VCSEL reliability comparison

Annex: possible cause behind results of [4]

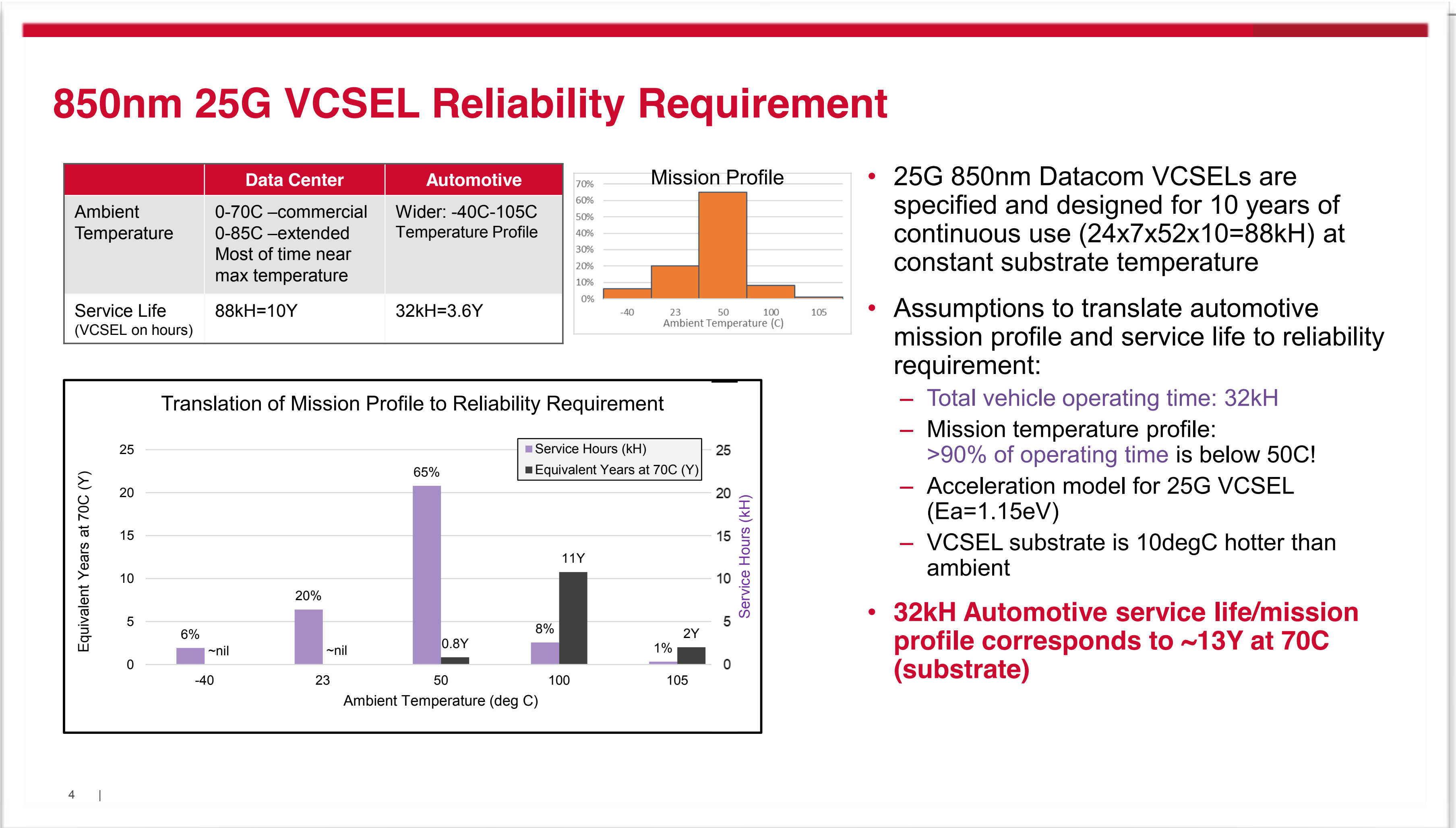
Rubén Pérez-Aranda, KDPOF
David Ortiz, KDPOF

IEEE 802.3cz Task Force - 15th June 2021

Overview

- This contribution provides additional information to the analysis presented in [5], and it presents a root cause that may explain the results obtained in [4]
- Results presented in [4] may be explained considering constant thermal resistance R_{TH} across temperature as well as constant voltage drop V_{AK}, which in principle is not consistent with physics governing the VCSEL device behavior
- Based on these hypotheses, it can be seen that calculated activation energy and acceleration factors are very consistent with [4]
- Reliability comparison of [4] vs [1, 2, 3] will be calculated, using the indicated hypotheses
- Finally, maximum operating current will be calculated to meet the automotive reliability requirements under the considered mission profile

Acceleration factors — ΔT_{SJ} constant



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)**

- 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
- **ΔT_{SJ} = 25ºC constant across T_S is considered as possible cause to explain the presented results**
  - **However, GaAs R_{TH} is expected to increase with T_S**
  - **Why ΔT_{SJ} is considered constant?**
  - **Data supporting this assumption is appreciated**
- **32kH Automotive mission profile corresponds to ~29Y at 70ºC (substrate)**

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

Calculated T_J as ΔT_{SJ} = 25ºC

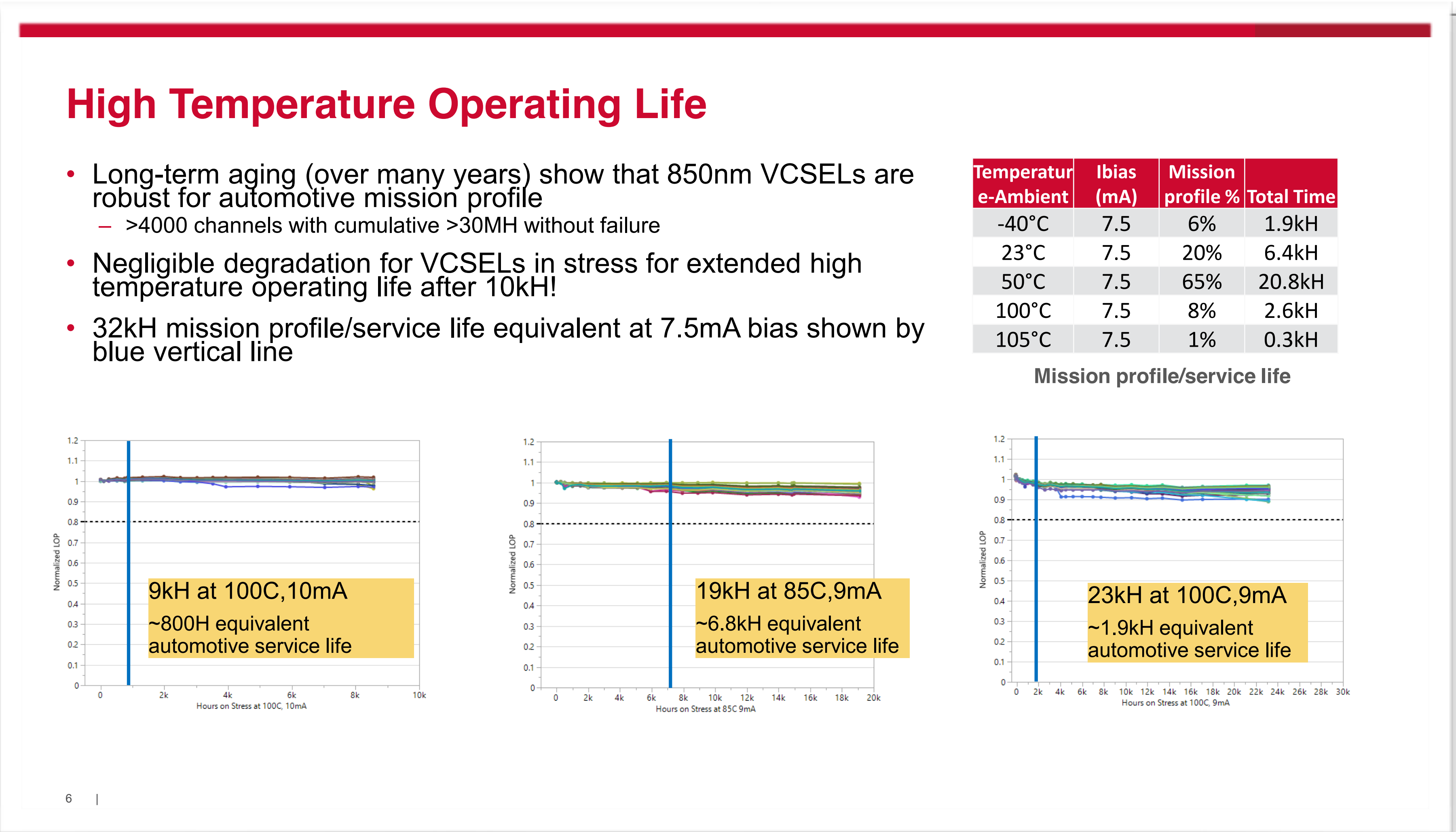
	Percentage	Operation time per Temperature (h)	T_A (ºC)	T_S (ºC) ΔT_{AS} = 20ºC	T_J (ºC) ΔT_{AS} = 20ºC ΔT_{SJ} = 25ºC	Acc Factor ΔT_{AS} = 20ºC	Equivalent time in T_{REF} (Years), ΔT_{AS} = 20ºC	T_S (ºC) ΔT_{AS} = 10ºC	T_J (ºC) ΔT_{AS} = 10ºC ΔT_{SJ} = 25ºC	Acc Factor ΔT_{AS} = 10ºC	Equivalent time in T_{REF} (Years), ΔT_{AS} = 10ºC
T_{REF}			—	70	95.0	$T_{J_{REF}}$		70	95.0	$T_{J_{REF}}$	
T0	6 %	1920	-40	-20	5.0	0.000	0.00	-30	-5.0	0.000	0.00
T1	20 %	6400	23	43	68.0	0.057	0.04	33	58.0	0.017	0.01
T2	65 %	20800	50	70	95.0	1.000	2.38	60	85.0	0.363	0.87
T3	8 %	2560	100	120	145.0	76.287	22.36	110	135.0	34.903	10.23
T4	1 %	320	105	125	150.0	111.231	4.07	115	140.0	51.845	1.90
Cumulative	100 %	32000				AF_i	28.85			AF_i	13.01

Result matches OK

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 — R_{TH}, V_{AK} constants



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

9kH at 100C,10mA
~800H equivalent automotive service life

19kH at 85C,9mA
~6.8kH equivalent automotive service life

23kH at 100C,9mA
~1.9kH equivalent automotive service life

- Using VCSEL reliability model, we can calculate *Ea* and *n* from reported data
- R_{TH} is considered constant with T_S
- V_{AK} is considered constant with I_{BIAS} and T_S
- $P_{DIS} >> P_{OPTICAL}$
- **Calculated *Ea* = 1.146 eV vs 1.15 eV: very good matching!**
  - However, V_{AK} and R_{TH} cannot be considered constants
  - Is there some reason for this consideration?
- **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 full model fitting would be appreciated**

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

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

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

Parameters

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

Ea and N consistency

Experiment	T_S (ºC)	I_{BIAS} (mA)	T_J (ºC) ΔT_{SJ} = 25ºC @ 7.5 mA	Equiv. Time (h)	Estim. Ea (eV) Using 2, 3	Estim. N Using 1,3
1	100	10	133.3	800		
2	85	9	115.0	6800		
3	100	9	130.0	1900	**1.146**	**8.210**

Reliability results of [4] — R_{TH}, V_{AK} constants

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} (ºC)	95.0
	ΔT_{AS} (ºC)	20.0		TTF_0 x% (hours)	873600
VCSEL model fitting	ΔT_{SJ} (ºC) @ 7.5mA	25.0		Arrhenius C factor (hours) @ T_J	6.155275E+00
				Qe	1.6022E-19
				K_B	1.3806E-23
				Qe/K_B	1.1605E+04
				ºC to Kelvin	273.15

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 70ºC substrate

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

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

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

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

Reliability result

	Temperature profile					Failure rate						
	Percentage	Operation time per Temperature (h)	T_A (ºC)	T_S (ºC)	T_J (ºC)	TTF x% (hours)	TTF_{5FIT} (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	5.0	1.084E+11	**11684618447**	0.00	27.2706			
T1	**20 %**	6400	**23**	43.0	68.0	1.539E+07	**1658406**	3.27	18.4104			
T2	**65 %**	20800	**50**	70.0	95.0	8.736E+05	**94131**	187.00	15.5415			
T3	**8 %**	2560	**100**	120.0	145.0	1.145E+04	**1234**	1755.75	11.2070			
T4	**1 %**	320	**105**	125.0	150.0	7.854E+03	**846**	320.00	10.8298	$\lambda(t)$		ppm
Cummulative	100 %	**32000**						t **2266.01**	μ' **10.8298**	**118.4411**	**5.0**	**3950**

>> 10 FIT !

850nm devices reliability comparison

Reliability comparison — 160 ppm (5 FIT)

T_A (°C)	850nm 25G VCSEL [1, 2, 3]	850nm 25G VCSEL [4]	Reliability improvement factor (RIF)
	$TTF_{5\,FIT}$ (hours)	$TTF_{5\,FIT}$ (hours)	
-40	36778496832	11684618447	0.318
23	2687026	1658406	0.617
50	116476	94131	0.808
100	906	1234	1.362
105	589	846	1.438

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

850nm VCSEL of [4] 1.4x more reliable than 850nm VCSEL of [1, 2, 3], same order

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

Reliability results of [1, 2, 3]. Max I_{BIAS}

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	**6.0000**		Log-normal σ’, ln (hours)	0.5
	J_{OP} (kA/cm²)	15.60		J_0 (kA/cm²)	19.50
	J_{OP} (mA/um²)	0.16		T_{J0} (ºC)	193
	ΔT_{AS} (ºC)	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 (ºC)	20.0		Qe/K_B	1.1605E+04
	R_{JS} Exponent	1.067		ºC 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			

- 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)
- Typical production oxide aperture is considered: 7 μm
- Lower shape parameter: σ’ = 0.5 (see [1])
- **Max I_{BIAS} is 6 mA**
- **5 mA was proposed in [6] to operate reliable with margin , i.e. 1 mA margin**

Reliability result

	Temperature profile							Failure rate						
	Percentage	Operation time per Temperature (h)	T_A (ºC)	T_S (ºC)	R_{JS} (K/W)	P_{DIS} (mW)	T_J (ºC)	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	1782.2	9.94	-2.3	2.194E+12	**170384985776**	0.00	28.4170			
T1	20 %	6400	**23**	43.0	2259.2	8.92	63.2	1.173E+08	**9106834**	1.23	18.5802			
T2	65 %	20800	**50**	70.0	2465.6	8.89	91.9	4.743E+06	**368291**	98.66	15.3723			
T4	8 %	2560	**100**	120.0	2850.7	9.47	147.0	3.472E+04	**2696**	1659.12	10.4550			
T5	1 %	320	**105**	125.0	2889.4	9.57	152.7	2.250E+04	**1747**	320.00	10.0213			
Cummulative	100 %	**32000**								**2079.01**	**10.0213**	4.5447	**5.0**	305

Reliability results of [4] — R_{TH}, V_{AK} constants. Max I_{BIAS}

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	**7.0000**		**Log-normal σ', ln (hours)**	0.8
	J_{OP} (kA/cm^2)	18.20		**J_0 (kA/cm^2)**	19.50
	J_{OP} (mA/um^2)	0.18		**T_{J0} (°C)**	95.0
	ΔT_{AS} (°C)	20.0		**TTF_0 x% (hours)**	873600
VCSEL model fitting	**ΔT_{SJ} (°C) @ 7.5mA**	25.0		**Arrhenius C factor (hours) @ T_J**	6.155275E+00
				Qe	1.6022E-19
				K_B	1.3806E-23
				Qe/K_B	1.1605E+04
				°C to Kelvin	273.15

Ea

n as calculad in slide 4

TTF for 1%

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

I_0 = 7.5 mA; J_0 = 19.50 kA/cm^2

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

- **Reliability 7.0 mA is in the limit assuming n = 8.21**
- **Considering 1 mA margin as in [6], the max I_{BIAS} = 6.0 mA**

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**	-20.0	3.3	2.552E+11	**27492788611**	0.00	28.1262			
T1	**20 %**	6400	**23**	43.0	66.3	3.286E+07	**3540745**	3.05	19.1689			
T2	**65 %**	20800	**50**	70.0	93.3	1.815E+06	**195580**	179.64	16.2727			
T3	**8 %**	2560	**100**	120.0	143.3	2.293E+04	**2470**	1750.48	11.9011			
T4	**1 %**	320	**105**	125.0	148.3	1.568E+04	**1689**	320.00	μ' 11.5210	$\lambda(t)$		ppm
Cummulative	100 %	**32000**						t **2253.17**	**11.5210**	**2.7762**	**5.0**	**249**

Reliability results of [4] — R_{TH}, V_{AK} constants. Max I_{BIAS}

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**	**3.000**
	Min oxide aperture diam. (um)	7.0		**TTF x%, location**	1.0
	I_{OP} (mA) max	**6.6000**		**Log-normal σ', ln (hours)**	0.8
	J_{OP} (kA/cm²)	17.16		**J_0 (kA/cm²)**	19.50
	J_{OP} (mA/um²)	0.17		**T_{J0} (ºC)**	95.0
	ΔT_{AS} (ºC)	20.0		**TTF_0 x% (hours)**	873600
VCSEL model fitting	**ΔT_{SJ} (ºC) @ 7.5mA**	25.0		**Arrhenius C factor (hours) @ T_J**	1.170498E-06
				Qe	1.6022E-19
				K_B	1.3806E-23
				Qe/K_B	1.1605E+04
				ºC to Kelvin	273.15

Ea

n as reported by Giovane in 8th June meeting

TTF for 1%

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

I_0 = 7.5 mA; J_0 = 19.50 kA/cm²

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

- **Reliability 6.6 mA is in the limit assuming n = 3.00**
- **Considering 1 mA margin as in [6], the max I_{BIAS} = 5.6 mA**

Reliability result

	Temperature profile					**Failure rate**						
	Percentage	**Operation time per Temperature (h)**	**T_A (ºC)**	**T_S (ºC)**	**T_J (ºC)**	**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	2.0	2.685E+11	**28930322117**	0.00	28.1772			
T1	**20 %**	6400	**23**	43.0	65.0	3.196E+07	**3443222**	2.89	19.1409			
T2	**65 %**	20800	**50**	70.0	92.0	1.727E+06	**186048**	173.90	16.2228			
T3	**8 %**	2560	**100**	120.0	142.0	2.116E+04	**2280**	1746.23	11.8211			
T4	**1 %**	320	**105**	125.0	147.0	1.444E+04	**1555**	320.00	μ' 11.4385	$\lambda(t)$		ppm
Cummulative	100 %	**32000**						t **2243.02**	**11.4385**	**4.4092**	**5.0**	**301**

Reliability results of [4] — R_{TH}, V_{AK} constants. Max I_{BIAS}

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**	**1.640**
	Min oxide aperture diam. (um)	7.0		**TTF x%, location**	1.0
	I_{OP} (mA) max	**6.3000**		**Log-normal σ', ln (hours)**	0.8
	J_{OP} (kA/cm²)	16.38		**J_0 (kA/cm²)**	19.50
	J_{OP} (mA/um²)	0.16		**T_{J0} (ºC)**	95.0
	ΔT_{AS} (ºC)	20.0		**TTF_0 x% (hours)**	873600
VCSEL model fitting	**ΔT_{SJ} (ºC) @ 7.5mA**	25.0		**Arrhenius C factor (hours) @ T_J**	2.060520E-08
				Qe	1.6022E-19
				K_B	1.3806E-23
				Qe/K_B	1.1605E+04
				ºC to Kelvin	273.15

Ea

n consistent with [1, 2, 3]

TTF for 1%

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

I_0 = 7.5 mA; J_0 = 19.50 kA/cm²

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

- **Reliability 6.3 mA is in the limit assuming n = 1.64**
- **Considering 1 mA margin as in [6], the max I_{BIAS} = 5.3 mA**

Reliability result

	Temperature profile					**Failure rate**						
	Percentage	**Operation time per Temperature (h)**	**T_A (ºC)**	**T_S (ºC)**	**T_J (ºC)**	**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	1.0	2.907E+11	**31319664416**	0.00	28.2565			
T1	**20 %**	6400	**23**	43.0	64.0	3.258E+07	**3511007**	2.77	19.1604			
T2	**65 %**	20800	**50**	70.0	91.0	1.732E+06	**186570**	169.67	16.2256			
T3	**8 %**	2560	**100**	120.0	141.0	2.075E+04	**2235**	1743.02	11.8011			
T4	**1 %**	320	**105**	125.0	146.0	1.412E+04	**1522**	320.00	11.4168	$\lambda(t)$		ppm
Cummulative	100 %	**32000**						t **2235.47**	μ' **11.4168**	**4.9229**	**5.0**	**318**

Conclusions 1 of 2

- This contribution provided additional information to the analysis presented in [5], and it presented a root cause that may explain the results obtained in [4]
- Results presented in [4] were explained considering constant thermal resistance R_{TH} across temperature as well as constant voltage drop V_{AK}
- Based on these hypotheses, it can be seen that calculated activation energy and acceleration factors are very consistent with [4]
- Based on these hypotheses, maximum operating current has been calculated to meet the automotive reliability requirements under the considered mission profile, being the result approx. **5 mA** for the VCSEL presented in [4], which is consistent with [1, 2, 3]
- **However, these hypotheses are not consistent with physics governing the VCSEL device behavior, so more transparency on R_{TH}, V_{AK}, T_J, current exponent n and reliability model fitting is requested to be able to carry out an apples with apples comparison and being able to replicate analysis**

Conclusions 2 of 2

- In [5] it was shown how important is a reliability assessment with margin and how the reliability results depend on reliability model parameters fitting. This contribution also shows how current exponent influences the max operation current
- **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)
  - More difficult VCSEL design, smaller number of players in the market
- **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, “VCSEL reliability comparison,” June 2021, [Online], Available: https://www.ieee802.org/3/cz/public/8_jun_2021/perezaranda_3cz_01b_080621_vcsel_reliability.pdf
- [6] R. Pérez-Aranda, “Revised link budget assessment,” May 2021, [Online], Available: https://www.ieee802.org/3/cz/public/11_may_2021/perezaranda_3cz_02_110521_revised_link_budget.pdf

Thank you!