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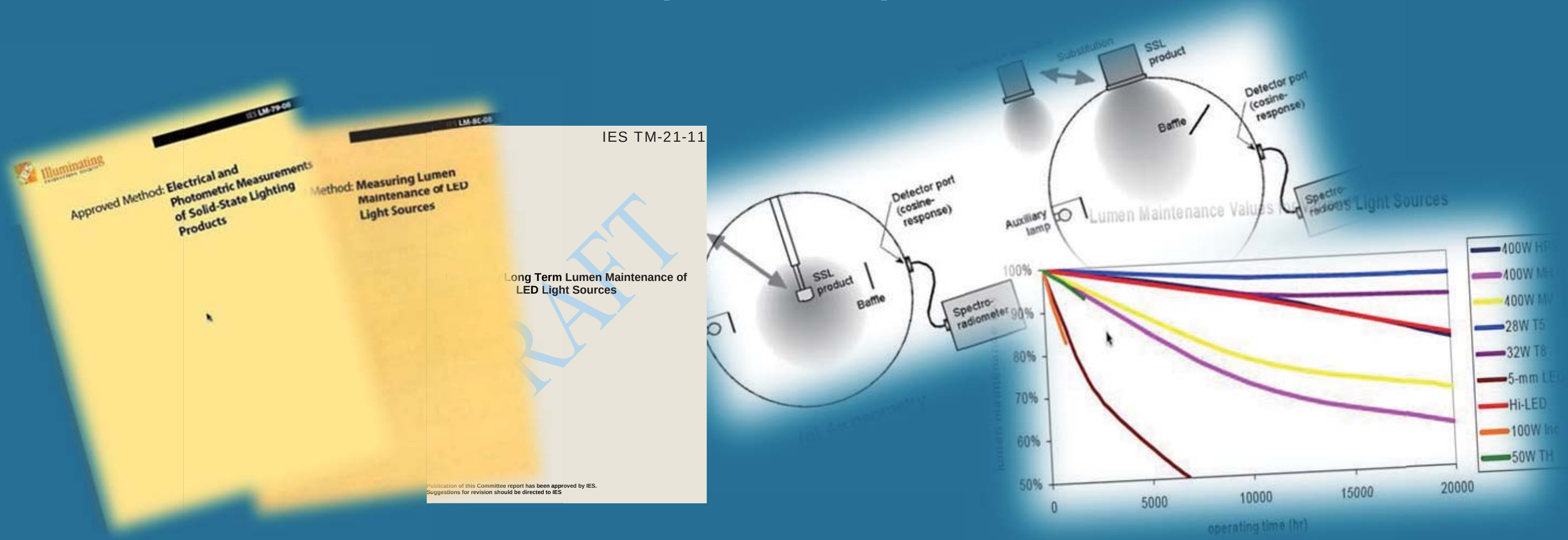
Understanding LED tests: IES LM-79, LM-80, and TM-21

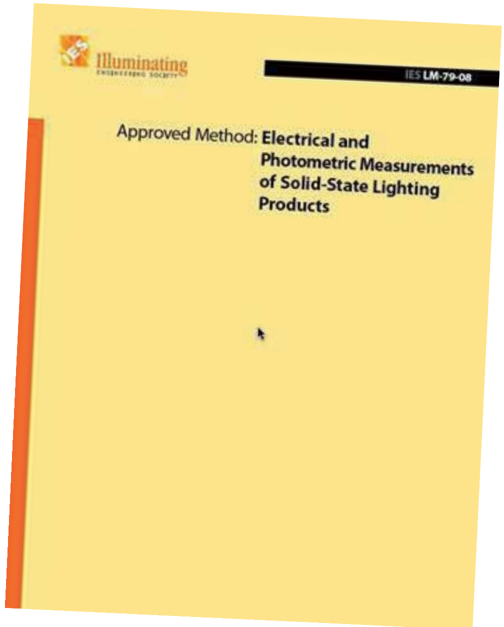


DOE SSL Workshop
July, 2011

Eric Richman
Pacific Northwest National Laboratory

Electrical and Photometric Measurements of Solid-State Lighting Products

- Approved method describing procedures and precautions in performing reproducible measurements of LEDs:
  - total flux,
  - electrical power,
  - efficacy (lm/watt), and
  - chromaticity



LM-79 Scope

- Applies to LED-based products incorporating control electronics and heat sinks:
  - Products requiring only line voltage or DC power supply
  - Includes complete LED luminaires and
  - Integrated LED products (LED chips with heat sinks)
- Does *not* cover
  - LED products requiring external operating circuits or heat sinks (bare LED chips, pkgs, and modules)
  - Fixtures designed for LED products but sold without a light source

LM-79 Absolute Photometry Basis

- LM-79 requires complete luminaire testing
- Traditionally, photometric evaluation of lighting products is based on separate tests for lamps and luminaires (“relative”)
- For SSL products, LED lamps typically *cannot* be separated from their luminaire because of heat effects (“absolute”)

LM-79 Procedures/Conditions

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- Ambient conditions
  - Temperature – maintain at 25C +/-1C (within 1m)
  - Mounting – limit thermal transfer
  - Air flow - limited
- Power Supply characteristics
  - AC waveshape limit to harmonic RMS of 3%
  - Voltage regulation to +/- 2%
- Seasoning and stabilization
- Testing orientation
- Electrical settings
- Instrumentation

LM-79 Method: Integrating Sphere

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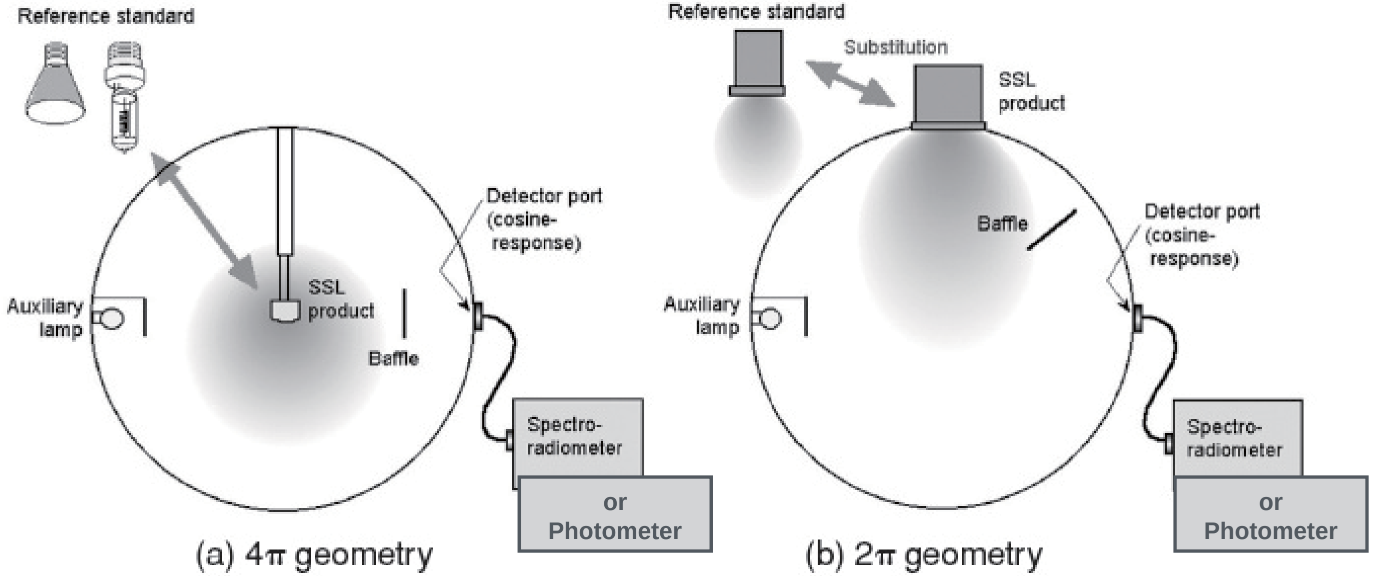
For measuring Total luminous flux and color:

- Photometer – Total Luminous Flux
- Spectral Radiometer (preferred) - Spectral Radiant Flux (to derive total luminous flux and color qualities)

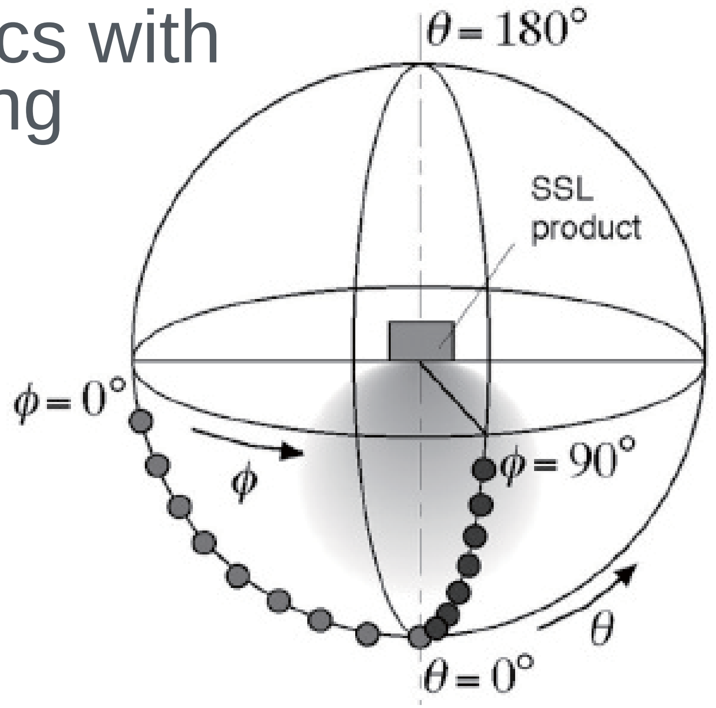


(a) Setup for all types of SSL products emission (b) Setup for SSL products with only forward output

LM-79 Method: Goniophotometer

For measuring luminous Intensity Distribution

- Total Luminous Flux is derived
- Provides color characteristics with Spectral radiometer including CCT, CRI

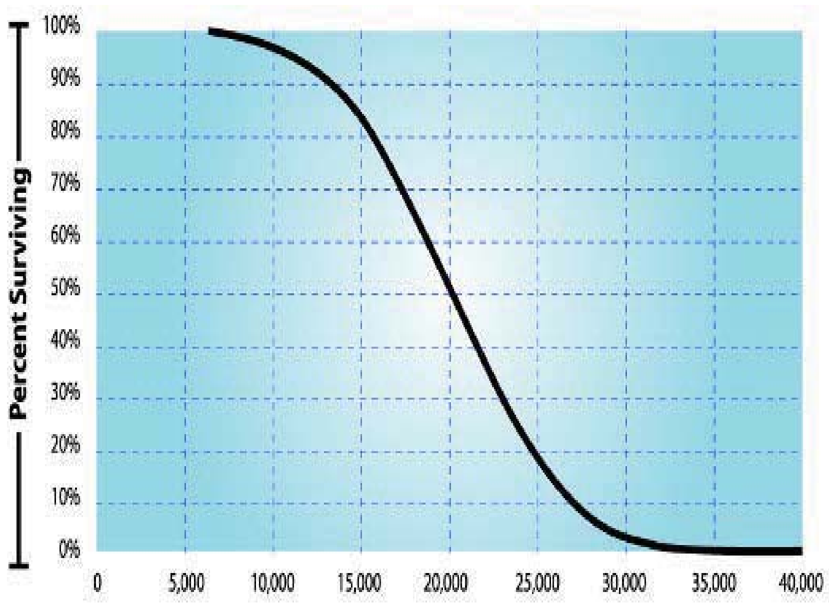


LM-79 Test Outputs/Calculations

- Total Luminous Flux
- Luminous Intensity Distribution
- Electrical Power
- Luminous Efficacy (calculation)
- Color Characteristics
  - Chromaticity
  - CCT
  - CRI

What is "Life" for Lighting?

- "Operational failure"
  - Most light sources "burn out" (End of "Life")
  - Lamp life is typically rated at 50% failure rate
  - ***LEDs** typically don't fail (no filament to "burn")*

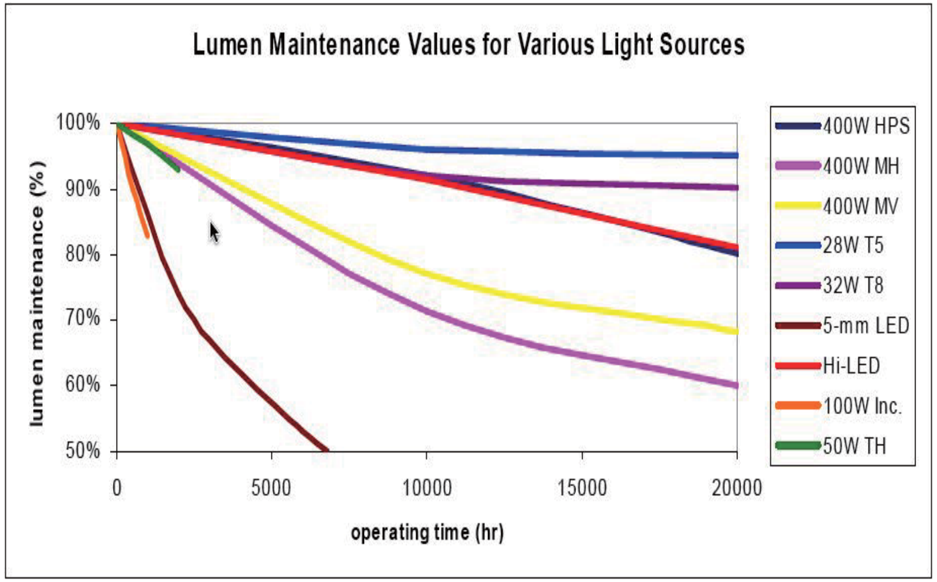


Rated lamp life is point where 50% of lamps have failed, or 20,000 hours on this curve.

“Life” for LEDs

Useful light output (Lumen Maintenance)

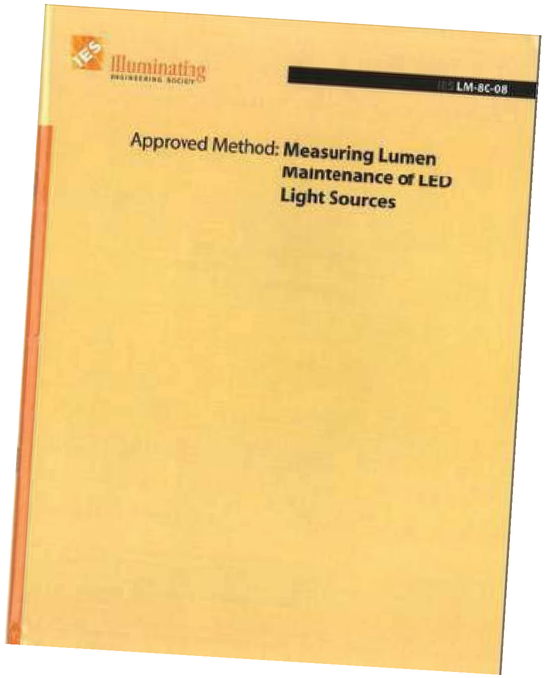
- All light sources degrade but most just “burn out” before serious loss of light output
- LEDs continue to degrade – eventually beyond useful light output



Source: Lighting Research Center - Rea 2000; Bullough 2003

Measuring Lumen Maintenance of LED Light Sources

- Approved method for measuring lumen depreciation of solid-state (LED) light sources, arrays and modules.
- Does not cover measurement of luminaires.
- Does not define or provide methods for estimation of life.



LM-80 Procedures/Conditions

- Ambient conditions and setup
  - Case Temperature measured and maintained
  - Case Temperature measurement point
  - Airflow minimized
  - Operating orientation & spacing per manufacturer
- Electrical
  - Voltage and Current (AC or DC levels)
  - Voltage waveshape (harmonic distortion <3%)
  - Current Regulation

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LM-80 Measurement Methods

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- Case Temperatures
  - Measurement performed at multiple temperatures to address in-situ conditions
  - 55C, 85C and 3rd manufacturer selected temperature
- Testing Intervals
  - 6000 hours min testing period. 10K preferred.
  - Minimum at least every 1000 hours

LM-80 Testing Output and Use

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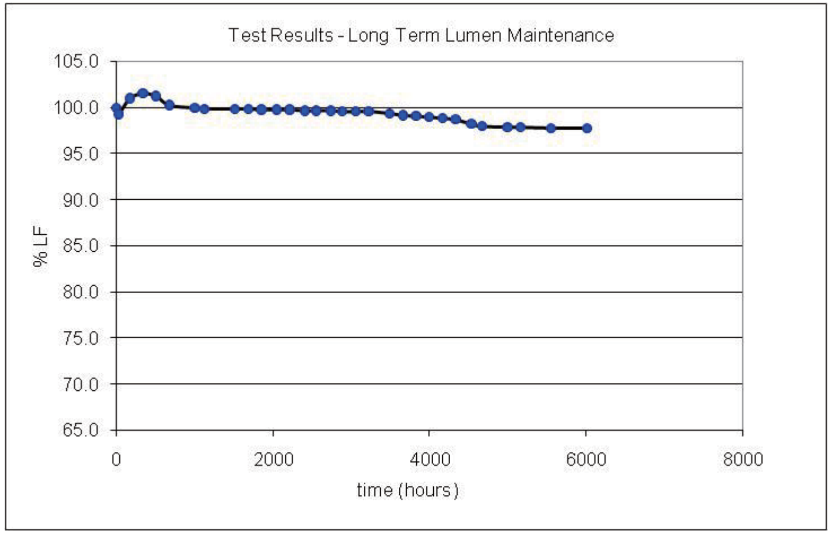
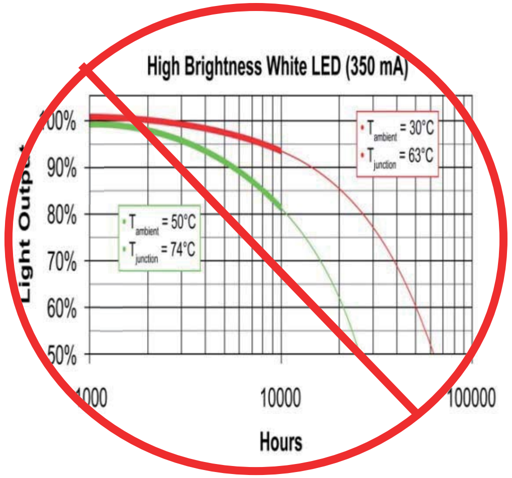
- Test report basics
  - Description of Sources tested
  - Ambient conditions (Airflow, temperature, RH etc)
  - Case Test point temperature
  - Electrical conditions
  - Lumen maintenance data
  - Observation of failures
  - LED monitoring interval
  - Chromaticity shift over time



LM-80 provides no determination or estimation of expected life or lumen output beyond test data.

Separate estimation method (TM-21) is in development

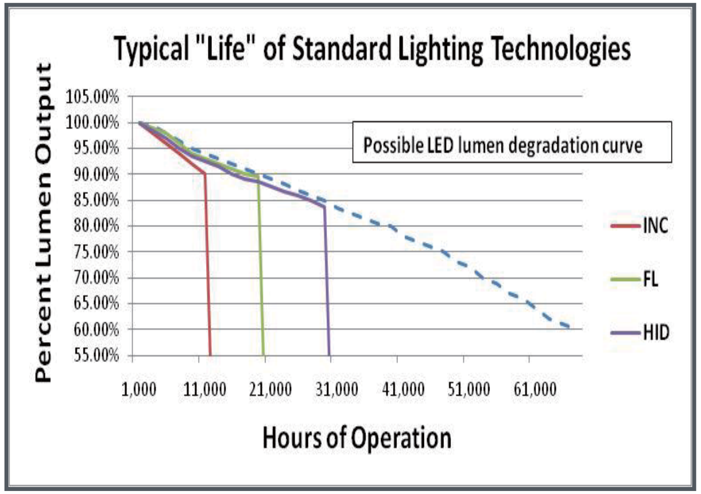


First, the CAVEAT…..

- TM-21 is a Technical Memorandum being developed by an Illuminating Engineering Society (IES) technical committee
- It is currently in the IES vote/comment stage and therefore, may change before final publication
- **Information provided here is preliminary and not approved by IES**

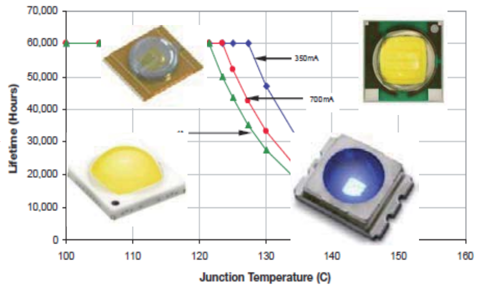
TM-21….What it IS and IS NOT!

- TM-21 does not determine traditional life or "time to failure" of an LED Lighting system
  - The useful life of an LED system has many components that need to be considered (lamp, driver, lens, etc.)
  - LEDs degrade (like all light sources) but for potentially very long periods of time. Instead of outright failure, LEDs will eventually dim to a point that is too low to serve their purpose



- TM-21 **does** project the lumen maintenance of an LED source (package/array/module)

  ….. Which can then be used to project the expected lumen output of the source as part of a system (fixture)



TM-21 Method:
Normalize and Average All Data

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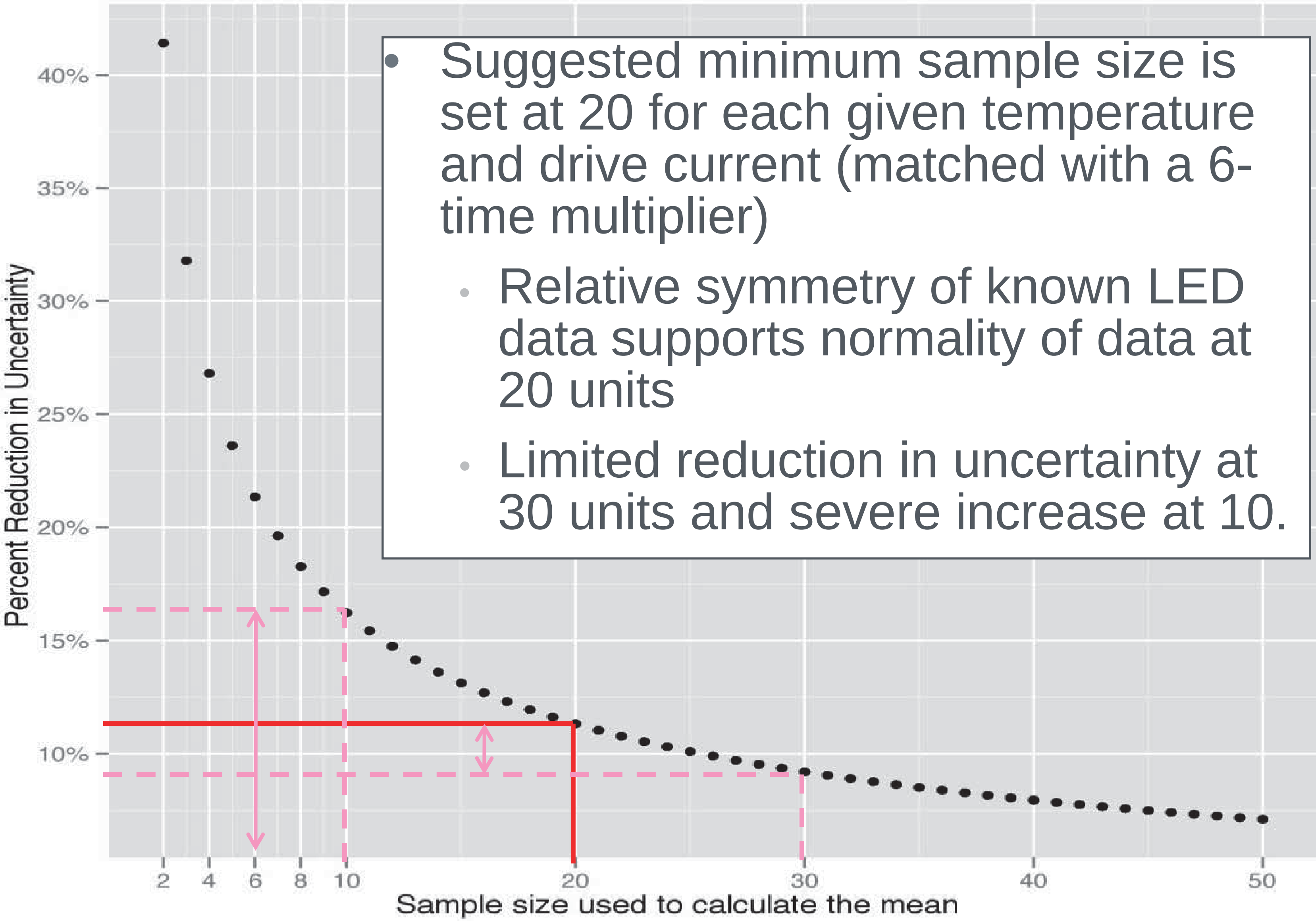
- Use all data.
  - LM-80 requires 6,000 hours with data at 1,000 hour increments.
  - TM-21 applies all test data at any increment
- Normalize all data to 1 (100%) at 0 hours
- Average each point for all samples of the device for each test condition
  - Averaging is done for simplicity of application
  - Variance associated with multiple samples is not considered usable 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

TM-21 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.

TM-21 Use Latest Data for Curve Fit

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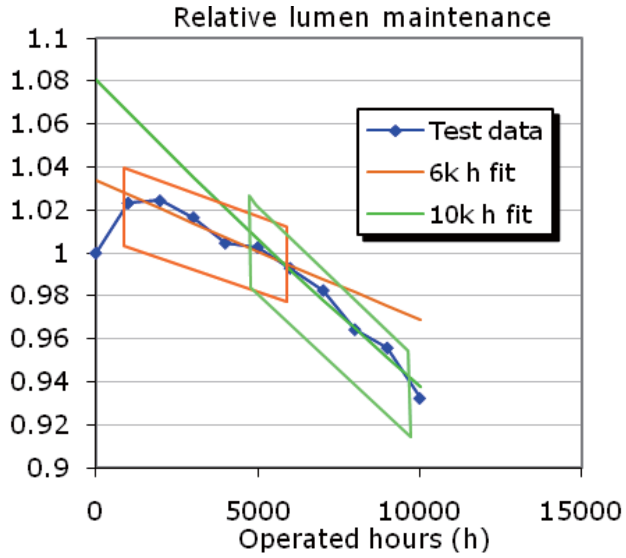
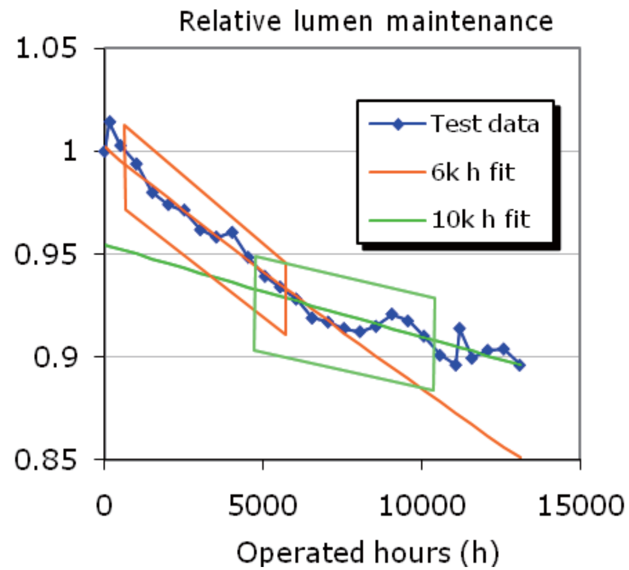
- Initial data variability (i.e., “hump”) is difficult for models to evaluate (0-1000 hr)
- Later data exhibits more characteristic decay curve of interest
  - Non-chip decay (encapsulant, etc.) occurs early and with varying effects on decay curve
  - Later decay is chip-driven and relatively consistent 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





TM-21 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

TM-21 Adjust Results (X-Times Rule)

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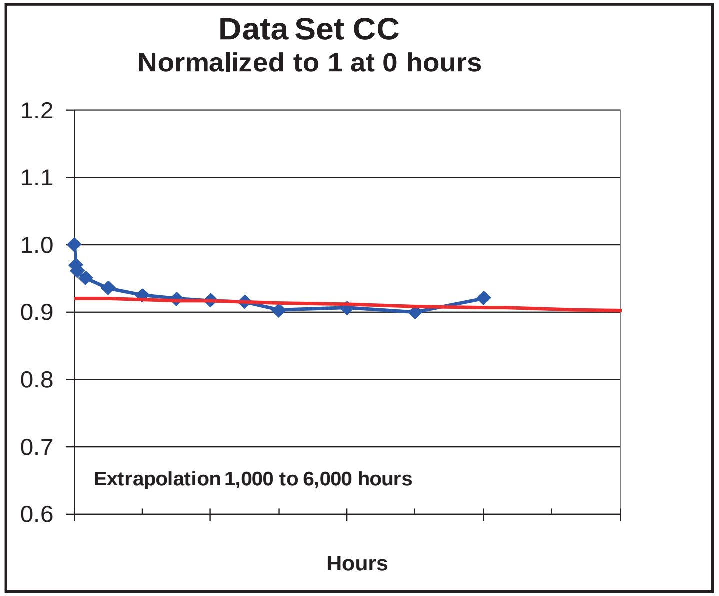
- Some indications from limited 6,000 hr data are not believable – limits on predictions are needed
- Analysis was completed on 40 sets of data to determine model fit uncertainty and relationship to prediction limits
  - A 0.40% relative combined uncertainty of the measurement system was assumed
  - 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 - 19, max projection = 5.5 times test duration**

TM-21 Interpolation of Results

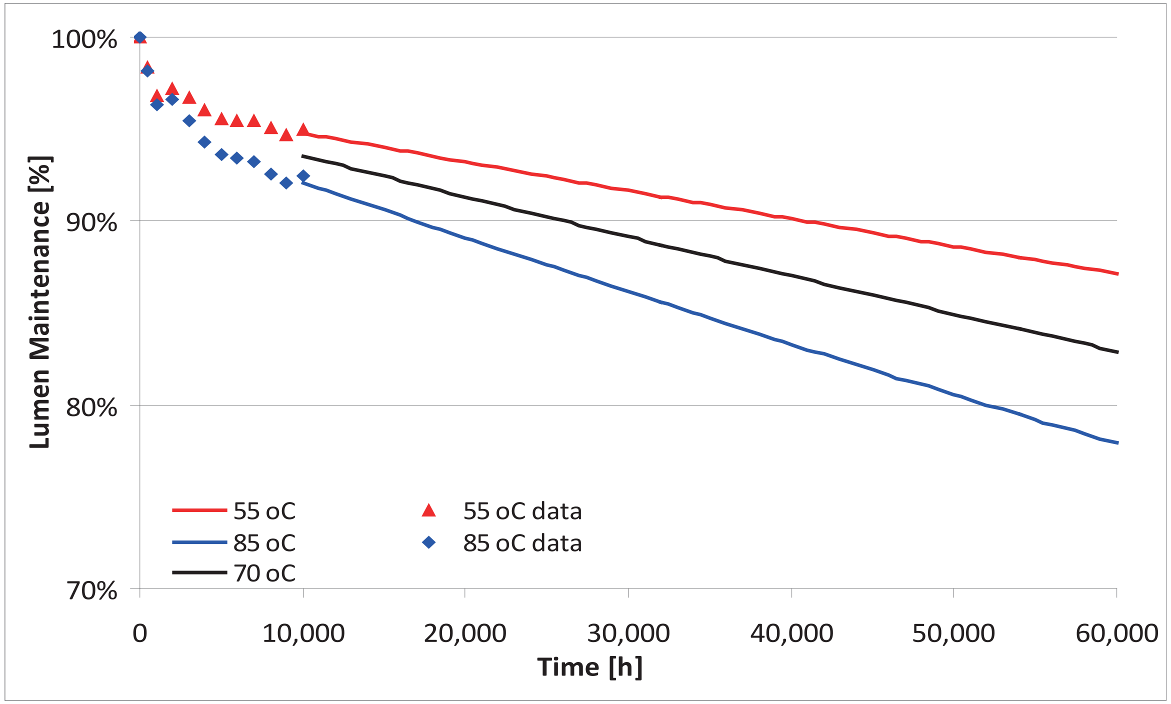
- The format of LM-80 testing (and followed by TM-21) is that testing LED modules at multiple temperatures provides data for matching in-situ performance (i.e., when installed in a luminaire)
- In-situ temperature must be within the LM-80 test temperatures (55° C, 85° C, and user chosen)
- Use Arrhenius 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

TM-21 Interpolation Example

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

$T_{s,1}$, (ºC)	55
$T_{s,1}$, (K)	328.15
α_1	1.684E-06
B_1	0.9639
$T_{s,2}$, (ºC)	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

$T_{s,i}$, (ºC)	70
$T_{s,i}$, (K)	343.15
α_i	2.413E-06
Projected L_{70}(Dk)	130,131
Reported L_{70}(Dk)	>60,000



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TM-21 Result Reporting Notation

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- Apply consistent "life" notation to results.

  General form: 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

TM-21 Reporting/Documentation

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

$T_{s,1}$, (^{0}C)	55
$T_{s,1}$, (K)	328.15
α_1	1.684E-06
B_1	0.9639
$T_{s,2}$, (^{0}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

$T_{s,i}$, (^{0}C)	70
$T_{s,i}$, (K)	343.15
α_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	**^{o}C**
α	
B	
Calculated L_{70}(*Dk*)	**hours**
Reported L_{70}(*Dk*)	**hours**

TM-21 Calculation Verification

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- 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 ºC

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

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