# LED Life Prediction: Towards A General Approach

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# Outline:

- Need for LED life prediction

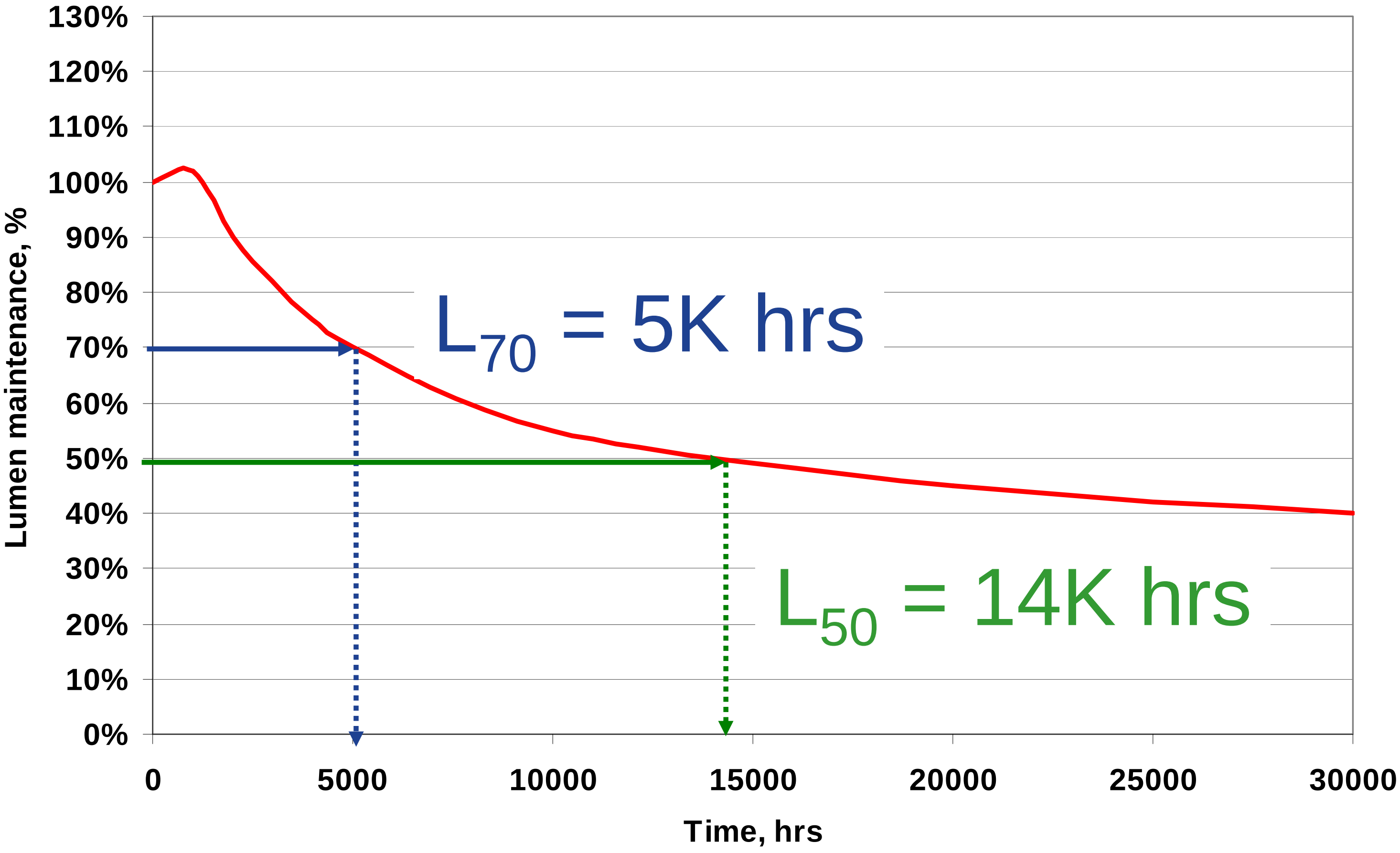
- Proposal for a new general approach

- Model examples & related learnings

- Additional comments & solutions for problem areas

- Future Work

# How is LED life defined?



$L_{70}$ = 5K hrs

$L_{50}$ = 14K hrs

Lumen maintenance to predetermined levels used
(since catastrophic failures are rare for LEDs)

**Problem:** LED “useful” life is too long for a direct measurement (typ. 50K hrs, or 5.7 yrs expected)

**Goal:** Project Lumen Maintenance curve using data collected over 6K-10K hrs of LED operation (either “regular” or “accelerated”)

**Implication:** Far extrapolation needed (as in from Valentine’s Day to New Year’s Eve)

**Issue:** LM curve can be complex and of varying shape for different LED packages

# Desired Properties of a Prediction Method

-Applicable to all LED packages

-LM-80 based

-Unambiguous (1 data set = 1 interpretation)

-Self-contained (providing all “tools”/references)

-Motivating to continue measurements beyond 6000 hrs (not currently required by LM-80)

**-** Providing statistical confidence & time limits to projection.

# A new general quantitative approach:

1. **Write a set of LM rate equation formulas** by combining systematically any potentially relevant terms.

2. **Differentiate the available LM data numerically.**

3. **Fit LM rate to the different rate equations.**

4. **Solve the fitted LM rate equations** to obtain the LM projection by each of them.

5. **Verify the projected LM curves by additional experimental measurements** to choose the best model.

**Based on broader scientific approach to modeling growth & decay problems**

# Mathematical implementation of the approach:

A general equation for the LED lumen decay rate can be written as:
$\mathbf{dI_v/dt = f(I_v,t)}$.

For a number of examples, **f** may be of the form $\mathbf{k_1} + \mathbf{k_2}\, I_v + \mathbf{k_3}\, /t$,

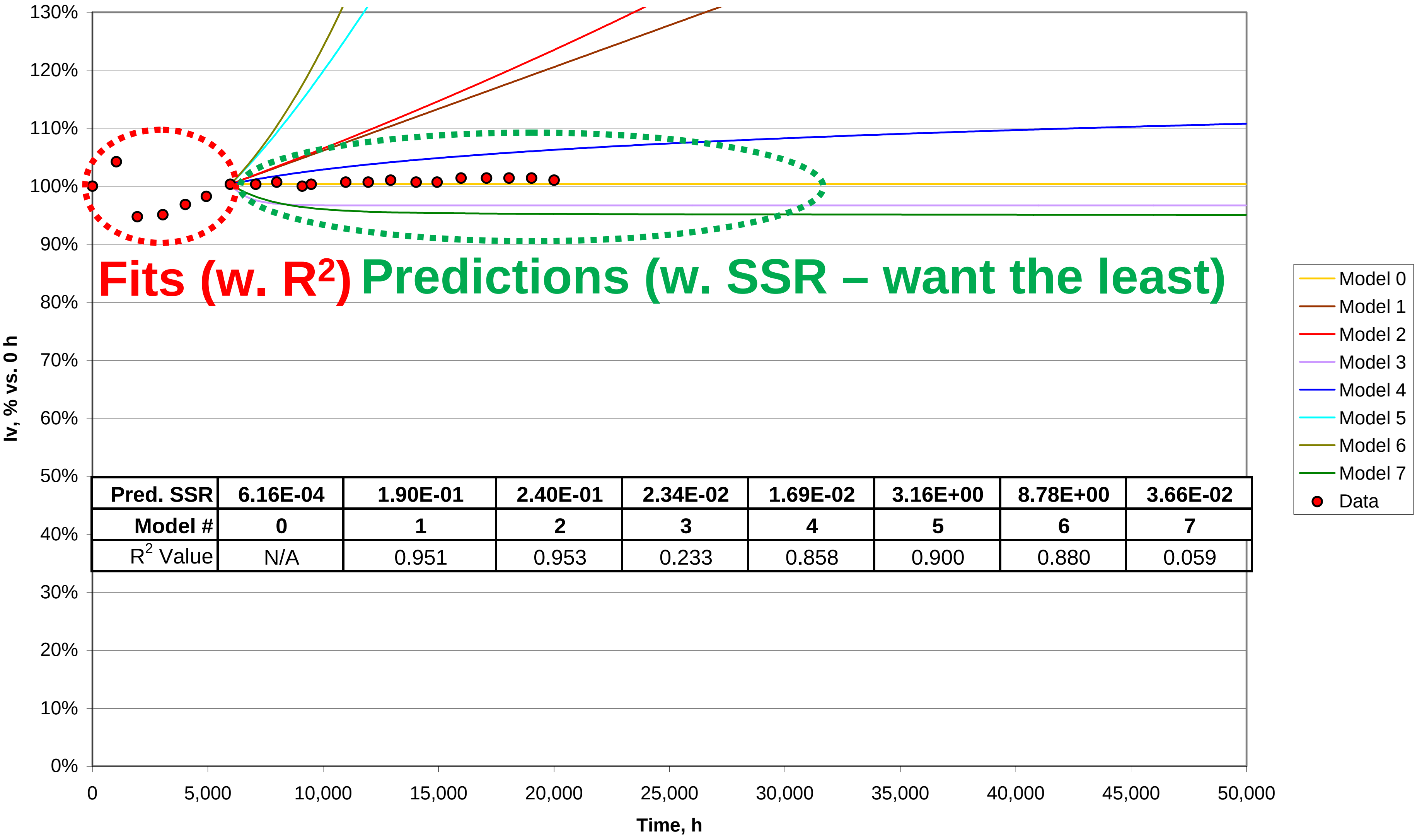
where $k_1$ - $k_3$ are rate parameters, subject to experimental determination.

The **f** form shown above incorporates the following 8 rate equation models ("0" is for "not used" and "1" is for "used" in the corresponding equation):

| **Eqn. #** | $\mathbf{k_3}$ | $\mathbf{k_2}$ | $\mathbf{k_1}$ | **Decay Rate Model** | **Closed Form Solution** |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | $dI_v/dt = 0$ | $I_v = I_v^0$ |
| 1 | 0 | 0 | 1 | $dI_v/dt = k_1$ | $I_v = I_v^0 + k_1(t-t^0)$ |
| 2 | 0 | 1 | 0 | $dI_v/dt = k_2 I_v$ | $I_v = I_v^0 \exp[(k_2(t-t^0)]$ |
| 3 | 0 | 1 | 1 | $dI_v/dt = k_1 + k_2 I_v$ | $I_v = (I_v^0 + k_1/k_2) \exp[k_2(t-t^0)] - k_1/k_2$ |
| 4 | 1 | 0 | 0 | $dI_v/dt = k_3/t$ | $I_v = I_v^0 + k_3 \ln(t/t^0)$ |
| 5 | 1 | 0 | 1 | $dI_v/dt = k_1 + k_3/t$ | $I_v = I_v^0 + k_1(t-t^0) + k_3 \ln(t/t^0)$ |
| 6 | 1 | 1 | 0 | $dI_v/dt = k_2 I_v + k_3/t$ | None Available |
| 7 | 1 | 1 | 1 | $dI_v/dt = k_1 + k_2 I_v + k_3/t$ | None Available |

## A complete Excel workbook is available separately

# Examples: Model 0 (“flat line”)

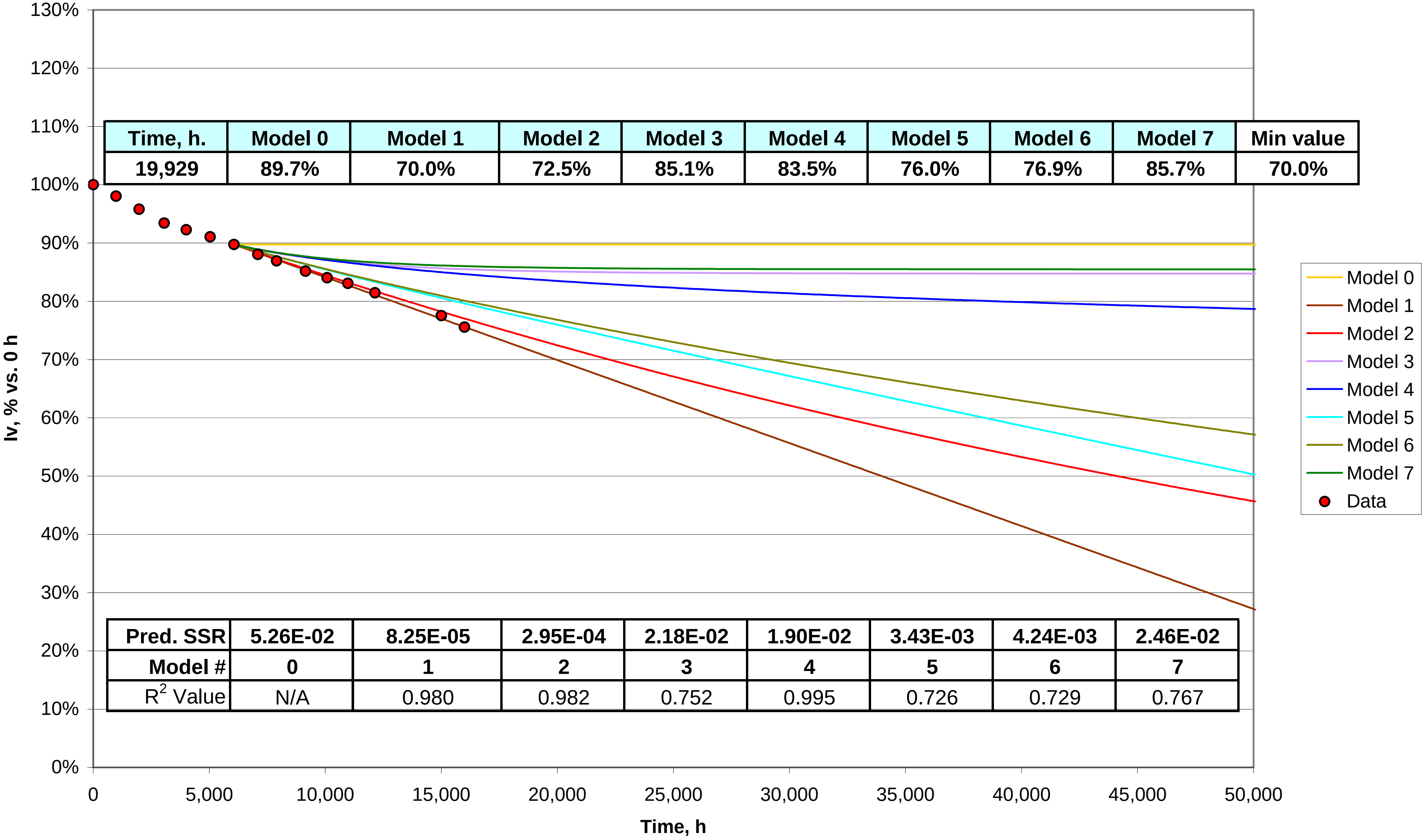


**Fits (w. $R^2$)** **Predictions (w. SSR – want the least)**

| Pred. SSR | 6.16E-04 | 1.90E-01 | 2.40E-01 | 2.34E-02 | 1.69E-02 | 3.16E+00 | 8.78E+00 | 3.66E-02 |
|---|---|---|---|---|---|---|---|---|
| **Model #** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| $R^2$ Value | N/A | 0.951 | 0.953 | 0.233 | 0.858 | 0.900 | 0.880 | 0.059 |

**Note high $R^2$ values for Models 1, 2 and 5**

# Examples: Model 1 (straight line)

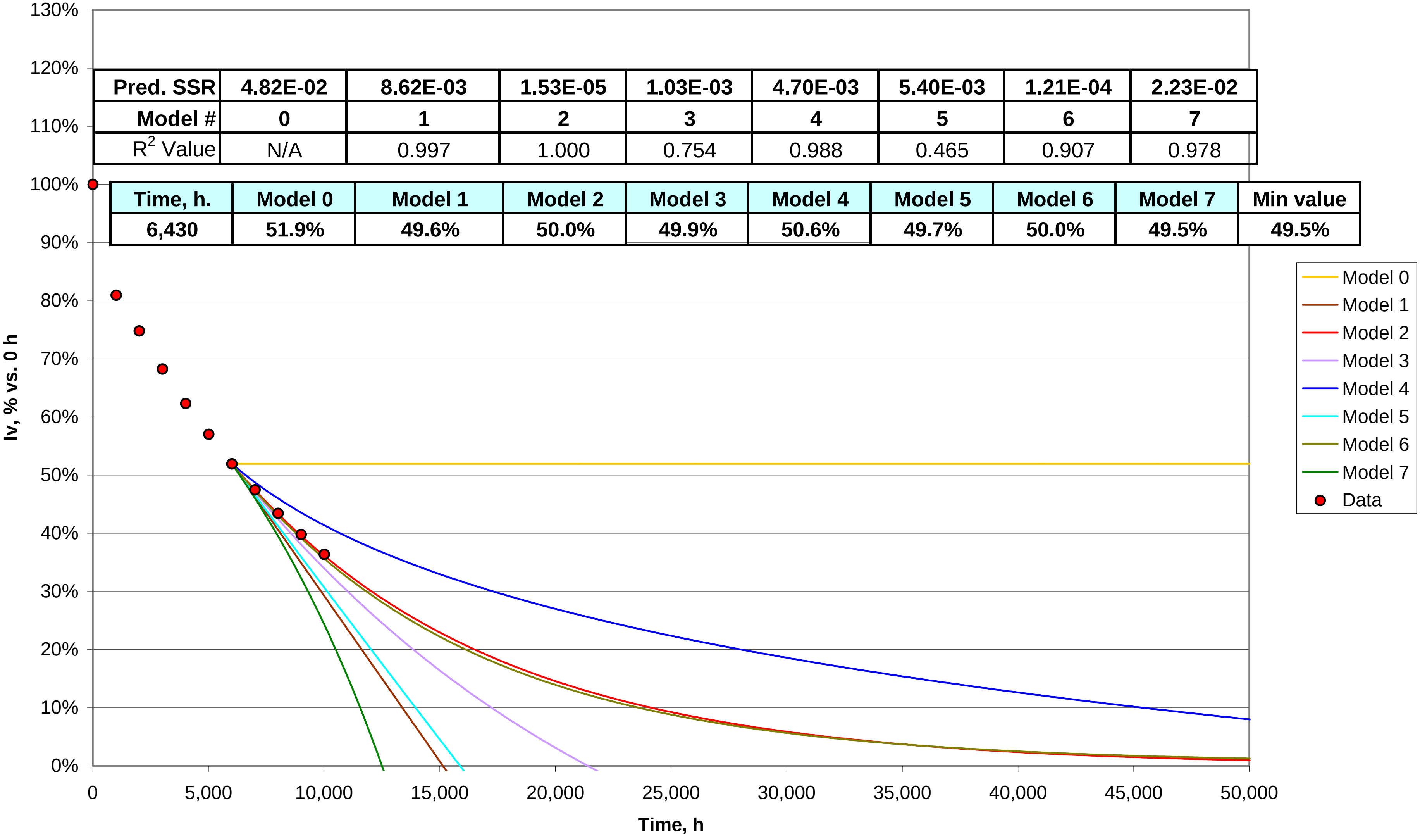


| Time, h. | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Min value |
|---|---|---|---|---|---|---|---|---|---|
| 19,929 | 89.7% | 70.0% | 72.5% | 85.1% | 83.5% | 76.0% | 76.9% | 85.7% | 70.0% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Pred. SSR** | **5.26E-02** | **8.25E-05** | **2.95E-04** | **2.18E-02** | **1.90E-02** | **3.43E-03** | **4.24E-03** | **2.46E-02** |
| **Model #** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| $R^2$ Value | N/A | 0.980 | 0.982 | 0.752 | 0.995 | 0.726 | 0.729 | 0.767 |

**Note higher $R^2$, much higher SSR for Model 4**

# Examples: Model 2 (simple exponential)

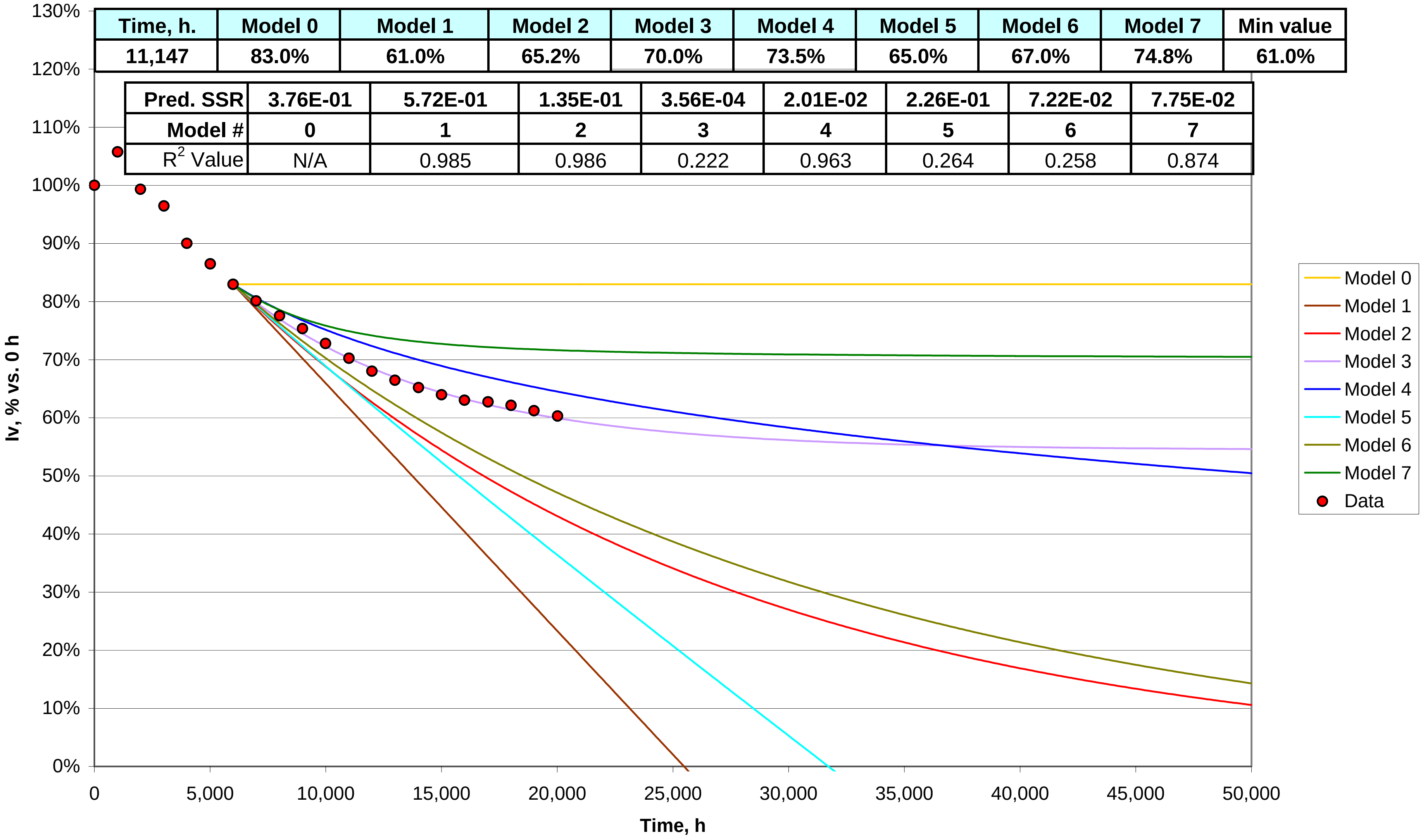


| Pred. SSR | 4.82E-02 | 8.62E-03 | 1.53E-05 | 1.03E-03 | 4.70E-03 | 5.40E-03 | 1.21E-04 | 2.23E-02 |
|---|---|---|---|---|---|---|---|---|
| **Model #** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| $R^2$ Value | N/A | 0.997 | 1.000 | 0.754 | 0.988 | 0.465 | 0.907 | 0.978 |

| Time, h. | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Min value |
|---|---|---|---|---|---|---|---|---|---|
| **6,430** | **51.9%** | **49.6%** | **50.0%** | **49.9%** | **50.6%** | **49.7%** | **50.0%** | **49.5%** | **49.5%** |

**Currently, widely used model by LED industry**

# Examples: Model 3 (two parameters)

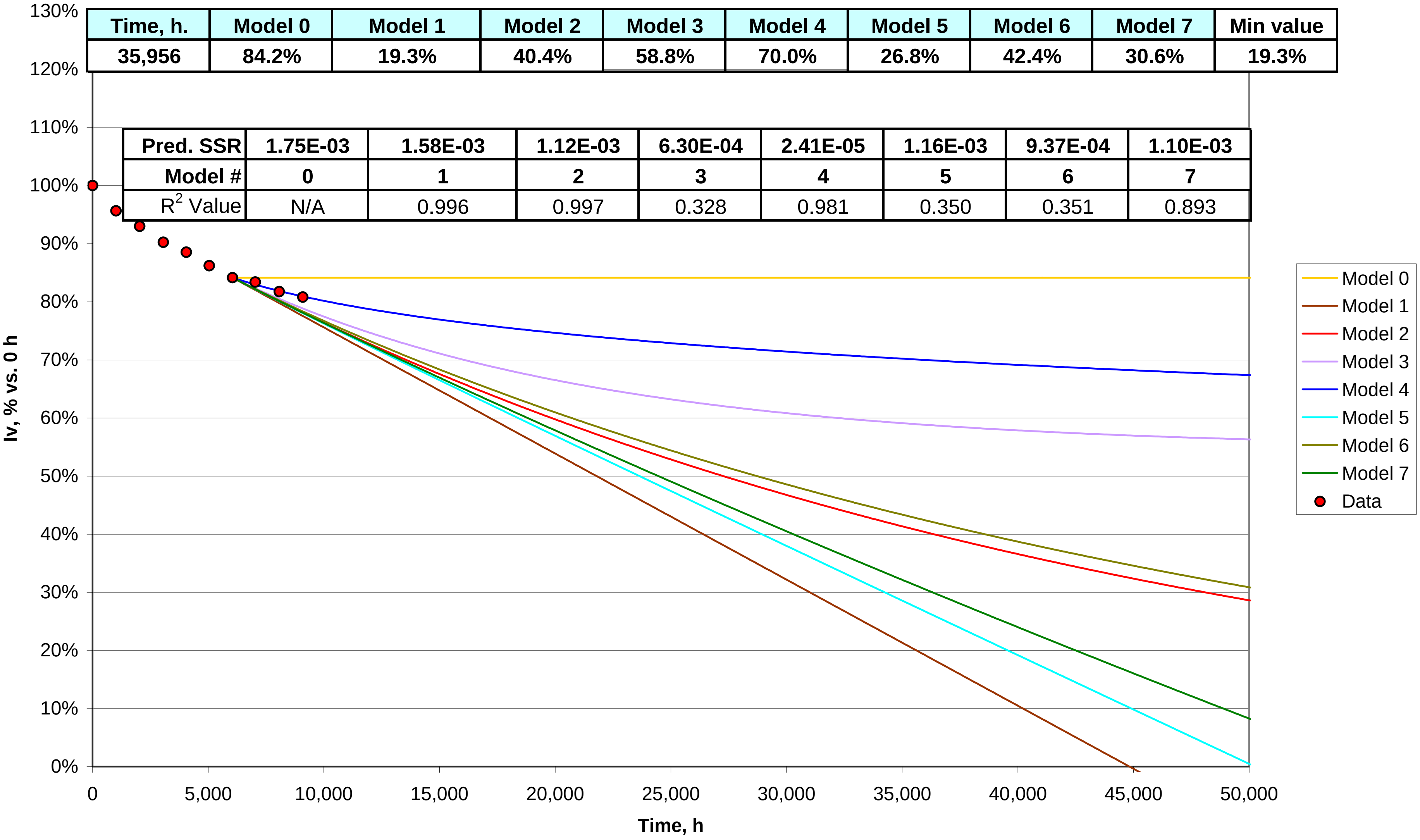


| Time, h. | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Min value |
|---|---|---|---|---|---|---|---|---|---|
| 11,147 | 83.0% | 61.0% | 65.2% | 70.0% | 73.5% | 65.0% | 67.0% | 74.8% | 61.0% |

| Pred. SSR | 3.76E-01 | 5.72E-01 | 1.35E-01 | 3.56E-04 | 2.01E-02 | 2.26E-01 | 7.22E-02 | 7.75E-02 |
|---|---|---|---|---|---|---|---|---|
| **Model #** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| $R^2$ Value | N/A | 0.985 | 0.986 | 0.222 | 0.963 | 0.264 | 0.258 | 0.874 |

**Only Model 3 gives exact prediction for L70 in this case (note $R^2$ value)**

# Examples: Model 4 (simple logarithmic)

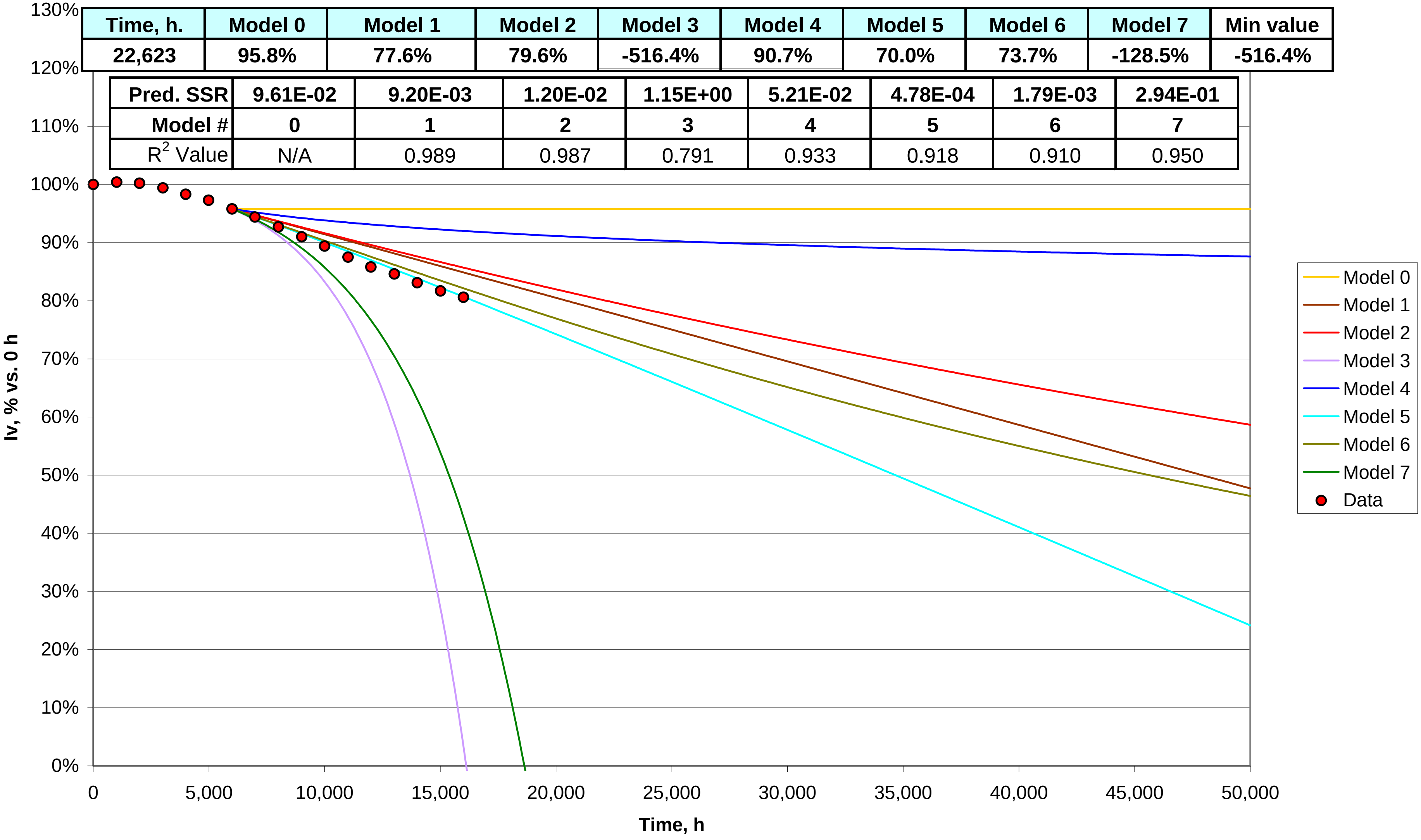


| Time, h. | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Min value |
|---|---|---|---|---|---|---|---|---|---|
| 35,956 | 84.2% | 19.3% | 40.4% | 58.8% | 70.0% | 26.8% | 42.4% | 30.6% | 19.3% |

| Pred. SSR | 1.75E-03 | 1.58E-03 | 1.12E-03 | 6.30E-04 | 2.41E-05 | 1.16E-03 | 9.37E-04 | 1.10E-03 |
|---|---|---|---|---|---|---|---|---|
| **Model #** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| $R^2$ Value | N/A | 0.996 | 0.997 | 0.328 | 0.981 | 0.350 | 0.351 | 0.893 |

**Note higher $R^2$, SSR values for Models 1 and 2**

# Examples: Model 5 (two parameters)

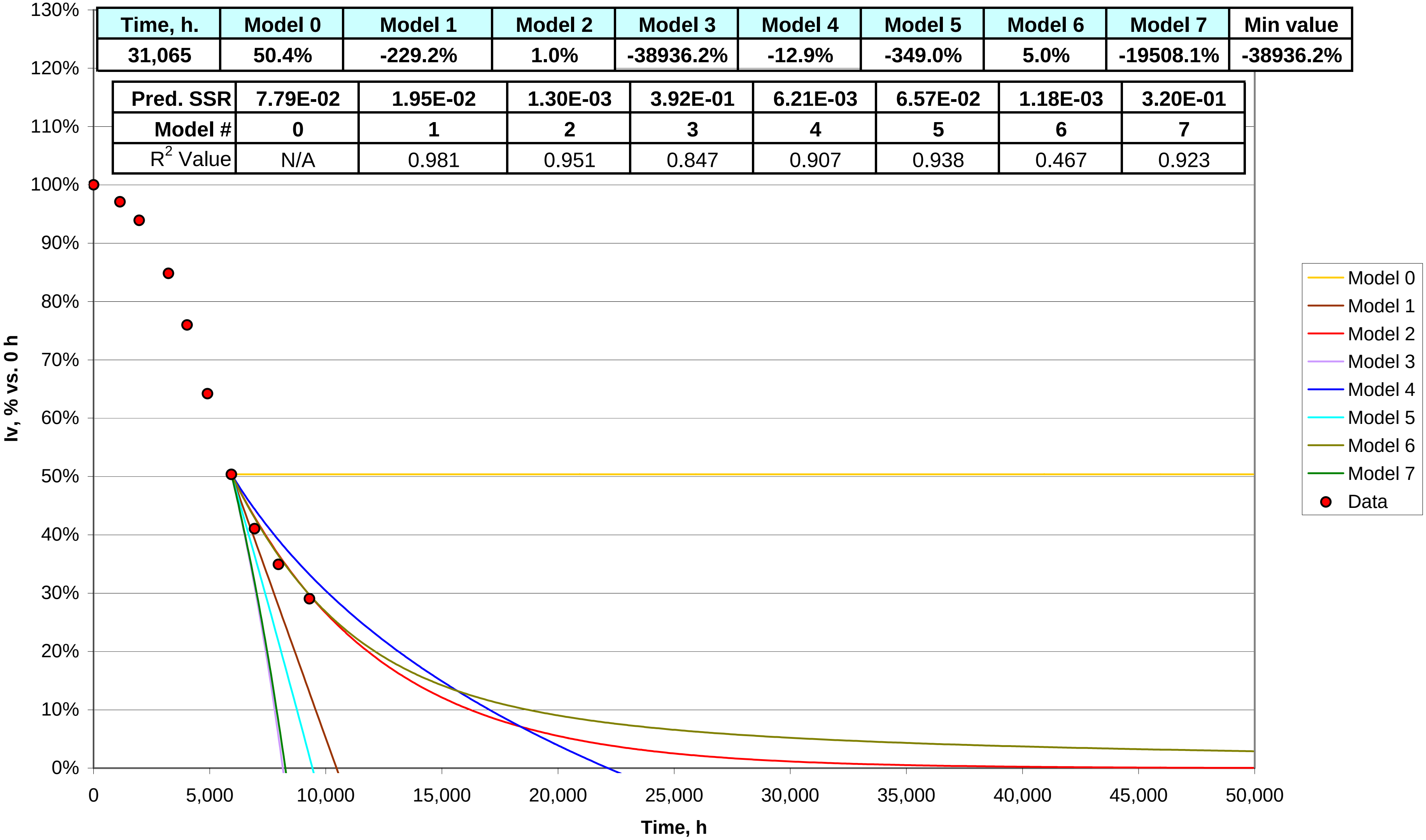


| Time, h. | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Min value |
|---|---|---|---|---|---|---|---|---|---|
| 22,623 | 95.8% | 77.6% | 79.6% | -516.4% | 90.7% | 70.0% | 73.7% | -128.5% | -516.4% |

| Pred. SSR | 9.61E-02 | 9.20E-03 | 1.20E-02 | 1.15E+00 | 5.21E-02 | 4.78E-04 | 1.79E-03 | 2.94E-01 |
|---|---|---|---|---|---|---|---|---|
| Model # | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| $R^2$ Value | N/A | 0.989 | 0.987 | 0.791 | 0.933 | 0.918 | 0.910 | 0.950 |

**Note higher $R^2$, SSR values for Models 1, 2, 4 and 7**

# Examples: Model 6 (two parameters)

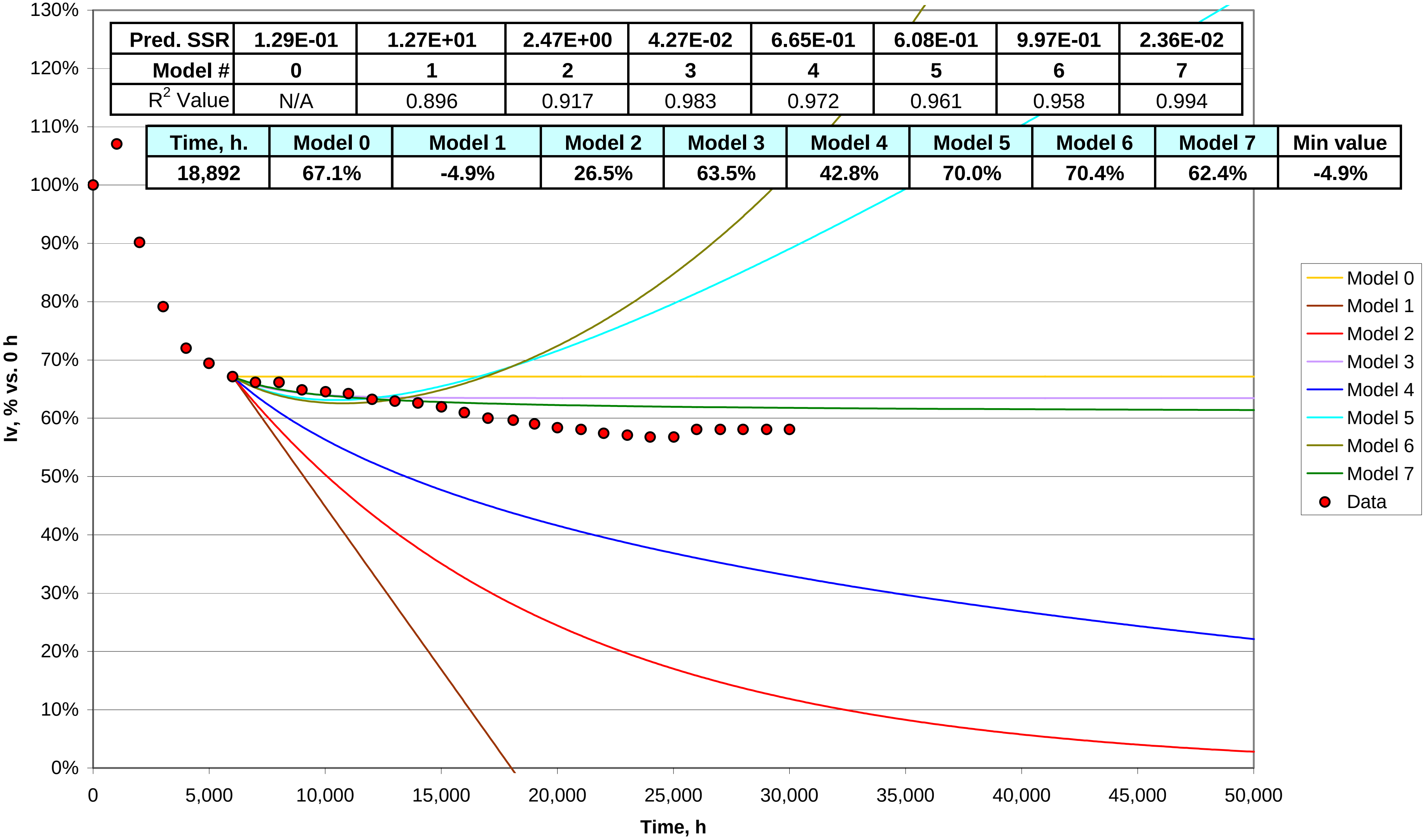


| Time, h. | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Min value |
|---|---|---|---|---|---|---|---|---|---|
| 31,065 | 50.4% | -229.2% | 1.0% | -38936.2% | -12.9% | -349.0% | 5.0% | -19508.1% | -38936.2% |

| Pred. SSR | 7.79E-02 | 1.95E-02 | 1.30E-03 | 3.92E-01 | 6.21E-03 | 6.57E-02 | 1.18E-03 | 3.20E-01 |
|---|---|---|---|---|---|---|---|---|
| Model # | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| $R^2$ Value | N/A | 0.981 | 0.951 | 0.847 | 0.907 | 0.938 | 0.467 | 0.923 |

**Note higher $R^2$, SSR values for Models 1, 2, 3, 4, 5 and 7**

# Examples: Model 7 (three parameters)



| Pred. SSR | 1.29E-01 | 1.27E+01 | 2.47E+00 | 4.27E-02 | 6.65E-01 | 6.08E-01 | 9.97E-01 | 2.36E-02 |
|---|---|---|---|---|---|---|---|---|
| **Model #** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| $R^2$ Value | N/A | 0.896 | 0.917 | 0.983 | 0.972 | 0.961 | 0.958 | 0.994 |

| Time, h. | Model 0 | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Min value |
|---|---|---|---|---|---|---|---|---|---|
| **18,892** | **67.1%** | **-4.9%** | **26.5%** | **63.5%** | **42.8%** | **70.0%** | **70.4%** | **62.4%** | **-4.9%** |

**Note that Models 5 and 6 predict an incorrect 2nd L70 value**

# Additional comments on Model 0

**Problem:** No L70 prediction can be made for LEDs following Model 0, based on 6K-10K data

**Implication:** The most reliable LEDs would (ironically) have to be tested for the longest time, in order to provide a good estimate for L70.

**Proposed Solution: Request provisional approval for LEDs with LM following Model 0, if this model is confirmed by data from 6K to 10K hrs.**

**Model 0 reflects "ideal" LM behavior which should not be unduly penalized**

# Additional comments on lumen decay accelerating over time ("cliff" type LM)

**Problem:** Although 4 of the proposed models (Models 3, 5, 6 and 7) are capable of "sensing" accelerating decay, they may miss it, if it were to manifest itself after 6K hrs.

**Implication:** A L70 value much larger than the real one may be projected by an incompletely validated model.

**Proposed Solution: Recalculate L70 projection for any chosen model, by including newer data points (measured after 6K hrs) at the expense of older ones.**

**Any decrease in a L70 projection when recalculated on more data is a red flag**

# Additional comments on poor fit of the experimental data by all models

**Problem:** It is conceivable that for some LEDs, the LM curve may not fit well any of the models previously presented, especially in the L70 region.

**Implication:** No good life projections would be possible (at least, without extending the data collection further).

**Proposed Solution: Introduce new models into the set (e.g. by adding new terms, such as $k_4t$, etc.). However, need to use Occam's razor (have no more parameters than absolutely needed for an acceptable fit).**

**The proposed set of models may be expanded further as necessary**

# Summary:

- All 8 LM models proposed here are found in real LEDs.

- $R^2$ of fitted models is not trustable for extrapolation.

- SSR on validation points is more appropriate (but a “sanity check” for unbound predictions is also needed).

- Regulatory leeway should be requested for LEDs having a “flat” (Model 0) type LM curve over the first 10K hrs.

- Extra care should be taken to detect accelerating lumen decay, especially if manifesting after 6K hrs.

- Additional models may be added as needed.

# Future work:

- Determine safeguard for un-validated projections based on no more than 6000 hrs of testing (using the worst prediction among all models proposed).

- Determine time limit for “too good to be true” projections based on testing duration (6x limit proposed).

- Determine number of minimum validation points for SSR calculation (4 proposed).

- Determine experimental noise budget for SSR in an acceptable model ($10^{-4}$ per validation point proposed).

- Determine procedure for uncertainty interval calculation (Weibull analysis proposed).

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