermore, uncertainty (noise) is inherent to measurement data due to apparatus accuracy, time dependent factors, measurement repeatability, etc. Initial statistical analyses on the effects of data noise suggest that even a small amount of data noise could result in poor model differentiation and large life projection variability. Therefore, to gain insight in the behaviors of the various mathematical models for LED degradation, life projection, and effects of various test related conditions, a statistical analysis approach was developed.

G2.0 Theoretical and Real Data

To cleanly but also realistically identify the fit of various models, statistical analyses were conducted on both theoretical data and real LED degradation data obtained from manufactures.

Theoretical data in the form of seven datasets that emulate typical LED decay behaviors were constructed to represent the potential variety of LED decay data and are presented in Figure AG1. The candy cane scenario exhibits a hump in the initial data that characterizes a transient effect in the LED lumen output during the "warming up" period. Linear and curve linear scenarios represent two other LED decay profiles commonly manifested in available LED test data. Accelerated decay is observed with some LED products in which the lumen output drops quickly. In the limited minimum test period defined in LM-80, lumen output of some LED products may not show any sign of lumen depreciation, some lumen output may flatten out after decreasing for a while, and some may rise again above the earlier lumen output after initial decrease. These are captured in the flat, asymptotic and U-shaped scenarios respectively. To make these simulation results applicable to real data taken using the LM-80 test method, theoretical data were designed with a 1000 hour interval and 6000 hour total duration. In most of these analyses, 500 simulated data sets were generated by adding 1% noise to represent laboratory equipment and measurement uncertainties. This 1% noise level is considered appropriate by taking into account both measurement system and ambient uncertainty budgets over time and is corroborated by work done on measurement uncertainty at the standard testing lab at the National Institute of Standards and Technology (NIST). The constitution of the data is described in the following subsections.

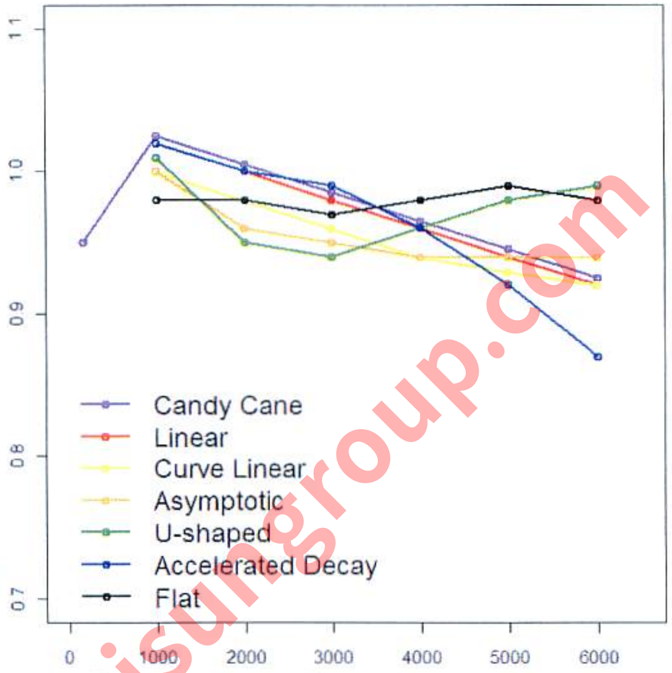


Figure G1 Theoretical decay scenarios reflecting typical/possible LED light source decay profiles

Appropriate exploration of the model selection behavior also included using decay data from real LED products obtained from LED manufacturers with product and manufacturers names and detailed operation conditions removed for unbiased analysis. These decay data were measured using the LM-80 test method, with some data sets containing additional measurements taken at shorter intervals (less than every 1000 hours) and/or beyond 6000 hours. All data were unprocessed prior to analysis with the exception of being normalized at the first data point. Decay data of 29 different LED products from various manufactures were obtained for this study. Among them the sample size of each product ranges from 6 to 30 samples.

G3.0 Analysis and Results

The models listed in Table G1 were programmed in the statistical software, R, and fit to each simulated dataset described above. Evaluations were made on the set of simulations based on analyzing the statistics of the goodness-of-fit for each model. L_{70} projection distributions or prediction bands were generated by combining the model standard errors of all simulations for each model. The subsections below describe the detailed analysis and results for each data type.

G3.1 Results from Theoretical Data

In the study of theoretical decay data (see Figure G1) the statistical distribution of RMSE values was chosen to present an overall picture of the goodness-of-fit for each model at a given set of decay data. Using the candy cane data as an example, as shown in Figure G2, the x-axis is the model number (refer to Table G1 for model details), and each dot is a calculated RMSE value from each simulation. The box and whisker plot visually aids in describing the distribution of RMSE values, where the bottom and top lines of the box show the 25th and 75th percentiles of the RMSE values.

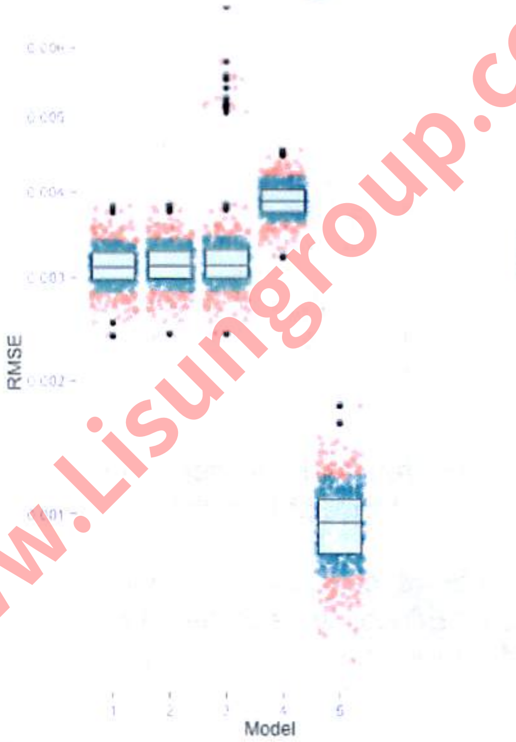


Figure G2 Box plot of RMSE values for each model – "Candy Cane" data

The decay profiles of the different models for the same dataset are plotted in Figure G3. The L_{70} projection distribution for each model is expressed using a trimmed mean (thick line) and an error bar representing 25th to 75th percentile of the L_{70} values on the x-axis of in Figure G3. . In this example, model 5 (combination of linear and logarithm models) has significantly smaller RMSE values than the other models (see Figure F2). It is the obvious selection as the "best fit" model for this data. Predicted L_{70} values could be anywhere within the distribution calculated for model 5. Therefore a conservative approach to life projection would be the use of the lower 25th percentile of the L_{70} values as the final life projection for this data. That way the uncertainty due to the fit is at least considered in an attempt to provide an estimate when using such drastic extrapolation.

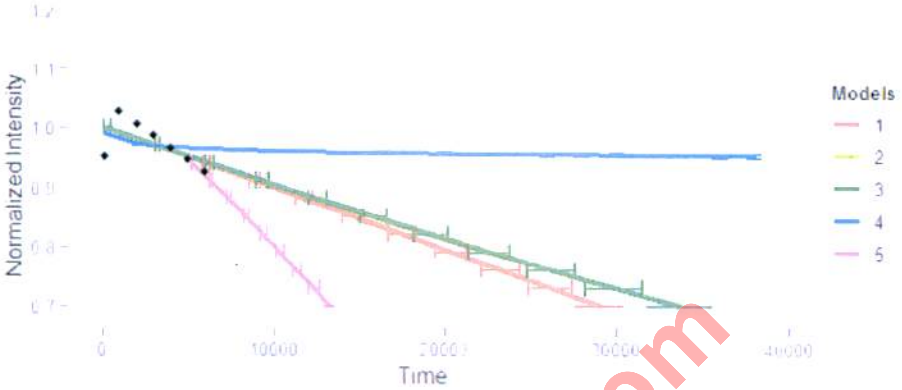


Figure AG3 Model projection – “Candy Cane” data

G3.2 Results from Real Data from LED Manufacturers

In many decay scenarios, the differences in RSME values among several models may not be sufficiently significant to pick an obvious winning model. In an example of a set of real LED decay data, shown in Figure G4, the differences of RSME values among all models are not large enough to make a selection of the “best fit” model. A method applied in this study was to use the 10th and 90th percentiles of the two adjacent models as the criteria to separate models for model selection. A model is selected only if its 90th percentile is equal to or lower than the 10th percentile of the adjacent models.

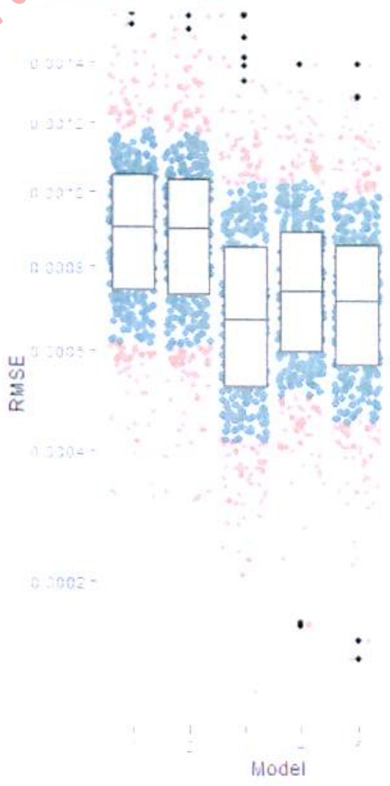


Figure G4 Box plot of RMSE values for each model – real LED data

In this case a winning model could not be chosen under the aforementioned criteria as all models had similar RMSE results. The L_{70} projection values calculated by the five models for this dataset are vastly different, as shown in Figure G5. To be realistic in LED life projection and protect consumers' interest, when none of the models stands out as the best fit, it is considered appropriate to choose the most conservative L_{70} life prediction from those models with the lowest RMSE (those demonstrating appropriate model fit). In this case, model 1 predicts the shortest L_{70} life with the lower 25th percentile of its distribution at approximately 36000 hours. This LED product may have a potential lifetime longer than the projection of model 1, but at the 6000 hour test duration and resulting model fitting, there is insufficient evidence to provide an accurate longer prediction.

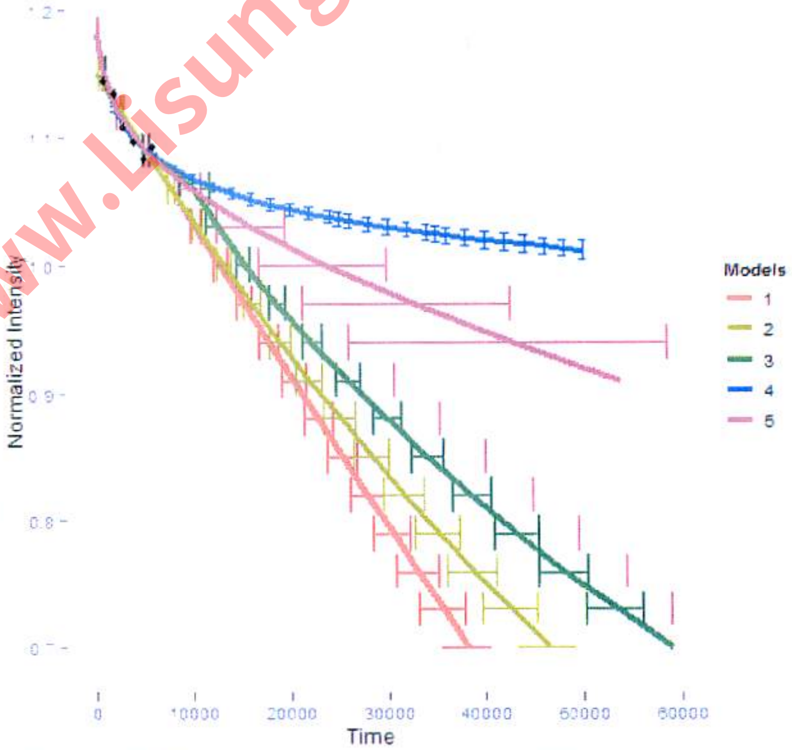


Figure G.5 Model projection – real LED data

The impact of noise from test condition variability on this small number of data points is detrimental to model fitting and always warrants larger errors, which translates to greater variability in L_{70} projections for a given model. Furthermore, the true decay profile of this particular LED may not yet manifest itself with only 6000 hours of data. When this same product was measured every 1000 hours up to a total of 15000 hours, the true decay profile was better represented by some of the models considered (see Figure F7). This is shown in Figure G6, where models 3, 4, and 5 clearly fit the data better, as indicated by their lower RMSE values than those of models 1 and 2. This would suggest that excluding models 1 and 2, due to their lack of fit, from model selection would be appropriate. Because the overlaps of RMSE values between models 3, 4 and 5 are greater than 10% of their populations respectively, one model among these does not dominate for L_{70} estimates. Instead, the L_{70} life prediction is chosen as the most conservative among this group. Model 5 has the smallest L_{70} estimate of the three better fitting models, as seen in Figure G7, and so the L_{70} life of this LED product is considered to be 130000 hours. In comparison, the results with only 6000 hours of data showed a much more variable distribution of the L_{70} estimate and a lower estimate of 36000 hours. The available longer test data demonstrated an expected reduction in decay over time, and reduced variability in the model parameters, thus improving the argument for use of a goodness-of-fit criterion.

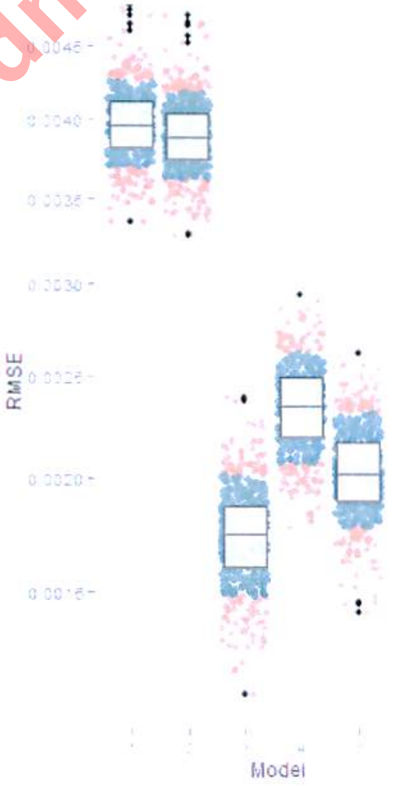


Figure G6 Box plot of RMSE values – real LED data with longer test duration

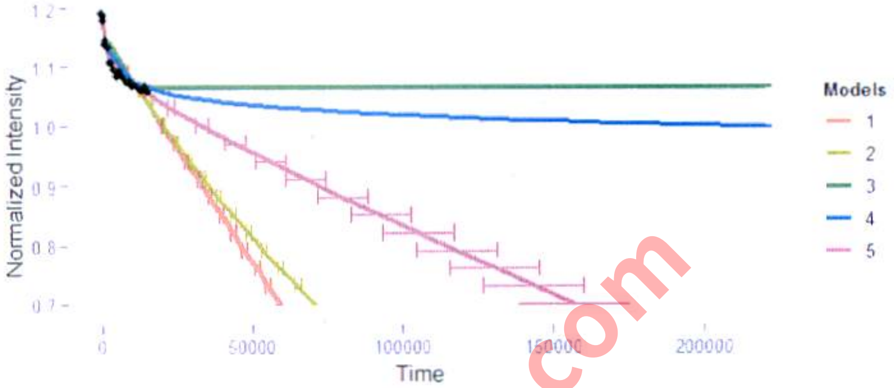


Figure G7 Model projection – real LED data with longer test duration

Additional modeling using the real product data was conducted on the longer datasets to attempt to validate an RMSE based model choice or elimination using a future actual data point. For this analysis, longer datasets (10000 hours and greater) were fit to the first 6000 hours (or longer if the datasets were longer than 10000 hours). The predicted light output at the end of the data stream using the first 6000 hours of data was compared with the actual output to determine if the model(s) with the best RMSE fit consistently had the closest match to the real data point. Unfortunately, with the data sets available, this verification was not confirmed. The best model fit to the real data values was not always the model with the best RMSE fit at 6000 hours and in some cases up to 10000 hours.

Other statistical techniques could be used to determine a "winning" model including using the PRESS statistic. However, such methods find only partial relevance to our problem. They are useful in predicting in the data space (region where data are available, such as 0 to 6000 hours), but not generally applicable when extrapolating well beyond the limits of the data range.

G.4.0 Summary and Conclusions

The summary findings from these analyses pointed to the inability of a statistical metric such as RMSE (or SSE, R^2) to always reasonably identify a model that could provide a "best fit" and therefore best projection (extrapolation) of LED lumen degradation. Specific conclusions include:

a) RMSE (or R^2, SSE, etc.) comparing model fits will not be significant enough to pick a best model with only 6000 hours of real data.

b) RMSE may help identify a group of models at longer data periods such as 15000 hours where the decay structure becomes more obvious.

c) Some models that may exhibit good fit at 6000 or 15000 hours may not be realistic.

d) Measurement uncertainty in the data could result in poor model fit and extravagant life estimates. To achieve an appropriate estimate, the standard errors on the parameters of the model fits are used to construct a confidence band around the mean prediction. This provides for the representation of a prediction based on a confidence that a specific sample will fall within a certain range around the mean value.

e) Measurement repetition, data length, measurement frequency can support better model fit, though data length is easily the best way to improve model selection (by seeing more of the degradation curve).

f) Use of models fit to only 6000 hours of a dataset, the model with the best RMSE fit does not consistently estimate the closest actual L_{70} at the end of the dataset (up to 15000 hrs) – this is because at 6000 hours often the product hasn't exposed its decay structure (the decay structure tends to change around 5000 to 6000 hours so predictions won't match expectation without sufficient hours of observations).

g) It may be reasonable to use RMSE to choose a group of possible models, which may be useful in eliminating poor fit models.

h) Other models may be appropriate to explore, but all (especially those more complicated ones) will be subject to the same restrictions/limitations as those that have already been explored.

i) For most accurate and statistically sound, predictions, models should be fit to all units of the product (not just the means) to reduce variability in the predictions as standard model fitting practice.

j) RMSE may be reasonable for choosing a single best model with data sets much longer than 6000 hours but most likely well above 10000 hours. However, for the fast emerging LED industry, longer testing isn't believed to be practical, though clearly important.

G5.0 References for Annex G

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Iluminating Engineering Society of North America
120 Wall St. 17th Floor New York, NY 10005
http://www.iesna.org