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OPTOELECTRONICS IN SPACE: MAIN QUALIFICATION PITFALLS AND HOW TO AVOID THEM

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INTRODUCTION

During the last decade the use of optoelectronic devices in space has strongly increased mainly because, in the recent years, the space market has taken advantage of the tremendous development of the optoelectronic technology on ground. Telecommunication, defence, industrial and mass-market applications lead to the development of new components that may also have an interest for the space community bringing up new perspectives for the designer of equipment.

However, before using these devices in the severe space environment, they have to be qualified for flight to be sure that they can withstand for years without performance loss, shocks, vibrations, extreme temperature changes, radiations, microgravity and vacuum exposure.

Today, a reduced amount of space standards is available to define the activities to carry out to qualify optoelectronic parts. In the absence of relevant space standards the normative literature from other sectors of activity can also be useful. For instance, military and telecommunication standards are often used as guidelines because, in these sectors, the qualification strategies are very close to the one required in space programs. Unfortunately, in certain cases, devices cannot be qualified using the available standards as they are. The test conditions proposed in these documents have to be adapted either because the technology is not robust enough to sustain the stress level imposed by the normative literature or because the mission environmental constraints require performing very specific non-standardized tests. In that case a customized qualification strategy has to be followed.

Anyway, whatever the approach retained, fully normative or customized, a good knowledge of the most common failure modes at devices level is mandatory to design relevant qualification plans. Unfortunately, due to the wide diversity of optoelectronic technologies the potential failure modes are numerous but the associate literature is very thin. Taking into account the relatively low maturity of these technologies in the space domain, it is therefore of high interest for the community to share information regarding the main pitfalls that can be encountered when qualifying devices as well as the possible strategies to avoid them. In this framework the purposes of this article are:

- to identify the main environmental constraints encountered during a space mission,
- to present the current and future space applications requiring optoelectronic parts,
- to identify the technologies of interest,
- to point out the main failure modes for the most strategic devices,
- to present the available standards that can be used for the qualification of optoelectronic devices,
- to propose some tools to design customized qualification test plans,
- to propose some recommendations to secure the procurement and the qualification of flight models.

I. ENVIRONMENTAL CONSTRAINTS

Radiations, microgravity, vacuum, thermal cycles, atomic oxygen, mechanical shocks and vibrations: the environmental constraints that may affect the reliability of a device during its lifetime in space are numerous. The purpose of this section is to give an overview of these constraints [1].

A. Vacuum

The atmospheric composition and pressure change with altitude. During the launch the depressurization rate is about 20 mbar/s in the payload compartment of an Ariane 5 launcher. At 200 km the pressure is about 10^{-9} bar while it is close to 10^{-14} bar at 800 km and below 10^{-18} bar in the interplanetary space.

When a material is exposed in vacuum its vapour pressure is greater than the environmental pressure and the consequence is an evaporation of the material itself. Material outgassing in vacuum can cause two types of effects, firstly, change of properties of the outgassing material itself and, secondly, contamination of other surfaces by the outgassing products. This last effect is particularly critical for optical surfaces (e.g. mirrors, filters, windows). To avoid such effects it is mandatory to use only materials with low outgassing rates. All materials intended for use in space systems must be evaluated to determine their outgassing characteristics using the appropriate standards (see Section V).

B. Thermal environment

The thermal environment of a device may greatly vary depending on the orbit and on the location of the device inside the satellite. Table I shows few examples of thermal environment for different kind of optoelectronic devices.

Table I. Thermal constraints for few optoelectronic devices.

Device	**Temperature requirements**
Solar generator (solar cells)	Low Earth Orbit (800 km – 5 years) : ~ 30 000 cycles between -100°C/+100°C Geostationary Orbit (36 000 km – 15 years): ~ 1300 cycles between -180°C/+100°C
Standard electronic unit base plate temperature (laser diode, LED, …)	-10°C/+50°C
Visible image sensors (CCD, CMOS sensors)	20°C±0.1°C – homogeneity requirement ΔT ~ 0.01°C
Cooled infra-red detectors	80 K±5K
Far Infrared bolometer	0.1 K

C. Microgravity

In a space environment the residual acceleration lies between 10^{-4} and 10^{-8} g above an altitude of about 250 km. This reduced acceleration tends to suppress certain phenomena such as convection and to increase certain effects usually hidden or lowered on ground (e.g. capillarity, wetting).

D. Atomic oxygen

Above an altitude of 200 km the main atmosphere constituent is the atomic oxygen generated by the dissociation, under UV-light, of the molecular oxygen O_2. The impact at high speed (about 8 km/s) of the atomic oxygen leads to an oxidation and to an erosion of the exposed surface of a satellite. The reactivity depends on the material considered (e.g. silver and kapton are highly reactive).

E. Radiative environment

1) Solar spectrum

The sun is emitting energy from its surface approximately like a black-body radiator at 6000 K. The total irradiance over the full solar spectrum at a distance of one astronomical unit is about 1370 W/m^2. Most of the solar energy is in the visible and near infrared wavelength range but the UV-part of the spectrum is the most important one regarding the effect on materials. Indeed, photons in the UV-range have an energy which is in the same order of magnitude as the main chemical binding energies. Under UV-light polymers could be weakened and could exhibit some changes with respect to their chemical and physical properties. Glasses may also have their optical properties affected by UV (e.g. cover-glass of solar cells). The darkening due to colour centres generation is the most common effect.

2) Particles

There are two categories of particles that exist in the natural radiation environment, transient particles and trapped particles. Transient particles originate outside the boundary of the Earth’s magnetic field, the magnetosphere, and the trapped particles exist within the Earth’s magnetosphere. These particles contribute to various radiation effects, such as Total Ionizing Dose (TID), Displacement Damage Dose (DDD), and Single Event Effects (SEE), which may impose risks to various space systems.

a) Transient Particles

There are two types of transient particles, Galactic Cosmic Rays (GCR) and solar particle events. GCR originate outside our solar system, but within our galaxy. GCRs pose a risk to space electronics because their high energies make them extremely penetrating. They pass through spacecraft shielding and strike sensitive regions in electronics causing SEEs. Solar particle events consist of solar protons and heavier ions. Solar proton events, which contribute to TID, DDD, and SEEs, originate from Coronal Mass Ejections (CMEs) and solar flares. It is important to assess the effect of SEEs induced by a solar particle event because these particle fluences are orders of magnitude higher than the cosmic ray fluences.

b) Trapped Particles

There are three types of trapped particles that exist in the near Earth radiation environment: energetic protons, electrons, and heavy ions. The trapped heavier ions do not pose a problem for electronics in regard to SEEs because of their low energies; hence, they are not able to penetrate shielding.

The trapped particles comprise the Earth's radiation belts, known as the Van Allen belts. The particles are divided into three sections, the inner belt (extending from altitudes of 300 to 1200 km), the outer belt (extending from altitudes of 10 000 km to 55 000 km depending on the solar wind), and the slot region.

Energetic protons, with an estimated energy range of 40 KeV to 400 MeV, are the prime component of the "inner" radiation belt to consider when evaluating radiation effects on electronics. Trapped protons are a hazard to electronics due to their ability to induce TID, DDD, and SEEs.

The most important component of the "outer" radiation belt to consider when evaluating radiation effects on electronics is the trapped electrons. The trapped electrons have an energy range up to approximately 10 MeV. As with the trapped protons, the trapped electrons and their secondary bremsstrahlung radiation contribute to total dose.

At low altitudes (<1000 km), there is an area of enhanced radiation known as the South Atlantic Anomaly (SAA). The SAA is caused by the offset and tilt of the geomagnetic axis with respect to the Earth's rotational axis, which brings the trapped particles to lower altitudes.

Table II shows few examples of dose level received by optoelectronic devices depending on the orbit and their location inside a satellite.

Table II. Typical radiation constraints.

Orbit and effective spherical aluminum shield thickness	**Total ionizing dose**	**Equivalent fluence of 60 MeV protons**
Low Earth Orbit (5 years) behind 1 mm of Al	~ 60 krad	~ 6×10^{10} protons/cm^2
Geostationary Orbit (15 years) behind 1 mm of Al	~ 20 Mrad	~ 10^{12} protons/cm^2
Low Earth Orbit (5 years) behind 10 mm of Al	~ 2 krad	~ 10^{10} protons/cm^2
Geostationary Orbit (15 years) behind 10 mm of Al	~ 10 krad	~ 2×10^{10} protons/cm^2

F. Mechanical environment

The launch and flight of a spacecraft is accompanied by a number of events that can cause significant mechanical stresses including:

- Quasi-static acceleration loads: aerodynamic origin (e.g. wind, gusts or buffeting at transonic velocity) or propulsion systems origin (e.g. longitudinal acceleration, thrust build-up or tail-off transients, or structure-propulsion coupling, etc.),
- Sine vibrations: powered flight, mainly the atmospheric flight, as well as during some of the transient phases,
- Random vibrations: engines functioning, structural response to broad-band acoustic loads, aerodynamic turbulent boundary layer,
- Acoustic field: during lift off and early phases of the launch,
- Pyrotechnic shocks: launch vehicle separation and from the solar arrays deployment.

Vibration and shock forces are transmitted to devices by structural members. The magnitudes and frequency spectra of the forces from their original sources are modified by the transmitting media before to reach the devices. The vibrational amplitude may be attenuated or amplified by the structure. Table III gives typical mechanical constraints obtained at device level.

Table III. Typical mechanical constraints.

Stress	**Level**
Random vibration	~ 20 - 30 g rms [20 Hz - 2000 Hz]
Shock	half sine : 500 g / 1 ms to 1500 g / 0.5 ms
Sine vibration	~ 20 g [10 Hz - 2000 Hz]

II. OPTOELECTRONICS IN SPACE

The maturity level reached today by optoelectronic parts makes them available to cover a wide range of missions [1]-[3]. Compared to other sectors of activity the space sector virtually uses all the available devices. Table IV shows examples of space applications for these parts, the main reasons for using the optoelectronic technology instead of an alternative one, and the associated key components.

Table IV. Examples of current and future applications for optoelectronic devices in space.

Application	**Function**	**Advantages of optoelectronics**	**Key components**
Telecommunications	- Equipment-to-equipment and board-to-board digital link - Local oscillator distribution with photonic/RF frequency conversion - Photonic/RF frequency mixing for both up- and down-conversion of microwave signals - Broadband, transparent, and flexible analogue repeater - Wireless infrared links - Optical Inter-Satellite Links and satellite to ground station link	Low mass, low volume, low consumption, mechanical flexibility, electromagnetic interference immunity, high bandwidth, high directivity of the optical beam for free space telecommunications, potentially low cost, high scalability	Optical transceivers, mono and multimode fibres, optical ribbons, optical connectors, electro-optical Mach-Zehnder modulators, erbium and erbium/ytterbium doped fibres, 155X nm DFB laser diodes, 980 nm pump laser diodes, 1480 nm pump laser diodes, PIN InGaAs-based photodiodes, optical micro-switches, IR LED, 850 nm VCSEL, Si-based photodiodes
Earth observation, Astronomy	-Imaging -Spectrometry -Radiometry	No alternative technology	CCD linear and 2D arrays, CMOS Active Pixel Sensor (visible) arrays, InGaAs linear and 2D arrays, HgCdTe 2D arrays, microbolometers 2D arrays, QWIP 2D arrays, micro channel plate detectors (UV), Electron-Bombarded CCD
	On-board sensor calibration	Flux uniformity, spectral selectivity	Visible to NIR LED
Attitude control	Fibre Optic Gyroscope (FOG)	Low angular noise, high angular resolution, high scale factor stability	980 nm pump laser diodes or superluminescent LED, erbium doped optical fibres, polarization maintaining optical fibres, phase modulators, InGaAs-based PIN photodiodes, isolators, Bragg gratings, couplers
	Star tracker	No alternative technology	CCD linear and 2D arrays, CMOS Active Pixel Sensor arrays
	Earth sensor	No alternative technology	Thermopiles, bolometers
	Sun sensor	No alternative technology	Si-based photodiodes

	Videometer	No alternative technology	Laser diodes, CCD or CMOS sensor 2D arrays
	Navigation camera	No alternative technology	CCD or CMOS sensor 2D arrays
Atomic sensing	Optical atomic clocks (Cs and Rb optical pumping)	Accuracy, long-term stability	852 nm laser diodes,780 nm laser diodes (DFB or FP), low noise Si-based photodiodes, acousto-optic modulators
	Optical magnetometry (^{4}He optical pumping)	Sensitivity, accuracy	980 nm pump laser diodes, ytterbium doped fibres, InGaAs-based, PIN photodiodes, isolators, Bragg gratings, couplers, 1083 nm DFB lasers
Fibre optic sensing	Strain, pressure and temperature sensors	Higher degree of multiplexing, sensitivity	Fibre Bragg gratings
Active remote sensing	-LIDAR (wind, backscattering, DIAL) -LIBS	No alternative technology	1.57 µm, 2 µm and 1.9 µm laser sources , 808 nm laser diode arrays, thulium and holmium doped crystals, 2 µm avalanche photodiodes, Nd-doped crystals, EM-CCD, Pockels cells
Pyrotechnics	-Optopyrotechnic initiator -Optopyrotechnic detonator	Low mass, low activation current, electromagnetic interference immunity, low cost	High power laser diodes, optical fibres
Mechanisms	Optical encoders (angular, linear)	Accuracy, reliability	Multi-channel LED, Si-based phototransistor or photodiode arrays
Power sources	Solar arrays	High safety, readily available (compared to Radioisotope Thermoelectric Generator)	Solar cells (triple junctions)
Power conversion	DC/DC convertors	High electrical insulation and signal isolation	Optocoupleurs (linear)
Data transfer	Switching	High electrical insulation and signal isolation	Optocoupleurs (digital)

III. TECHNOLOGIES

A. *Chip level*

One peculiarity of optoelectronic components lies in the great variety of the materials used for their manufacturing. Table V shows for each family of devices the associated chip technologies.

Table V. Key technologies for optoelectronic devices.

Family	**Device**		**Technology**
Emitters	Laser diodes	blue	InGaN
		red	AlGaInP
		800 nm -850 nm	AlGaAs

		980 nm	GaInAs
		1310 nm – 1600 nm	InGaAsP
		>1600 nm	InGaAsSb
		>3µm	Quantum cascade lasers (GaInAs/AlInAs)
	Light emitting diodes	IR	AlGaAs
		red	AlGaAs,GaAsP, AlGaInP, GaP
		orange to yellow	GaAsP, AlGaInP, GaP
		green	GaP, AlGaInP, AlGaP, InGaN, GaN
		blue	ZnSe, InGaN, SiC
		UV	GaN, AlGaN
Receivers	UV		Si, GaN, AlGaN, SiC, diamond
	Visible		Si
	NIR (0.74-1 µm)		InGaAs
	SWIR (1-3 µm)		InGaAs, HgCdTe
	MWIR (3-5 µm)		HgCdTe, InSb, GaAs quantum well (QWIP)
	LWIR (8-14 µm)		HgCdTe, GaAs quantum well (QWIP), a-Si, vanadium oxide and YBaCuO-based micro-bolometers, InAs/GaSb superlattices
	VLWIR (14-1000 µm)		HgCdTe, Si:As, Si:Sb, Ge:Sb, InAs/GaSb superlattice
	Solar cells		InGaP/Ga(In)As/Ge, Si
Optical functions	Modulators		LiNbO3, electro-optic polymers
	Passive optical devices (optical fibres, couplers, Bragg gratings, multiplexers, …)		SiO2 + doping species (P, F, Ge, …)
	Active optical devices		Rare earth (Er, Yb, …) doped optical fibres, nonlinear crystals (KNbO3, LiNbO3, KD(*)P, KTP, ADP), active laser materials (Nd:YAG/YLF, Ho:Tm:YAG/YLF,…)
	Isolators		Yttrium iron garnet, bismuth iron garnet
	Optocouplers		Vis-IR LED, Si photodiode, phototransistors

This wide technology range makes the component qualification activity very challenging because each device, each technology features specific failure modes that need to be known.

B. Assembly and packaging level

The packaging of optoelectronic devices is also very specific. Compared to other electronic components the package shall ensure an optical function and has also to be optimized from that point of view leading to the use of a huge number of materials. This variety of materials is one factor that distinguishes optoelectronic device assembly from conventional microelectronic assembly. Tight optical alignment requirements (e.g. chip to fibre, filter to detector), cleanliness constraints (e.g. particle, molecular contamination), hermeticity specification, parasitic light management, mechanical and thermal optimization of the assembly makes the package of optoelectronic devices very complex to design and to manufacture. This is the reason why for low volume production, which is generally the case for optoelectronic devices, package assembly is usually a manual process leading to high fabrication cost. In optoelectronics the package accounts for 60 to 80 % of current manufacturing expenses in component assembly while in standard electronics the proportion is reversed [4].

IV. MAIN FAILURE MODES OF OPTOELECTRONIC DEVICES

The knowledge of the main failure modes is mandatory to propose relevant qualification plans, to anticipate qualification issues or to zoom down to possible failure root causes. The purpose of that section is to present failure mechanisms encountered in the most important optoelectronic devices.

A. Laser diodes [5]-[6]

1) General

a) Inner region degradation

In AlGaAs/GaAs laser diodes the rapid decrease of the optical output power is usually due to <100> Dark Line Defects (DLD) growth in the active layer of the device. The DLD results from the formation of a dislocation network due to the climbing motion from a threading dislocation continued from a substrate or staking fault introduced from crystal growth. The climbing motion may result from the absorption of interstitial point defects or from the emission of vacancy pairs at the dislocation. The DLD tends to increase the absorption loss and to shorten the injected carrier lifetime leading to an increase of the threshold current and a decrease of the external efficiency.

The <110> DLD is also a cause of rapid degradation of lasers. These defects are related to the growth of dislocation due to gliding motion from the surface of the device. This motion occurs when the chips are operated under a residual mechanical stress due to the assembly.

The growth of DLD and subsequent degradation of the device is aided by Recombination Enhanced Defect Motion (REDM). When an electron-hole recombination occurs at the recombination centre (DLD), the excess energy released to the lattice as vibrational energy increases the rate of defect reaction such as diffusion, dissociation and annihilation. In laser diodes and light emitting diodes this effect is enhanced under electrical injection.

The suppression of <100> DLD relies on the optimization of the growth process and on the choice of substrate featuring a low density of defects. The elimination of <110> DLD can be obtained by minimizing the residual mechanical stress in the chip during the assembly process. From this point of view the use of soft solders (e.g. indium-based solder) is favourable to absorb the stress originated from the mismatch of the Coefficient of Thermal Expansion (CTE) between the chip and the heat sink. However some issues can also be met regarding the use of such solder materials: growth of friable $AuIn_2$ intermetallic compounds, creeping and whisker formation [7]. If possible the thermal mismatch has to be minimized and a harder, less ductile, but more stable solder shall be preferred (e.g. AuSn eutectic).

Another point concerns the thermal resistance of the laser assembly: it has to be kept as low as possible because a high temperature of the active region could lead to a premature failure (see Section VI). The laser chip substrate contributes significantly to the total thermal resistance. Since the epitaxial layers containing the active region are much thinner than the substrate, the epi-down configuration shall be preferred to mount the laser chip in order to minimize the thermal resistance. The difficulty with the epi-down bonding is the mechanical and thermal stresses caused by the CTE mismatches between the semiconductor and the bonding substrate, and the semiconductor and solder interface. This can be critical especially if hard solders are used.

Consequently a thermal and mechanical optimization of the assembly has to be conducted to minimize both thermal resistance and residual mechanical stress in the laser chip. SiC, AlN and CuW appear to be good candidates to achieve a low residual stress in GaAs-based laser chip and an efficient thermal dissipation.

In InGaAsP/InP devices the growth of DLD is no more a problem today. The main cause limiting the lifetime of current InGaAsP/InP laser diodes is the degradation of the edges of the active region (i.e. the Buried Heterostucture (BH) interface). The defect density increases at the interface between the active region and the burying layer leading, in severe cases, to the generation of dislocation networks.

b) Catastrophic damage

After cleavage, the facet region of a laser diode generally features a high density of defects (surface states) that need to be properly passivated to achieve reliable operation. If it is not the case these surface states, whose energy levels lie within the band gap of the semiconductor, act as non-radiative recombination centres leading to an increase of the temperature when carriers are injected. The temperature increase introduces the reduction of bandgap energy and then the increase in absorption coefficient at the facet. In addition the mirror may heat simply because the edge of the laser diode is in less-than-perfect contact with the mount that provides a path for heat removal. The band gap shrinkage tends to enhance the absorption of photons near the facet and brings more electron-hole pairs generation. These pairs can in turn recombine on non-radiative centres leading again to a rise of the facet temperature. This is thermal runaway, a form of positive feedback, and the result can be melting of the facet, known as Catastrophic Optical Mirror Damage (COMD).

Deterioration of the laser facets with aging and effects of the environment increases light absorption by the surface, and decreases the COMD threshold. A sudden catastrophic failure of the laser due to COMD then can occur after many thousands hours in service.

Catastrophic failure can also take place accidentally by current surge (Electro-Static Discharge (ESD), Electrical Over Stress (EOS)) or by strong optical excitation at high power density. The degradation occurs predominantly at the mirror surface by COMD but not necessarily. Catastrophic optical damage can also occur within the laser cavity, this failure mode is usually called Bulk-defect initiated Catastrophic Optical Damage (BCOD). The bulk-defect could be an epi-grown defect or a process-induced defect during manufacturing process or handling.

When a BCOD occurs, <110> DLD are also observed. However, they do not originate from the mirror but are generated inside the active region from defects (e.g. inclusions, precipitates) usually generated during growth.

These results lead to the conclusion that protection of mirrors with dielectric films and reduction of inclusions and/or precipitates during growth is essential for eliminating catastrophic failure in lasers. The facet heating can also be reduced using a current blocking layer (Un-Pumped Window) located near the front facet of the laser to prevent surface recombination.

c) Package induced failure

The term Package-Induced Failure (PIF) was introduced to name the phenomenon of the very fast degradation of 980-nm, high-power laser diode operated in hermetic packages under neutral gas atmosphere [8]. This degradation corresponds to the growth of carbon deposit on the mirrors of the laser during its operation generally leading to COMD. It was shown that the reaction is related to the photo-induced decomposition of organic compounds under high power density (few MW/cm^2). The source of these contaminants may be the package atmosphere or the package material (e.g. adhesive, solder flux, cleaning agents, etc.). This carbon deposit can be prevented or even removed by adding oxygen (e.g. about 10% in volume) to the sealing atmosphere. However the oxidation of residual organic contaminants may generate water that need to be trapped to avoid other potential reliability issues: corrosion, leakage current, etc. This can be obtained using a getter material (i.e. porous silica or a zeolite) within the laser package which is also capable of adsorbing or absorbing part of organic materials. Operating a high power laser chip directly under vacuum can also be risky because of that specific failure mode.

d) Optical alignment stability

In certain laser modules the laser chip to fibre optical coupling relies on a configuration where a metallized fibre is directly soldered onto a substrate. Changes in the position of the fibre lens relative to the laser chip active facet due to the degradation of solder joint integrity in the lifetime application will result in the loss of stability of the power output and in worst cases, in the complete loss of the power. The gradual degradation of the coupling efficiency of module is the result of the slow plastic deformation of the alignment solder called creep relaxation. Creep could happen during isothermal storage and thermal cycling tests.

Another issue can be encountered regarding the alignment of an optical fibre to the laser diode when laser welding is used to fix the optical fibre in front of the laser waveguide. It is called Post-Weld-Shift (PWS). Namely, the laser welding process intrinsically involves the melting of metal pieces that fuse together upon re-solidification, thus forming a weld joint. The shrinkage of the molten metal upon returning to its solid form creates shrinkage forces that shift the components from their predetermined locations, consequently misaligning the fibre tip and the laser diode chip from their optimum relative position which results in a reduction in light coupling efficiency.

2) Radiation

Laser diodes are marginally impacted by radiations. Ionizing effects are nearly inexistent at chip level even if some optical devices encountered in laser modules (e.g. lenses, window, optical fibres, fibre Bragg grating) may feature a certain sensitivity at very high dose level (>100 krad). The effect of displacement damage is more pronounced. One can observe a significant increase of the threshold current at high fluence (>10^{12} protons (60 MeV)/cm^2) due to the generation of non-radiative recombination centres in the active region of the device. Displacement damage effect can be partly annealed by carrier injection (REDM).

B. Light Emitting Diodes

1) General

The degradation of Light Emitting Diodes (LED) is usually related to a gradual decrease of their emitted optical power [9]. Several failure mechanisms can be involved: nucleation and growth of dislocation in GaAs-based devices, metal and dopants migration, temperature activated ohmic contact degradation, die or encapsulation cracking due to thermal stress, yellowing of the encapsulant due to UV exposure (UV LEDs) and LED self-heating, phosphor degradation under high drive current and excessive temperature (white LED).

2) Radiation

Diffused LED (amphoteric doping) may be sensitive to DDD while heterojunctions exhibit a far better behaviour. Basically, LED degradation is due to the generation of non-radiative recombination centres within the active region of the device. As for laser diodes, LED are also sensitive to carrier injection annealing. One can also observe encapsulant or window darkening due to ionizing dose effects [10].

C. Photodiodes

irradiation especially after proton and neutron tests. In CCDs, displacement damages impact the charge transfer efficiency as well due to the generation of trapping centres within the buried channel (e.g. di-vacancy and phosphorus-vacancy centres).
An ELDRS effect has been observed in CCDs biased in dynamic mode and with an ON/OFF duty cycle [14]. Thus, the dose rate has proven to be an important test parameter and has to be taken into account to avoid any under-evaluation of the device degradation.
CMOS imagers are also sensitive to SEE (Single Event Upsets, Single Event Latch-Up, Single Event Functional Interrupt).

G) HgCdTe cooled infrared focal plane array

1) General

A Focal Plane Array (FPA) is made up of two components: a detector array and a silicon-based Readout Integrated Circuit (ROIC) multiplexer. The HgCdTe detector array consists in photovoltaic diodes processed in epitaxially grown material on a suitable substrate ideally lattice matched to the active layer. The other component of the FPA, the ROIC, reads the photo-current from each pixel of the detector array and outputs the signal in a desired sequence that is used to form a two-dimensional image. The hybrid FPA is fabricated by depositing indium bumps or columns onto the detector and the ROIC and mating the two devices together.
Each element of the FPA (HgCdTe detector, ROIC and indium interconnections) has its own failure modes. The main ones are listed below [15]:

- HgCdTe detectors: Diodes degradations (i.e. increase of defective pixels) during on-ground room temperature storage. Different failure mechanisms can explain such behavior:
  - long term defects diffusion (e.g. Hg vacancies, dislocations),
  - passivation layer degradation,
  - ohmic contact degradation,
  - indium interdiffusion with gold through a defective barrier layer from the interconnects in the contact structure into the HgCdTe detector material [16],
  - $AuIn_2$ intermetallic expansion inducing strain and lattice dislocation damage to the HgCdTe.
- ROIC: hot carriers injection at cryogenic temperature
  Infrared detectors require low operation temperature sometime as low as 50 K. At this temperature hot carriers injection may be a primary reliability concern.
- Interconnections: due to the CTE mismatch between the ROIC and the detection circuit, degradation by themo-mechanical stress during cool down cycling from room to cryogenic temperature can occur in the photodiodes arrays, with local cleavage for instance, and in the indium interconnection [17]. This effect is especially expected in large focal plane arrays.

One can also mention that Fe-Ni-Co alloys used in cryogenic packages can exhibit metallurgical and physical property changes (i.e. martensitic phase transformation) and have to be carefully selected [18].

2) Radiation

Radiation effects are quite similar to the one experienced by visible imagers. Ideally irradiations should be conducted at or near the expected operating temperature with measurements performed without changing the temperature or, at least, following typical changes of temperature expected during the mission to avoid spurious annealing effects of displacement damage.
The sensitivity of the ROIC to Single Event Latch-Up is decreased at low temperature.

H) Microbolometer arrays

1) General

Assembly is one of the most important topics that need to be carefully checked for this kind of devices. Since microbolometer arrays require temperature stabilization, it is essential for the sensitive element of the bolometer to be thermally isolated. Heat loss by conduction or convection requires a medium, and if a vacuum package is used the loss will be minimal because the parasitic leakage path will be eliminated. Consequently, hermeticity requirements are very stringent especially if the devices have to be stored during a long period on ground. Indeed if a residual leak is present the pressure inside the package will tend to increase in time degrading the performance of the sensor. The standard seal tests, which should allow controlling the internal pressure inside the package, may not be sufficient and a reinforced survey of the bolometer performance may be necessary during the on-ground storage period. To maintain the vacuum integrity over long periods of time, vacuum getters may also be used. Their mechanical robustness toward vibrations and shocks has to be checked.

2) Radiation

Microbolometers arrays employ CMOS readout circuitry. They are sensitive to the same effects as the ones described for CMOS image sensors [19].

I) $LiNbO_3$ (LN) electro-optical modulator

1) General

Both z-cut and x-cut LN modulators, especially in optical intensity modulators, have an inherent problem of DC drift [20]. Due to the dielectric nature of the LN, a DC bias voltage applied to the device to adjust the optical output modulation state reduces gradually, resulting in a drift of optical output state. In order to keep the optical output stable, via a feedback loop, the DC bias is cumulatively applied to the device and ultimately will exceed the limitations of the system driver. In other words, the DC drift is a main cause of wear-out failure of LN devices and a reliability risk. Extrinsic sources of drift are due to changes of environmental conditions including, for example, temperature, humidity, or stress. This effect is related to long term charge transport in the device structure.

2) Radiation

Previous data has shown that in general, LN devices are not very susceptible to radiation induced effects (ionizing and displacement damage effects) [21].

J) Optical fibre [22]

1) General

Many of the materials used in the cabling of fibre optics for protection are either extruded onto the cable or are applied while the cable and coating are not at the same temperature. Thus, there are residual stresses in the cable layers after manufacturing. This alone does not cause a problem for the cable, but when it is subjected to thermal cycling (a fibre optic cable on a satellite may have to reliably function over a temperature range of -50°C up to 125°C), the cable can shrink to relieve some of the stress. This phenomenon can lead to the catastrophic failure of the cable assembly. To mitigate this effect the jacketed cable has to be “preconditioned” by thermal cycling before connectorization, to ensure that little or no shrinkage will occur in subsequent thermal cycles.

2) Radiation [23]

When optical fibres are exposed to ionizing radiation their optical absorption tends to increase. This Radiation Induced Absorption (RIA) results from colour centres generation due to the trapping of holes or electrons at pre-existing or radiation-induced defect sites. The presence of certain dopants in the core may lead to the generation of such colour centres. For instance the phosphorous, which is often incorporated as a co-dopant in Ge-doped preforms to lower their melting temperature, can lead to the creation of several types of phosphorous related colour centres. One of them, the P1 centre, features a strong absorption band around 1.6 µm showing that phosphorus should be avoided in fibres for telecom applications (C+L windows). In the same way, the aluminum which is used as a co-dopant in active erbium-doped fibres to facilitate the inclusion of erbium ions in the silica matrix and to reduce quenching effects (i.e. energy transfer between two neighbouring excited ions which reduces the population inversion) also induces structural defects in the host matrix, resulting in strong RIA levels after irradiation. An external action, like photobleaching or thermal annealing, may untrap the carriers for a later possible recombination. Usually, RIA is considerably more intense at shorter wavelengths but also strongly depends on temperature and dose rate. On that topic, it is worth noting that evidence for an ELDRS has been reported in certain types of erbium-doped fibres [24].

One can keep in mind that Pure-Silica Core (PSC) and Fluorine-doped (F-doped) optical fibres usually present the highest radiation tolerance.

V. AVAILABLE STANDARDS

At this stage it is valuable to have an overview of the available standards that may be used to evaluate or qualify a new optoelectronic device for a space application.

Because the European space industry needs stable sources and supply of components, the European Space Agency (ESA) has put in place the ESCC (European Space Components Coordination) system whose purpose is to provide strategically important EEE components for space applications [25]. It is based on a two steps approach: an evaluation phase and a qualification phase.

During the evaluation components are tested at their limits to destruction wherever possible. Indeed, the purpose of this phase is to stress the devices by simulating the space environment constraints (i.e. thermal cycles, vibrations, mechanical shocks, vacuum, and radiation) to point out typical failure modes and robustness margins.

At the end of the evaluation phase and before starting the qualification phase a Detail Specification (i.e. comprehensive data-sheet) and a Process Identification Document (PID) shall be written and frozen by the manufacturer. The PID is an instantaneous picture of the actual manufacturing flow and practices (travellers sheet specimen, detailed manufacturing flow-chart and related specifications, test/inspection procedures, list of materials, equipment, tools, list of subcontractors).
After the completion of the evaluation phase, the qualification testing phase could be conducted. In case of success the qualification is actually a general and long term authorization for using the qualified devices in space. The components required for qualification testing must be produced strictly in accordance with the PID. Qualification testing of the component must be in:

- Accordance with the requirements of the relevant ESCC Generic & Detail Specification.
- Successful completion of the testing phase results in listing on ESCC-QPL (Qualified part list).
- A qualification, once established, is valid up to 2 years.

Components of interest are found in the EPPL (European Preferred Parts List) which is a list of preferred and suitable components to be used by European manufacturers of spacecraft hardware and associated equipment. The EPPL is made up of two parts:

- Part 1: Components which are fully qualified or evaluated to recognized space standards giving full confidence for space usage.
- Part 2: Components for which the potential capability to satisfy space application requirements has been demonstrated but which have not yet reached the level of full confidence.

The EPPL is not a list of qualified components even if the ESCC qualified components are included.

For optoelectronic devices there is actually a very few number of ESCC documents available to support this evaluation/qualification approach and no optoelectronic device is available in the EPPL and QPL so far. The relevant ESCC documents are listed below:

Basic specifications (provide test methods, qualification methodology and general requirements applicable to all ESCC components)

- ESCC Basic Specification No. 25000: Electro-optical test methods for charge coupled devices.
- ESCC Basic Specification No. 2263010: Evaluation test programme for optical fibre connector sets.
- ESCC Basic Specification No. 23201: Evaluation test programme guidelines for laser diode modules.

Generic specifications (provide the requirements for screening, periodic or lot acceptance testing and qualification testing for individual families of components)

- ESCC Generic Specification No. 9020: Photosensitive charge coupled devices and CMOS imaging sensors with hermetic and non-hermetic packages.

Detail specifications (provide the performance requirements for individual or ranges of particular components (basically, detail specifications are comprehensive data sheets)

- ESCC Detail Specification No. 2139020: Terms Definitions Abbreviations Symbols and Units for Charge Coupled Devices.
- ESCC Detail Specification No. 9610/004: Charge coupled devices, silicon, photosensitive advanced inverted mode sensor, back illuminated, 740x514 image area, frame transfer based on CCD55-20.
- ESCC Detail Specification No. 5402/005: Light Emitting Diode Infrared GaAlAs Hermetic, based on type OP224.
- ESCC Detail Specification No. 9610/005: Charge Coupled Devices, Silicon, Photosensitive, Front Illuminated, 512 X 512 Image Area, Frame Transfer, based on Type CCD57-10.
- ESCC Detail Specification No. 5403/001 : Photodiode, based on Type AE9493.

Guidelines (provide recommendations for evaluation, screening, lot acceptance and validation)

- Laser diodes validation and lot acceptance testing guidelines (in draft)
- Evaluation test programme guidelines for cooled infrared detectors (in draft).

Figure 1 shows an example of qualification test programme applicable for CCD and CMOS image sensors.

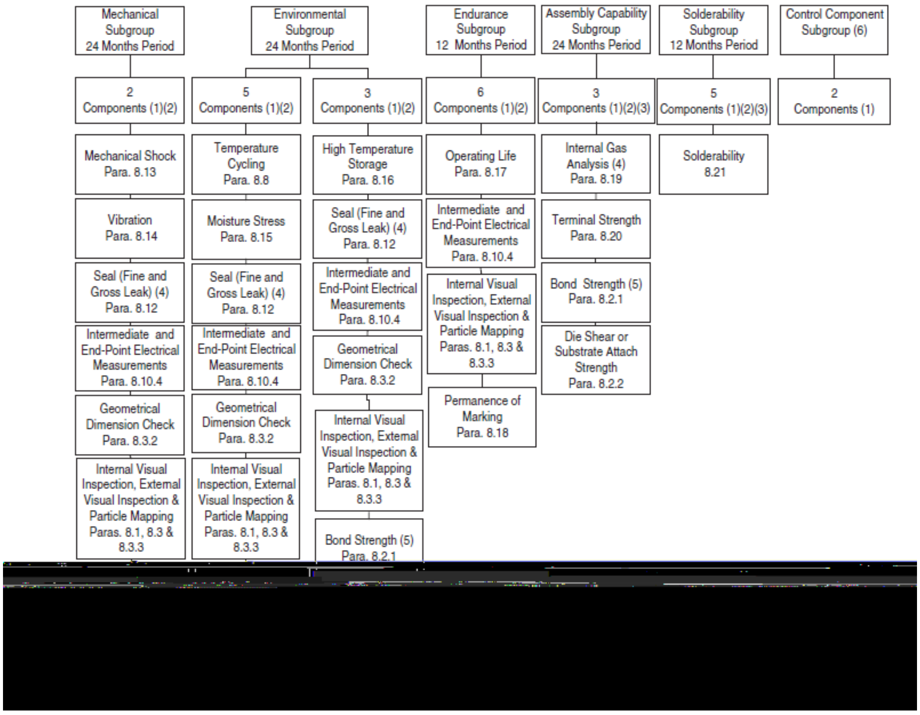

Fig. 1. Qualification test diagram for CCD and CMOS image sensors (from ESCC Generic Specification No. 9020).

Even if it is not specific to optoelectronic devices the ESCC Generic Specification No. 5000 “Discrete semiconductor components, hermetically sealed” may also have an interest for the qualification of certain kind of hermetic devices. One can also mention the following ESCC basic specifications that define the requirements related to radiation testing.

- ESCC Basic Specification No. 25100: Single Event Effects Test Method and Guidelines.
- ESCC Basic Specification No. 22900: Total Dose steady-state irradiation test method.

In addition to the ESCC standards, other documents created through the European Cooperation for Space Standardization (ECSS) can be useful for the design of procurement, screening and qualification plans. One can mention for instance the:

- ECSS-Q-ST-60-05: Generic procurement requirements for hybrid microcircuits.
- ECSS-E-20-08: Photovoltaic Assemblies and Components (solar cells).
- ECSS-Q-70-02: Thermal vacuum outgassing test for the screening of space materials (outgassing requirements for materials).

Even if they are not specific to optoelectronic devices, the military standards published by the US Department of Defense can also be useful to define evaluation and qualification tests programs. The most important test methods are listed below:

- MIL-STD-883: Test Method Standard for Microcircuits.
- MIL-STD-750: Test Method Standard for Semiconductors.

More relevant reliability standards can also be used for optoelectronic devices. In this domain the Telcordia standards could be valuably used for the test of the optoelectronic devices also used on-ground for telecommunication applications. Some useful Telcordia specifications are given below:

- Telcordia-GR-468-CORE: Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment.
- Telcordia GR-20: Generic Requirements for Optical Fibre and Optical Fibre Cable.
- Telcordia GR-1221: Generic Reliability Assurance Requirements for Passive Optical Components.

Other standards such as the ones prepared by the Telecommunications Industry Association (TIA), the International Electrotechnical Commission (IEC) and the JEDEC Solid State Technology Association may also have an interest for the test and the procurement of optoelectronic devices.

Of course these last specifications have to be customized to take into account some specificities of the space environment (i.e. vacuum, radiations, high mechanical shocks, etc.).

Finally, when no normative literature is available, a more customized qualification strategy as to be used. It is presented in the next section.

VI. DESIGNING A CUSTOMIZED QUALIFICATION (VALIDATION) PLAN

As shown in Fig. 1 the qualification of optoelectronic devices usually requires performing several accelerated tests to demonstrate that the devices are reliable enough to resist to the different phases of their life: on-ground storage, launch and operational life. Indeed, time constraints dictate that we cannot duplicate intended life, but typically have to accelerate the test time to a reasonable value.

We have seen in Section V that the design of these tests can rely on standards (e.g. ESCC, Telcordia, MIL-STD) but, when the standardized tests are suspected to be unadapted to the device to qualify or when the environments to cover for a given mission are out of the scope of the standards, it can also be desirable to take the robustness limit of the device into account and to tailor a test sequence to the life profile of the component.

The design of customized accelerated tests is a real challenge for optoelectronics especially for space applications. Indeed, the cost optimization policy applied on space programs has a direct impact on the number of devices available to design a reliability test and also on the duration of the test itself. A short test with a little number of devices will be cost effective but a meaningful conclusion will be hard to obtain in the end. At the opposite, if the sample of devices is too large, information obtained through the test may be beyond the needs leading to extra costs. It is thus of primary interest to have in hand a comprehensive methodology to demonstrate that a minimum reliability target is reached after a test. This kind of methodology is usually based on the realization of accelerated tests of fixed duration carried out on several devices under a constant stress level. Based on that, the main issue for the reliability engineer is to optimize the acceleration factor, the test duration and the number of devices under test with respect to the reliability objective [26].

It is important to have in mind that the purpose of such tests is not to determine the actual reliability of a device (this kind of exercise would require few tens to few hundreds of devices) but rather to ensure that the selected devices is compliant with respect to the mission reliability specification.

Finally, it is worth noting that for the procurement of unqualified components the term “validation” can also be used instead of “qualification” taking into account that this last term is usually reserved to formal ESCC qualifications (see Section V).

A. Recall on accelerated testing

The assumption made is that tests can be carried out under conditions of higher than usual stress, and the effects of this stress can be represented by an acceleration factor AF. This factor is an unitless number that relates a product's life at an accelerated stress level to the life at the use (or mission) stress level. It is defined by the following relationship:

$$R_{test}(t) = R_{mission}(AF \times t) \qquad (1)$$

where R_{test} is the device reliability under stress (accelerated test) and $R_{mission}$ the device reliability under mission condition The reliability law could be either exponential, Weibull or lognormal.

One of the most general form for the acceleration factor is given below:

$$AF = \left(\frac{S_{test}}{S_{mission}} \right)^{n} e^{\frac{E_a}{k}\left(\frac{1}{T_{mission}} - \frac{1}{T_{test}} \right)} \qquad (2)$$

where E_a is the activation energy related to the main failure mechanisms, $T_{mission}$ and T_{test} are the temperature in nominal and accelerated conditions respectively. In addition to the effect of the temperature the model allows to take into account a second stress factor, S that can be indifferently bias current, voltage, optical power, relative humidity,… n is the acceleration exponent related to this factor of stress.

Even if they are not specific to optoelectronic parts some acceleration models commonly used to design humidity and thermal cycling tests are given in Appendix A. The reader can also consult the 2009 FIDES guideline “Reliability Methodology for Electronic Systems” that gives more details on some useful acceleration models.

It is important noting that testing at high levels of acceleration, far away from the use condition may lead to the activation of non-relevant failure modes (e.g. the test temperature shall be kept below the glass temperature of adhesives to evaluate glued assemblies). This has to be accounted for during the design of the tests.

B. Acceleration model parameters

Before setting the accelerated test conditions it is necessary:

- to identify the potential failure mode to address during the test,
- to select the parameters of the acceleration model: activation energy, acceleration exponent in current, bias, etc.

This information shall be provided by the manufacturer on the basis of reliability test results performed on devices similar to the ones to be qualified. If experimental data are not available the activation energies given in Table VI can be used to design the tests.

Table VI. Recommended activation energy values for random and wear-out failure modes.

Device	**Type of failure**	**Activation energy**
Laser diodes	random (operating life)	Ea=0.35 eV (Telcordia-GR-468-CORE)
	wear-out (operating life)	Ea=0.4 eV (Telcordia-GR-468-CORE)
Light emitting diodes	random (operating life)	Ea=0.35 eV (Telcordia-GR-468-CORE) Ea=0.4 eV (2009 FIDES guideline)
	wear-out (operating life)	Ea=0.5 eV (Telcordia-GR-468-CORE)
Detectors	random (operating life)	Ea=0.35 eV (Telcordia-GR-468-CORE)
	wear-out (operating life)	Ea=0.7 eV (Telcordia-GR-468-CORE)
$LiNbO_3$ electro-optical modulators	wear-out (operating life – DC drift)	Ea=1.4 eV [20]
	random (operating life)	Ea=0.7 eV (Telcordia-GR-468-CORE)
	wear-out (operating life)	
HgCdTe detectors	wear-out (high temperature storage)	Ea=0.76 eV [15]
	wear-out (low temperature operating life – hot carrier injection in ROIC)	Ea=-0.2 to -0.1 eV (JEDEC JEP122C)
Optocouplers	random (operating life)	Ea=0.4 eV (2009 FIDES guideline)

It is worth noting that for silicon-based devices and in the absence of a reliable model, an activation energy of 0.7 eV is generally assumed as an average value for random failures occurring during the operating life.

It is important emphasizing that it is the responsibility of the technology owner to identify for each test the most probable failure mode and to demonstrate that the acceleration model used for the design of this test is truly conservative.

C. How to design a reliability demonstration plan?

An accelerated reliability test is specified by the following parameters:

- N_{test} : number of devices under test
- d_{test} : duration of the test

- AF : acceleration factor

The design of the plan consists in choosing the correct values for these parameters to demonstrate that a certain reliability target is reached, under use condition, at the end of a mission of duration $d_{mission}$. It is worth noting that this reliability target has to be defined for all the qualification tests (i.e. operating life test, thermal cycling test, moisture test, etc.). Indeed, the overall reliability objective $R_{mission}^{overall}$ is defined as the product of individual reliability targets each of them being related to a specific qualification test, we have:

$$R_{mission}^{operating\_life} \times R_{mission}^{moisture} \times R_{mission}^{thermal\_cyles} \times ... = R_{mission}^{overall} \qquad (3)$$

To determine these reliability targets the simplest way to proceed is to assign to each test a common value $R_{mission}{}^{\frac{1}{n}}$ (equal allocation technique) where n is the number of qualification tests. For instance, if three tests are performed (e.g. operating life, moisture, thermal cycling), and if the goal is to demonstrate an overall device reliability of 0.9 at the end of the mission, the target to demonstrate for each test will be $0.9^{\frac{1}{3}} = 0.965$. To simplify the notation, in the following the reliability target for a single test will be noted $R_{mission}$.

To be largely used, the statistical approach to follow for sizing reliability demonstration plans should be as simple and intelligible as possible with a minimum mathematical formalism. In this section we propose a set of simple equations based on the use of the Weibull function statistic that can be used to design zero failure demonstration plans (see Appendix B).

The first proposed equation allows the calculation of the number of devices to put under test to demonstrate, at a confidence level γ, that a minimum reliability target $R_{mission}$ is reached at the end of the mission.

$$N_{test} = \left\lceil \frac{\ln(1-\gamma)}{\ln\left(R_{mission}^{\left(\frac{AFd_{test}}{d_{mission}}\right)^{\beta}} \right)} \right\rceil \qquad (4)$$

where β is the shape factor of the Weibull function.

This relationship can be used either for wear-out failures (β >1) or for random failures (β =1). For wear-out failure modes it is usually the manufacturer responsibility to provide the relevant value of β for the device to qualify. However, it is fair to mention that it is not always obvious to obtain, before starting a test, a consolidated value for β or even to know if the failure mode to address is a wear-out or a random mode. It is worth noting that depending on the value of β the number of devices to put under test can be very different. For instance using Eq. (4) with γ =0.6, AF =50, d_{test} =1500 h and $d_{mission}$ =15 years one can calculate that 27 devices are needed to demonstrate $R_{mission}$ =0.9 assuming a wear-out mechanism with β =2 while 47 devices are requested if β =3 and only 16 devices if a random failure mode is assumed. Because the statistical treatment of random failures is easier than the one related to wear-out failures, it can be tempting to design the test based on a “random failure” hypothesis. However, if after the test a wear-out mode is identified, the number of tested devices may not be sufficient to demonstrate the reliability target. Thus, it can be of interest to determine the condition to respect to ensure that the most demanding test in term of number of devices is obtained under the “random failure” assumption ($N_{test}^{random} > N_{test}^{wear\_out}$).

Using Eq. (4) one can easily demonstrate that this condition is given by:

$$AFd_{test} > d_{mission} \qquad (5)$$

If Eq. (5) is satisfied and even if a wear-out mechanism is observed, the number of device under test will be sufficient to demonstrate the reliability target whatever the value of β.

In certain cases it could also be valuable to express the mission reliability target in terms of failure rate $\lambda_{mission}$. Equation (6) is equivalent to Eq. (4) but the reliability objective is now interpreted in term of failure rate (in FIT).

$$N_{test} = \left\lceil \frac{-10^9 \beta \ln(1-\gamma)}{\lambda_{mission} d_{mission} \left(\frac{AF d_{test}}{d_{mission}} \right)^{\beta}} \right\rceil \tag{6}$$

D. Example of test design

The objective is to design an operating life test for a lithium niobate electro-optical modulator exhibiting a wear-out failure mode (DC drift) in order to demonstrate a reliability target of 0.99 for a mission duration of 15 years at a 60% confidence level. One supposes that the temperature is the only acceleration parameter. The activation energy recommended by the manufacturer is 1.4 eV but no value for β is available. The temperature under use condition is 20°C and the maximum operating temperature is 85°C. The other constraint concerns the duration of the test that cannot exceed 2000 h.

Problem: Specify the operating life test conditions to demonstrate the reliability target.

Solution: We have seen in the previous section that if the condition given by Eq. (5) is fulfilled, Eq. (4) with β =1 allows to calculate a worst case number of devices to put under test to demonstrate the required reliability. If the test duration is set to 2000 h the remaining degrees of freedom to design the test are the temperature and the number of devices. The relationship between these two parameters (using Eq. (4) and Eq. (5)) is shown in Fig. 1.

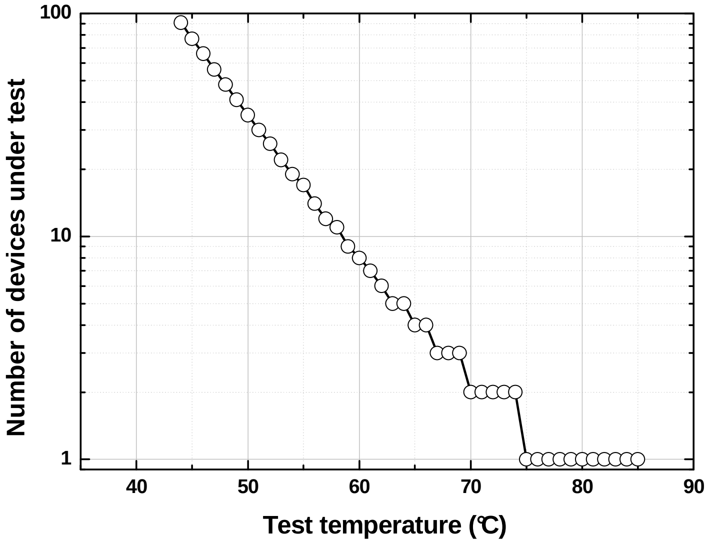

Fig. 2. Number of devices under test versus test temperature to achieve à 0.99 reliability target à 60% CL. Test duration is set to 2000 h.

The goal is now to find a reasonable compromise regarding the choice of these two parameters, for instance a 85°C test on one device will not be meaningful and a 45°C test on 77 devices will be too expensive. One can propose an intermediate solution with, for instance, 8 devices tested at 60°C.

To conclude, one has to have in mind that the quantitative evaluation of the reliability makes sense only if consolidated or truly conservative acceleration models are available. It is the customer responsibility to analyze the validity of the reliability data provided by the manufacturer.

VII. GENERIC RECOMMENDATIONS TO SECURE THE PROCUREMENT OF FLIGTH MODELS

To ensure the success of the qualification of a new device, preliminary component quality engineering tasks have to be undertaken to secure the procurement of the component to qualify. In this section we summarized some important points to have in mind when procuring optoelectronic devices for flight in the framework of a specific project.

- Define your needs in terms of performance, environmental and reliability constraints (mission duration, operating temperature, radiation levels, end-of-life reliability target, etc.).
- Perform a survey to identify a short list of device references.
- As far as possible identify an independent test house to perform the reliability tests.
- Procure a set of devices from 2 different manufacturers, same reference (or similar in terms of technology) as the one to qualify.
- Check for the metrology of the characterization test benches to be used for the evaluation/qualification phases. Use at least two control devices to check for the repeatability/reproducibility of the measurements during these phases.
- Perform an extended performance characterization in the temperature range to be covered during the mission (+ margins).
- Perform a full constructional analysis on part of the procured devices (i.e. external visual inspection, seal test, Residual Gas Analysis, internal visual inspection, internal element shear test, materials analysis (outgassing), fibre pull (if applicable), micro-section, …).
- Select the best reference among the two tested ones.
- If necessary sign a Non-Disclosure Agreement with the selected manufacturer.
- Visit the manufacturer. At minima, the following points shall be reviewed during this visit:
  - ➢ General organization of the company
    - o Management Organization
    - o Quality Assurance System and Organization
    - o Quality manual presentation
  - ➢ Manufacturing
    - o Manufacturing line overview
      - ▪ Available technologies
      - ▪ Past, current and future activities (markets, technology perenity)
      - ▪ Facilities
      - ▪ Production capacity, manufacturing time cycles, yield
      - ▪ High-rel heritage (space, defence, telecommunication)
    - o Environment
      - ▪ Environmental control (humidity, temperature, …)
      - ▪ ESD, EOS control
      - ▪ Clean concept (particle count, contamination and associated specifications)
    - o People
      - ▪ Operators training and certification
      - ▪ Internal audits outcomes
      - ▪ Subcontractors follow-up policy

  - Machines
    - Main production equipment (manufacturing, test and inspection, list of critical equipment)
    - Equipment qualification process
  - Materials
    - Raw material incoming controls
    - Raw material storage
    - Segregation of damage items
    - Review of the Declared Material list
  - Methods
    - PID or manufacturing flow-chart presentation
    - Review of the Declared Process list
    - Process qualification methodology
    - Lot control registers, traveller sheet specimens
    - Traceability management
    - In-line and off-line quality control (QA gates)
    - Statistical Process Control or Advanced Process Control (process control, equipment control (Fault Detection and Classification) , Run-to-Run control loops, control charts, capability studies, yields analysis, alarm rules, in and off-line control points and reporting, Out of Control Action Plan (OCAP) management)
    - Metrology (Gauge R&R)
    - Process change management, list of authorized reworks and associated qualification strategy
    - Non-conformance management
    - Screening (facilities, test conditions, selection criteria)
    - Maverick lot (or outliers) detection strategy and segregation
  - Reliability
    - Early Failure Rates metrics
    - Technology qualification methodology and results
    - In-line and off-line reliability indicators follow-up
    - Operational reliability figures (acceleration models, wear-out and random failure rates)
    - Qualification/evaluation results on devices (ESCC, Telcordia, ...)
  - Outcomes of the characterization phase (customer)
    - Performance
    - Constructional analysis

- Make a synthesis of this visit and establish a list of the points to be improved by the manufacturer before procuring a lot for a first evaluation. Check that all the actions are closed before engaging the next step.

- Procure a set of evaluation models based on a preliminary procurement specification and conduct a test program to identify the main failure modes. Identify the relevant set of electro-optical characterizations to perform to track any reliability degradation. As far as possible use the available standards to define the evaluation test conditions (ESCC, MIL, Telcordia, etc.).

- Carefully analyse the evaluation results, if any, identify possible paths of fabrication improvements before starting the qualification phase. Be sure that these modifications will not have a negative impact on the quality of the final product (perform a risk analysis with the manufacturer).

- Prepare the procurement specification applicable for flight models (performances requirements, lot definition, visual inspection criteria, screening conditions and rejection criteria, material list, PID reference, list of requested documentation, etc.).

- Procure a single lot of devices (lot unicity at chip and assembly level shall be warranty).

- Perform a 100 % visual inspection of the devices before sealing (pre-cap inspection) or ask for the manufacturer to do it, insist to have pictures of the opened devices. UV inspection can be performed to increase the detection level of contamination (particle, organic compounds) which can be of high interest for detectors. For each device a visual inspection file shall be prepared with pictures of the main salient points.

- Perform screening or up-screening tests on the whole set of procured devices. The goal is to discard devices presenting early failure modes. Thermal cycling, high temperature storage, high temperature burn-in test, hermeticity test, Particle Induced Noise Detection (PIND) test may be performed in the screening sequence. The evaluation outcomes can be used to determine relevant conditions for screening tests.

- Based on the screening test results and on the pre-cap inspection proceed to the device affectation (rejected devices, qualification models, flight models).

- Perform a full constructional analysis as soon as possible on the flight model batch to detect any lot related anomaly.

- Check for device storage conditions (dry atmosphere).

- Design the qualification test plan based on the mission environmental constraint requirements and the available standards. If it is not possible use the acceleration models provided by the manufacturer or those proposed in Table III. Define the accelerated test conditions following the methodology exposed in Section VI.C. Take a margin on the test duration with respect to the mission requirements to account for device-to-device dispersion and acceleration model uncertainties.

- Define the qualification success criteria taking into account the loss of performance that can be accepted at the end of the mission.

- Perform the qualification tests, analyse the results.

- Review all the available documentation (test reports).

- Validate the packing and dispatch procedure with the manufacturer. The transportation box shall prevent the device from any mechanical or contamination injury.

This list is obviously not exhaustive and shall be adapted taking account of the device class (COTS, high-rel, customized).

VIII. CONCLUSION

The field of applications for optoelectronic devices in space is immense and its full potential is yet to be fully unleashed. Basically the main critical points that still limit their use are the lack of space standards and qualification heritage. A standardization effort is, therefore, necessary in the next future. Even if the wide range of technologies to address is clearly a limiting factor for the emergence of new standards, it is important to have in mind that space standards are not the only documents available to define qualification test plans. Standards used in other sectors of activity (e.g. telecommunication, defence) can also be useful to address the qualification of certain kind of components and customized validation approaches are always possible. All these alternative strategies can be used as starting points to design qualification test plans and to initiate the drafting of space standards. It is also noteworthy to mention that the qualification is actually the final outcome of a set of component engineering tasks that have to be correctly performed first (i.e. component selection, procurement, characterization, evaluation, screening, etc.). Taking into account our existing heritage and lessons learnt on these devices, some risk mitigation strategies to secure the procurement and the qualification of flight models have been presented in this paper. Finally, considering the impressive deployment of optoelectronics in several industrial sectors, one can also expect in a near future to take advantage of the possible synergies between these sectors to promote the emergence of new reliability standards and to consolidate the qualification heritage on new promising devices.

ACKNOWLEDGMENT

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APPENDIX A - USEFUL ACCELERATION MODELS

A. *Moisture test*

a. *Hallberg-Peck model[27]*

$$AF = \left(\frac{RH_{test}}{RH_{mission}} \right)^{3} e^{\frac{0.9}{8.62\times10^{-5}}\left(\frac{1}{T_{mission}} - \frac{1}{T_{test}} \right)} \quad \text{(A-1)}$$

where $RH_{mission}$ and RH_{test} are the relative humidity level (in %) under mission and test conditions respectively. In the same way, $T_{mission}$ and T_{test} are the temperature under mission and test conditions respectively.

The most common values used for the relative humidity exponent in (A-1) are between 2.7 and 3, but according to the 2009 FIDES Guideline several trials have shown that a power of 4.4 is more realistic for non-operating conditions. An exponent equals to 3 is thus rather conservative.

b. *Sinnadurai model[28]*

$$AF = e^{\frac{0.6}{8.62\times10^{-5}}\left(\frac{1}{T_{mission}} - \frac{1}{T_{test}} \right) - 0.00044\left(RH_{mission}{}^{2} - RH_{test}{}^{2} \right)} \quad \text{(A-2)}$$

where $RH_{mission}$ and RH_{test} are the relative humidity level (in %) under mission and test conditions respectively. In the same way, $T_{mission}$ and T_{test} are the temperature under mission and test conditions respectively.

Because the validity of these models is often debated, one can recommend using low acceleration levels to avoid failures unrelated to mission operation conditions.

If the on-ground period storage if sufficiently short, one can also propose to reproduce the moisture/temperature conditions actually seen by the device during this period with an appropriate margin regarding the test duration. Anyway, the best way to avoid moisture issue is to store the devices in a dry environment (either nitrogen of dry air).

B. *Thermal cycling*

a. *Coffin-Manson model[29]*

$$AF = \frac{N_{test}}{N_{mission}} = \left(\frac{\Delta T_{test}}{\Delta T_{mission}} \right)^{m} \quad \text{(A-3)}$$

where $N_{mission}$ and N_{test} are the number of cycles to failure under mission and test conditions respectively, $\Delta T_{mission}$ and ΔT_{test} are the thermal cycles amplitude under mission and test conditions respectively. m is a constant, typical value for a given failure mechanism or derived from empirical data.

Values for m for common materials are:

• ductile metal, solder:	1-3
• hard metal alloys / intermetallics (e.g. Al-Au):	3-5

- brittle fracture (e.g. Si & dielectrics : SiO_2, Si_3N_4): 6-9

For package related failure, the 2009 FIDES guideline recommend using an m exponent equals to 4.

b. Norris-Landzberg model (solder joint low-cycle fatigue)[30]

$$AF = \frac{N_{test}}{N_{mission}} = \left(\frac{\Delta T_{test}}{\Delta T_{mission}}\right)^2 \left(\frac{f_{mission}}{f_{test}}\right)^{\frac{1}{3}} e^{1414\left(\frac{1}{T_{mission}^{\max}} - \frac{1}{T_{test}^{\max}}\right)} \qquad \text{(A-4)}$$

where $N_{mission}$ and N_{test} are the number of cycles to failure under mission and test conditions respectively, $\Delta T_{mission}$ and ΔT_{test} are the thermal cycles amplitude under mission and test conditions respectively. $f_{mission}$ and f_{test} are the cycling frequency under mission and test conditions respectively, $T_{mission}^{\max}$ and $T_{test}^{\max}$ are the maximum temperature under mission and test conditions respectively.
The activation energy, temperature and frequency exponents in Eq. (A-4) were derived from test results obtained on SnPb eutectic solder. Care should be taken to use these parameters for other kind of solders.

APPENDIX B – ZERO FAILURE DEMONSTRATION PLAN STATISTICS

A. Weibull law

The Weibull reliability function is defined by

$$R(t,\eta,\beta) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad \text{(B-1)}$$

where η and β are the scale and the shape factors respectively.

The Weibull law is versatile and can be used to represent the three regions of the classic reliability "bathtub" curve: the decreasing failure rate associated with infant mortality, the constant failure rate of useful life, and the wear-out period of increasing failure rate.

Using this law, the MTTF is given by

$$MTTF = \eta\Gamma\left(1 + \frac{1}{\beta}\right) \qquad \text{(B-2)}$$

where Γ is the Gamma function.

Considering Eq. (1) of §VI.A, one can observe that the acceleration factor has an effect on the scale factor and not on the shape factor. We have

$$\begin{aligned} \eta_{mission} &= AF \times \eta_{test} \\ MTTF_{mission} &= AF \times MTTF_{test} \end{aligned} \qquad \text{(B-3)}$$

It is worth noting that when the shape factor β of the Weibull distribution is equal to 1 the Weibull reduces to the exponential model.

$$R(t) = e^{-\lambda t} \qquad \text{(B-4)}$$

where λ is the failure rate. It is directly related to the scale factor of the Weibull function $\lambda = \frac{1}{\eta}$.

Consequently the Weibull function can be used to describe either wear-out failures ($\beta > 1$) or random failures ($\beta = 1$).

B. Zero-failure demonstration plan

A zero failure plan assumes that at the end of a test of duration d_{test} no failure should occur. With N_{test} devices under test, the demonstrated reliability level R_{test} at the end of the test, at a confidence level γ, is given by:

$$1-\gamma = R_{test}^{\;N_{test}} \qquad \text{(B-5)}$$

This also means that the probability of passing this test with no failure is $1-\gamma$ only if the reliability of the system is less than or equal to R_{test} (i.e. the reliability of the device is greater than R_{test} with a confidence level equals to γ).

Taking into account Eq. (B-3), we have

$$AF = \frac{\eta_{mission}}{\eta_{test}} \qquad \text{(B-6)}$$

where $\eta_{mission}$ and η_{test} are the Weibull function shape factors in operational (“mission”) and test conditions.

Using Eq. (B-1) the scale factor in “mission” condition is given by:

$$\eta_{mission} = \frac{-d_{mission}}{\left[\ln\left(R_{mission}\right)\right]^{\frac{1}{\beta}}} \qquad \text{(B-7)}$$

Mixing Eq. (B-6) and (B-7) we obtain:

$$\eta_{test} = \frac{d_{mission}}{AF\left[\ln\left(\frac{1}{R_{mission}}\right)\right]^{\frac{1}{\beta}}} \qquad \text{(B-8)}$$

It is now possible to relate R_{test} to $R_{mission}$, we have:

$$R_{test} = e^{-\left[\frac{d_{test}AF\left[\ln\left(\frac{1}{R_{mission}}\right)\right]^{\frac{1}{\beta}}}{d_{mission}}\right]^{\beta}} \qquad \text{(B-9)}$$

$$R_{test} = R_{mission}^{\left(\frac{AFd_{test}}{d_{mission}}\right)^{\beta}}$$

Using (B-9) and (B-5) we obtain a relationship that gives the number of devices to put in test to demonstrate (if no failure occur) a certain reliability $R_{mission}$ of the mission.

$$N_{test} = \left\lceil \frac{\ln(1-\gamma)}{\ln\left(R_{mission}^{\left(\frac{AFd_{test}}{d_{mission}}\right)^{\beta}} \right)} \right\rceil \qquad \text{(B-10)}$$

The notation $\lceil \ \rceil$ corresponds to the ceiling function.
In certain cases it could be valuable to express the reliability target in terms of failure rate. For a Weibull law, the failure rate (in FIT) at the end of the mission is given by:

$$\lambda_{mission} = \frac{10^9 \beta}{\eta_{mission}} \left(\frac{d_{mission}}{\eta_{mission}} \right)^{\beta-1} \qquad \text{(B-11)}$$

The scale factor is thus given by

$$\eta_{mission} = \left[\frac{10^9 \beta d_{mission}{}^{\beta-1}}{\lambda_{mission}} \right]^{\frac{1}{\beta}} \qquad \text{(B-12)}$$

and consequently we have

$$R_{mission} = e^{-\frac{\lambda_{mission} d_{mission}}{10^9 \beta}} \qquad \text{(B-13)}$$

Hence Eq. (B-10) becomes

$$N_{test} = \left\lceil \frac{-10^9 \beta \ln(1-\gamma)}{\lambda_{mission} d_{mission} \left(\frac{AFd_{test}}{d_{mission}} \right)^{\beta}} \right\rceil \qquad \text{(B-14)}$$

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