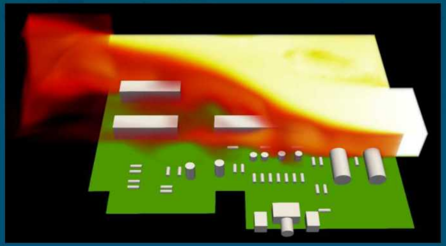
SAND2018-9841PE

TSS Sterilization Sensitivity Analysis



PRESENTED BY

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Overview and Motivations

Literature survey of governing equations

Surrogate thermal model for sensitivity analysis

Sensitivity of TSS system mass to sterilization model and timing requirements

What effect does changing the sterilization requirement have on TSS mass?

How much “sterilization margin” are we carrying?

Governing Equations

$$\frac{n(t)}{n_0} = exp\left(-\int_0^t k\big(T(t)\big)\partial t\right)$$

Translate a temperature history (T(t)) into a biological reduction level (n(t)) [3,6]

$$k(T) = \frac{\ln(10)}{D(T)}$$

Compare the effect of using different models for D(T)

Account for hardies and non-hardies (regulars) separately

- Initial fraction of hardies (F_H) is 10^{-3} [5]

$$\frac{n(t)}{n_0} = F_H exp\left(-\int_0^t k_H\big(T(t)\big)\partial t\right) + (1 - F_H)exp\left(-\int_0^t k_R\big(T(t)\big)\partial t\right)$$

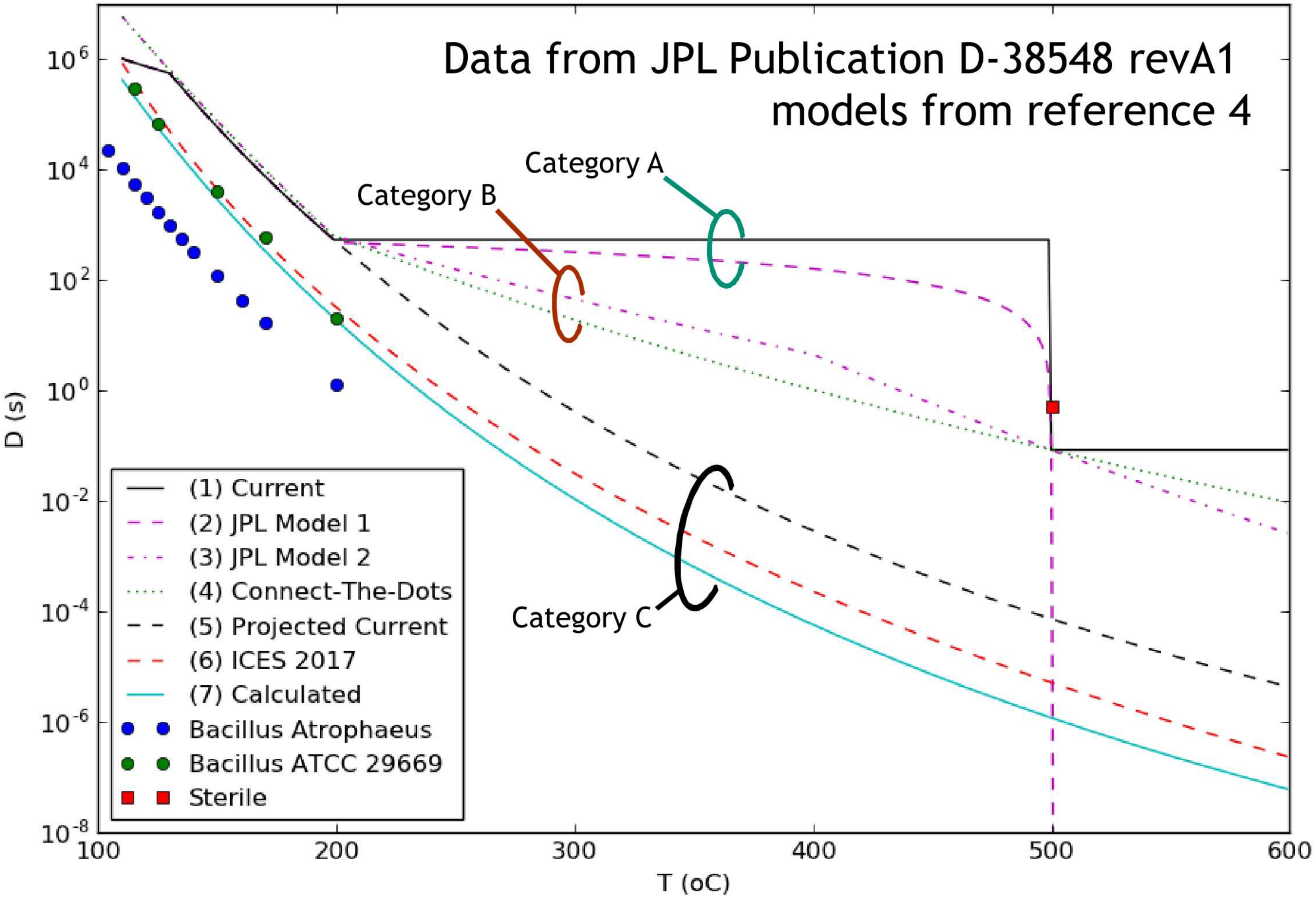
[3] Schubert and Beaudet, JPL 2011
[5] Spry, Schubert, and Beaudet, JPL 2010
[6] Kempf, Schubert, and Beaudet, JPL 2008

k is a lethality rate constant (1/s)

D is a time value (s) for a 10x reduction in population

D-Value Models

1. **Existing**: Constant D-value from 200 to 500 °C [4] (6-log)
2. **JPL Model 1**: Linear D-value from 200 to 500 °C (Ray & Brian)
3. **JPL Model 2**: Modified log-linear model based on additional points from Ray (at 300 °C and 400 °C)
4. **Connect-The-Dots**: Straight line (in log-space) from 200 °C to 500 °C
5. **Projected**: Allow current model to extend beyond 200 °C (6-log)
6. **ICES**: Logarithmic projection from [4] based on fit of data for hardies (12-log)
7. **Calculated**: Using a population with 10^{-3} initial fraction of hardies, calculate using data for both hardies and non-hardies from [5] (12-log)


Data from JPL Publication D-38548 revA1 models from reference 4

Category A
Close to existing standard

Category B
Attempts to connect 200 °C point to 500 °C point with Arrhenius law

Category C
Ignores 500 °C point and extrapolates measured Arrhenius rates

[4] Shirey, Schubert, and Bernardini, JPL 2017
[5] Spry, Schubert, and Beaudet, JPL 2010

Margin

Existing DHMR standard carries a lot of margin/safety factors

- Previously this margin did not translate directly into spacecraft mass, but for the TSS it does

Sources of margin at 200 ^{o}C:

- Measured D value for hardy spore (*Bacillus ATCC 29669*) – 20.5 s at 200 ^{o}C (ambient humidity) [5]
- Added 3-sigma to D value – 22.9 s at 200 ^{o}C (12% increase, overall 16x greater than *B. atrophaeus*) [5]
- Applied 10x margin for encapsulated bioburden (229 s at 200 ^{o}C) [4,5]
- Actual standard D = 478.9 s [4] (another factor > 2x – comes from assuming 40x greater than *B. atrophaeus*)

Overall: ~2,000% margin at 200 ^{o}C (20x)

Sources of margin at 300 ^{o}C:

- Arrhenius extrapolated D value for hardy spore (*Bacillus ATCC 29669*) – 14 ms at 300 ^{o}C [5]
- Actual standard D = 478.9 s [4] (no decrease permitted relative to 200 ^{o}C)

Overall: ~3,400,000% margin at 300 ^{o}C (34,000x)

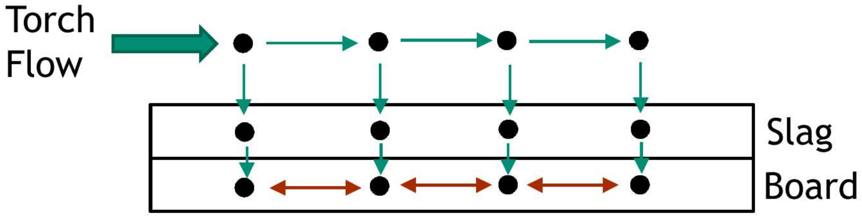
Note: D-value margin does not translate 1:1 into mass margin
(the 20x margin translates to about a 50 ^{o}C higher temperature requirement)

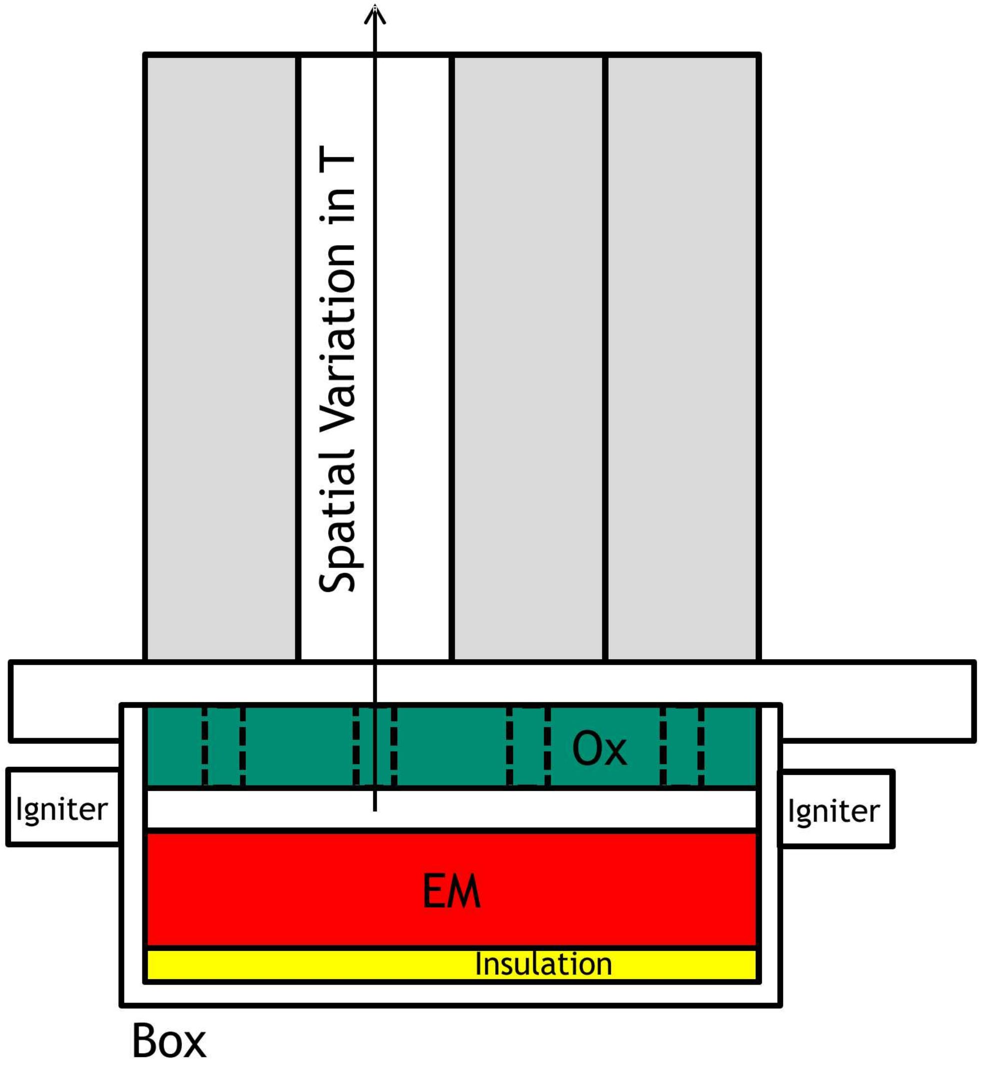
[4] Shirey, Schubert, and Bernardini, JPL 2017
[5] Spry, Schubert, and Beaudet, JPL 2010

Thermal Model

Same model we presented previously (1D pipe flow model) with a couple modifications:

1. Implemented all 7 bio burden models, including the calculated form that tracks hardies and non-hardies separately
   - Takes T(t,x) in board and calculates BioBurden(t,x)
   - Sterilized when max BioBurden < 10^{-6} (or 10^{-12})
2. Implemented lateral conduction in boards (if the coldest section of board reaches 495 °C when the torch stops at 5 s, we could still hit 500 °C by 10 s)





Parameters of Interest

1. TSS (system) mass change with change in sterilization time (nominally 10 seconds)
2. TSS (system) mass change with change in bio burden model

Base model is for a fixed number of boxes (fewer than currently scoped for the lander), so we will express the results relative to the baseline configuration (sterilization in 10 seconds with bio burden model 1)

Reduction in TSS Mass Relative to Baseline

	← Most Conservative			**Bio Model**	*Least Conservative→*		
Time Target (s)	1	2	3	4	5	6	7
10	0%	3%	14%	25%	58%	65%	67%
15	12%	12%	27%	37%	60%	66%	68%
20	14%	14%	31%	41%	61%	67%	68%
25	15%	15%	33%	44%	62%	67%	69%
30	15%	15%	35%	46%	63%	68%	69%
	Category A <5 %		Category B 15-30%		Category C 60-70%		

Model Key:

1. Existing
2. JPL Linear
3. JPL Extra Points
4. Connect-the-dots
5. Projected
6. ICES
7. Calculated

Mass Effects

Current approach applies each bio burden model until a 6-log total reduction is achieved

Increasing that to a 12-log reduction increases mass of all options by about 5-7% (does not significantly alter the trends in the table below)

Factor of Decrease in TSS Mass
(“TSS will be X times lighter”)

	← Most Conservative			**Bio Model**	*Least Conservative→*		
Time Target (s)	1	2	3	4	5	6	7
10	1.00	1.04	1.16	1.32	2.36	2.82	3.00
15	1.14	1.14	1.36	1.58	2.51	2.94	3.10
20	1.16	1.16	1.44	1.70	2.57	3.00	3.16
25	1.17	1.17	1.50	1.78	2.64	3.06	3.24
30	1.18	1.18	1.54	1.84	2.67	3.10	3.27
	Category A		Category B		Category C		

Model Key:
1. Existing
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Alternate Approach

In contrast to prior method, in this section we take Model 1 and simply shift the temperature where the "step" occurs in 50 ^{o}C increments and make the same comparisons as before (X ^{o}C for 0.5 seconds)

Percent Decrease in TSS System Mass

	← Most Conservative		***Sterilization Temperature***		*Least Conservative→*	
Time Target (s)	500 ^{o}C	450 ^{o}C	400 ^{o}C	350 ^{o}C	300 ^{o}C	250 ^{o}C
10	0%	18%	32%	45%	56%	64%
15	12%	24%	35%	46%	57%	64%
20	14%	25%	36%	46%	57%	65%
25	15%	26%	36%	47%	57%	65%
30	15%	26%	37%	47%	57%	65%

Factor of Decrease in TSS System Mass

	← Most Conservative		***Sterilization Temperature***		*Least Conservative→*	
Time Target (s)	500 ^{o}C	450 ^{o}C	400 ^{o}C	350 ^{o}C	300 ^{o}C	250 ^{o}C
10	1.00	1.22	1.48	1.82	2.27	2.77
15	1.14	1.31	1.54	1.85	2.31	2.80
20	1.16	1.33	1.55	1.86	2.31	2.82
25	1.17	1.34	1.57	1.87	2.33	2.82
30	1.18	1.35	1.58	1.89	2.33	2.82

250-300 ^{o}C
Requirement is similar to a Category C model

400-450 ^{o}C
Requirement is similar to a Category B model

Conclusions

Category B models (trying to tie data from 200 to 500 C point) offer 15-30% mass reduction

Category C models (ignoring 500 C point and extrapolating actual data) offer 60-70% mass reduction

Increasing time allotment offers small potential gains (10-15% mass reduction) with diminishing returns above 20 s

Based on published data of lethality rates, existing design likely holding *a lot* of margin

References

1. K. Tsuji and S. Harrison, Dry-Heat Destruction of Lipopolysaccharide: Dry-Heat Destruction Kinetics, Applied and Environmental Microbiology, 1978, Vol 36, p 710-714
2. M. Kempf, L. Kirschner, R. Beaudet, Extended temperature range studies for dry heat microbial reduction, 2005, JPL Web Archive
3. W. Schubert, R. Beaudet, Determination of Lethality Rate Constants and D-Values for Heat-Resistant *Bacillus* Spores ATC 29669 Exposed to Dry Heat from 125 ^oC to 200 ^oC, Astrobiology, 2011, Vol 11, pp 213
4. T. Shirey, W. Schubert, and J. Benardini, An Overview of Surface Heat Microbial Reduction as a Viable Microbial Reduction Modality for Spacecraft Surfaces, 47th International Conference on Environmental Systems, July 16-20, 2017, ICES-2017-201
5. J. Spry, W. Schubert, R. Beaudet, Proposal for Modification of the NASA Specifications for the Dry Heat Microbial Reduction of Space Hardware, 2010, JPL Publication D-38548 revA1
6. M. Kempf, W. Schubert, R. Beaudet, Determination of Lethality Rate Constants and D-Values for Bacillus atrophaeus (ATCC 9372) Spores Exposed to Dry Heat from 115 ^oC to 170 ^oC, Astrobiology, 2008, Vol 8, pp 1169-1182

Appendix

NPR 8020.12D Lists “*Hoffman, R. K., et al. Thermal Inactivation of Aerosolized Bacillus subtilis var. niger Spores. Appl. Microbiol. 22(4): Oct. 1971.*” as a reference for the 500 °C number

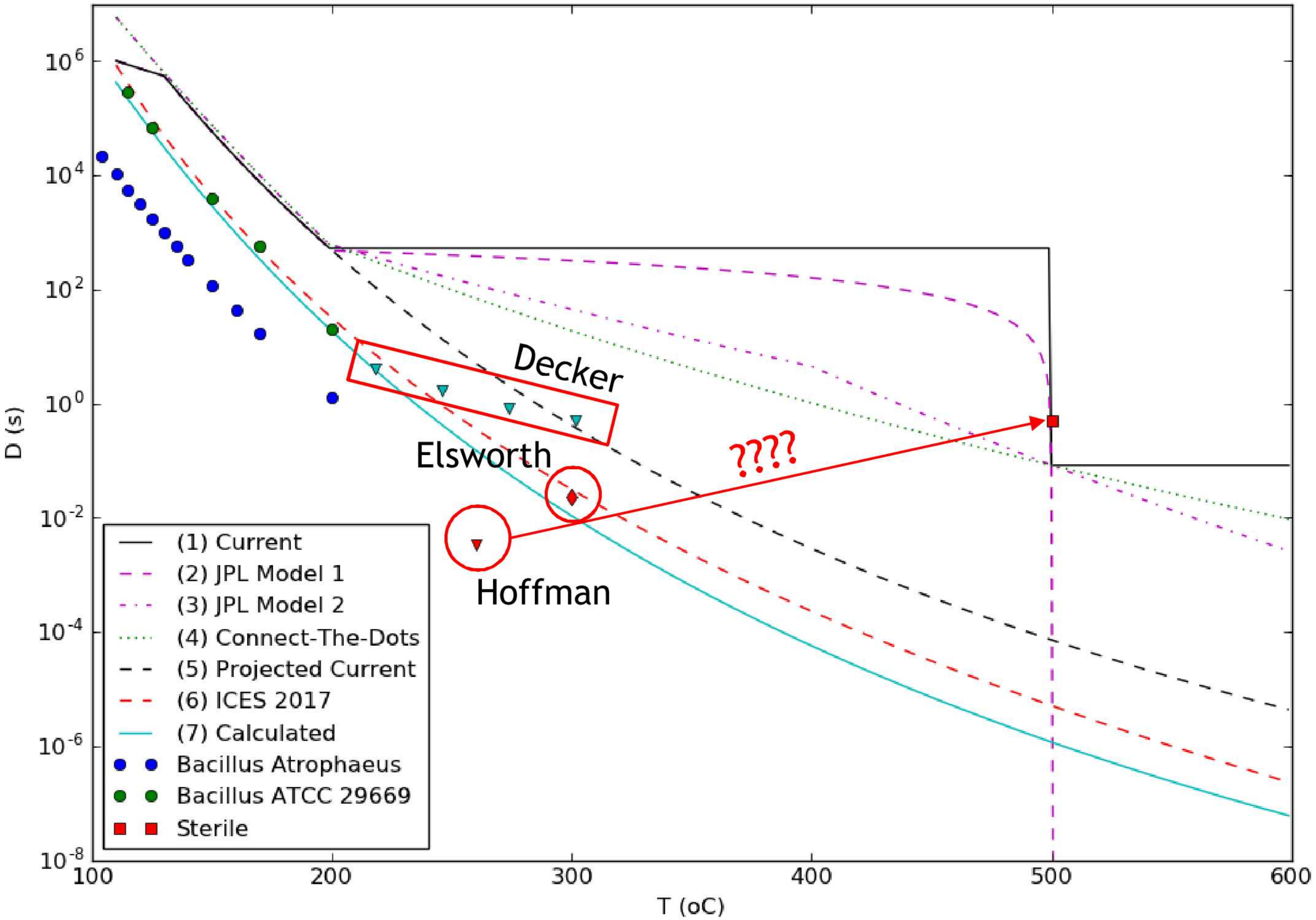
The experimental data point from Hoffman is added to the plot on the right (0.02 seconds at 260 °C for 6-log)

Abstract:

> […] With this apparatus, aerosolized *Bacillus subtilis var. niger* spores were killed in about 0.02 sec when exposed to temperatures above 260 C. This is about 500 times faster than killing times reported by others. Extrapolation and comparison of data on the time and temperature required to kill […] on surfaces show that approximately the same killing time is required as is necessary for spores in air […]

“Others” here is Decker et al. (also added to plot)

Elsworth reported sterilization in 0.14 s at 300 °C



Difference between Hoffman and Decker attributed to heat transfer rates (Decker results show time to heat rather than time to kill)

Decker et al., Appl Microbiol. 1954. Vol 2, pp 33
Elsworth et al. J Hyg (Lond). 1955. Vol 53, pp 445

Appendix

k is a lethality rate constant (1/s)

D is a time value (s) for a 10x reduction in population → $k(T) = \frac{\ln(10)}{D(T)}$

$$\frac{\partial n}{\partial t} = -nk = -nk(T(t))$$ 1st Order Kinetics with time-varying rate constant

$$\int_{n_0}^{n(t)} \frac{1}{n} \partial n = \int_0^t -k(T(t)) \partial t$$ Integrate from initial state to state at time *t*

$$\frac{n(t)}{n_0} = exp\left(-\int_0^t k\big(T(t)\big) \partial t\right)$$ <u>Our simplifications will stop here</u>

$$\frac{k(T)}{k_0} = exp\left(-B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$ Kempf (2008) assumed Arrhenius function for *k* with a constant *B* value

$$t_{eff} = \int_0^{t_{act}} exp\left(B\left(\frac{T(t) - T_0}{T(t)T_0}\right)\right) \partial t$$ Calculated an “effective time” at reference temperature T_0

Appendix

$$\frac{n(t)}{n_0} = exp\left(-\int_0^t k\big(T(t)\big)\partial t\right) = exp\left(-\ln(10)\int_0^t \frac{1}{D(T(t))}\partial t\right) = 10^{-\int_0^t 1/D\left(T(t)\right)\partial t}$$

$$\frac{n(t)}{n_0} = 10^{-K_i(t)} \qquad K_i(t) = \int_0^t \frac{1}{D_i(T(t))}\partial t$$

$K_i(t)$ is the number of orders (logs) of reduction achieved at time *t*

$$\frac{n(t)}{n_0} = \frac{n_H(t) + n_R(t)}{n_0} = F_H exp\left(-\int_0^t k_H\big(T(t)\big)\partial t\right) + (1 - F_H)exp\left(-\int_0^t k_R\big(T(t)\big)\partial t\right)$$

$F_H = 10^{-3}$ From reference 5

Appendix

Easy to lose perspective of things on a log-scale