TM-21 Update: Method for Projecting Lumen Maintenance of LEDs

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The TM-21 Working Group:

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TM-21….What and When will we see it?

- What is TM-21?
  - An IES Technical Memorandum - Intended to be a companion to LM-80 (LED lumen degradation measurement method)
  - A method of projecting long term lumen maintenance of an LED light source based on 6,000 hours (or more) of lumen depreciation data collected per LM-80
- When will it be available?
  - The working group has completed its development work
  - A final draft is ready and is (or soon will be) out for full IES TPC vote/comment
  - IES Board approval and publication will follow (don't expect a published document until at least July)
- THE CAVEAT!!!!!!!!
  - TM-21 is still in IES vote/comment stage
  - Document may change with comments
  - Information provided here is preliminary and not sanctioned by IES

Development Background

- Almost 3 years in the making
- Initial work looking at multiple models that may be useful in projections of lumen depreciation
- Much analysis on model fit methods and “goodness of fit” metrics
- Realization of the limited capability of statistics with streams of data 1/10 or less of desired projections
- Extensive analysis results lead to consideration of basic decay model (exponential) but applied to “end” data
- Additional work on developing appropriate “multiplier” rule and associated acceptable sample size.
- Final extensive development of technical support annex material and a calculation verification sample set

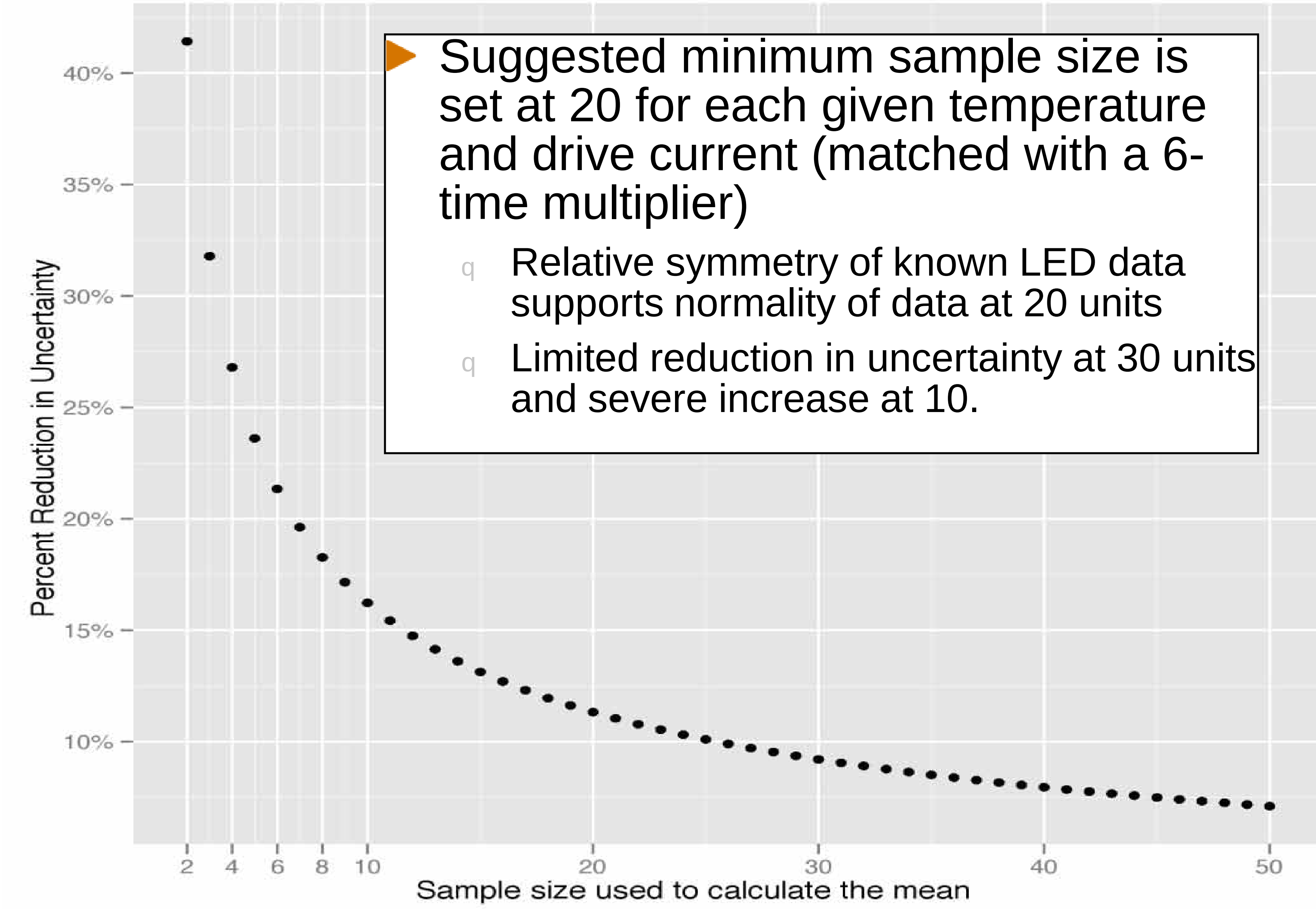
The Method: First, Normalize and Average

- Normalize all data to 1 (100%) at 0 hours
- Average each point for all samples of the device for each test condition
  - Averaging is done for simplicity of application
  - Variance associated with multiple samples is not considered actionable for projection

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**

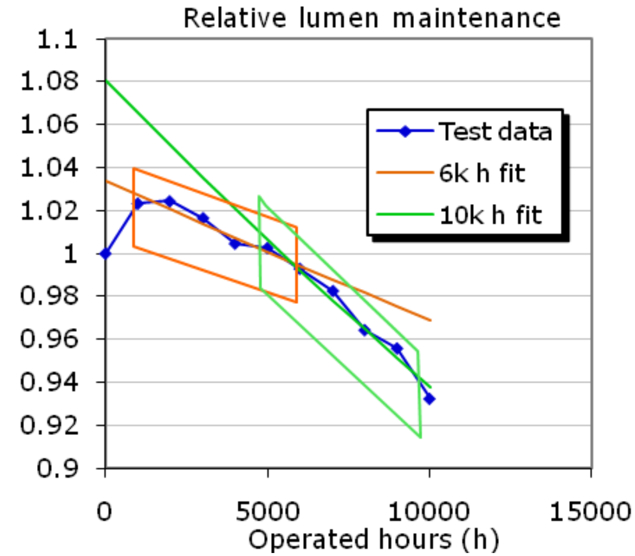
Sample Size

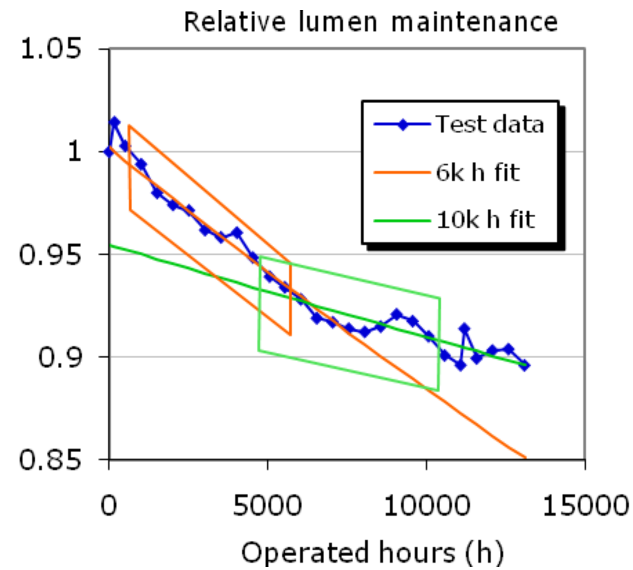
- Suggested minimum sample size is set at 20 for each given temperature and drive current (matched with a 6-time multiplier)
  - Relative symmetry of known LED data supports normality of data at 20 units
  - Limited reduction in uncertainty at 30 units and severe increase at 10.



Use Latest Data

- Initial data variability (i.e. "hump") is difficult for models to evaluate (0-1000 hr)
- Later data exhibits more characteristic decay curve of interest
  - Non-chip decay (encapsulant, etc.) occurs early and with varying effects on decay curve
  - Later decay is chip-driven and relatively consistent with exponential curve
  - Verification with long duration data sets (>10,000 hr) shows better model to reality fit with last 5,000 hours of 10,000 hour data
- For 6,000 hours of data (LM-80 minimum) and up to 10,000 hours: Use last 5,000 hours
- For > 10,000 hours: Use the last ½ of the collected data





Curve Fit and Projection

- Apply 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.

- Project lumen maintenance "life"

$$L_p = \ln(100*B/\mathrm{p})/\alpha$$

Where:

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

- Can accommodate user identified L_p (I.e. L_{70} L_{50})
- If L_p reached during testing – must use that value

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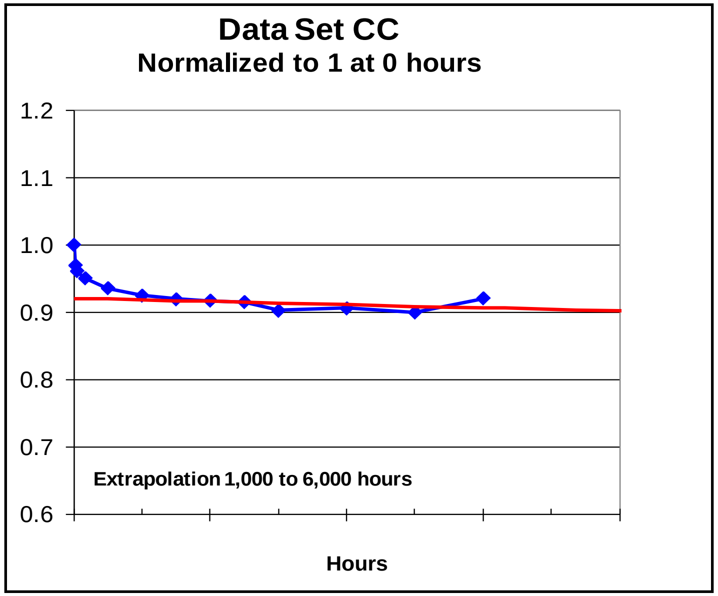
Adjust Results (X-times rule)

- Some indications from limited 6000 hr data are not believable – reasonable limits on predictions are needed
- Analysis was completed on 40 sets of data to determine model fit uncertainty and relationship to prediction limits
  - A 0.40% relative combined uncertainty of the measurement system was assumed
  - Prediction confidence of 90% applied
  - Multiplier (i.e. 6 times) is tested to see if it falls within confidence band of projections at a given sample size



Results:

For sample size of 20, max projection = 6 times test duration

For sample size of 10, max projection = 5.5 times test duration

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Interpolation of Results

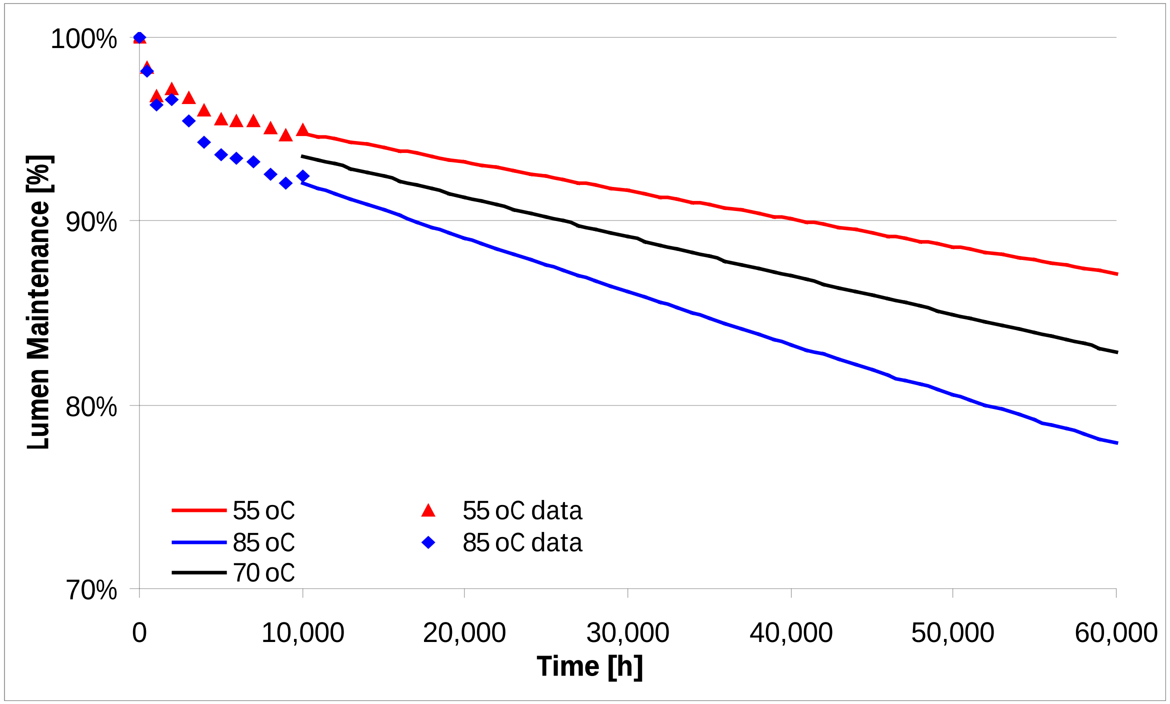
- The format of LM-80 testing (and followed by TM-21) is that testing LED modules at multiple temperatures provides data for matching in-situ performance (i.e. when installed in a luminaire)
- In-situ temperature must be within the LM-80 test temperatures (55°C, 85°C, and user chosen)
- Use Arrhenius equation to interpolate between test temperatures
  - Arrhenius accounts for the temperature effect on decay rate constants – important for temperature dependant LEDs!
  - Multi-step process
- Extrapolation outside of LM-80 test temperatures is not recommended or supported

Interpolation Example

Parameters of interpolation using 10,000 hours of LM-80 data for in-situ case temperature $T_{s,i}$ = 70 °C

$T_{s,1}$, (°C)	55
$T_{s,1}$, (K)	328.15
a_1	1.684E-06
B_1	0.9639
$T_{s,2}$, (°C)	85
$T_{s,2}$, (K)	358.15
a_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)	343.15
a_i	2.413E-06
Projected L_{70}(Dk)	130,131
Reported L_{70}(Dk)	>60,000



Result Reporting Notation

- Apply consistent "life" notation to results.

  General form: $\boldsymbol{L_p}$ **(*D*k)**

  p = the percentage of initial lumen output that is maintained

  D = the total duration of the test in hours divided by 1000 and rounded to a nearest integer

- Examples:

L_{70}(6k) = 34000 hours	for 6000 hours test data
L_{70}(10k) = 51000 hours	for 10000 hours test data
L_{70}(6k) > 36000 hours	for values with the 6 times rule applied
L_{70}(4k) = 4400 hours	for value reached experimentally

Reporting/Documentation

- Report test and calculation details using consistent and complete format
- When interpolation used, calculation results must also be shown

$T_{s,1}$, (°C)	55
$T_{s,1}$, (K)	328.15
a_1	1.684E-06
B_1	0.9639
$T_{s,2}$, (°C)	85
$T_{s,2}$, (K)	358.15
a_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
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a_i	2.413E-06
Projected L_{70}(Dk)	130,131
Reported L_{70}(Dk)	>60,000

Recommended reporting information	
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
a	
B	
Calculated L_{70}(Dk)	hours
Reported L_{70}(Dk)	hours

Calculation Verification

- The method is provided as formulas and procedure
- This can be easily developed in spreadsheet or similar common software tools

  ….but calculations can be easily miss-coded

- A verification example – data + calculation results is provided to allow checking of process and results

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

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How Will TM-21 be Applied

- TM-21 may be adopted by organizations/programs as documentation of performance (i.e. Energy Star)
  - Program may define who does calculations (lab, manuf, other)
  - Program could do calculations themselves
- TM-21 may be requested as part of LM-80 testing
  - Test lab will need to develop calculation sheet
- TM-21 may be applied by a manufacturer
  - Oversight/random checking of calculations will be prudent

It is likely that TM-21 will achieve widespread adoption and use

- Questions?

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