850nm VCSELs
Log-normal shape in reliability analysis

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Wear-out reliability model — unreliability function

$$TTF_{x\%} = C \cdot J^{-n} \cdot \exp\left(\frac{E_a \cdot e}{k_B \cdot T_J}\right) = F^{-1}\left(\frac{x}{100}\right); \quad F(t) = \Phi\left(\frac{\ln(t) - \mu'}{\sigma'}\right)$$

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

$$f(t) = \frac{dF}{dt}(t), \; f(t) \geq 0 \text{ for } \forall t \geq 0, \; \int_0^\infty f(\tau)\, d\tau = 1$$

$$f(t') = \frac{1}{\sigma'\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{t' - \mu'}{\sigma'}\right)^2\right)$$

$$MTTF = \int_0^\infty \tau f(\tau)\, d\tau$$

$$TTF_{1\%} = F^{-1}(0.01)$$

$$TTF_{50\%} = F^{-1}(0.5) = \exp(\mu')$$

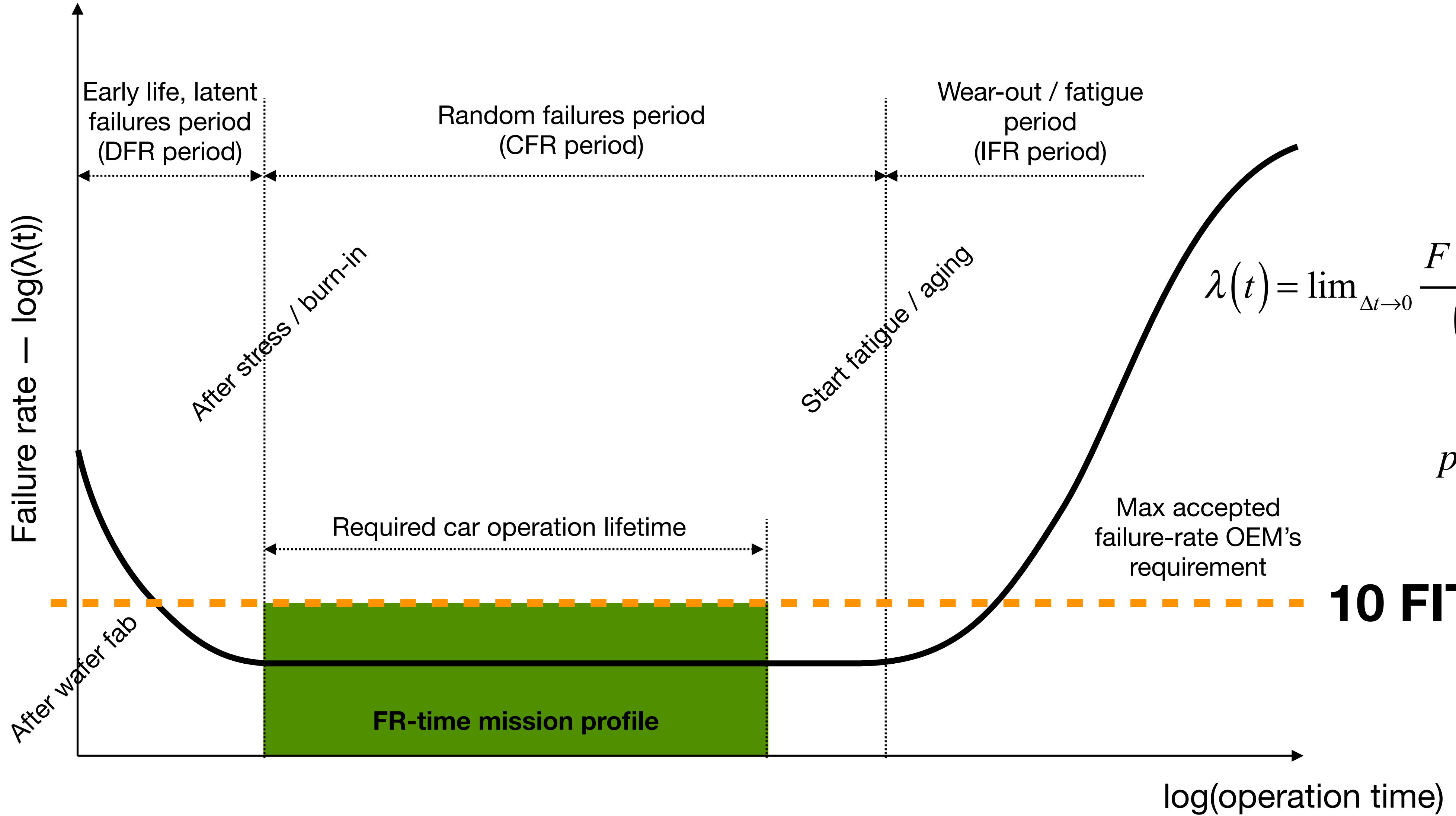
$$TTF_{x\%} = \exp\left(\mu' + \sigma' \cdot \Phi^{-1}\left(\frac{x}{100}\right)\right)$$

- For a given *t*, *F(t)* is the probability that failure occurs before *t*
- *F(t)* is the cumulative distribution function (CDF) of the failure probability
  - Φ is the standard normal distribution (i.e. N(0,1))
  - *t* is the time to failure
  - *t'* is the natural logarithm of the time to failure
  - *μ'* mean of the natural logarithms of the time to failure
  - *σ'* standard deviation of the natural logarithms of the time to failure

- Arrhenius's equation
  - E_a is the activation energy of failure mechanism (eV)
  - *e* is the electron charge (SI units)
  - k_B is the Boltzmann's constant (SI units)
  - T_J is absolute temperature (Kelvin)
  - *J* is the current density (e.g. in kA/cm^2)
  - *n* is the current exponent
  - *C* is a constant
  - $TTF_{x\%}$ is the time to x% failures (e.g. in hours)

Reliability model — failure rate

- Pay attention that **in general failure-rate λ(t) is not constant** and depends on how much time the component has survived in operation
- Failure-rate is typically measured in Failures In Time (FIT), number of failures per 10^9 (billion) **device-hours**
  - 1 FIT = probability of failure is 10^{-9} / 1 hour (operation)
  - 1 FIT = probability of failure is 1 ppm / 1000 hours
  - 1 FIT = 1 failure per 1000 devices operating 1 million hours = 1 failure per 10 million devices operating 100 hours



10 FIT: OEM requirement

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{\left(1 - F(t)\right)\Delta t} = -\frac{d\ln\left(1 - F(t)\right)}{dt}$$

$$ppm(t) = \int_0^t \frac{\lambda(\tau)}{1000} d\tau$$

Wear-out reliability model — acceleration factors

$$\frac{TTF_1}{TTF_0} = \left|\exp\left(\frac{E_a e}{K_B}\left(\frac{1}{T_{J_1}} - \frac{1}{T_{J_0}}\right)\right)\right|_{J_1=J_0}$$

$$\frac{TTF_1}{TTF_0} = \left|\left(\frac{J_1}{J_0}\right)^{-n}\right|_{T_{J_1}=T_{J_0}}$$

$$\frac{TTF_1}{TTF_0} = \left|\left(\frac{A_0}{A_1}\right)^{-n}\right|_{I_1=I_0} = \left|\left(\frac{D_0}{D_1}\right)^{-2n}\right|_{I_1=I_0}$$

- Acceleration factors relate the times to failure between different conditions
  - We can calculate acceleration factor between two temperatures considering same current density condition
  - We can calculate acceleration factor between two current densities, considering same junction temperature
  - We can calculate acceleration factor between two oxide aperture diameters considering same junction temperature and the same bias current

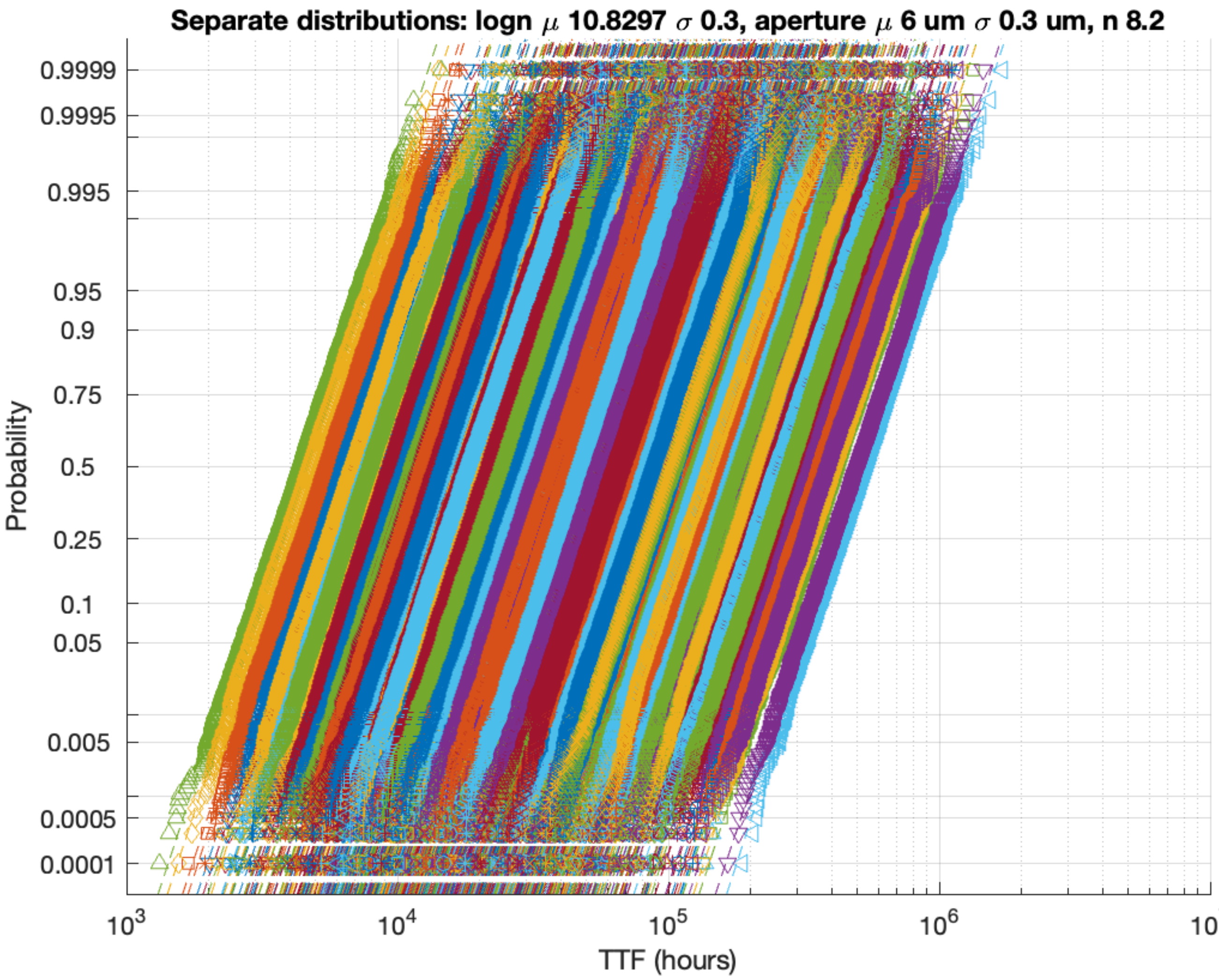
Reasons behind of a higher log-normal shape

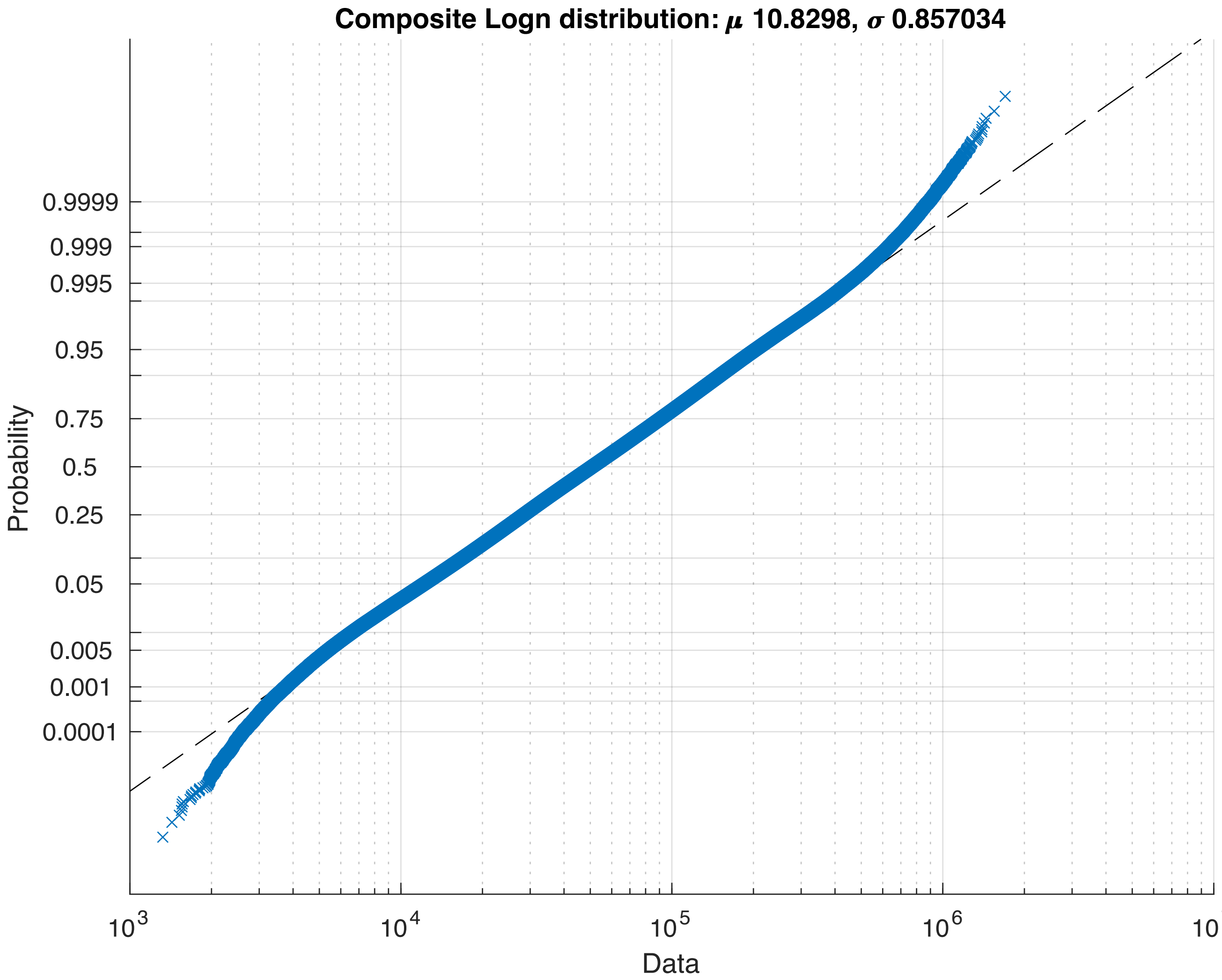
- Oxide aperture diameter is a parameter of VCSEL design that experiences deviation in the manufacturing process
  - There will be lot-to-lot variations
  - There will be wafer-to-wafer variations
  - There will be intra-wafer variations
- Wafer level test of VCSELs and final-test in assembled PHYs cannot detect oxide aperture deviations with low cost
  - Oxide aperture is usually tracked for each wafer by random sampling, much lower than 1%, i.e. only by measurement of some devices per wafer with limited precision
- Oxide aperture is not the only parameter affecting the log-normal shape
  - Even same oxide aperture devices will show different reliability when high volume and long term productions are considered
- VCSEL drivers bias current have production deviation (they do not have instrumentation precision)
- VCSEL manufacturers usually assume $\sigma' > 0.5$ due to the above reasons

Reasons behind of a higher log-normal shape

- As example, let's consider the oxide aperture diameter distributes in a wafer according to a normal distribution with mean μ_D and standard deviation σ_D
- Let's consider TTF$_{50\%}$ = 50500 hours ($\mu' = 10.8297$) and shape $\sigma' = 0.3$ at T$_{BS}$ = 125ºC for oxide aperture diameter of μ_D and current density exponent *n*
- Let's consider a MC simulation:
  - 1000 log-normal distributions that result of considering 1000 different oxide aperture diameters from the normal distribution, each one with location μ' calculated with the acceleration factor with respect to μ_D and with shape $\sigma' = 0.3$
  - 5000 runs (i.e. devices) for each log-normal
  - Composite log-normal distribution is calculated for $5 \cdot 10^6$ devices
- Simulation results indicate that the location parameter is preserved, and shape is made wider

Example: aperture μ_D = 6 um σ_D = 0.3 um, n = 8.2





Conclusions

- This contribution illustrates using mathematical analysis that log-normal shape parameter cannot be based on single populations
    - Single population reliability assessments are not reported in literature, not only for VCSEL failures but for the whole semiconductor industry
- Use of single population for reliability assessment requires the implementation of a quality control which is not currently implemented by the VCSEL industry
    - Actual 850nm VCSEL products do not meet automotive reliability requirements
    - Big effort would be needed to improve reliability of 850 nm devices
- The P802.3cz has selected the most suitable wavelength based on the standard reliability analysis
    - 980 nm is orders of magnitude more reliable than 850 nm
    - This has been widely reported by the industry
- Reliability needs to be considered with big margin
    - OEMs might need to adjust the mission profile increasing high temperature usage
- The standardization of a wide range wavelength, i.e. 840 ~ 990 nm, does not provide any benefit, but has many drawbacks
    - Cost is increased due to test in different wavelengths
    - Cost is increased due to the full optical link (cables and connectors) and receiver have to support the full wavelength range

Thank you