VCSEL reliability comparison

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Overview

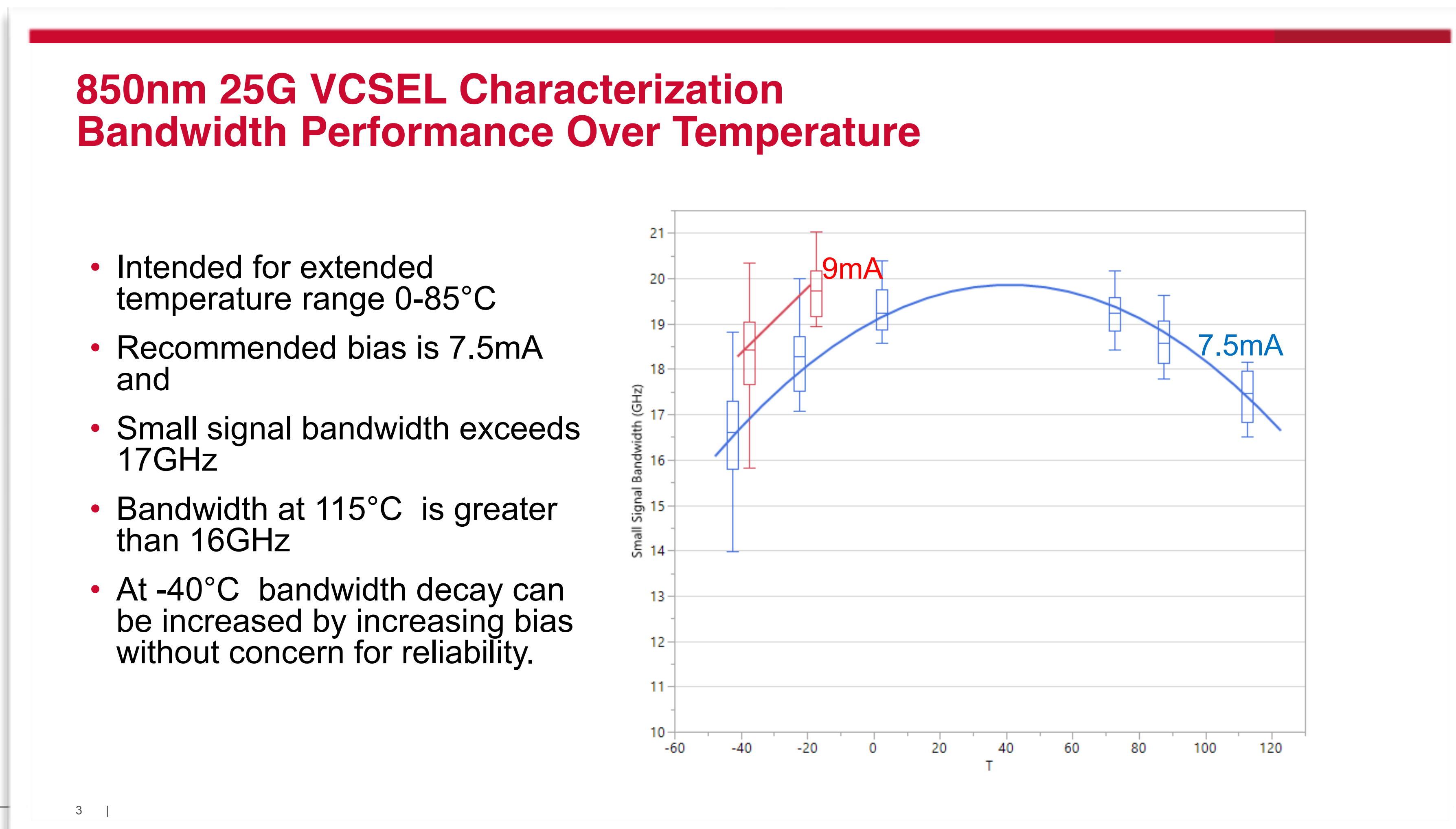
- This contribution provides an analysis of the data reported in [4] to carry out a comparison against the reliability results of 850nm 25G VCSELs considered in P802.3cz until now [1, 2, 3]
- Reliability mathematical analysis will be presented that shows the reliability data presented in [4] is consistent with [1, 2, 3] for 850nm devices, i.e. same order of reliability
- A parametric sensitivity analysis will be provided for VCSEL reliability model in order to make easier understanding how reliability is greatly affected by parameters like ECU heat dissipation, PVT variations of driving current, and imprecisions of the reliability model and mission profile

Knowledge Development

Analysis of data reported in [4]

Performance

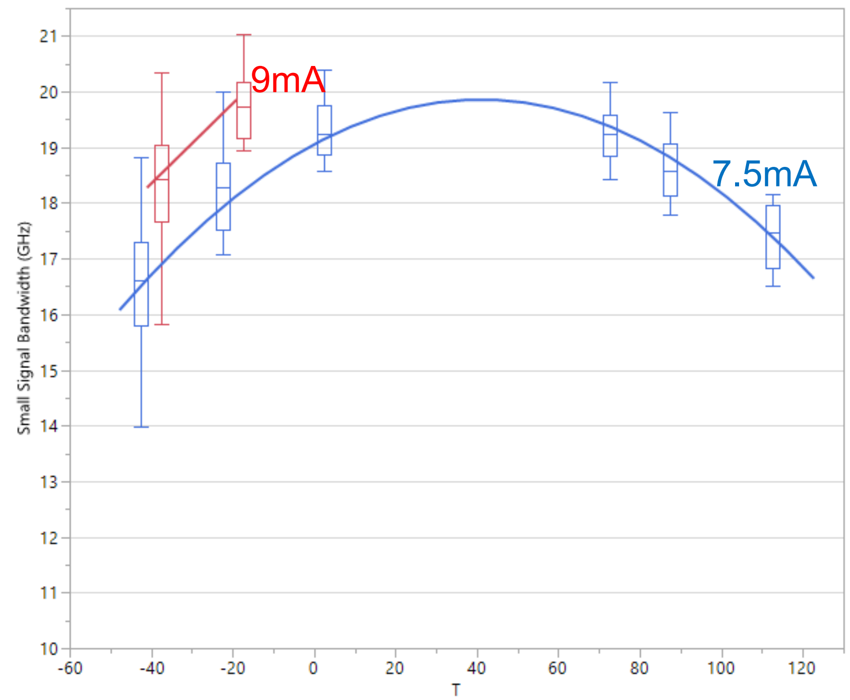
- Small signal bandwidth is an important parameter, however it is not sufficient for feasibility assessment
    - Different combinations of extrinsic pole, resonance frequency and damping rate can produce the same small-signal BW
- It is very important to characterize the non-linear large-signal response of VCSEL, specially in extreme temperatures (-40 and 125ºC) as well as the RIN
    - Non linearity and damping-ratio (resonance below Nyquist frequency) are critical, specially for 25 Gb/s NRZ and 50 Gb/s PAM4
    - RIN can degrade significantly in cold and hot temperatures
- VCSEL devices with the same small-signal bandwidth can produce very different time-domain eye diagrams and reliability performance
- **More detailed characterization data for T_S between -40 and +125ºC would be appreciated**



Temperature

850nm 25G VCSEL Characterization
Bandwidth Performance Over Temperature

- Intended for extended temperature range 0-85°C
- Recommended bias is 7.5mA and
- Small signal bandwidth exceeds 17GHz
- Bandwidth at 115°C is greater than 16GHz
- At -40°C bandwidth decay can be increased by increasing bias without concern for reliability.



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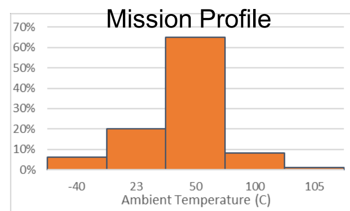
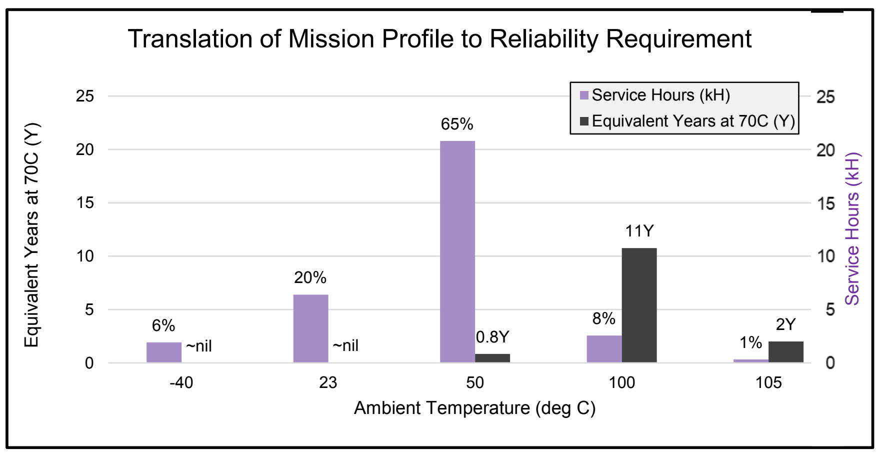
- IEEE P802.3cz has considered AEC-Q100 Grade 2 ($T_{AMB-ECU}$ from -40ºC to +105ºC) as reference for nGBASE-AU PHY qualification with delta $T_{AMB-ECU}$ to T_J CMOS die of 20 ºC, according to experience with 1 Gb/s PHYs in series production
- Delta between $T_{AMB-ECU}$ and T_J is very determined by heat dissipation of others ICs sharing the same PCB, the density of components and the enclosure without forced air (i.e. no convection)
- nGBASE-AU PHYs are expected to be integrated with high density in size constrained ECUs, as it is usual in automotive, therefore a very different scenario of data-centers
- Si CMOS die (PHY electronics) T_J will be similar to photonics T_S (substrate), expecting the maximum photonics T_J to be much higher than 125ºC
- **Information supporting the use in reliability assessment of $T_{AMB-ECU}$ to T_S of only 10 ºC would be appreciated**

Acceleration factors

850nm 25G VCSEL Reliability Requirement

	Data Center	Automotive
Ambient Temperature	0-70C –commercial 0-85C –extended Most of time near max temperature	Wider: -40C-105C Temperature Profile
Service Life (VCSEL on hours)	88kH=10Y	32kH=3.6Y





- 25G 850nm Datacom VCSELs are specified and designed for 10 years of continuous use (24x7x52x10=88kH) at constant substrate temperature
- Assumptions to translate automotive mission profile and service life to reliability requirement:
  - Total vehicle operating time: 32kH
  - Mission temperature profile: >90% of operating time is below 50C!
  - Acceleration model for 25G VCSEL (Ea=1.15eV)
  - VCSEL substrate is 10degC hotter than ambient
- **32kH Automotive service life/mission profile corresponds to ~13Y at 70C (substrate)**

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- Acceleration factors can be calculated based on reliability model (Arrhenius's Eq for absolute temperature)
- Assumed that Ea = 1.15 eV is given in terms of T_J, as it is generally the case
- T_J is calculated using data from other InGaAs 850nm 25G VCSEL providers [1]
- There is a big dependency with T_{AMB} to T_S delta; results are given for 20 and 10 °C using same mission profile of [4]
- More restrictive results are obtained
- **32kH Automotive mission profile corresponds to ~<u>42Y</u> at 70ºC (substrate)**
- **T_J data would be appreciated for cross checking**

$$AF_i = \exp\left(\frac{E_a \cdot e}{k_B}\left(\frac{1}{T_{J_{REF}}} - \frac{1}{T_{J_i}}\right)\right)$$

Calculated T_J

	Percentage	Operation time per Temperature (h)	T_A (°C)	T_S (°C) ΔT_{AS} = 20°C	T_J (°C) ΔT_{AS} = 20°C	Acc Factor ΔT_{AS} = 20°C	Equivalent time in T_{REF} (Years), ΔT_{AS} = 20°C	T_S (°C) ΔT_{AS} = 10°C	T_J (°C) ΔT_{AS} = 10°C	Acc Factor ΔT_{AS} = 10°C	Equivalent time in T_{REF} (Years), ΔT_{AS} = 10°C
T_{REF}			–	70	99.7	$T_{J_{REF}}$		70	99.7	$T_{J_{REF}}$	
T0	6 %	1920	-40	-20	4.1	0.000	0.00	-30	-6.2	0.000	0.00
T1	20 %	6400	23	43	70.4	0.047	0.03	33	59.7	0.013	0.01
T2	65 %	20800	50	70	99.7	1.000	2.38	60	88.8	0.338	0.81
T3	8 %	2560	100	120	156.5	113.619	33.29	110	144.9	47.756	13.99
T4	1 %	320	105	125	162.4	173.002	6.34	115	150.7	73.987	2.71
Cumulative	100 %	32000				AF_i	42.05			AF_i	17.52

Parameters

I_{OP} (mA)	7.5
Ea (eV)	1.15
Qe	1.6022E-19
KB	1.3806E-23
Qe/KB	1.1605E+04
ºC to Kelvin	273.15
Operation total time (h)	32000

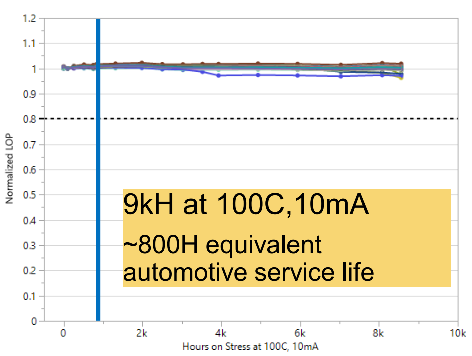
Ea and *n* calculation

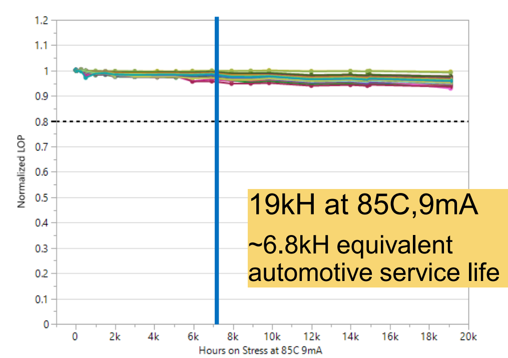
High Temperature Operating Life

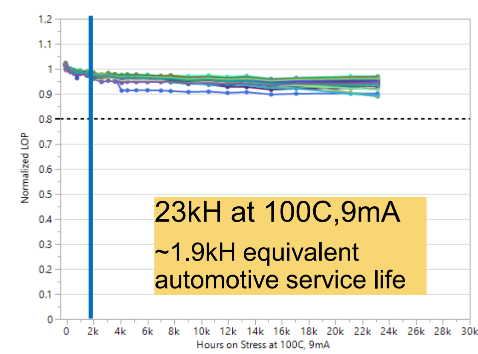
- Long-term aging (over many years) show that 850nm VCSELs are robust for automotive mission profile
  - >4000 channels with cumulative >30MH without failure
- Negligible degradation for VCSELs in stress for extended high temperature operating life after 10kH!
- 32kH mission profile/service life equivalent at 7.5mA bias shown by blue vertical line

Temperature-Ambient	Ibias (mA)	Mission profile %	Total Time
-40°C	7.5	6%	1.9kH
23°C	7.5	20%	6.4kH
50°C	7.5	65%	20.8kH
100°C	7.5	8%	2.6kH
105°C	7.5	1%	0.3kH

Mission profile/service life







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- Using VCSEL reliability model, we can calculate *Ea* and *n* from the reported data
- Calculated ***Ea* = 1.044 eV vs. 1.15 eV**
  - *Ea* is in the exponent of Arrhenius's Eq, so reliability is very sensitive to this parameter
- Calculated ***n* = 8.2 >> 1.64** in [1] for other 850nm 25G VCSEL
  - Possible root cause may be current density over stress, producing extra current acceleration factor not consistent with actual operation condition
- **More visibility on test matrix and *n* fitting would be appreciated**

$$E_a = \frac{\frac{k_B}{e}\cdot \ln\left(\frac{TTF_1}{TTF_0}\right)}{\frac{1}{T_{J1}} - \frac{1}{T_{J0}}} \quad for\ I_1 = I_0$$

$$n = -\frac{\ln\left(\frac{TTF_1}{TTF_0}\right)}{\ln\left(\frac{I_1}{I_0}\right)} \quad for\ T_{J1} = T_{J0}$$

Parameters

Qe	1.6022E-19
KB	1.3806E-23
Qe/KB	1.1605E+04
°C to Kelvin	273.15

Ea and N calculation

Experiment	T_S (°C)	I_{BIAS} (mA)	T_J (°C)	Equiv. Time (h)	Estim. Ea (eV) Using 2, 3	Estim. N Using 1,3
1	100	10	150.9	800		
2	85	9	125.9	6800		
3	100	9	143.4	1900	1.044	8.210

Reliability results — 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)

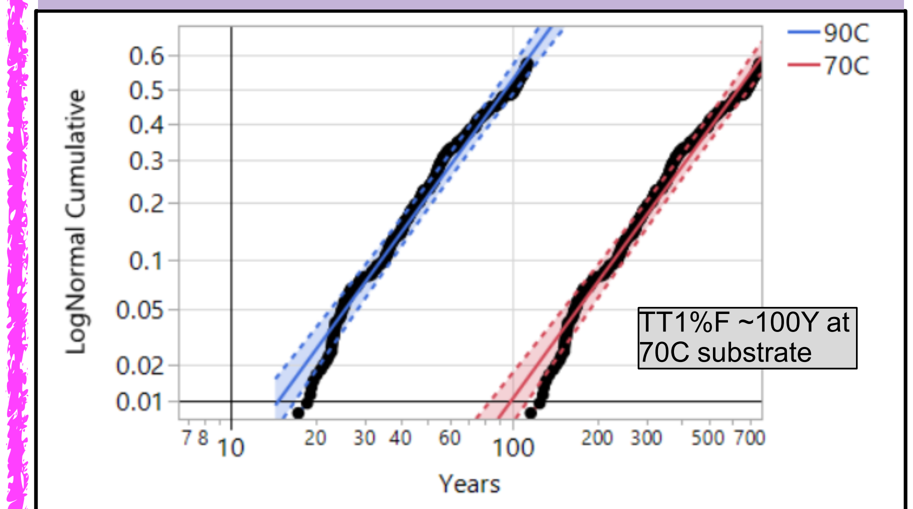
Reliability results — unreliability function

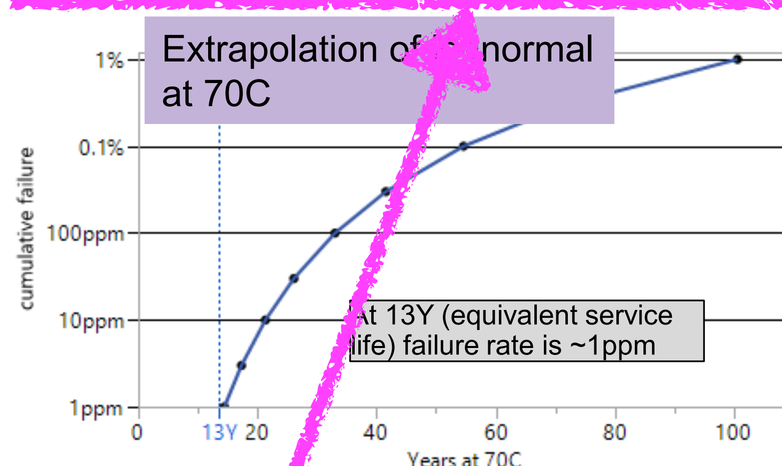
Extended Temperature 25G 850nm VCSEL Characteristic

Wearout Lifetime

- Equivalent of ~13Y of life at 70C (substrate) required for automotive application
- Extended Temperature Datacom VCSEL specified at >10Y at 85C and >40Y wearout life at 70C
  - Characteristic TT1%F 25G VCSEL is ~100 Years at 70C (substrate)
  - Extrapolation shows low-level cumulative failure at 13Y, 70C that corresponds to automotive mission life corresponds to <1ppm
- 850 nm 25G VCSELs are capable of performing in automotive application for duration of service life

Wearout lifetime of 850nm 25G Extended Temperature VCSEL





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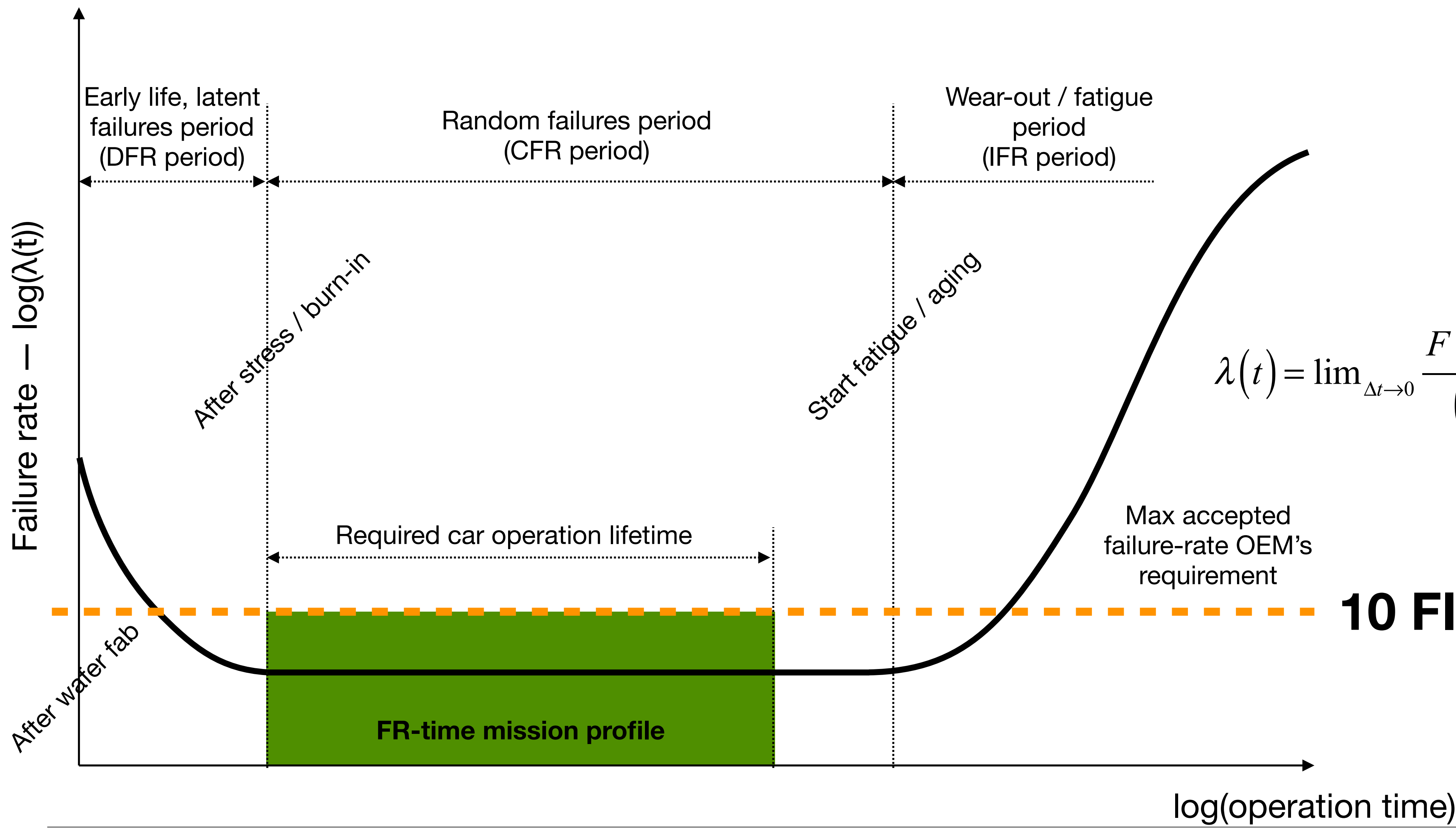
$$C = TTF_{x\%} \cdot J_0^{\,n} \cdot \exp\left(-\frac{E_a \cdot e}{k_B \cdot T_{J_0}}\right)$$

$$\sigma' = \frac{\ln\left(TTF_{1\%}\right) - \ln\left(TTF_{50\%}\right)}{\Phi^{-1}\left(0.01\right)} \simeq 0.8$$

Reliability results — 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



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

10 FIT: OEM requirement

Reliability results — calculation

Reliability parameters

Operation	**Operation total time (h)**	**32000**	**Reliability model**	**Wear out Ea (eV) @ T_J**	1.150
	Service life (years)	15		**Wear out n @ T_J**	8.210
	Min oxide aperture diam. (um)	7.0		**TTF x%, location**	1.0
	I_{OP} (mA) max	**7.5000**		**Log-normal σ', ln (hours)**	0.8
	J_{OP} (kA/cm^2)	19.50		**J_0 (kA/cm^2)**	19.50
	J_{OP} (mA/um^2)	0.19		**T_{J0} (°C)**	99.7
	ΔT_{AS} (°C)	20.0		**TTF_0 x% (hours)**	873600
VCSEL model fitting	R_{JS} (K/W) @ room Ts reference	1950		**Arrhenius C factor (hours) @ T_J**	9.720679E+00
	R_{JS} factor	100 %		**Qe**	1.6022E-19
	R_{JS} (K/W) @ room Ts	1950		**K_B**	1.3806E-23
	R_{JS} room Ts (°C)	20.0		**Qe/K_B**	1.1605E+04
	R_{JS} Exponent	1.067		**°C to Kelvin**	273.15
	R_{JS} Current fitting p0	0.01754	VCSEL model fitting	P_{DIS} poly-fitting p11	-0.006889
	R_{JS} Current fitting p1	0.9636		P_{DIS} poly-fitting p02	-5.203E-05
	P_{DIS} poly-fitting p00	-0.3481		P_{DIS} poly-fitting p21	0.0001612
	P_{DIS} poly-fitting p10	1.291		P_{DIS} poly-fitting p12	3.641E-05
	P_{DIS} poly-fitting p01	0.01552		P_{DIS} poly-fitting p03	1.736E-15
	P_{DIS} poly-fitting p20	0.05763			

Ea

n can take any value w/o effect because reference $J_0 = J_{OP}$ (oxide diam. does not affect the result too)

TTF for 1%

σ' calculated from $TTF_{50\%}$ and $TTF_{1\%}$

$I_0 = I_{OP}$ = 7.5 mA; $J_0 = J_{OP}$ = 19.50 kA/cm^2

$TTF_{1\%}$ ~100 years for 70°C substrate

$$C = TTF_{x\%} \cdot J_0^{\,n} \cdot \exp\left(-\frac{E_a \cdot e}{k_B \cdot T_{J_0}}\right)$$

- Lognormal (vs. Exponential) wear out unreliability CDF, produces monotonic increase failure-rate that depends on aging history of the device. However, $T_J = T_J(t)$ is unknown
- FR results depend of referenced temperature
- **The analysis should be conservative considering equivalent time in max temperature vs. 70°C, where location parameter μ' is much lower. This is the same criteria used for other VCSELs**

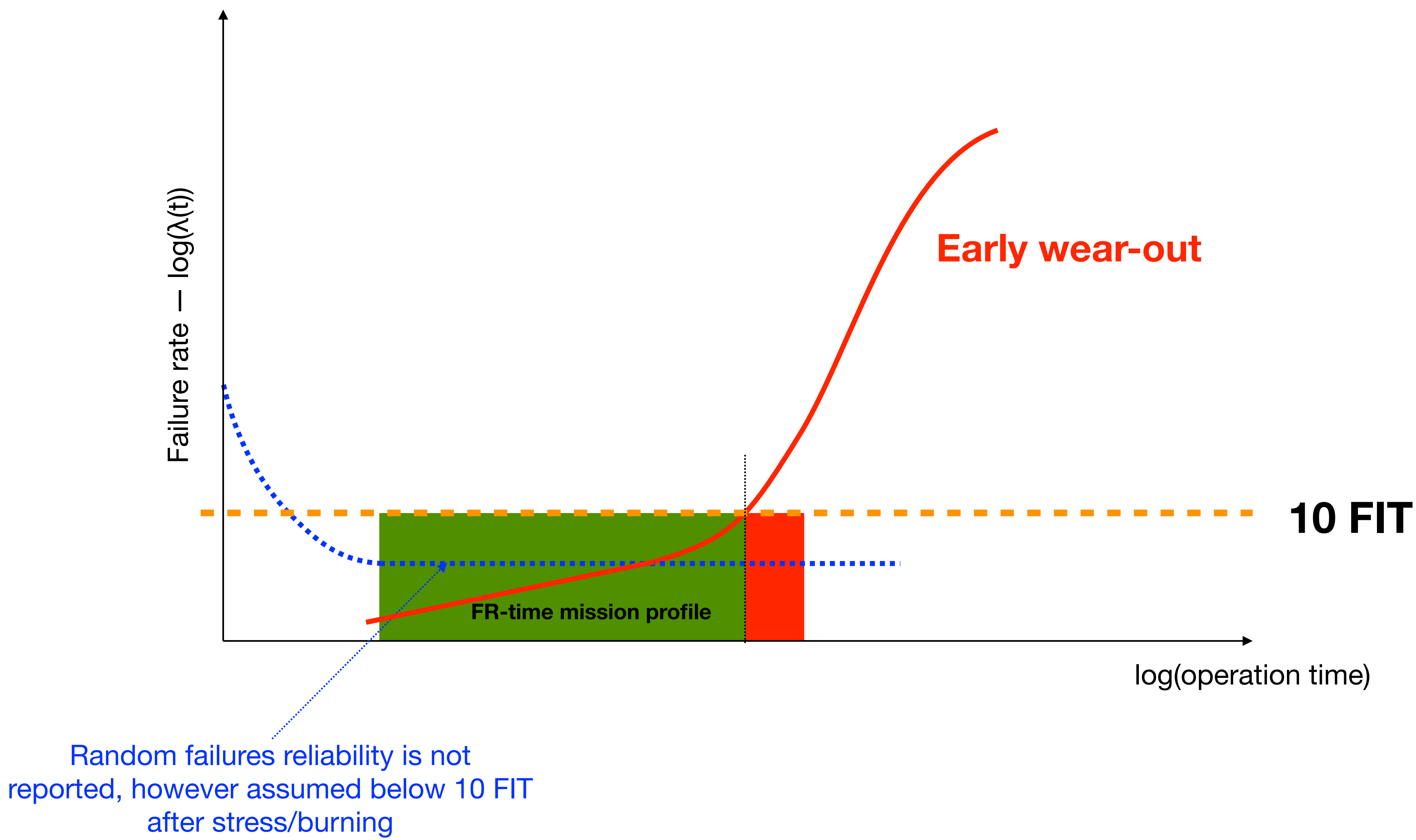
$$TTF_{5FIT} = \exp\left(\mu' + \sigma' \cdot \Phi^{-1}\left(\frac{5 \cdot 32000}{1000} 10^{-9}\right)\right)$$

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

	Temperature profile								Failure rate					
	Percentage	Operation time per Temperature (h)	T_A (°C)	T_S (°C)	R_{JS} (K/W)	P_{DIS} (mW)	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**	-20.0	1826.1	13.21	4.1	1.996E+11	**21503519548**	0.00	27.8805			
T1	**20 %**	6400	**23**	43.0	2314.8	11.82	70.4	1.858E+07	**2001466**	1.74	18.5984			
T2	**65 %**	20800	**50**	70.0	2526.3	11.76	99.7	8.721E+05	**93965**	120.23	15.5397			
T3	**8 %**	2560	**100**	120.0	2920.9	12.51	156.5	7.675E+03	**827**	1681.28	10.8068			
T4	**1 %**	320	**105**	125.0	2960.6	12.64	162.4	5.041E+03	**543**	320.00	10.3864	$\lambda(t)$		ppm
Cummulative	100 %	**32000**								t **2123.24**	μ' **10.3864**	**708.4**	**5.0**	**22830**

>> 10 FIT !

Reliability results — illustration



VCSEL reliability comparison

850nm devices reliability comparison: VCSEL [1, 2, 3]

Reliability parameters

Operation	**Operation total time (h)**	**32000**	**Reliability model**	**Wear out Ea (eV) @ T_J**	1.180
	Service life (years)	15		**Wear out n @ T_J**	1.640
	Min oxide aperture diam. (um)	7.0		**TTF x%, location**	50.0
	I_{OP} (mA) max	**7.5000**		**Log-normal σ', ln (hours)**	0.5
	J_{OP} (kA/cm²)	19.50		**J_0 (kA/cm²)**	19.50
	J_{OP} (mA/um²)	0.19		**T_{J0} (°C)**	193
	ΔT_{AS} (°C)	20.0		**TTF_0 x% (hours)**	965
VCSEL model fitting	R_{JS} (K/W) @ room Ts reference	1950		**Arrhenius C factor (hours) @ T_J**	2.200519E-08
	R_{JS} factor	100 %		**Qe**	1.6022E-19
	R_{JS} (K/W) @ room Ts	1950		**K_B**	1.3806E-23
	R_{JS} room Ts (°C)	20.0		**Qe/K_B**	1.1605E+04
	R_{JS} Exponent	1.067		**°C to Kelvin**	273.15
	R_{JS} Current fitting p0	0.01754	VCSEL model fitting	P_{DIS} poly-fitting p11	-0.006889
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	P_{DIS} poly-fitting p01	0.01552		P_{DIS} poly-fitting p03	1.736E-15
	P_{DIS} poly-fitting p20	0.05763			

- Same math behind is used
- Same thermal resistance and power dissipation, hence same T_J
- Slightly different *Ea*
- Much lower *n* with no effect (*n* is not used for reliability results of [4], and here J_0 = J_{OP} too)
- Same current is considered: 7.5 mA
- Typical production oxide aperture is considered: 7 μm
- Lower shape parameter: σ' = 0.5 (see [1])
- **We got a much higher failure rate (however, expected)**
- **How can we compare reliability of [1, 2, 3] vs [4]?**

Reliability result

	Temperature profile							**Failure rate**						
	Percentage	**Operation time per Temperature (h)**	**T_A (°C)**	**T_S (°C)**	**R_{JS} (K/W)**	**P_{DIS} (mW)**	**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**	-20.0	1826.1	13.21	4.1	4.737E+11	**36778496832**	0.00	26.8838			
T1	**20 %**	6400	**23**	43.0	2314.8	11.82	70.4	3.461E+07	**2687026**	1.40	17.3596			
T2	**65 %**	20800	**50**	70.0	2526.3	11.76	99.7	1.500E+06	**116476**	105.11	14.2211			
T4	**8 %**	2560	**100**	120.0	2920.9	12.51	156.5	1.167E+04	**906**	1662.94	9.3648			
T5	**1 %**	320	**105**	125.0	2960.6	12.64	162.4	7.580E+03	**589**	320.00	8.9333			
Cummulative	100 %	**32000**								**2089.45**	**8.9333**	**13858.2**	**5.0**	**443622**

>>>> 10 FIT !

850nm devices reliability comparison

Reliability comparison — 160 ppm (5 FIT)

T_A (ºC)	850nm 25G VCSEL [1, 2, 3] TTF$_{5\ FIT}$ (hours)	850nm 25G VCSEL [4] TTF$_{5\ FIT}$ (hours)	Reliability improvement factor (RIF)
-40	36778496832	21503519548	0.585
23	2687026	2001466	0.745
50	116476	93965	0.807
100	906	827	0.913
105	589	543	0.923

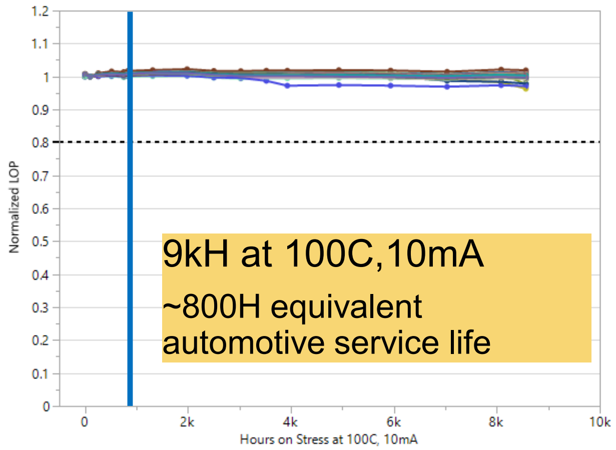
$$RIF = \frac{TTF_{5FIT}[4]}{TTF_{5FIT}[1,2,3]}$$

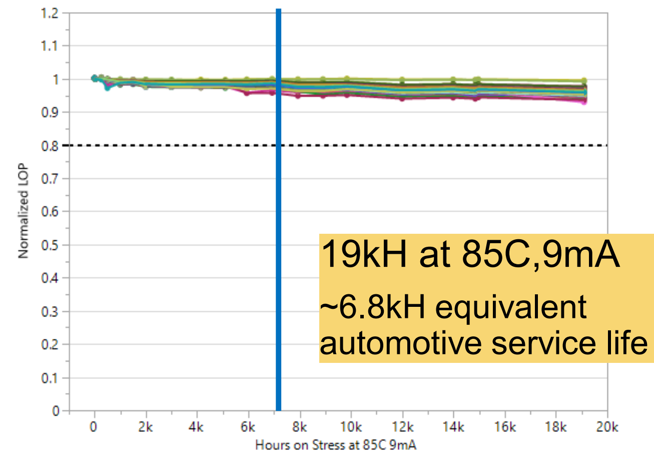
850nm VCSEL of [4] has similar reliability of 850nm VCSEL of [1, 2, 3]

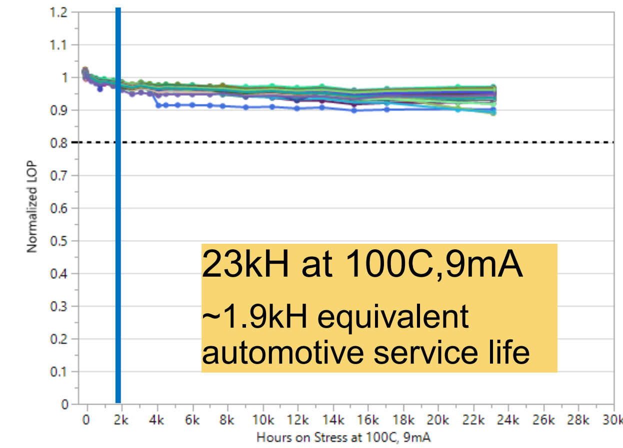
Consistent with currently considered data for 850nm 25G VCSELs [1, 2, 3], still insufficient for automotive

850nm vs 980nm reliability comparison

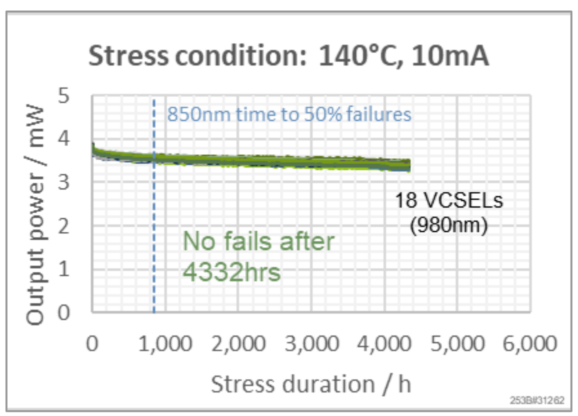
In [4], stress conditions do not cover operation, i.e. < T_S = 125ºC

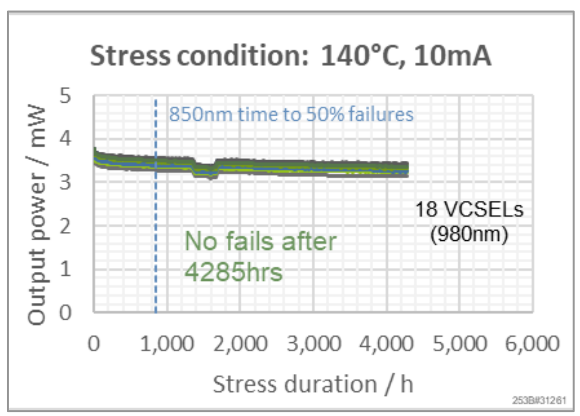


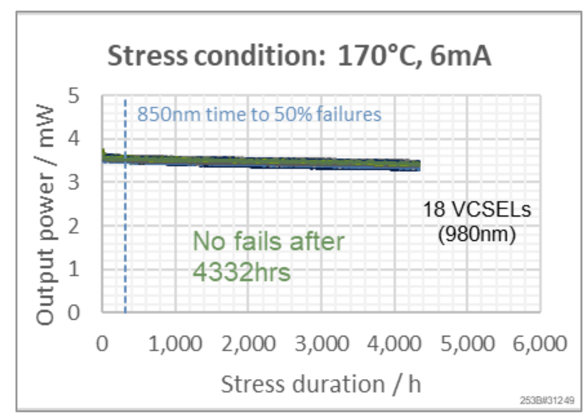


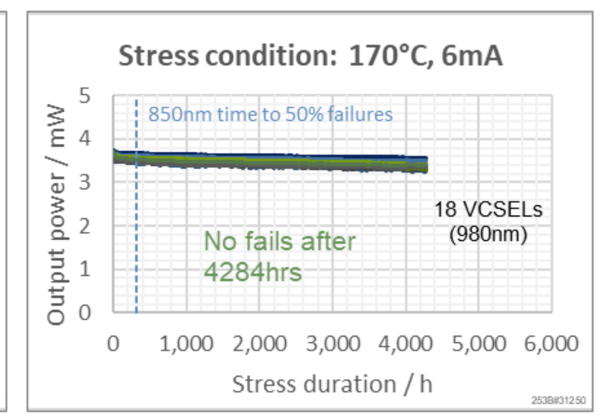


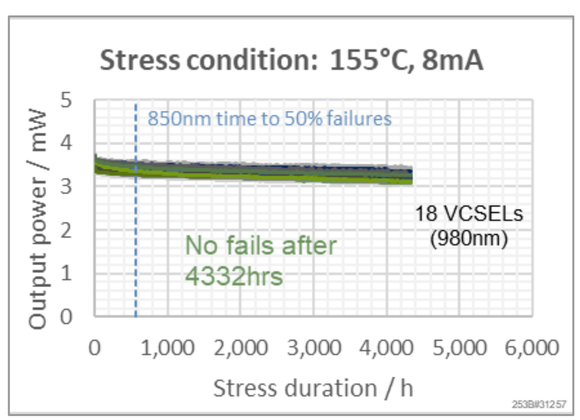
In [3], stress conditions exceed operation

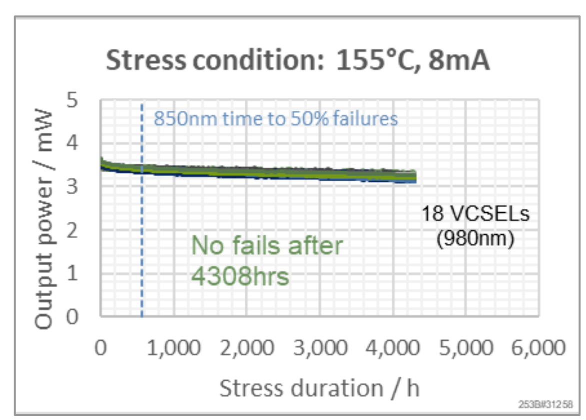












Parametric sensitivity analysis

Parametric sensitivity analysis

Parametric sensitivity analysis for reliability of device [4]

Parametric deviation	Failure-rate wear out (FIT)	Failure-rate maverick (FIT)	Total failure-rate (FIT)	ppm	Notes
Reference	708.4	5	713.4	22829	
ΔT_{AS} + 5ºC	3722.3	5	3727.3	119274	Due to different heat dissipation conditions inside the ECU Big impact
ΔT_{AS} - 5ºC	97.8	5	102.8	3290	
Ea + 10%	4488.4	5	4493.4	143789	Due to imprecisions in the reliability model fitting Big impact
Ea - 10%	85.0	5	90	2880	
σ' = 0.85	826.4	5	831.4	26605	Due to imprecisions in the reliability model fitting Moderate impact
σ' = 0.75	589.6	5	594.6	19027	
I_{OP} + 10%	35736.9	5	35741.9	1143741	Due to PVT variations of the VCSEL driver in the PHY IC. Assumed n = 8.21 Big impact
I_{OP} - 10%	1.2	5	6.2	198	
T3 + 2%, T4 + 2%, T2 - 4%	2322.3	5	2327.3	74472	Due to imprecisions in the mission profile (reality vs estimation) Big impact

- Most of the light sources follow the same reliability model (Arrhenius with current exponent + lognormal unreliability CDF)
  - Different devices (e.g. LED, FP lasers, VCSELs) use different parameters' values
- These examples are given to illustrate the sensitivity of reliability to some parameters and to understand how important is having margin in reliability assessment

Conclusions

- Reliability data presented in [4] for 850nm VCSEL has been analyzed and compared to [1, 2, 3]. Reliability results are consistent with currently considered reliability data for 850nm VCSELs in [1, 2, 3]
- **Going for 850nm may be possible, but coming with several penalties compared with 980nm VCSEL [5, 6]**
  - Driving current reduction is required
  - Reduced speed and signal integrity
  - Increased transceiver complexity and power consumption (TX FFE, RX EQ, ADC)
- Parametric sensitivity analysis showed how important is a reliability assessment with margin
- **Going for 980nm is a much safer bet and not hampered by compatibility issues. Why should the Automotive industry let go an undebated reliability advantage, for no good reason [3]**
  - 980nm VCSELs are far more robust than 850nm VCSELs
  - Automotive is not requiring backwards compatibility and offers the chance to take advantage of higher reliability at 980nm
  - There are plenty of suppliers capable of delivering robust 980nm VCSELs

References

- [1] R. Pérez-Aranda, “Reliability constrained link budget assessment for 25 and 10 Gb/s,” Dec 2020, [Online], Available: https://www.ieee802.org/3/cz/public/22_dec_2020/perezaranda_3cz_02a_221220_reliability_linkbdget.pdf
- [2] R. King, “A comparison between 850 nm and 980 nm VCSEL for automotive datacom,” November 2020, [Online], Available: https://www.ieee802.org/3/cz/public/nov_2020/king_3cz_01_1120.pdf
- [3] R. King, “VCSEL design for automotive datacom Experimental results for 980 nm versus 850 nm,” https://www.ieee802.org/3/cz/public/may_2021/king_3cz_01a_0521.pdf
- [4] L. Giovane, “850 nm 25G VCSEL Reliability,” June 2021, [Online], Available: http://www.ieee802.org/3/cz/public/8_june_2021/giovane_3cz_01_adhoc_060821.pdf
- [5] R. Pérez-Aranda, “980nm VCSEL Performance in extreme temperatures,” May 2021, [Online], Available: https://www.ieee802.org/3/cz/public/may_2021/perezaranda_3cz_01_0521_VCSEL_980nm.pdf
- [6] R. Pérez-Aranda, “50 Gb/s demonstration in extreme temperatures using 850nm VCSELs,” May 2021, [Online], Available: https://www.ieee802.org/3/cz/public/11_may_2021/perezaranda_3cz_01a_110521_50Gbps_850nm_demo.pdf

Thank you!