LED Lumen Maintenance Prediction Method

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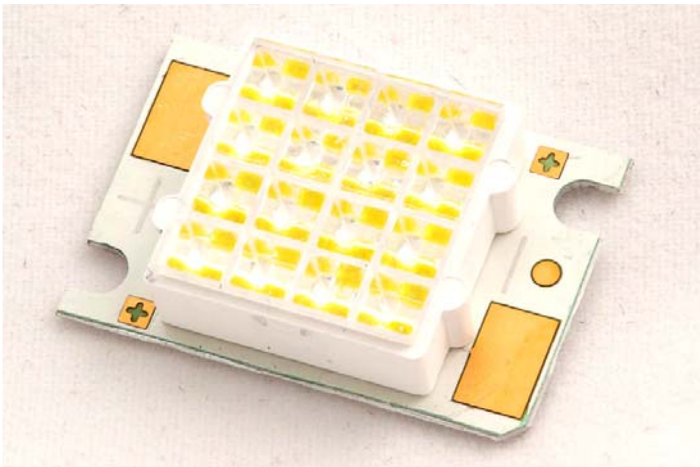
Illumitex: Changing the World through LED Innovation



Illumitex is a clean-tech company developing high-brightness LEDs to revolutionize the world of lighting. Beyond our first product which provides more usable lumens with better light quality and no secondary optics, Illumitex is continuing to generate bright ideas that illuminate the globe.

Founded in 2005 in Austin, Texas, we have assembled a world-class team working to bring key technologies to market and enable society's transformation to energy-saving solid state lighting for all illumination, from laptop screens to HDTVs to household lighting.

Outline:

- Issues related to using LM-80 data for lumen maintenance prediction

- Issues related to accelerated testing

- Proposal for a new general approach

- Examples and related learnings

- Additional comments & solutions for problem areas

- Future work

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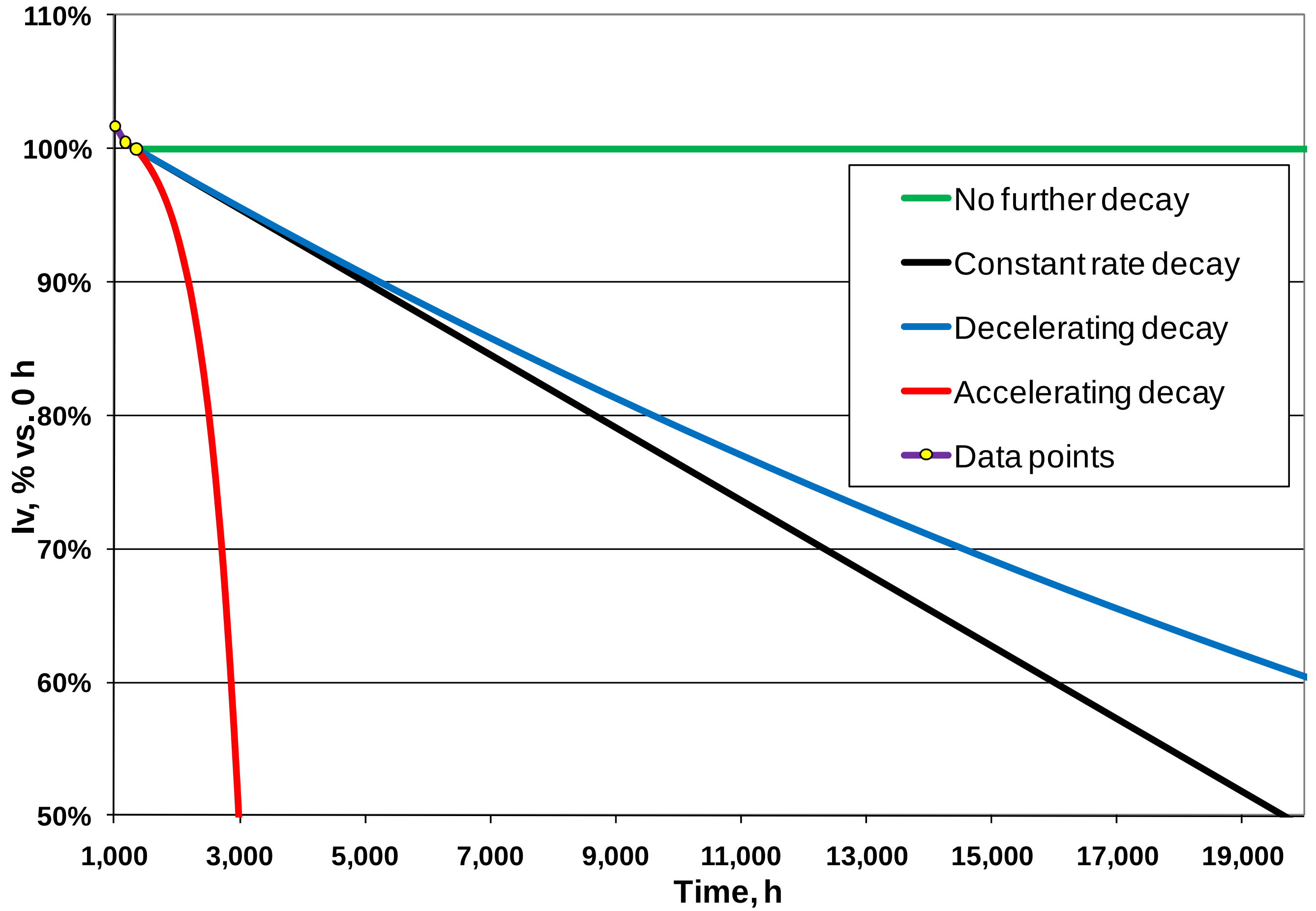
Basic LED Lumen Maintenance Types



All of these (plus combinations) are found in real LEDs - Cannot use just one model, e.g. simple exponential decay

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Specific Restrictions/Issues Arising from LM-80:

1. Small number of data points (minimum of 7 required)
-Need some redundancy (a.k.a. degrees of freedom) for proper modeling
->Cannot extract more than a few model parameters from the lumen maintenance curve over 0 to 6000 hrs (danger of over-fitting the data)
->>Need to use fairly simple models

2. Relatively large time intervals between points (1000 hrs)
-Cannot force more frequent measurements
->Random data noise may have significant impact on projections

3. No requirement to continue testing beyond 6000 hrs.
-Cannot force verification of LM projections after 6000 hrs
-For state of the art LEDs, the lumen depreciation observed over the first 6000 hrs can be comparable in magnitude to the measurement system drift

Developing a universal prediction method is a tall order (and best efforts should be made to that end)

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Issues with Using Accelerated Life Testing to Get L70:

1. Cannot force the use of Ts or Ta values higher than 85 ºC, or the use of any currents discommended by the manufacturer at a given Ts for testing according to LM-80, in order to reach L70 experimentally

2. High enough acceleration can introduce entirely new failure modes, not occurring within manufacturer-recommended operating parameters
Example: "Oven-roasting" the LEDs at **>180 ºC** will darken *any* silicone encapsulant, even if perfectly stable under normal operating conditions

3. Some state of the art LEDs may not lose 30% of their initial lumens by 6000 hrs, at any acceptable Ts/Ta setting

4. The catastrophic failure rate is also accelerated, making reaching 6000 hrs life by all/any samples problematic at Ts, Ta well above 85 ºC

ALT offers a "glimpse into the future" but cannot guarantee attaining the L70 threshold within 6000 hrs

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A General Quantitative Prediction Approach:

1. Write a set of LM rate equation formulas by combining any potentially relevant terms (from first principles etc.).

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:
$dI_v/dt = f(I_v,t)$.

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. #	k_3	k_2	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

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Issues Related to Using R^2 Values to Judge Models:

-**Tendency to approach 0 for "flat" data sets that show little decay over the testing duration**

-**Impossible to even define for Model 0 ("flat line")**

-**Values may differ greatly when calculated on fits of the lumen decay curve itself vs. fits on its first derivative (i.e. the decay rate) for the same data set.** For example, a perfectly straight decay line would have R^2=1 for the raw undifferentiated data but R^2=0 for the decay rate fit.

The sum of squared residuals (SSR) obtained on predicted points is proposed to verify models

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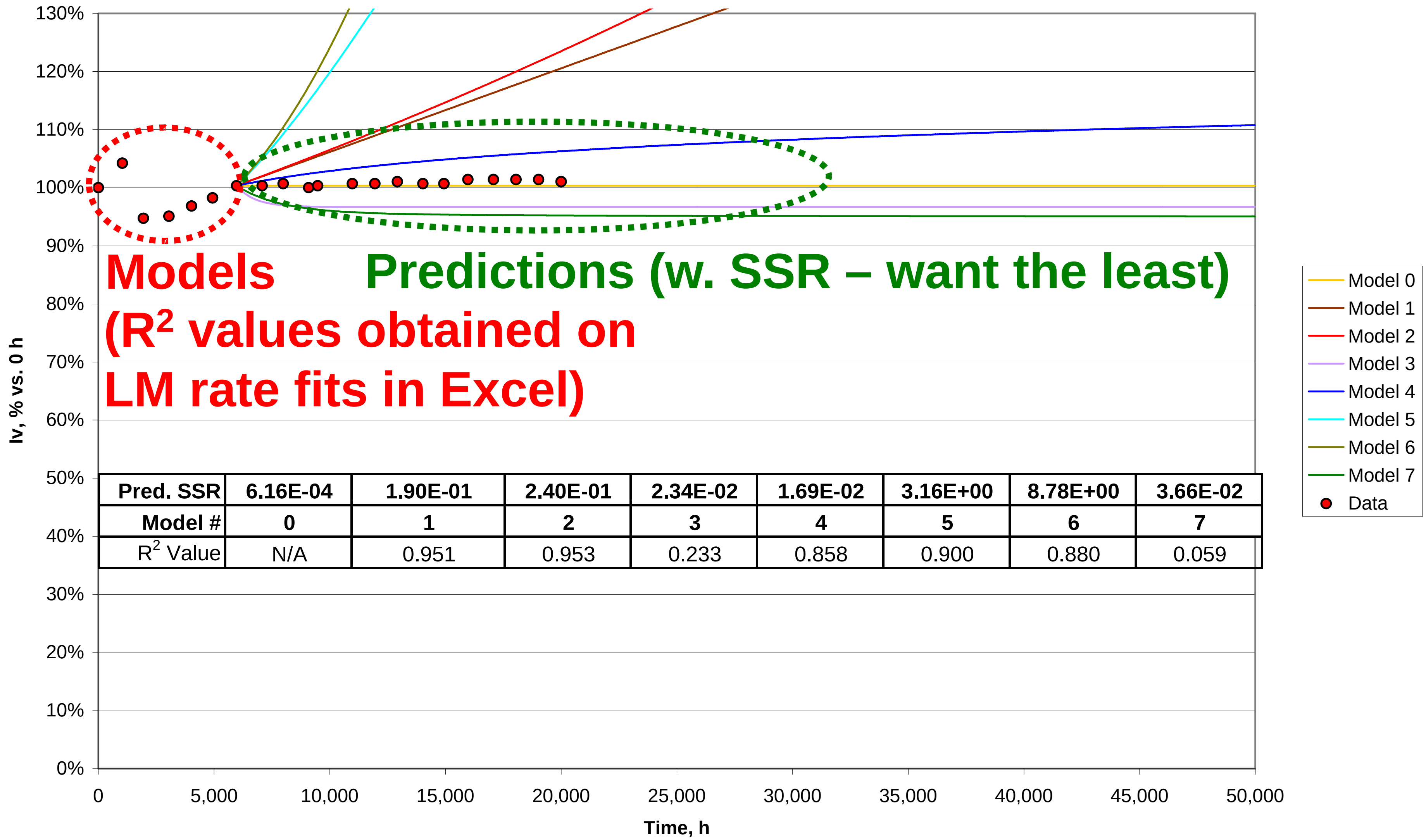
Examples: Model 0 (“Flat Line”)



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 unbound LM predictions by some of the models (1 and 2 in particular)

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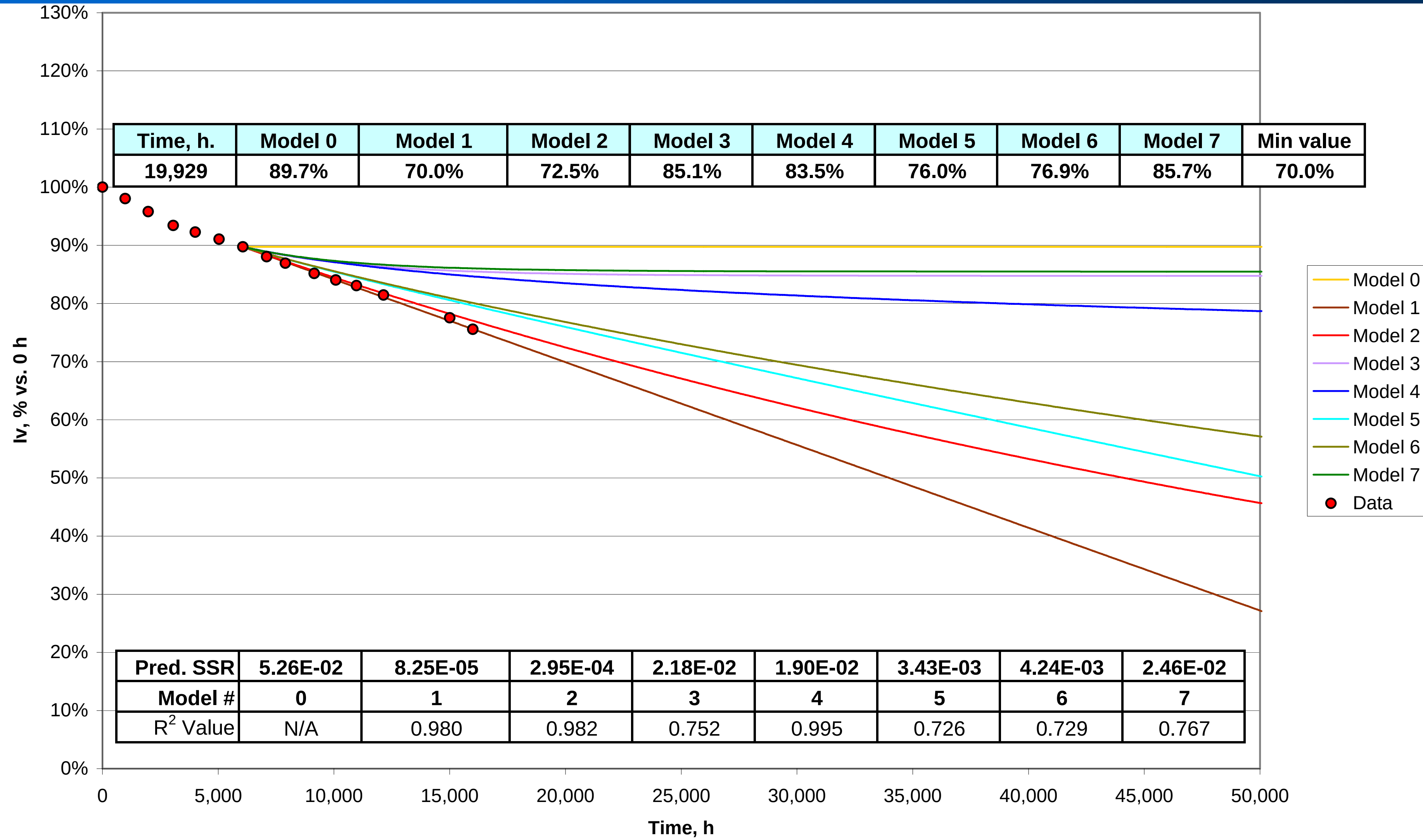
Examples: Model 1 (Straight Line)



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

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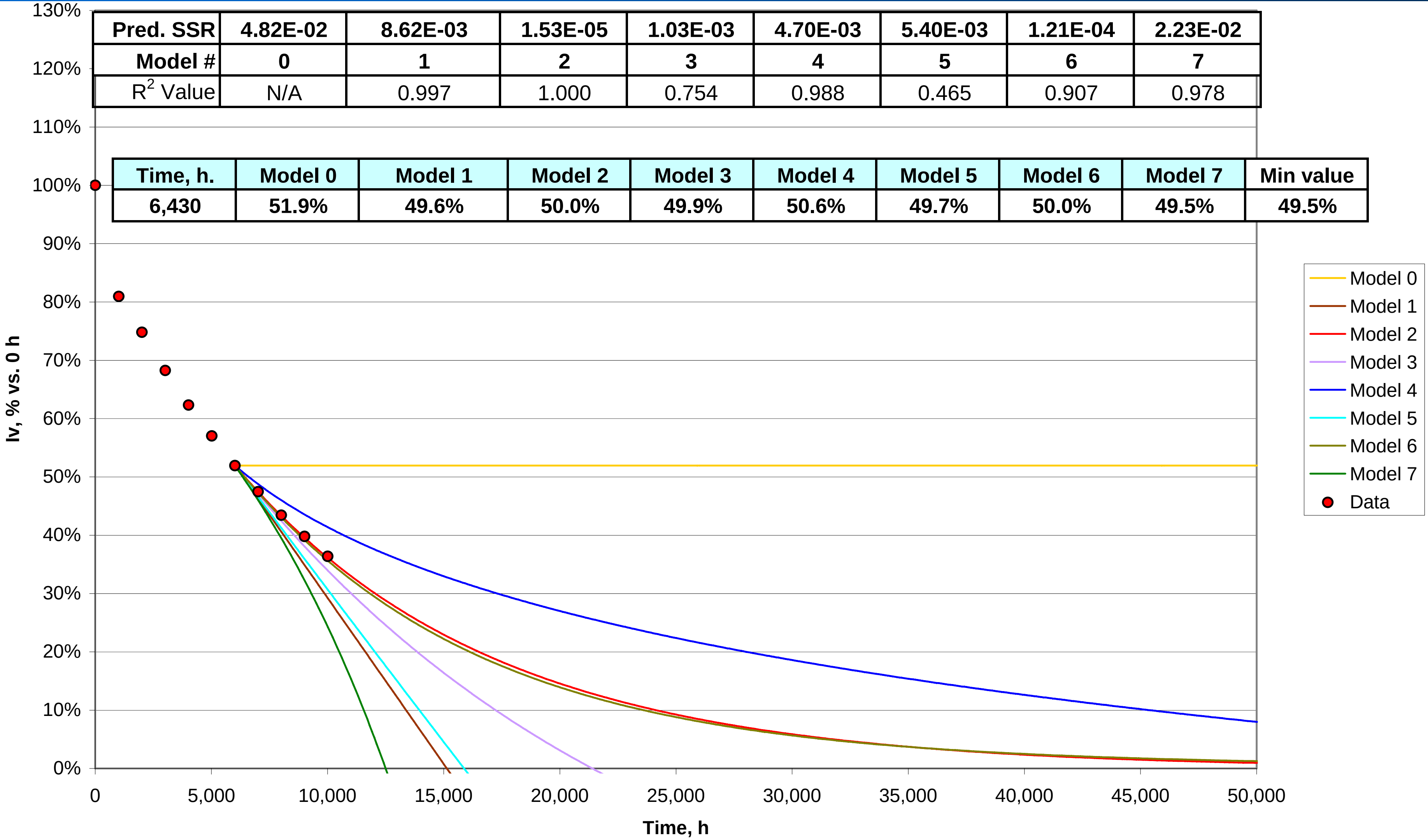
Examples: Model 2 (Simple Exponential)

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, the sole model used by SSL Energy Star criteria

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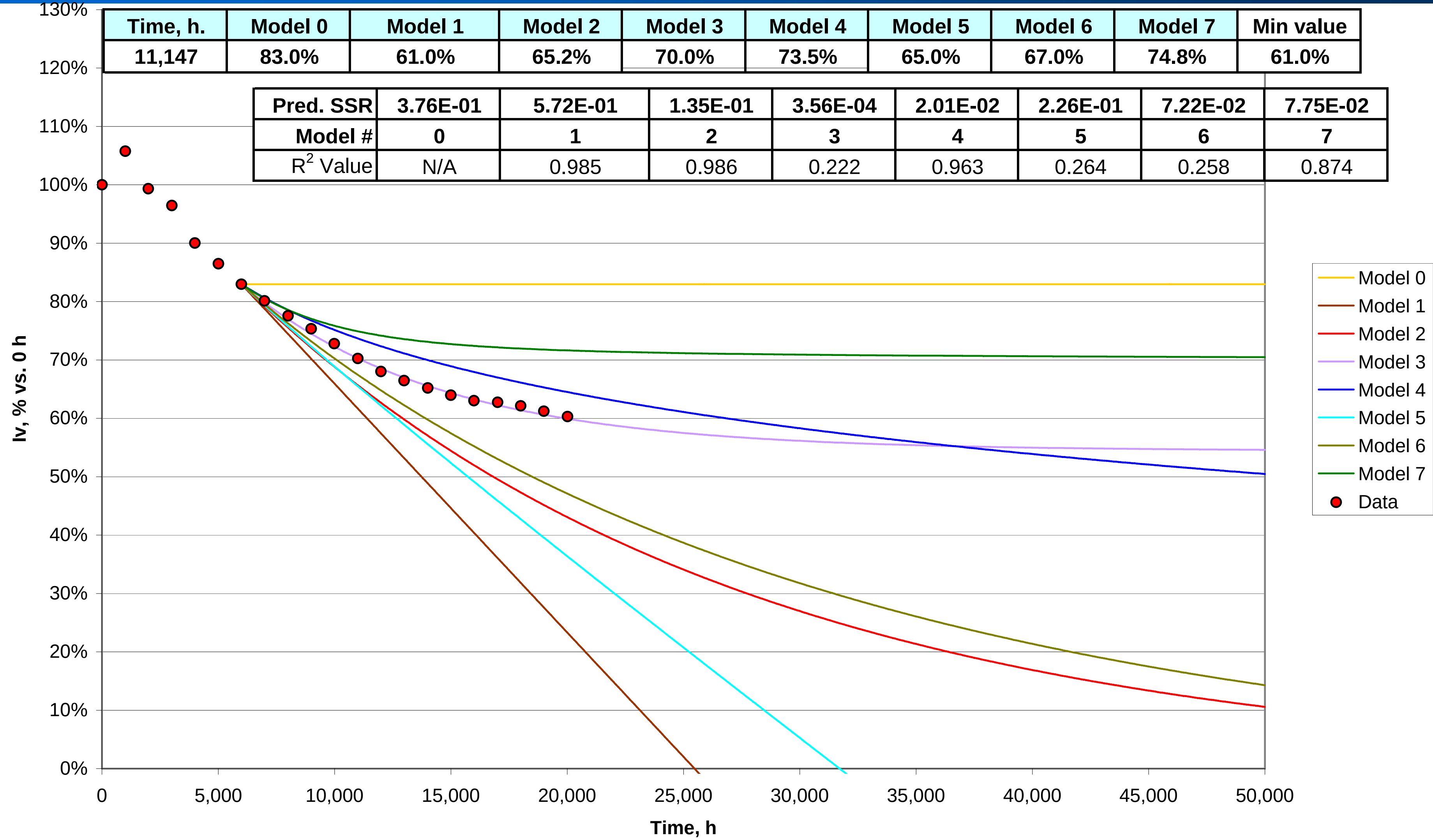
Examples: Model 3 (Two Parameters)

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 L_{70} in this case (note R^2 value)

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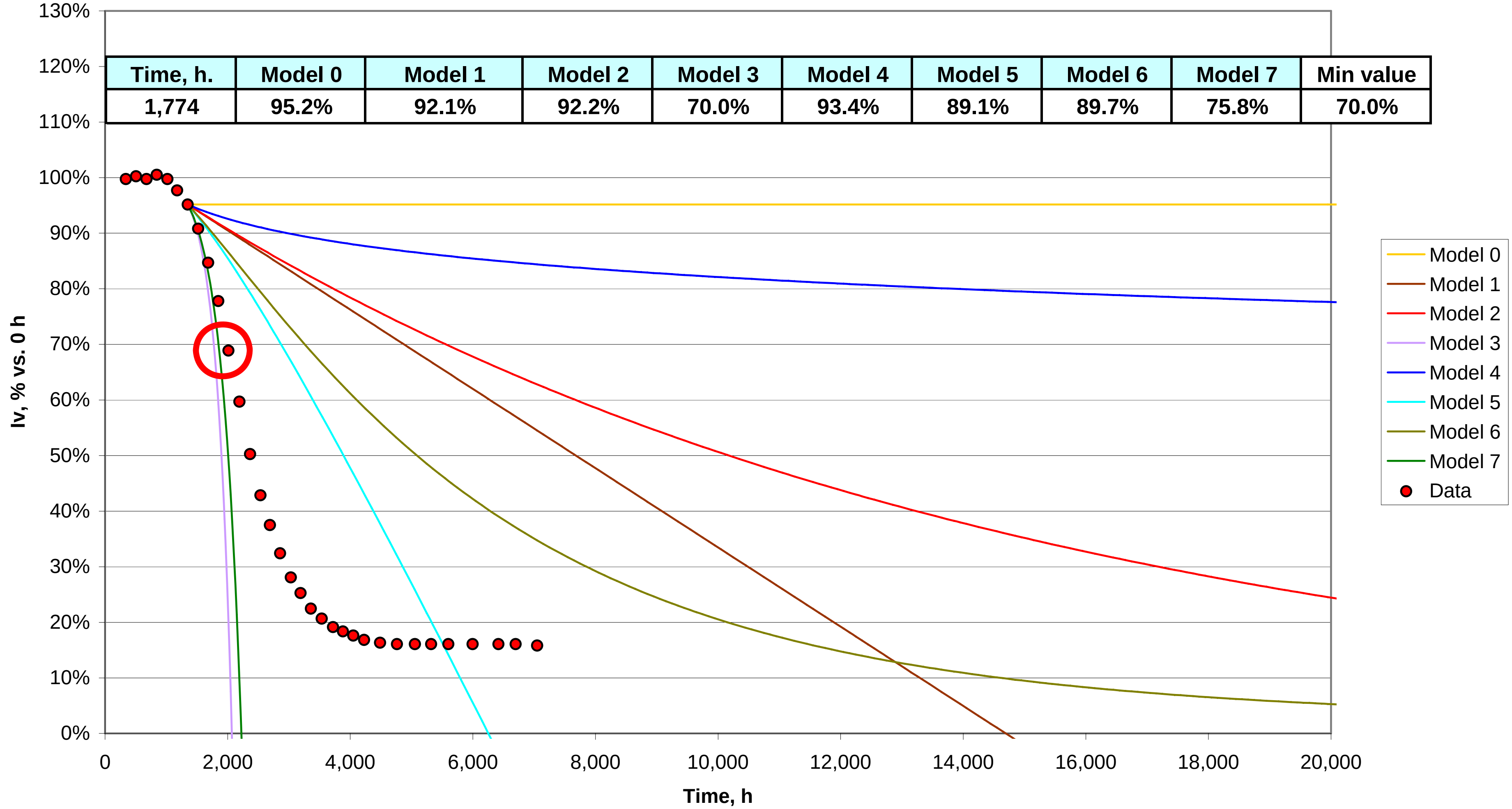
Examples: Model 3 – "Cliff Type LM Curve"



Time, h.	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Min value
1,774	95.2%	92.1%	92.2%	70.0%	93.4%	89.1%	89.7%	75.8%	70.0%

Models 3 and 7 are also capable of predicting <u>accelerating</u> lumen decay

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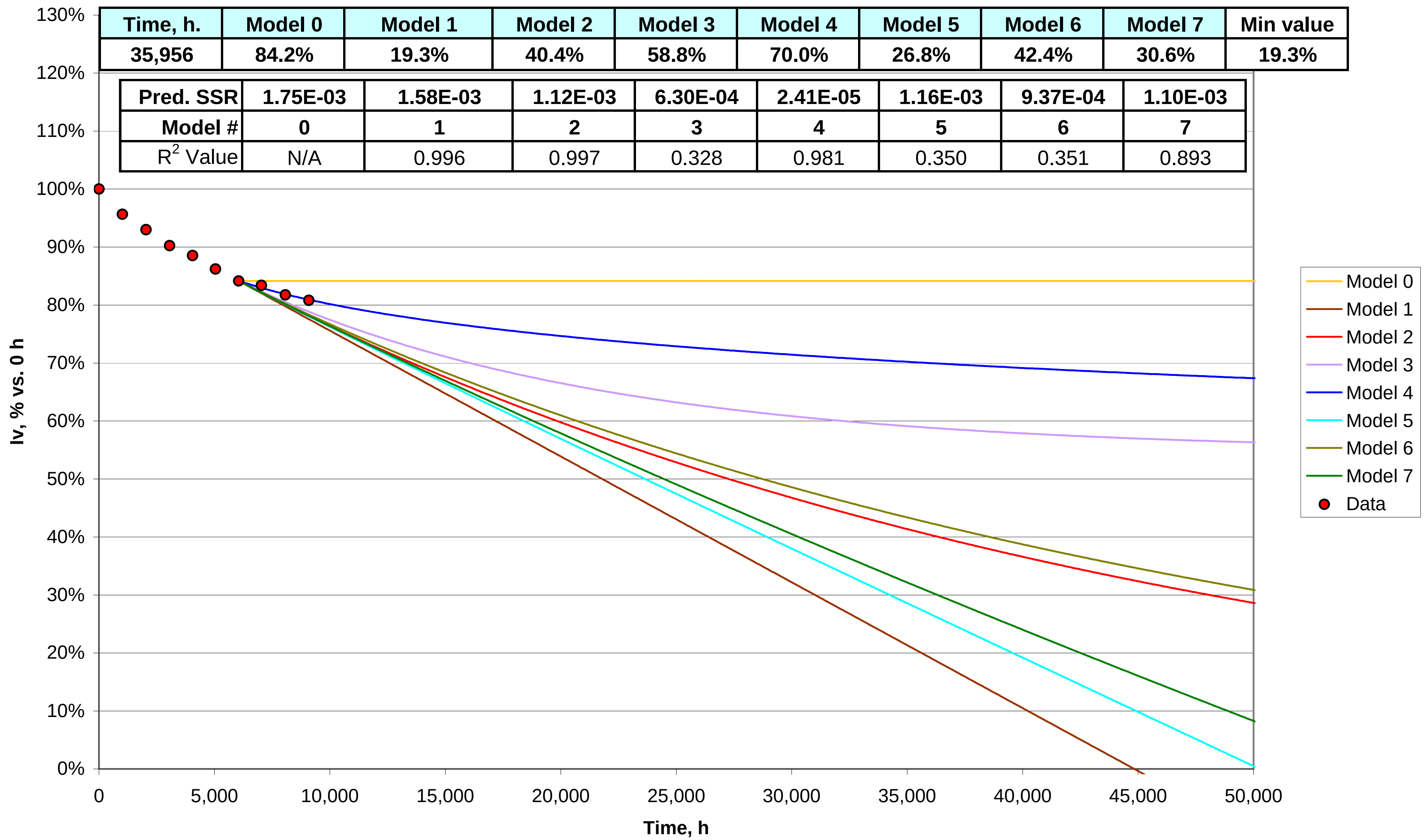
Examples: Model 4 (Simple Logarithmic)

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

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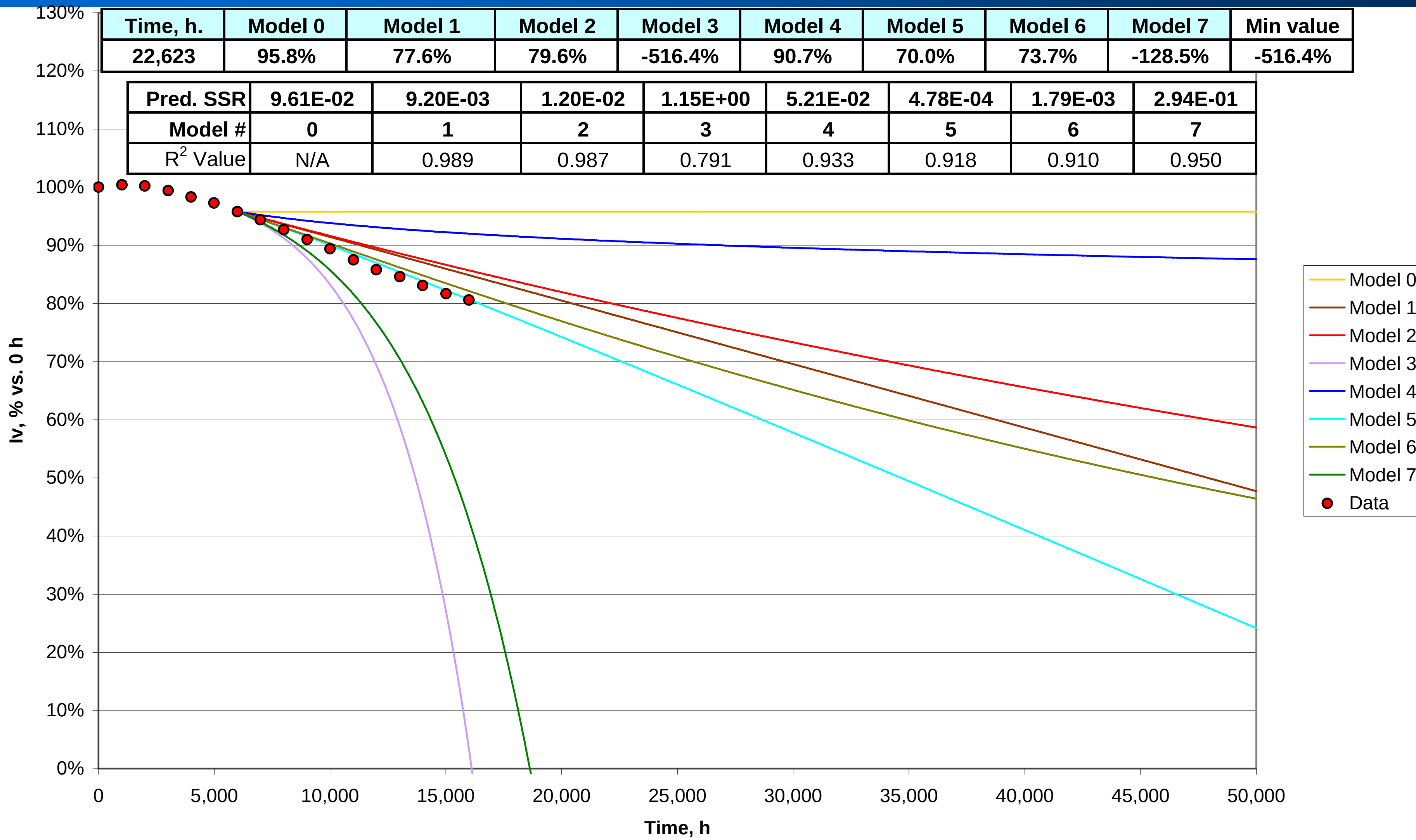
Examples: Model 5 (Two Parameters)

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

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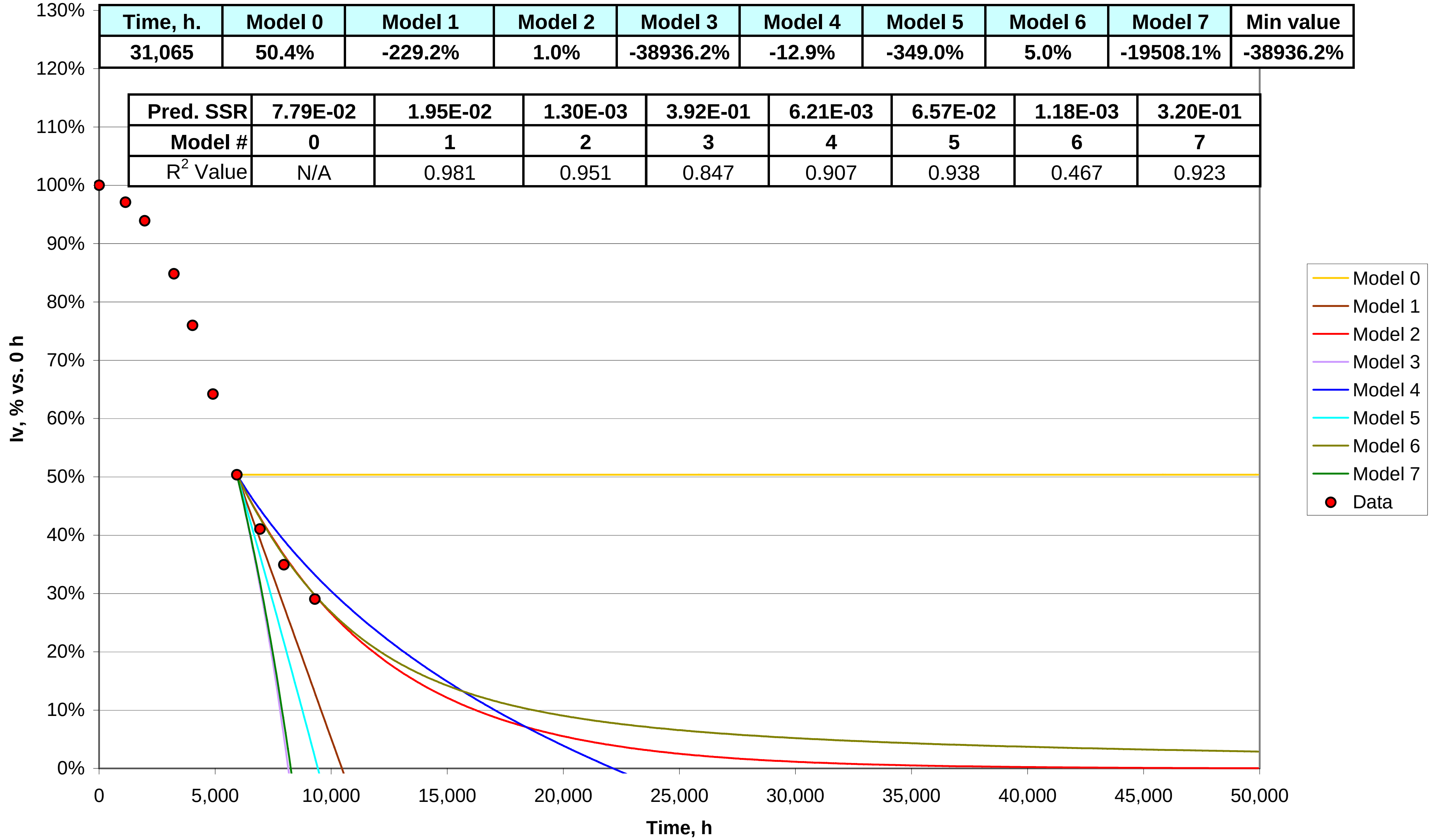
Examples: Model 6 (Two Parameters)

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

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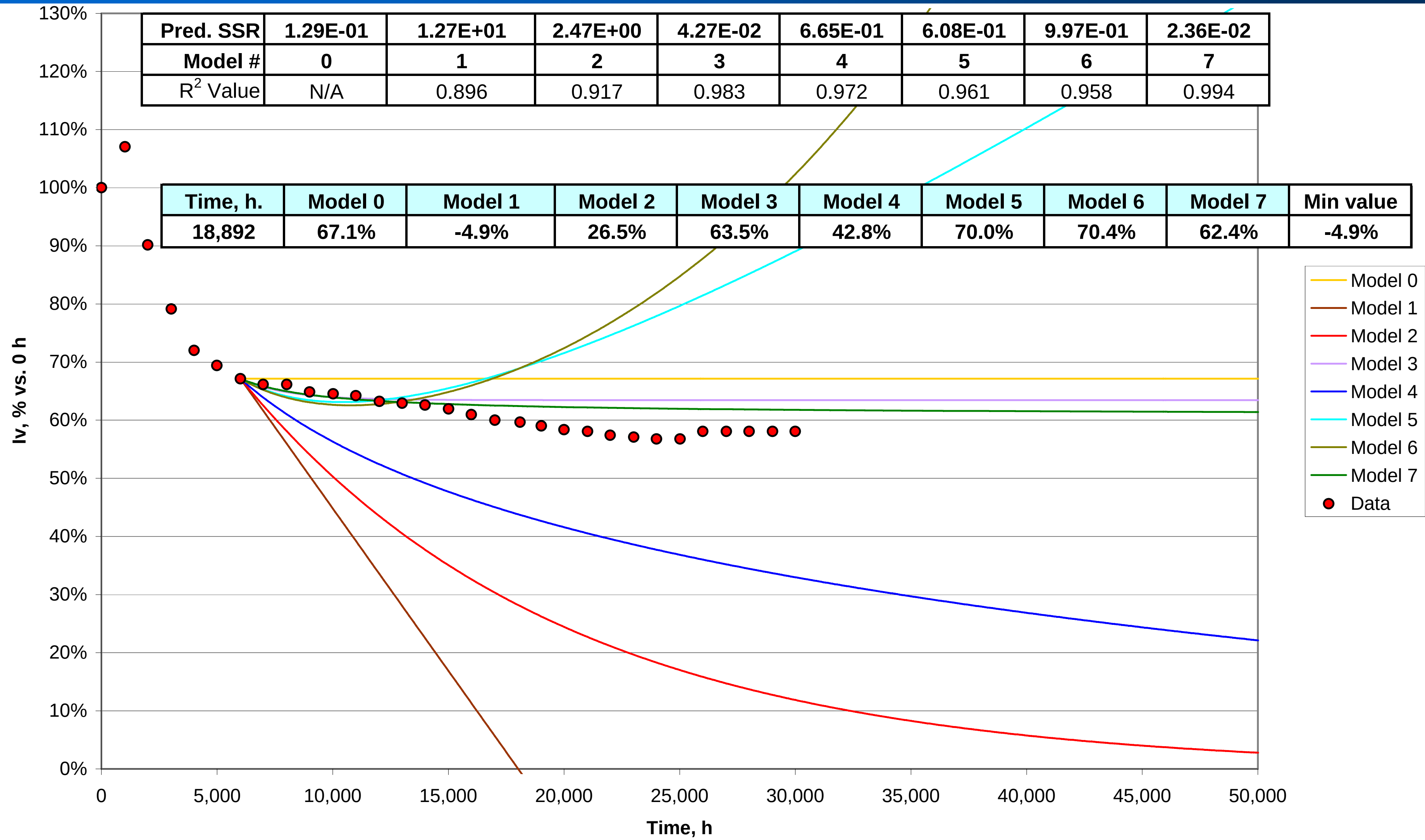
Examples: Model 7 (Three Parameters)

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

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Additional Comments on Large L70 Projected Values

Problem: No L_{70} prediction can be calculated for LEDs following Model 0 (and some others), based on data collected over the first 6000 hrs of testing only.

Implication: The most reliable LEDs would (ironically) have to be tested for the longest times, in order for the data or the model projection to cross the L_{70} line.

Proposed Solution: Impose a time limit on any prediction, e.g. 6x the testing time interval (i.e. 36000 hrs for a 6000 hr test).

Time limits on "too good to be true" L70 projections would protect the consumer

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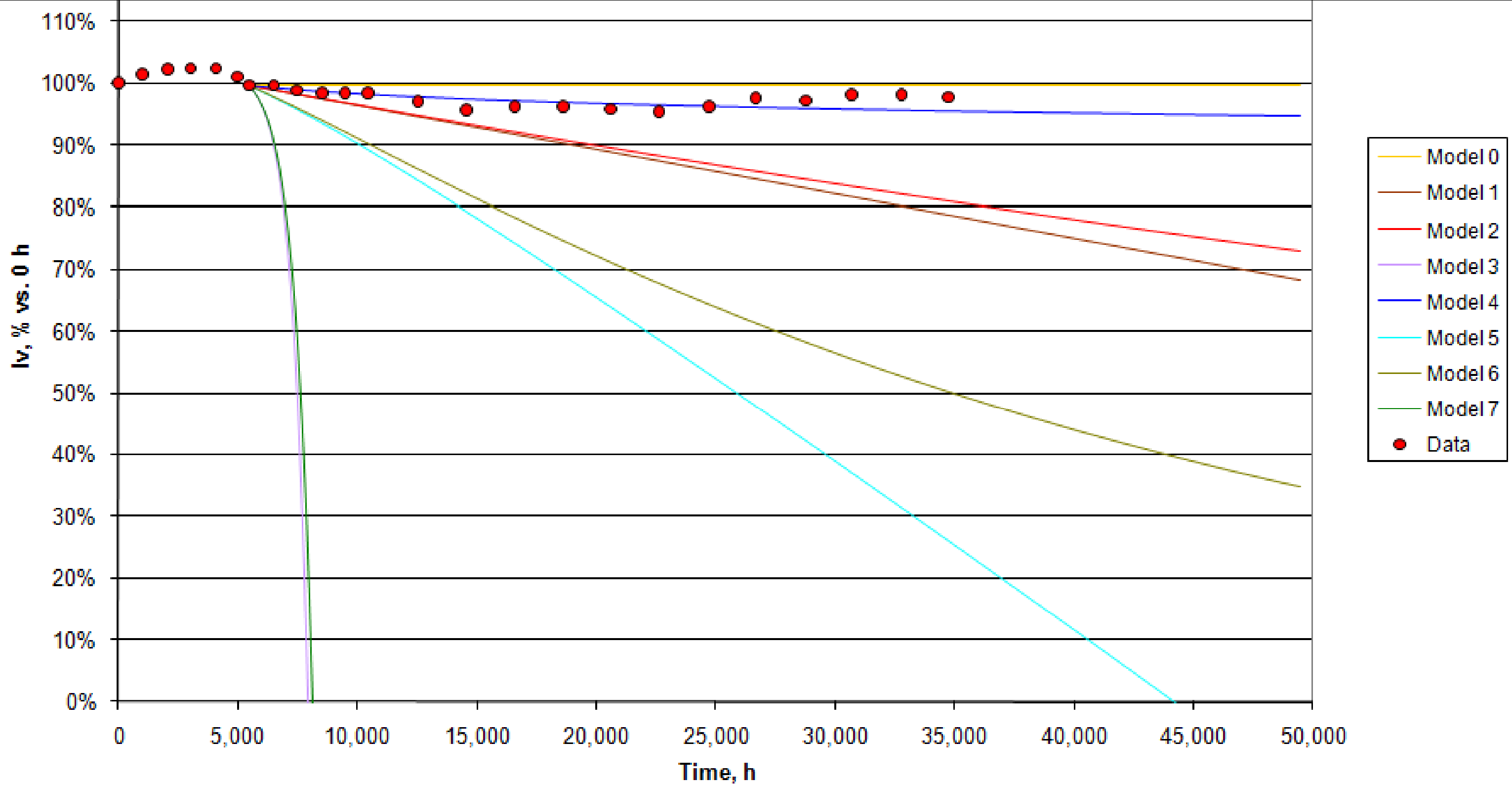
Example of Large L70 Projected Value

LM Projections by Various Models

Time, h.	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
2,424,978,792	99.7%	-1731189.4%	0.0%	#NUM!	70.0%	-7082466.9%	#NUM!	#NUM!
SSR (predicted points)	1.17E-02	1.52E-01	1.21E-01	4.97E+34	3.30E-03	2.30E+00	1.16E+00	5.75E+30
R^2 value (decay rates)	N/A	0.680	0.679	0.709	0.565	0.672	0.729	0.933



The projection by Model 4 is supported by the data out to 6x the test duration

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Additional Comments on Accelerating Decay

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 6000 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 6000 hrs) at the expense of older ones.

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

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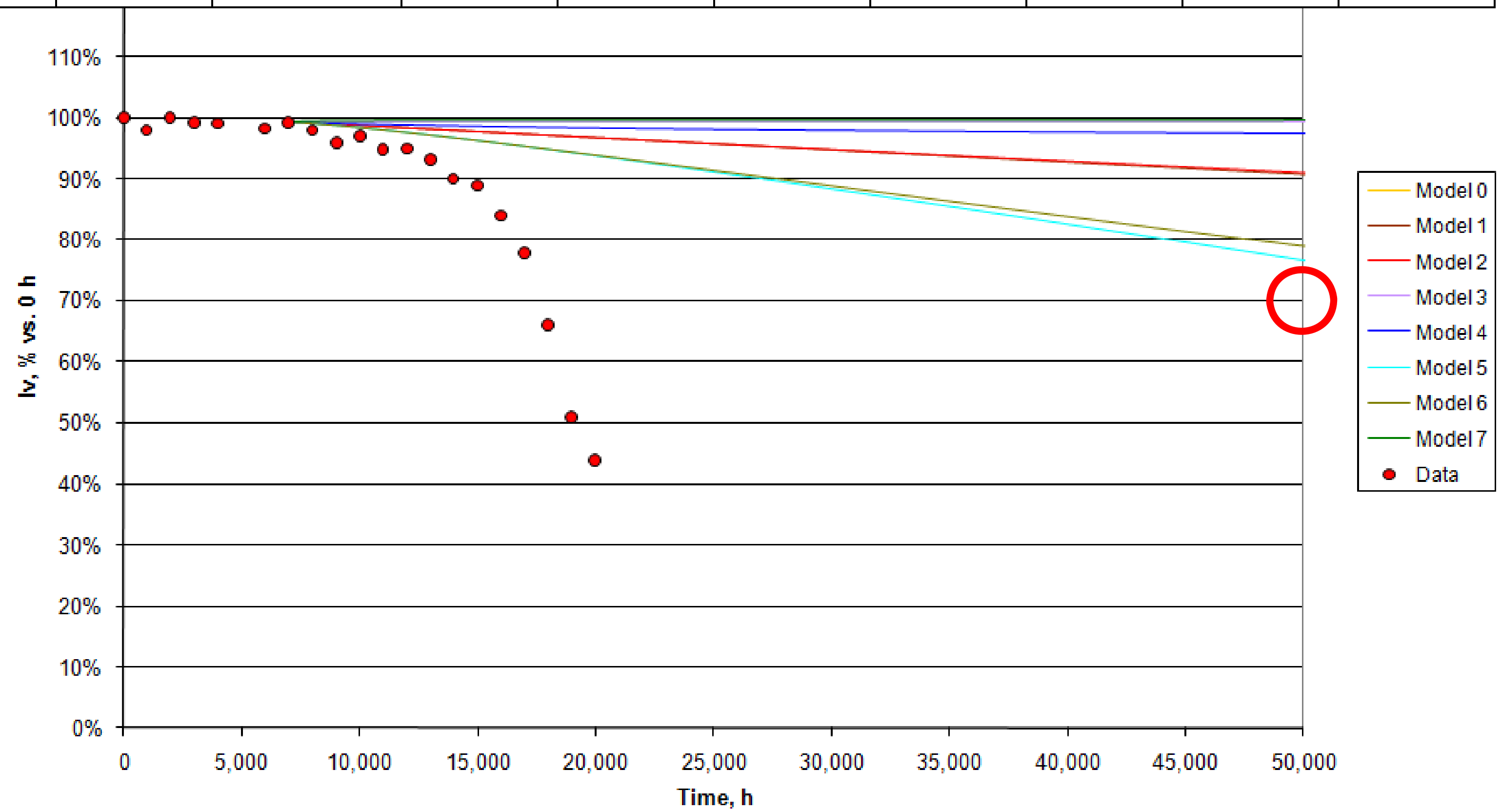
Worst Example of Accelerating Decay (1/3)

LM Projections by Various Models

Time, h.	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Min value
60,754	99.2%	88.6%	89.2%	99.3%	97.3%	70.0%	73.9%	99.7%	70.0%



The decay acceleration is not detected by any model fit over the first 7000 hrs…

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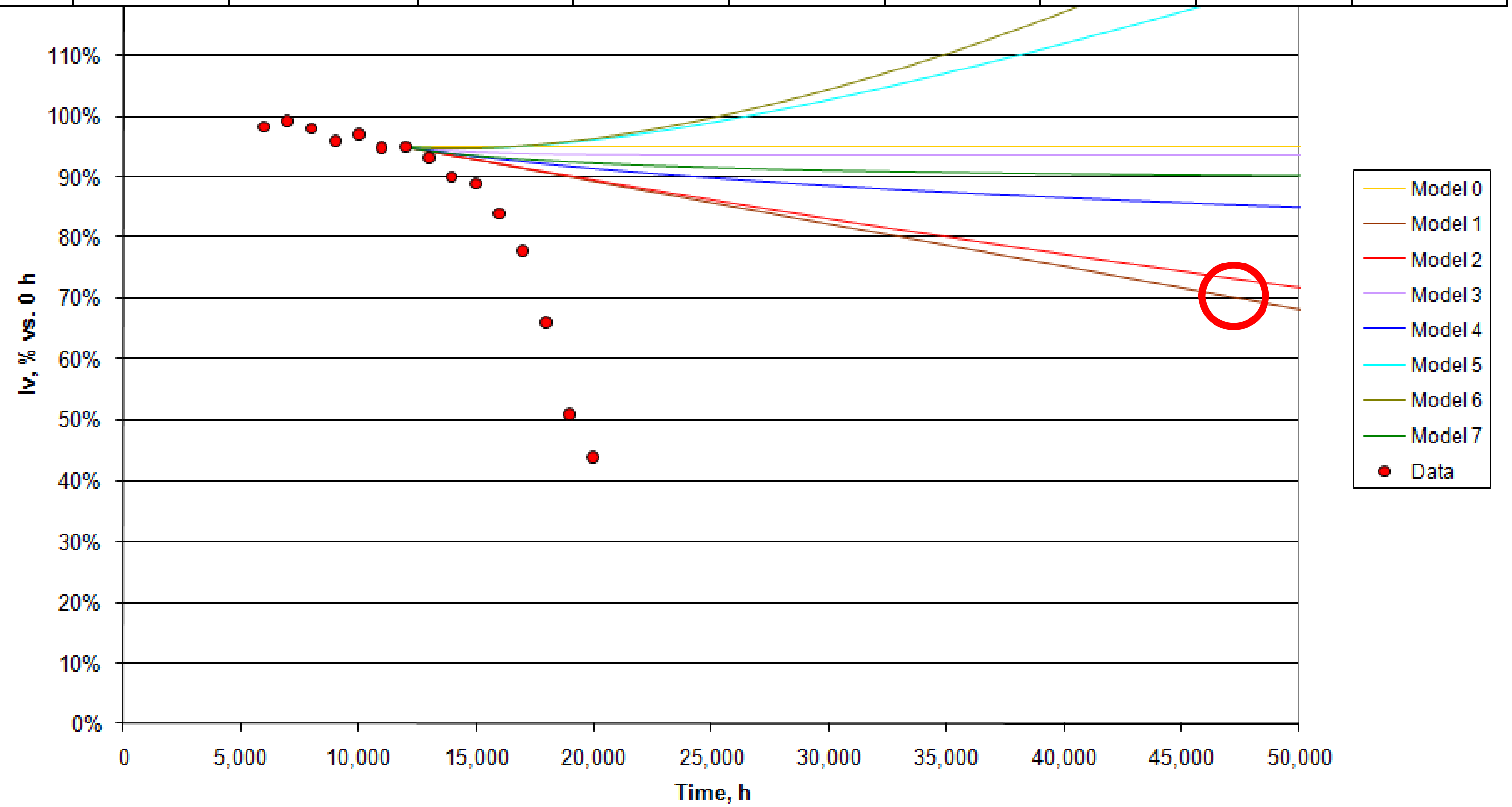
Worst Example of Accelerating Decay (2/3)

LM Projections by Various Models

Time, h.	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Min value
47,204	94.9%	70.0%	73.3%	93.7%	85.3%	119.6%	129.1%	90.4%	70.0%



...but the <u>lowest</u> L70 projection keeps decreasing for later data points...

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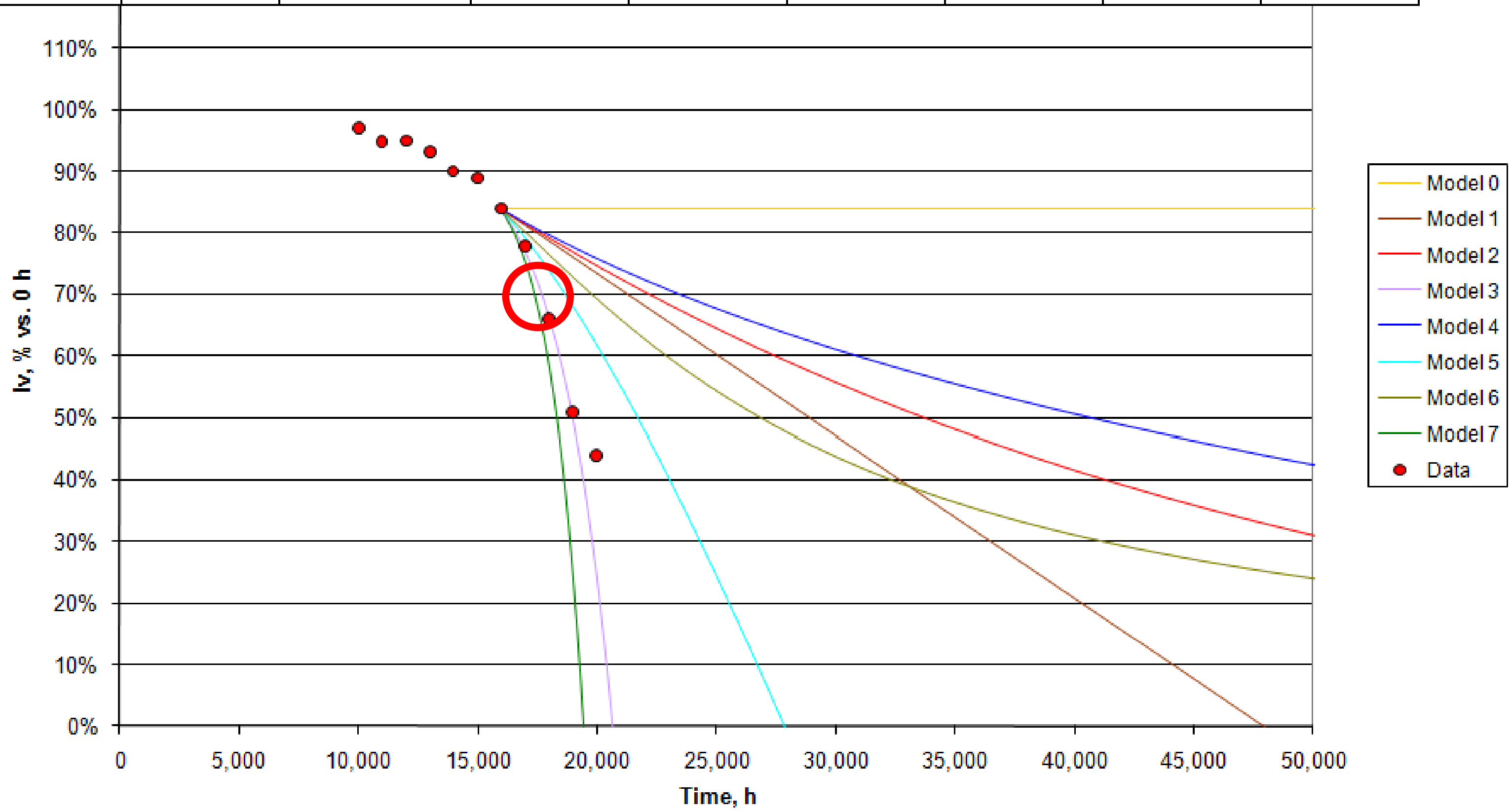
Worst Example of Accelerating Decay (3/3)

LM Projections by Various Models

Time, h.	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
17,375	84.0%	80.3%	80.6%	73.3%	80.9%	77.2%	78.8%	70.0%
17,679	84.0%	79.5%	79.9%	70.0%	80.3%	75.6%	77.6%	64.7%



...until Model 3 locks onto both the L70 and the L50 values by 16000 hrs of testing

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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 L_{70} region.

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

Proposed Solution: Introduce new models into the set (e.g. by adding new terms, such as k_4t, etc.). *However, need to watch out for over-fitting the data.*

The proposed set of models may be expanded further as necessary

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Summary:

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

- R^2 values calculated from the 1st derivative (LM rate) fits are not trustable for down-selecting the best model for extrapolation.

- SSR on validation points after 6000 hrs is an appropriate criterion for the extrapolation models.

- A time limit (e.g. the 6 times rule) should be imposed on any L70 projection.

- Extra care should be taken to detect accelerating lumen decay, especially if manifesting after 6000 hrs.

- Additional terms & models may be introduced as needed.

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Future Work:

- Determine safeguard for un-validated projections based on no more than 6000 hrs of testing **(using the lowest L_{70} prediction among all models proposed)**

- Determine number of minimum validation points for SSR calculation **(4 proposed, i.e. minimum 10000 hrs of testing)**

- 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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