EPA ENERGY STAR Lamp Round Table
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IES TM-21-11 Overview, History and Q&A Session

Cameron Miller
Sensor Science Division
National Institute of Standards & Technology

Outline

1. TM-21-11 scope and definitions (Section 1.0 & 3.0)
2. Test data and sample size (Section 4.0)
3. Lumen maintenance life projection (Section 5.0)
   - Mathematical models (Annex G)
   - Limit of duration for prediction (Annex D)
4. Temperature data interpolation (Section 6.0)
5. Example calculation (Annex E)
6. Questions

TM-21-11 Scope and Definitions

1.0 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."

TM-21-11 Scope and Definitions

3.2 LED Light Sources

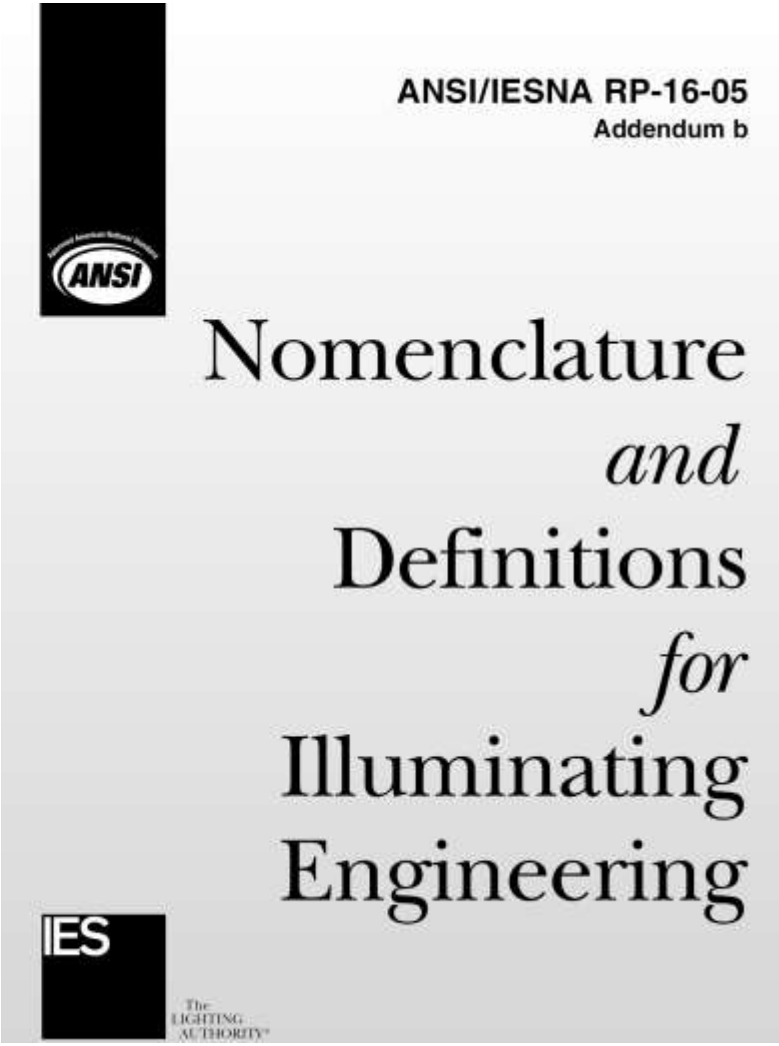
LED package, array, or module that is operated via an auxiliary driver.

3.6 Rated Lumen Maintenance Life, (Lp)

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

TM-21-11 Scope and Definitions



6.8.5.1 LED package

An assembly of one or more LED dies that includes wire bond or other type of electrical connections, possibly with an optical element and thermal, mechanical, and electrical interfaces.

6.8.5.2 LED array or module

An assembly of LED packages (components), or dies on a printed circuit board or substrate, possibly with optical elements and additional thermal, mechanical, and electrical interfaces that are intended to connect to the load side of a LED driver.

Power source and ANSI standard base are not incorporated into the device. The device cannot be connected directly to the branch circuit.

Test Data and Sample Size

4.1 Data to be Used

Collected according to 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 should be used

Minimum of 20 units to use a multiplication factor of 6 times the duration

Sample size of 10 to 19 units a multiplication factor of 5.5 shall be used

Sample size less than 10 this method shall not be used

4.3 Luminous Flux Data Collection

Additional measurements at intervals less than 1000 hours encouraged

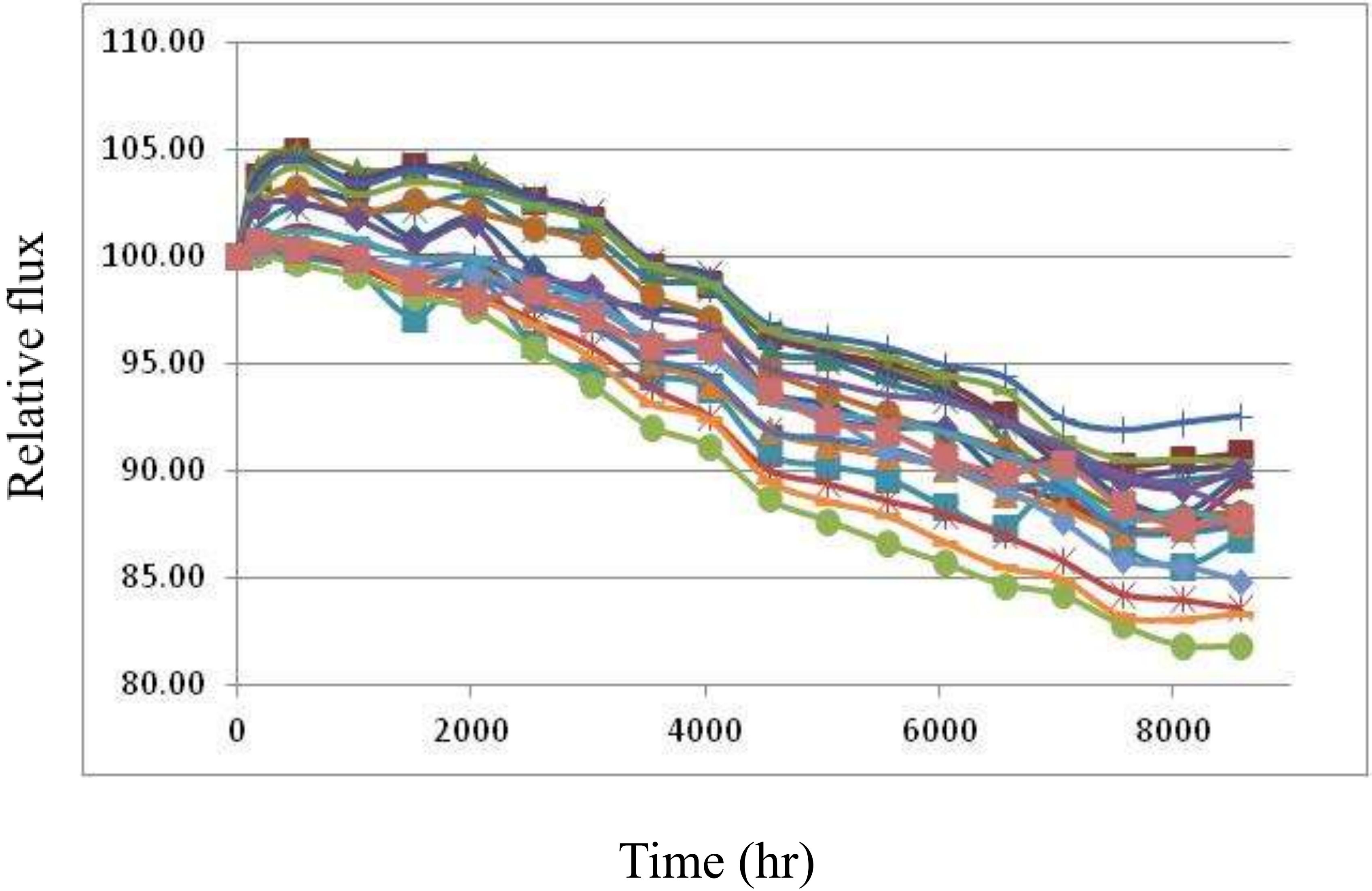
Additional measurements beyond 6000 hours encouraged

Lumen Maintenance Life Projection

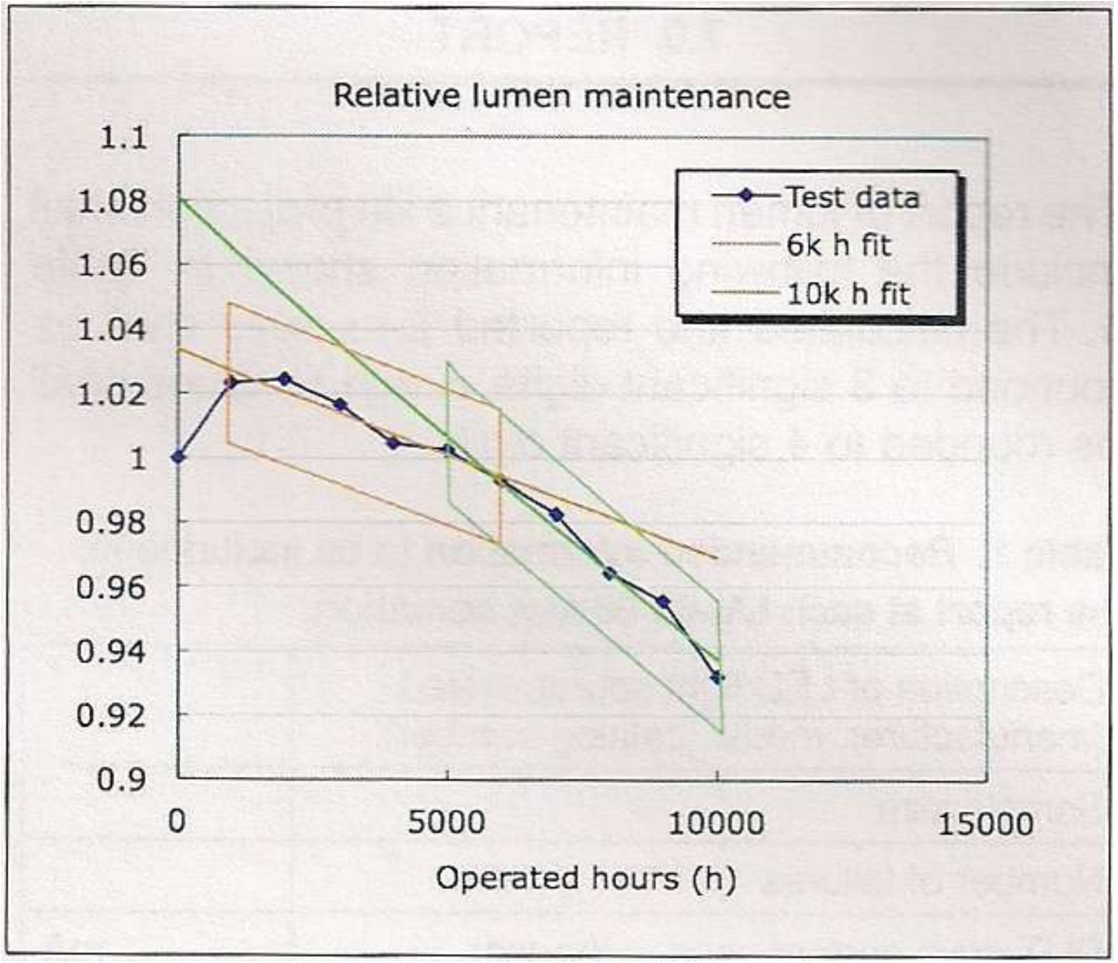
1. Normalize all data to a value of 1 at 0 hrs
2. Average the normalized data at each measurement point
3. Data used for curve-fit
   1. Data less 1000 hrs shall not be used
   2. For data 6000 to 10,000 hrs in duration, the last 5000 hrs of data shall be used
   3. For data longer than 10,000 hrs in duration, the data for the last 50% of the total duration shall be used. If there is no data point at the 50% point of the total duration, use the next lower time point.

Example: 13,000 hr duration use 6500 hr – 13,000 hr
if there is no 6500 hr point, use 6000 hr point

Lumen Maintenance Life Projection

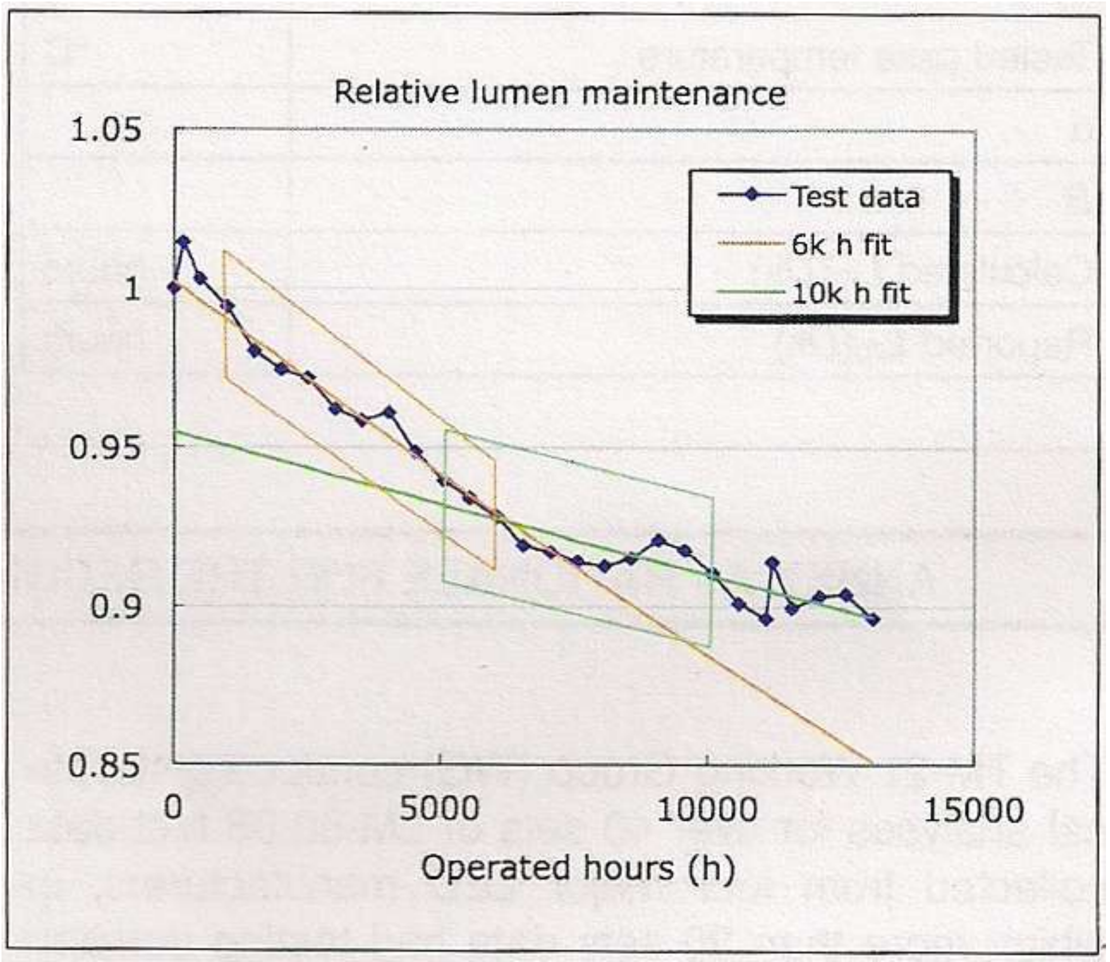


Lumen Maintenance Life Projection



1000 – 6000 hr: $L_{70}(6k) = 60{,}000$ hr
5000 – 10000 hr: $L_{70}(10k) = 30{,}000$ hr

Lumen Maintenance Life Projection



1000 – 6000 hr: $L_{70}(6k) = 30{,}000$ hr

5000 – 10000 hr: $L_{70}(10k) > 60{,}000$ hr limited by 6X

Lumen Maintenance Life Projection

4. Perform an exponential least squares curve-fit

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

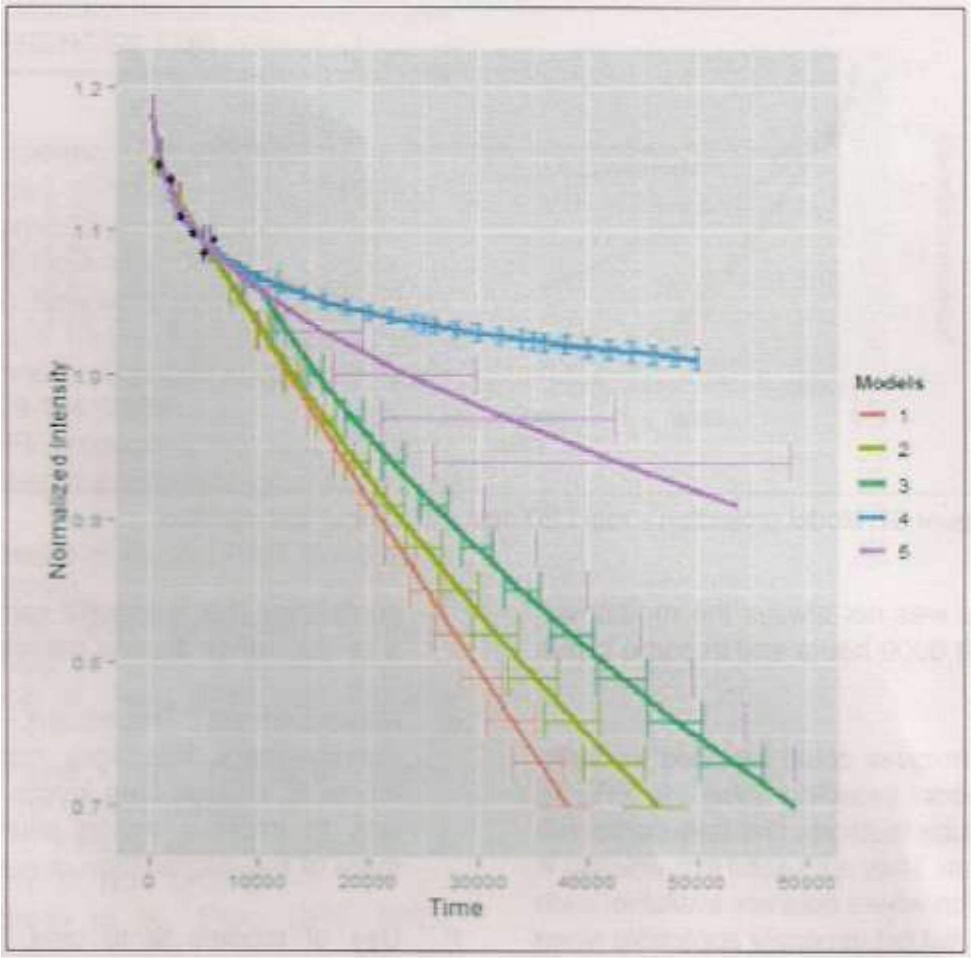
where:

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

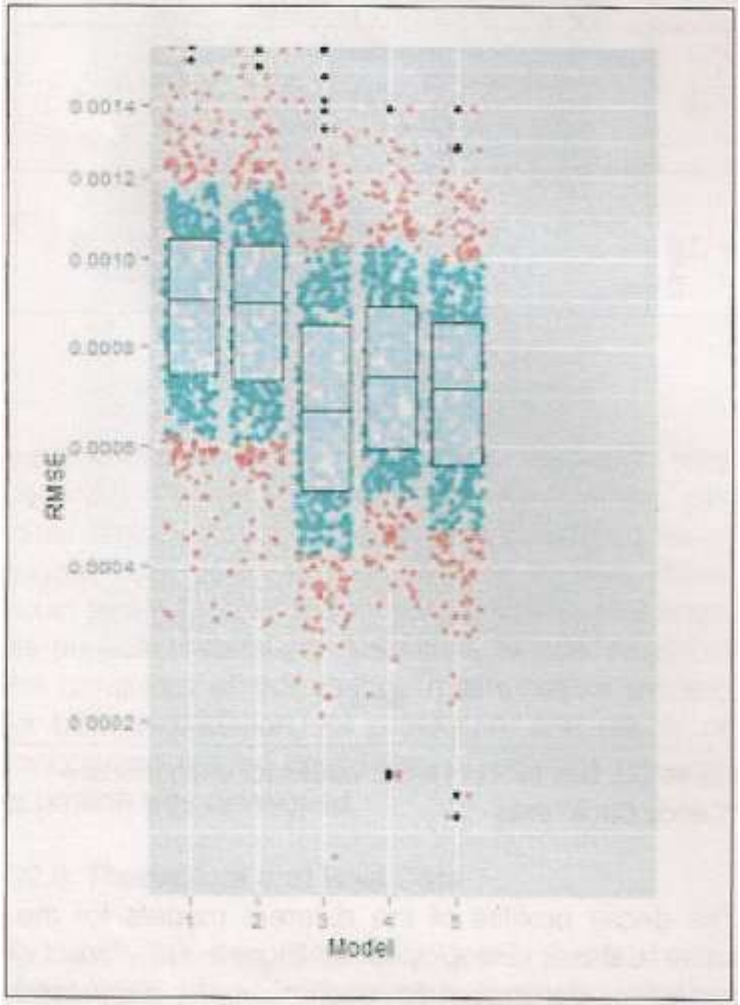
Lumen Maintenance Life Projection

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

Lumen Maintenance Life Projection

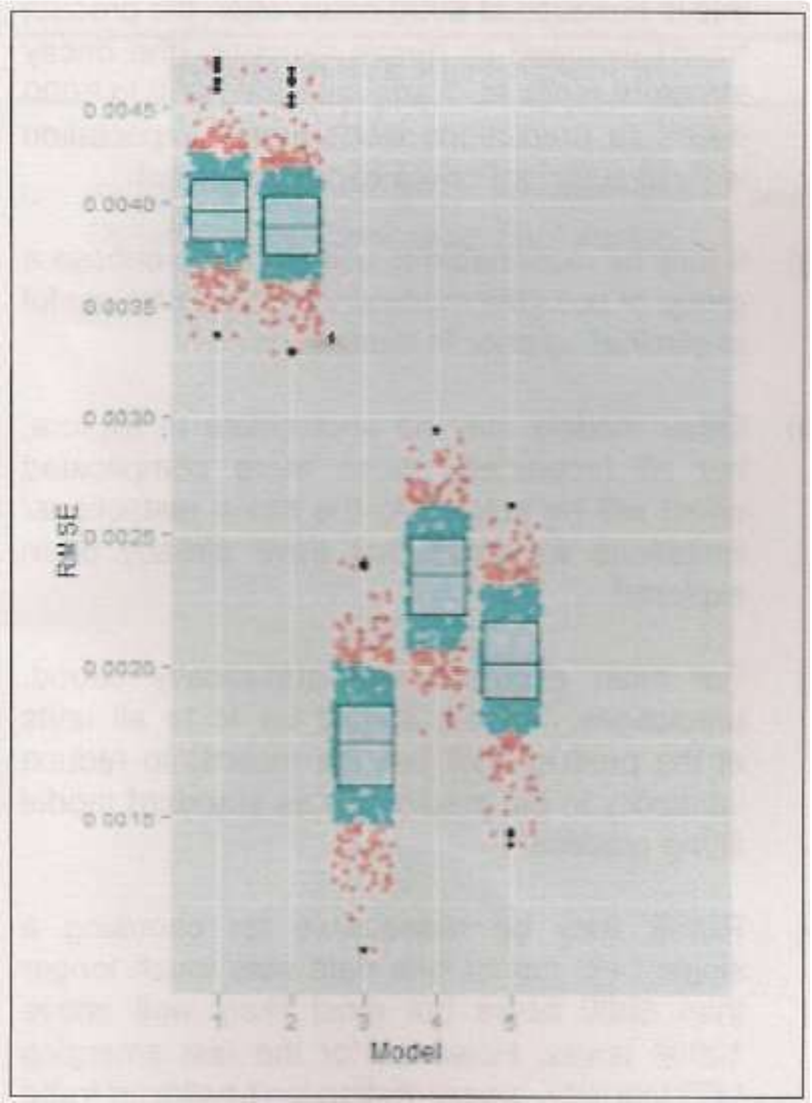


Use 10th and 90th percentiles from Monte Carlo runs



Models not distinguishable
use most conservative, L_{70}=36,000 hr

Lumen Maintenance Life Projection



- Comparing model fits by RMSE not good enough to pick best with 6000 hr of data
- Models that may exhibit good fit at 6000 hrs do not represent later data
- Many sets of data showed that a single model rarely had the best RMSE
- Complicated implementation

Lumen Maintenance Life Projection

5. Calculate the lumen maintenance life

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

where:

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

D = total duration time divided by 1000 and rounded to the nearest integer

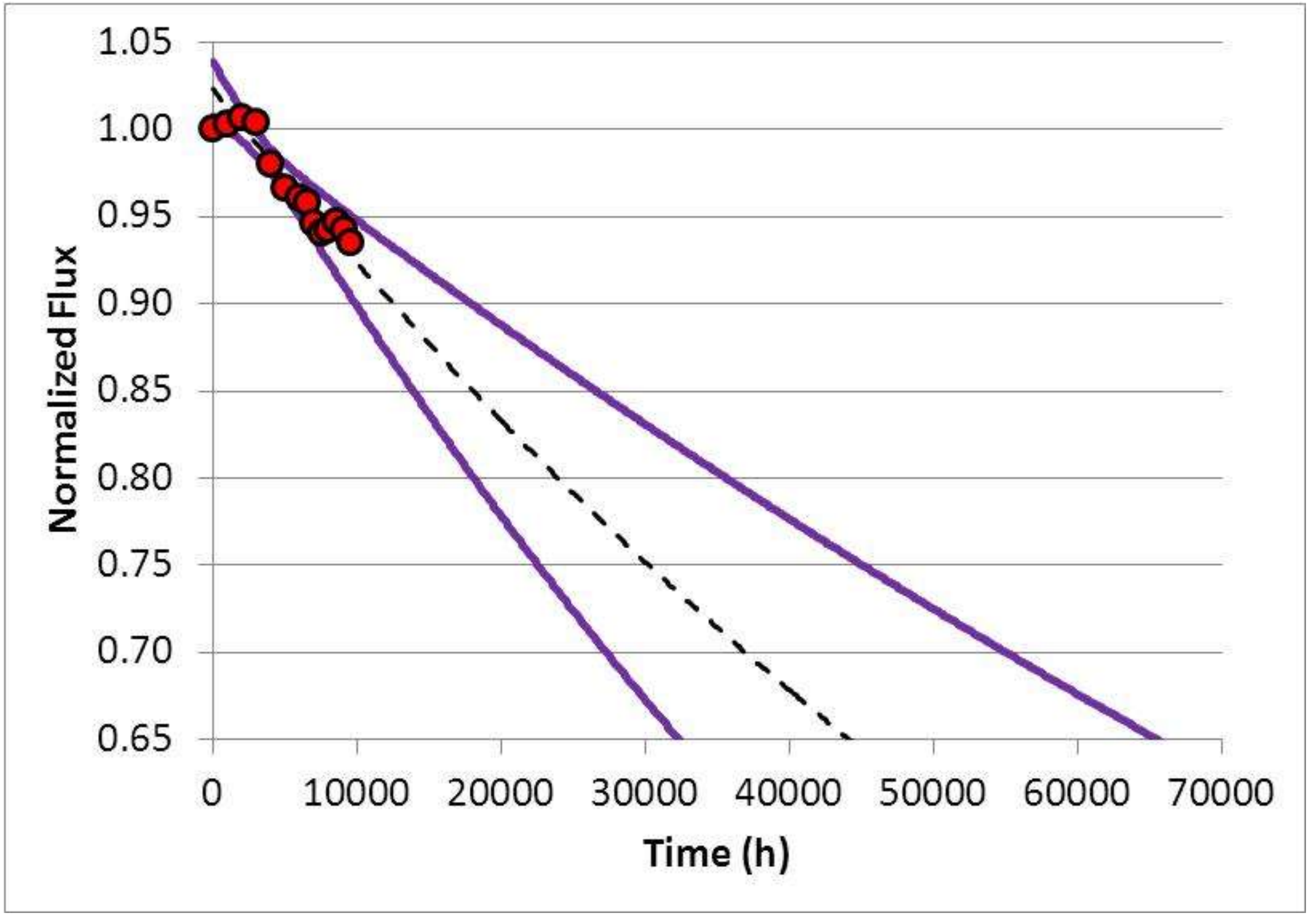
Whenever L_p value is reached experimentally, the reported value shall be obtained by linear interpolation between the two nearest test points.

Lumen Maintenance Life Projection

Adjustment of Results

- Sample size 20 or more, L_p shall not be projected longer than 6 times D
- Sample size 10 to 19, L_p shall not be projected longer than 5.5 times D
- When the calculated L_p is negative ($\alpha < 0$), the report L_p is 6 times D (5.5 times D for sample size 10 to 19)
- If the calculated L_p value is reduced by the 6 times rule, the L_p value shall be expressed with a greater than symbol.
  Example: (6k) > 36,000 hrs
- If the L_p value is reached experimentally, then the L_p value shall be expressed with the D value to be equal to the L_p value in hours divided by 1000 and rounded to the nearest integer.
  Example: (4k) = 4400 hrs

Lumen Maintenance Life Projection



‘6X Rule’

Confidence band – region within which the model is expected to fall with a certain level of probability

Lumen Maintenance Life Projection

Confidence band:

Student's t-function, coefficients of the model, and the estimated uncertainties of the coefficients

Estimated uncertainty of each data point:

component 1: standard deviation of the dataset for a given time divided by the square root of the number of points

component 2: the standard uncertainty of the measurement system for relative measurements over the time frame of the measurements

Analyze a matrix by adjusting these two components

Lumen Maintenance Life Projection

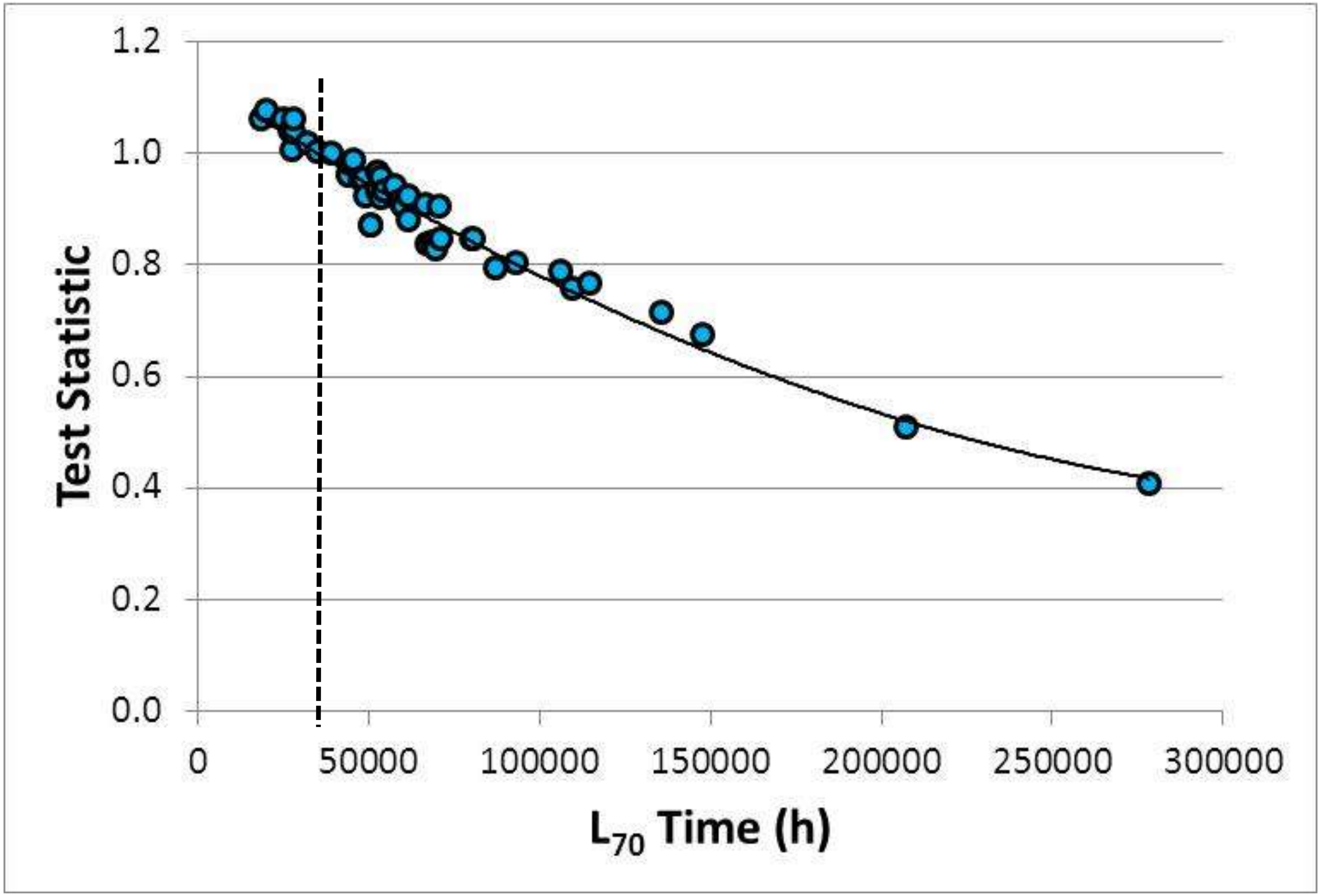
Number of points: 5, 10, 20, 30, 50, and 100

Relative standard uncertainty of the measurement system over time:
0.10%, 0.25%, 0.40%, 0.50%, 0.75%, and 1.0%

Level of probability was set a 90% using a one-sided distribution

1. Determine combined relative uncertainty
2. For same data calculate the lower confidence band L_{70}
3. Divide the lower confidence band L_{70} by the duration and the test multiplier
4. Repeat for all the data sets

Lumen Maintenance Life Projection



6X

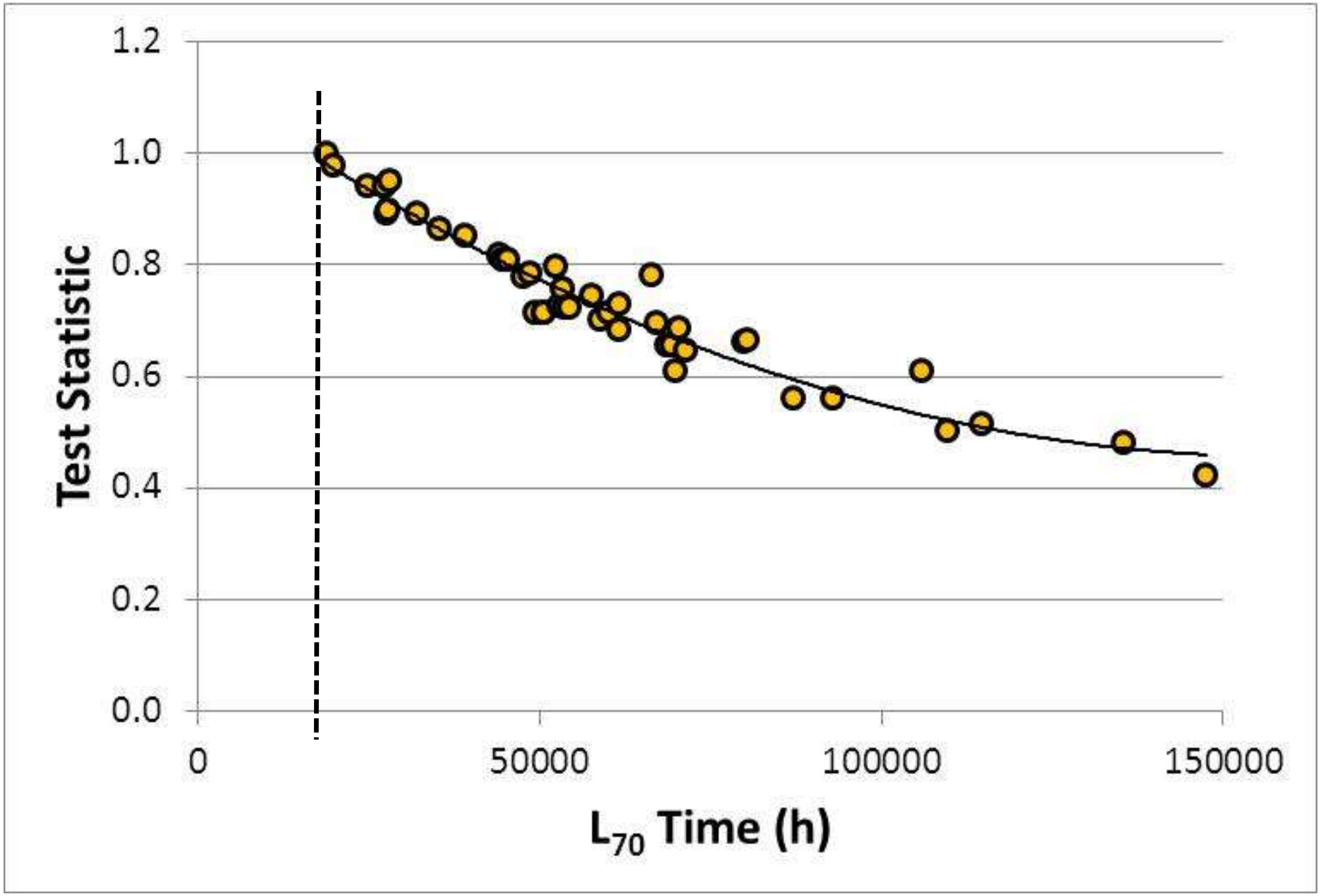
6000 hr

0.40 %

20 points

Hypothesis: Test statistic > 1 at the multiplier times the duration

Lumen Maintenance Life Projection



6X

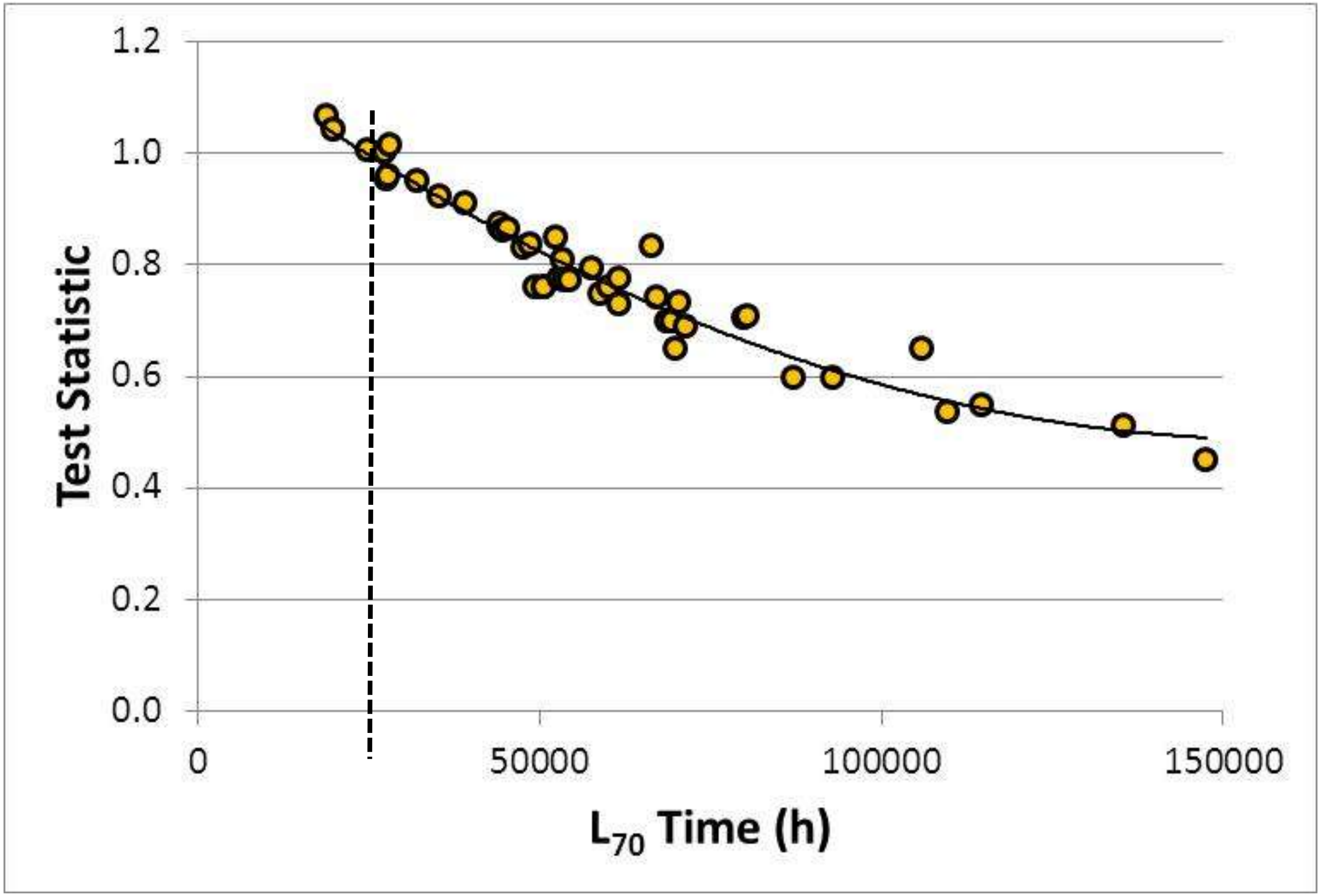
6000 hr

1.0 %

20 points

Test fails: 6X is too large for 1.0 % system uncertainty and 20 points

Lumen Maintenance Life Projection



4.1X

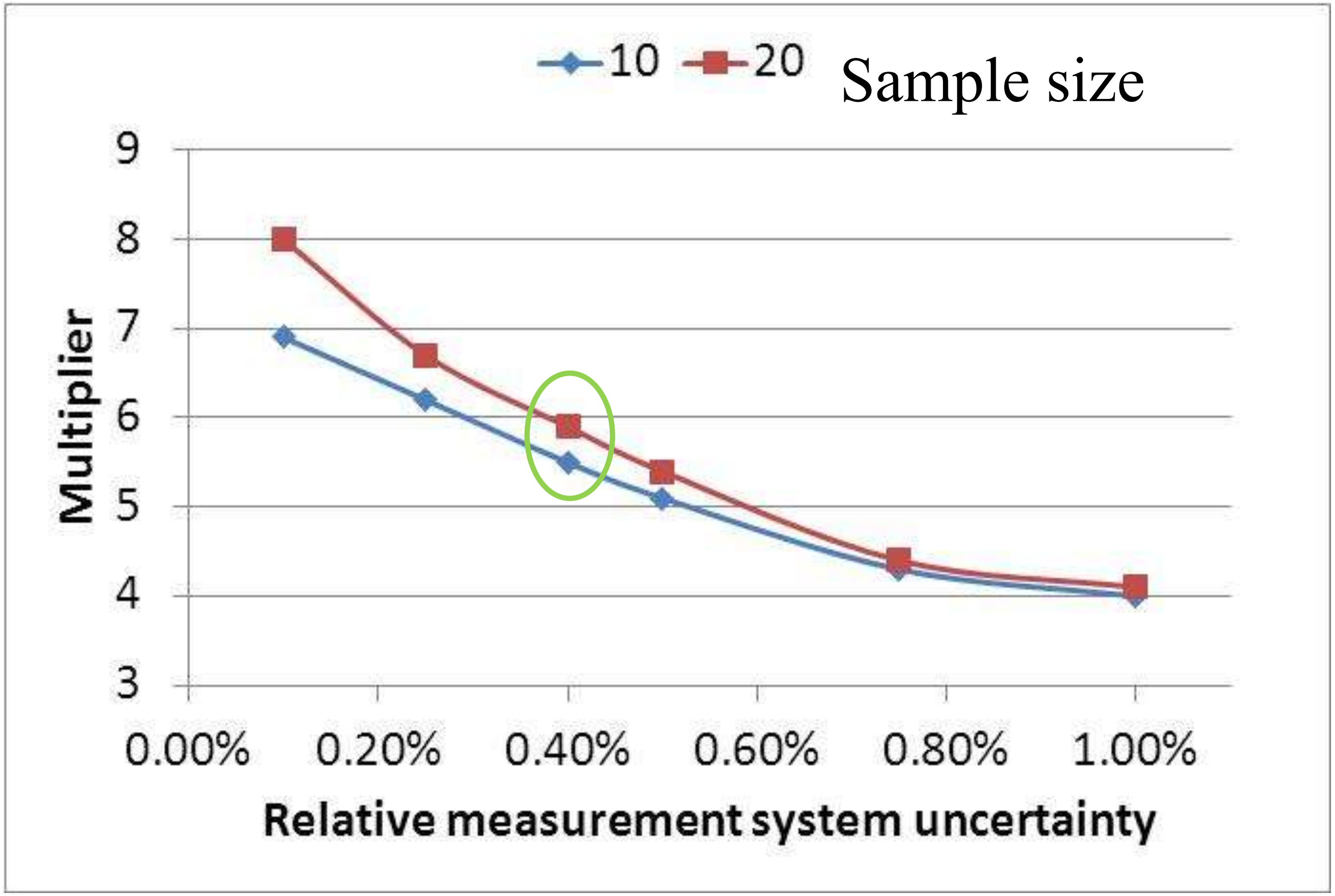
6000 hr

1.0 %

20 points

Test passes: Critical time 24600 hrs and fit determines 24680 hr

Lumen Maintenance Life Projection



Measurement laboratories surveyed are roughly 0.40 %

Assumption: model describes the system accurately

Temperature Data Interpolation

1. Select the closest lower and higher temperature
2. Convert all temperatures to Kelvin: $T_s[K] = T_s[°C] + 273.15$
3. Calculate decay rate at test temperature using Arrhenius Equation

$$\alpha_i = A\exp\left(\frac{-E_a}{k_B T_{s,i}}\right)$$

where:

A = pre-exponential factor

E_a = activation energy (eV)

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

k_B = Boltzmann's constant (8.6173x10-5 eV/K)

Temperature Data Interpolation

To complete step 3

Calculate the ratio of E_a/k_B

$$\frac{E_a}{k_B} = \frac{\ln \alpha_1 - \ln \alpha_2}{\dfrac{1}{T_{s,2}} - \dfrac{1}{T_{s,1}}}$$

Plug in $T_{s,1}$ to calculate A

$$A = \alpha_1 \exp\left(\frac{E_a}{k_B T_{s,1}}\right)$$

Temperature Data Interpolation

4. Calculate project initial constant for test temperature, B_0

$$B_0 = \sqrt{B_1 B_2}$$

where: B_1 = project initial constant for lower temperature

B_2 = project initial constant for higher temperature

5. Calculate L_p for in-situ case temperature

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

Temperature Data Interpolation

1. Use Arrhenius equation if α_1 and α_2 are positive
2. If only one a is positive, the corresponding lumen maintenance projections and L_p values shall be used for $T_{s,i}$
3. If neither is positive, the reported L_{70} at $T_{s,i}$ shall be the multiplier times the duration
4. Extrapolation shall not be performed for operating temperatures greater than the LM-80-08 test data
5. If the in-situ temperature is lower than the LM-80-08 test data the lowest LM-80-08 test data shall be used.

Example Calculation

Sample#	0	1000	2000	3000	4000	5000	6000
1	1.000	0.994	0.983	0.988	0.962	0.947	0.943
2	1.000	0.995	0.998	1.001	0.977	0.961	0.958
3	1.000	1.003	1.004	1.010	0.989	0.971	0.966
4	1.000	1.012	1.017	1.021	0.991	0.971	0.970
5	1.000	1.001	1.003	1.011	0.985	0.964	0.958
6	1.000	0.996	1.004	1.003	0.979	0.967	0.957
7	1.000	1.014	1.019	1.016	0.988	0.978	0.968
8	1.000	1.010	1.015	1.017	0.990	0.984	0.972
9	1.000	1.011	1.016	1.009	0.984	0.972	0.960
10	1.000	0.996	0.998	0.997	0.977	0.964	0.949
11	1.000	0.988	0.991	0.980	0.960	0.937	0.934
12	1.000	1.002	1.002	0.993	0.968	0.954	0.951
13	1.000	1.007	1.012	0.998	0.976	0.960	0.955
14	1.000	1.019	1.025	1.016	0.995	0.978	0.975
15	1.000	1.000	1.008	1.000	0.980	0.967	0.967
16	1.000	1.000	1.008	1.002	0.973	0.963	0.951
17	1.000	1.006	1.014	1.011	0.984	0.973	0.967
18	1.000	1.002	1.005	1.005	0.980	0.970	0.969
19	1.000	0.999	1.001	0.997	0.974	0.964	0.962
20	1.000	0.997	1.005	1.001	0.978	0.967	0.972

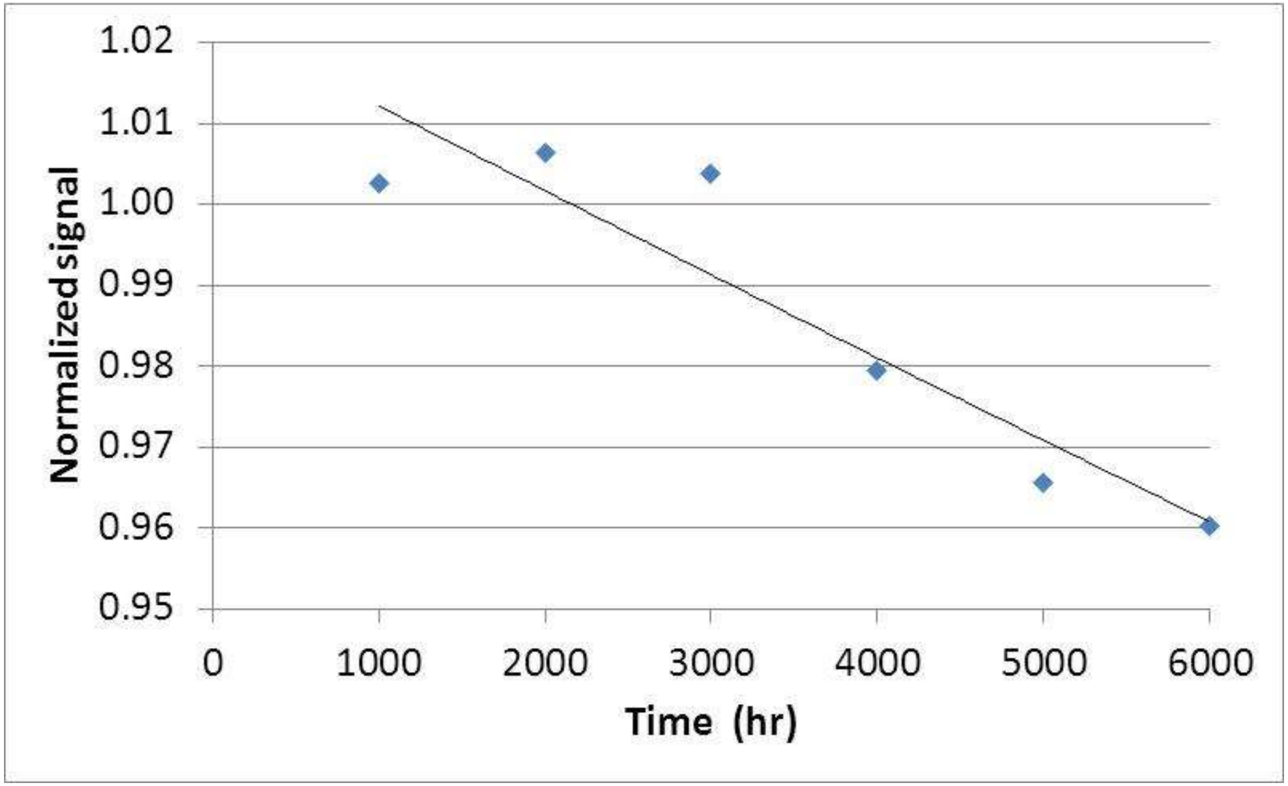
Case Temp: 55°C

20 units

Normalized

Example Calculation

Time	0	1000	2000	3000	4000	5000	6000
Average	1.0000	1.0026	1.0064	1.0038	0.9795	0.9656	0.9602



$$B = 1.023$$

$$\alpha = 1.042 \cdot 10^{-5}$$

$$L_{70} = 36392 \text{ hr}$$

Example Calculation

Sample#	0	1000	2000	3000	4000	5000	6000
1	1.000	1.000	0.974	0.981	0.967	0.950	0.909
2	1.000	1.008	1.003	1.005	0.986	0.964	0.942
3	1.000	1.000	0.981	0.984	0.955	0.939	0.914
4	1.000	1.010	1.006	1.003	0.979	0.958	0.937
5	1.000	1.002	0.992	0.997	0.977	0.962	0.933
6	1.000	1.002	1.003	1.003	0.980	0.965	0.946
7	1.000	1.012	1.014	1.018	1.001	0.984	0.963
8	1.000	1.002	0.997	1.008	0.987	0.976	0.948
9	1.000	1.002	1.003	1.007	0.989	0.972	0.947
10	1.000	1.000	0.984	0.991	0.974	0.958	0.926
11	1.000	0.998	0.963	0.963	0.941	0.924	0.890
12	1.000	1.004	0.997	0.987	0.961	0.940	0.924
13	1.000	0.996	0.981	0.981	0.957	0.943	0.917
14	1.000	1.013	1.002	0.995	0.968	0.945	0.930
15	1.000	1.006	0.991	0.992	0.961	0.945	0.919
16	1.000	1.004	0.997	0.983	0.953	0.937	0.919
17	1.000	1.005	0.999	0.988	0.962	0.940	0.922
18	1.000	1.001	0.987	0.987	0.950	0.937	0.911
19	1.000	1.008	1.001	0.988	0.962	0.938	0.924
20	1.000	0.991	0.973	0.977	0.944	0.909	0.895

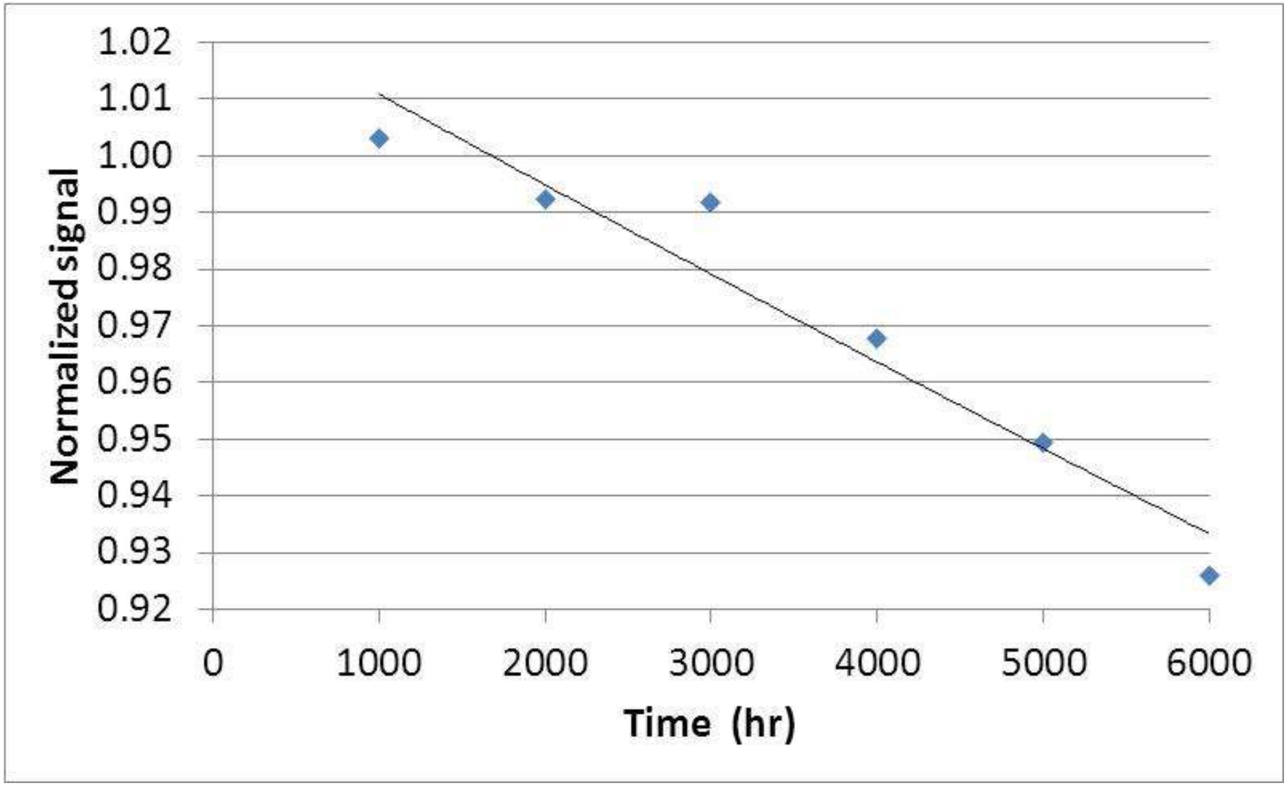
Case Temp: 85°C

20 units

Normalized

Example Calculation

Time	0	1000	2000	3000	4000	5000	6000
Average	1.0000	1.0032	0.9924	0.9919	0.9677	0.9493	0.9258



$B = 1.027$

$\alpha = 1.598 \cdot 10^{-5}$

$L_{70} = 23997$ hr

Example Calculation

Temperature Data Interpolation: L_{70} at 70°C

55°C = 328.15 K	85°C = 358.15 K
$B_1 = 1.023$	$B_2 = 1.027$
$\alpha_1 = 1.042 \cdot 10^{-5}$	$\alpha_2 = 1.598 \cdot 10^{-5}$
$L_{70}(6\text{k}) = 36392$ hr	$L_{70}(6\text{k}) = 23997$ hr

$$\frac{E_a}{k_B} = \frac{\ln \alpha_1 - \ln \alpha_2}{\frac{1}{T_{s,2}} - \frac{1}{T_{s,1}}} = 1675.5\text{K}$$

$$A = \alpha_1 \exp\left(\frac{E_a}{k_B T_{s,1}}\right) = 1.719 \cdot 10^{-3}$$

$$B_0 = \sqrt{B_1 B_2} = 1.025$$

Example Calculation

Temperature Data Interpolation: L_{70} at 70°C (343.15 K)

$$\alpha_i = A \exp\left(\frac{-E_\mathrm{a}}{k_\mathrm{B} T_{\mathrm{s},i}}\right) = 1.303 \cdot 10^{-5}$$

$$L_p = \frac{\ln\left(100 \times \frac{B_0}{p}\right)}{\alpha_i} = 29277\,\mathrm{hr}$$

Questions?