VCSEL Reliability Calculations

(In support of comment # TBD)

Ramana Murty

October 13, 2022

802.3cz D3.0 Comment Resolution

Outline

- Reliability Statement
- Reliability Statistics
- Application to VCSEL
- Summary

Calculations reported in Refs. [1] and [2]

❑ Comments on the calculations (slide 23 in Ref. [1], and slide 11 in Ref. [2])

$$T_J = T_S + \frac{I_{BIAS}(mA)}{7.5} \cdot \Delta T_{SJ@7.5mA}$$

$$TTF_{5FIT} = \exp\left(\mu' + \sigma' \cdot \Phi^{-1}\left(\frac{5 \cdot 32000}{1000} 10^{-9}\right)\right)$$

Reliability result

	Temperature profile					Failure rate						
	Percentage	Operation time per Temperature (h)	T_A (°C)	T_S (°C)	T_J (°C)	TTF x% (hours)	$TTF_{5\,FIT}$ (hours)	Equivalent time in max T (hours)	Log-normal mu', ln (hours)	Failure-rate wear out (FIT)	Failure-rate maverick (FIT)	ppm
T0	6 %	1920	-40	-20.00	5.0	1.084E+11	11684618447	0.00	27.2706			
T1	20 %	6400	23	43.00	68.0	1.539E+07	1658406	3.27	16.4104			
T2	65 %	20800	50	70.00	95.0	8.736E+05	94131	187.00	15.5415			
T3	8 %	2560	100	120.00	145.0	1.145E+04	1234	1755.75	11.2070			
T4	1 %	320	105	125.00	150.0	7.854E+03	846	320.00	10.8298			
Cummulative	100 %	32000						t 2266.01	μ' 10.8298	$\lambda(t)$ 118.4411	5.0	ppm 3950

Incorrect values even for the composite line.

> 10 FIT !

λ(t) in the expression is the same as the hazard rate h(t) defined on slide 4.

$$\lambda(t) = -\frac{d\ln(1-F(t))}{dt} \qquad ppm = \frac{\lambda(t) \cdot 32000}{1000}$$

a) Does not follow from λ(t).
b) Expression is not valid for wear out lognormal failure distribution.
c) Vastly overstates failure.

Incorrect value

Mechanics of the calculation appear fine. Inputs are incorrect.
a) This is calculated for Δt at 125°C (100%, not 1% as in the mission profile)
b) It should be de-rated by the percent time spent at 125°C. Saying worst case is for all units to be at 125C at EOL is equivalent to the ensemble being at the lowest entropy configuration – doesn't happen.
c) **Calculated with an extrapolation of the composite line that leads to an incorrect answer.**

[1] Ruben Perez-Aranda, perezaranda_3dh_01a_221005_vcsels.pdf
[2] Ruben Perez-Aranda and David Ortiz, perezaranda_3cz_01b_080621_vcsel_reliability.pdf

850 nm VCSEL Reliability

1. Time to 1% failure exceeds automotive requirement by a wide margin (murty_3dh_01a_220713.pdf).

2. Field experience of over 100M units has demonstrated random failure rate lower than 1 FIT.

3. Hazard rate

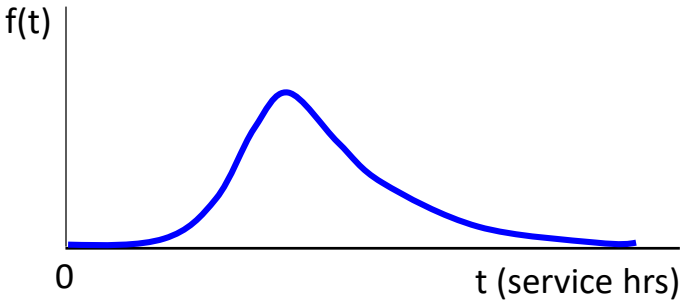
   The presentations perezaranda_3dh_01a_221005_vcsels.pdf and perezaranda_3cz_01b_080621_vcsel_reliability.pdf argue that the hazard rate is too high for wear out.

   Careful analysis shows hazard rate for wear out is very small.

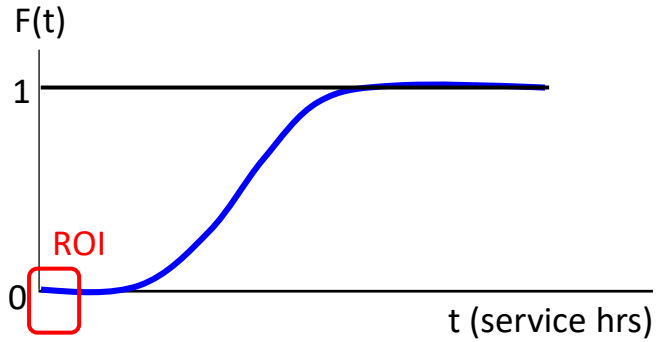
This presentation does not say anything about 980 nm VCSEL.

Probability Distribution

Probability distribution function f(t)



Cumulative distribution function F(t)



$$F(t) = \int_0^t f(\tau)d\tau$$

Units	
cdf	ppm (fraction)
pdf	ppm per unit time

Time is in service hours

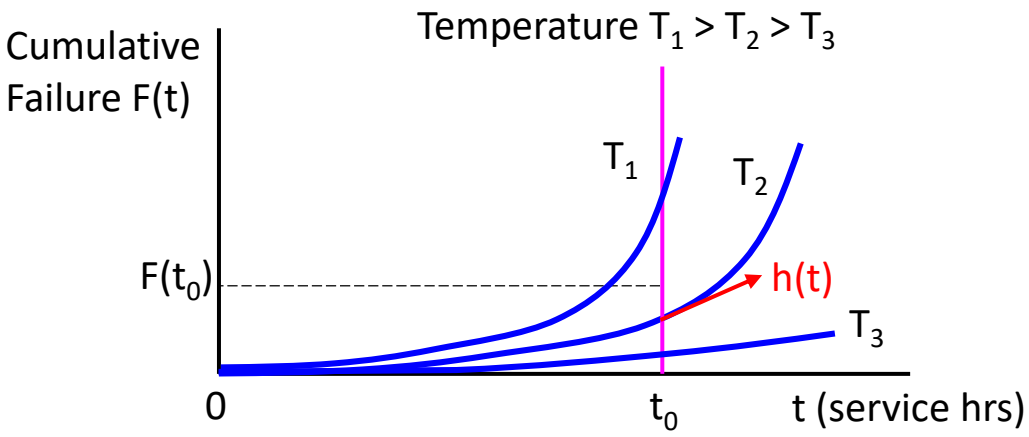
Lognormal distribution is commonly used to fit a failure distribution for wear out

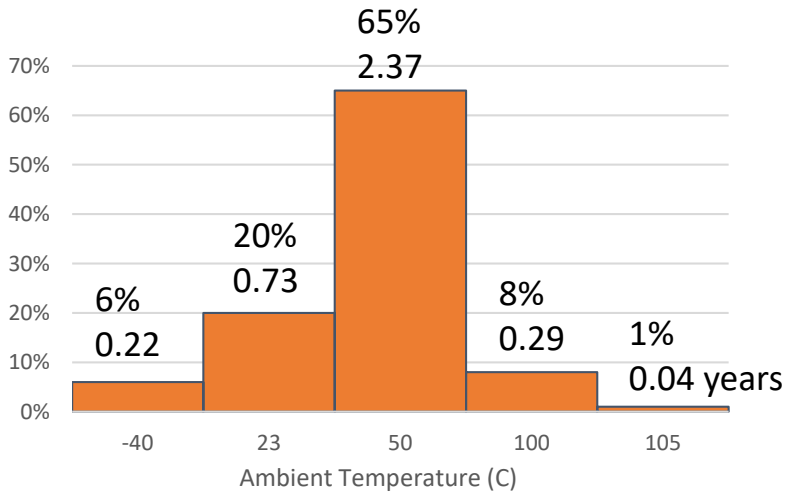
$$f(t) = \frac{1}{\sigma t\sqrt{2\pi}} \exp\left(-\frac{(\ln t - \mu)^2}{2\sigma^2}\right) \qquad \text{pdf}$$

$$F(t) = \frac{1}{2}\left(1 + \text{erf}\left(\frac{\ln t - \mu}{\sigma\sqrt{2}}\right)\right) \qquad \text{cdf}$$

Region of interest (ROI) is failures at very short times.

Hazard Rate





Total 32000 hrs ≡ 3.7 service years

ΔT = 20K is assumed between ambient and VCSEL substrate temperature

Hazard Rate (Instantaneous failure rate)

This is the rate of failure of devices still operating at time t

$$h(t) = -\frac{d(1-F(t))}{dt}\frac{1}{1-F(t)} = \frac{f(t)}{1-F(t)} \approx f(t) \quad \text{[for F(t) << 1]}$$

- For practical purposes, h(t) is the same as the pdf f(t)
- h(t) increases rapidly towards end of life (EOL)
- $h(t_0)$ Additional failures (ppm) per unit time (at time t_0)

- Hazard rate is a function of temperature:
  1 service year at 50°C is not the same as 1 service year at 100°C
- Quoting a value at 125°C is not meaningful if the device spends only a fraction of the time at 125°C
- Unit time is determined by following the automotive mission profile:
  Scale hazard rate by the fraction of time spent at each of the five temperatures (this is equivalent to running a Monte Carlo simulation)

NIST Engineering Statistics Handbook, Section 8.1.2.3.

Application to VCSEL

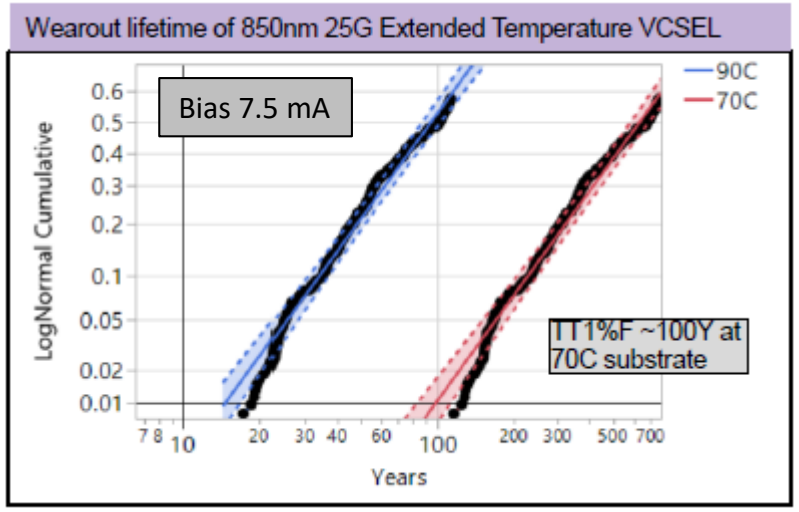
Experimental data and extrapolation

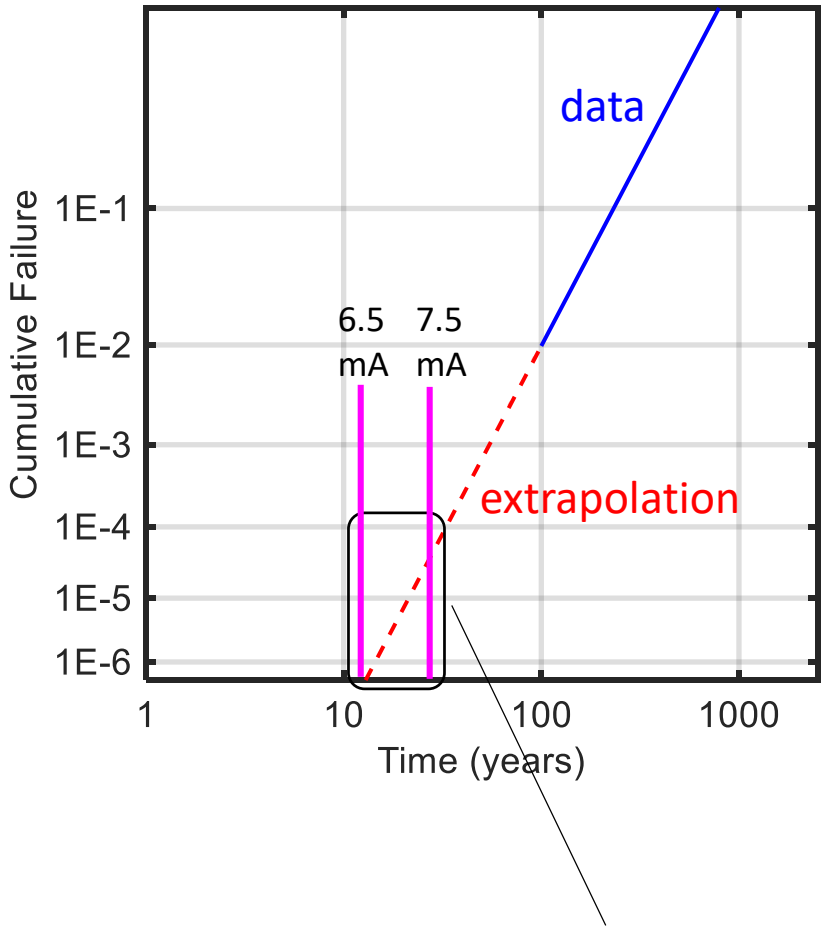
Reading the cumulative failure graph

Hazard rate from wear out

Calculation of Hazard Rate Requires Extrapolation

Experimental data*





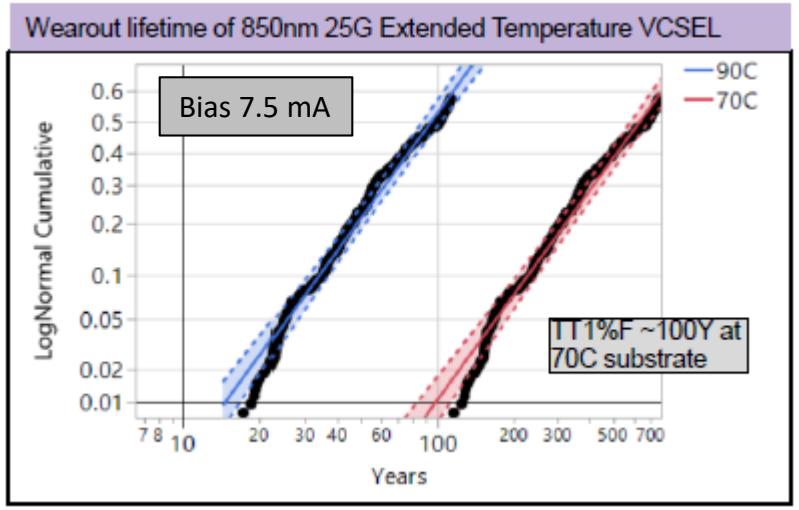
- Estimating hazard rate requires a lot of extrapolation
- Calculation of hazard rate requires taking the derivative of the cumulative distribution function F(t)
  - **amplifies uncertainty**
  - **cannot make bold claims**

What is the hazard rate (derivative of F(t)) over here?

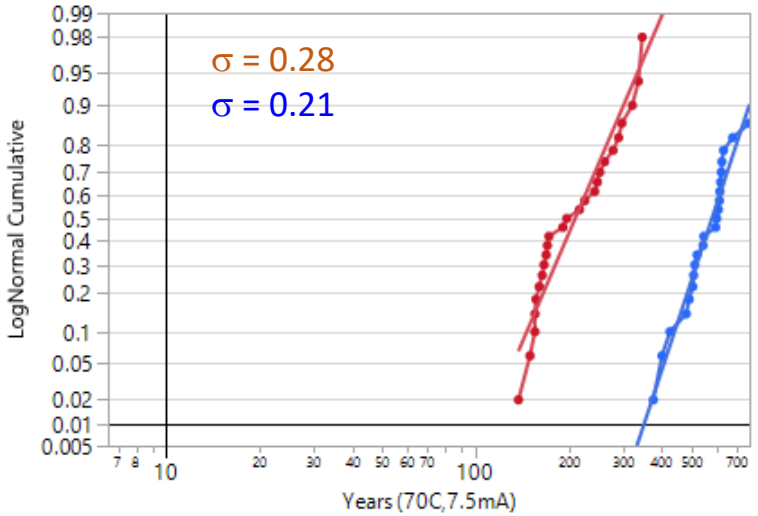
* Laura Giovane, "850 nm 25G VCSEL reliability," giovane_3cz_01a_080621.pdf

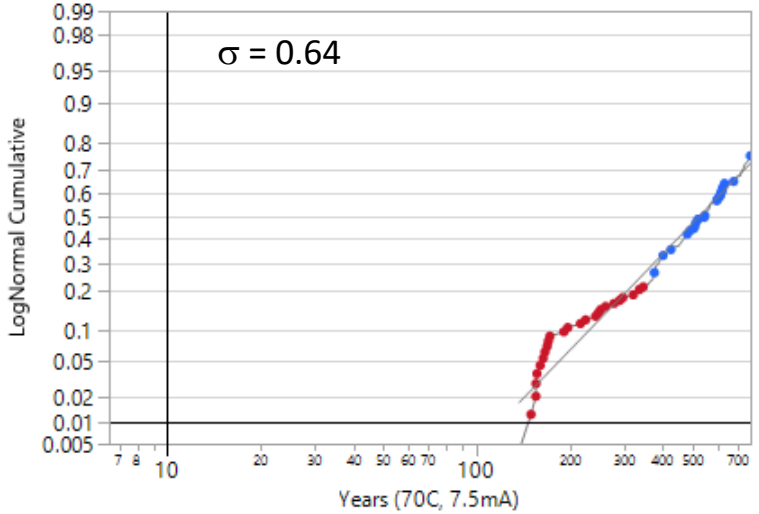
Reading the Cumulative Failure Graph

Plot of cumulative failure is a composite of many VCSELs



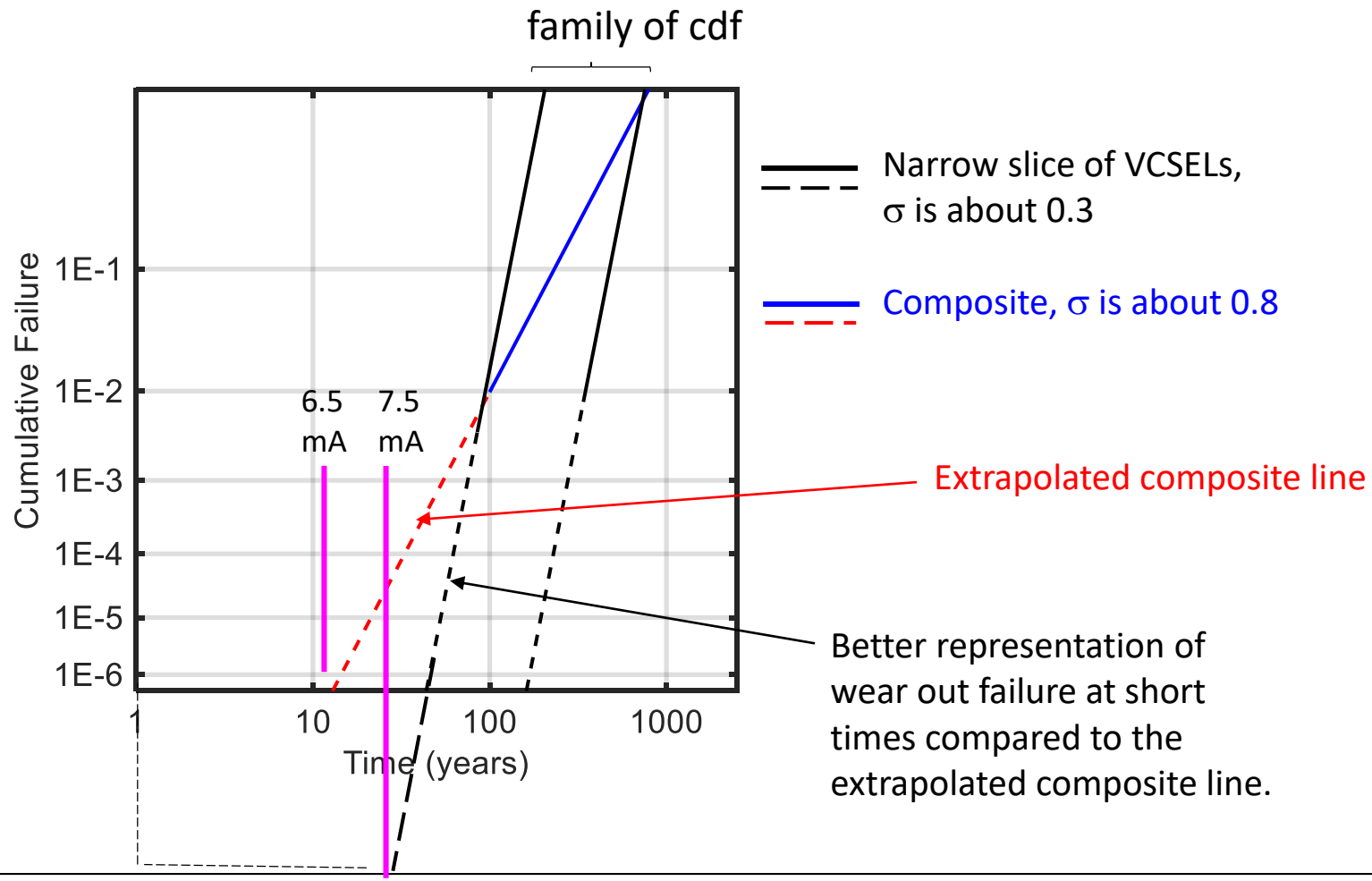
Narrow slice of VCSELs shows a much smaller variation (σ)
When combined, variation (σ) becomes very large





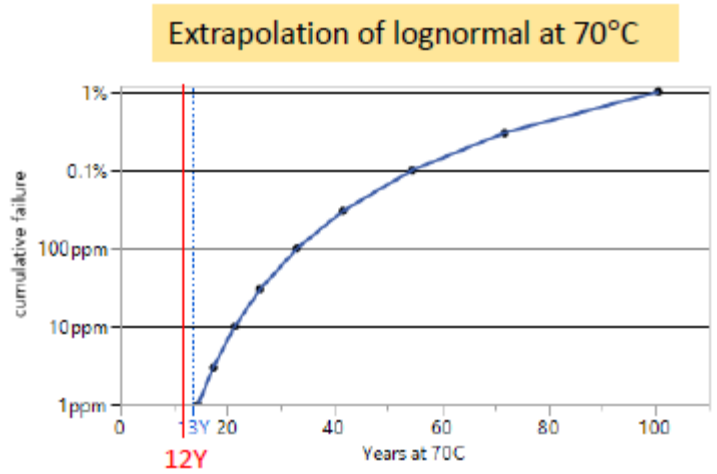
- Experimental data comes from a wide distribution of VCSELs.
- Physics: A large part of the variation (σ) in the composite line comes from the heterogeneous population of VCSELs.
- Without injecting the physics, extrapolation will lead to an incorrect estimate for hazard rate.

Reading the Cumulative Failure Graph



- Both cumulative failure and hazard rate will be vastly overstated if composite line **(- - -)** is extrapolated to times shorter that TT 1%F.
- True wear out failure rate at short times would be lower than the leftmost lognormal curve for the "narrow slice" of VCSELs.
- Expected hazard rate from wear out is very small.

What about extrapolation shown in our presentations?



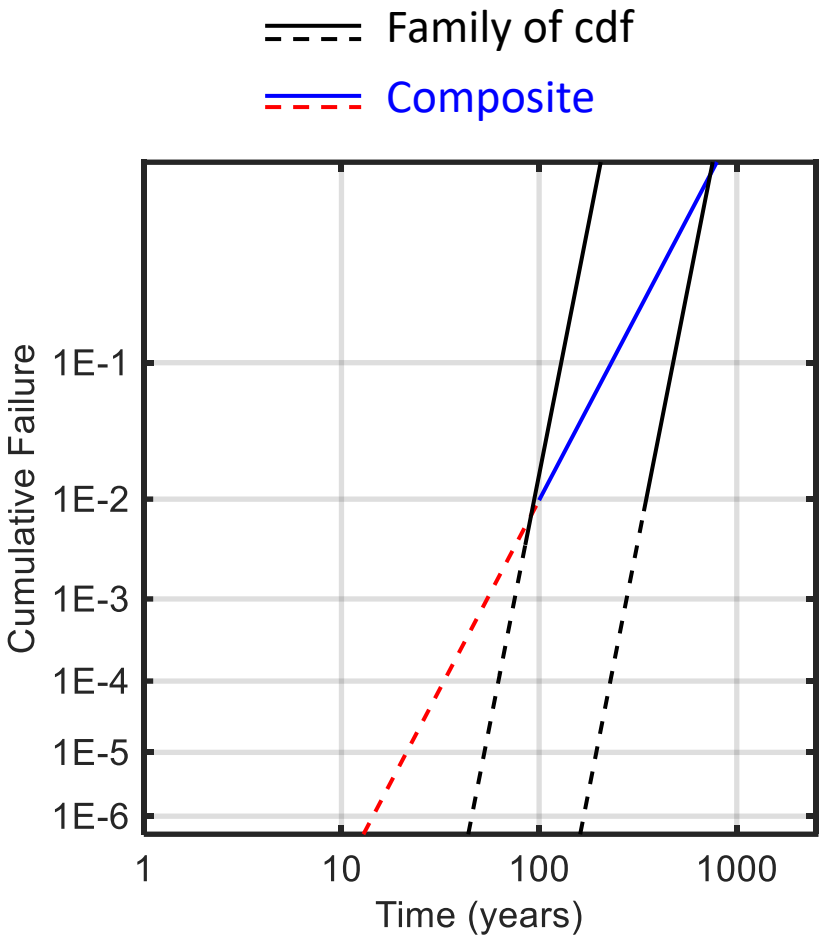
Operating Condition	Equivalent number of years at 70°C
ΔT = 20K, Bias 6.5 mA	12 years

This extrapolation of the composite line was done to show how far TT 1%F was from the automotive service life.

The use of this extrapolation for calculation of hazard rate was not intended !

Laura Giovane, “850 nm 25G VCSEL reliability,” giovane_3cz_01a_080621.pdf
Ramana Murty, “850 nm VCSEL for GI POF links,” murty_3dh_01a_220713.pdf

Estimates for Wear Out Average Failure Rate and Hazard Rate



Invalid extrapolation

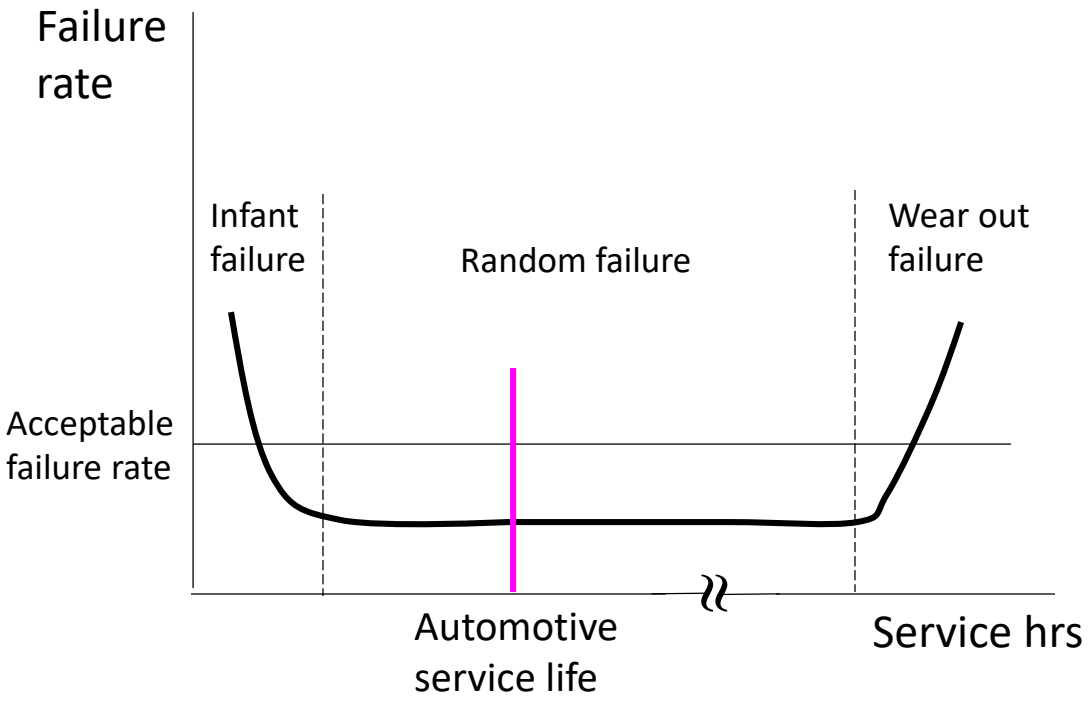
Bias	Item	Family of cdf ✓	Composite ✗
6.5 mA	Hazard rate[a] (FIT)	<< 1	< 1
7.5 mA	Hazard rate[a] (FIT)	<< 1	~10

[a] Unit time follows by the automotive mission profile.

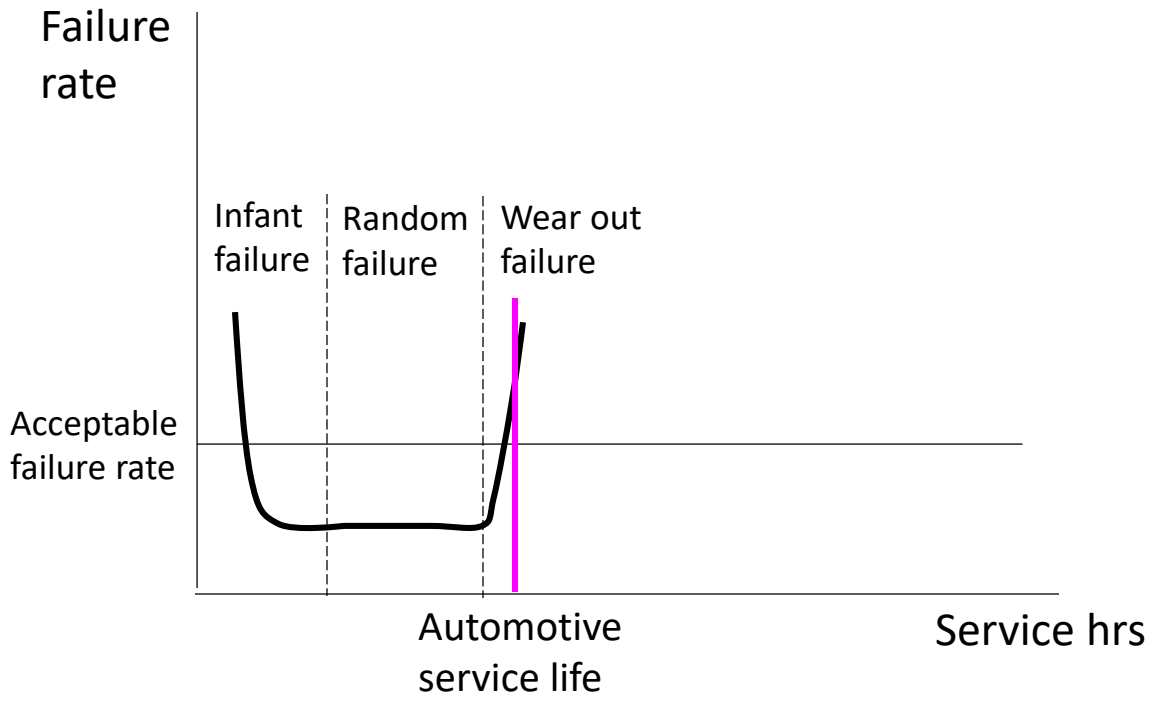
- The hazard rate for wear out is very small
- The values derived from the extrapolated composite line are invalid but may generate discussion

Failure Rate and Automotive Service Life

Correct Picture



Claim in Ref [1]
This is incorrect.



[1] Ruben Perez-Aranda and David Ortiz, "VCSEL reliability comparison," perezaranda_3cz_01b_080621_vcsel_reliability.pdf.

Summary

Calculations presented in .3cz and .3dh showing high hazard rate for 850 nm VCSEL use an invalid extrapolation of the presented data. Exclusion of 850 nm wavelength based on these calculations is not justified.

Adopt a wide wavelength band (840 – 990 nm) to enable a wide range on suppliers.