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TECHNICAL REPORT

Fibre optic active components and devices – Reliability standards –
Part 2: Laser module degradation

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FIBRE OPTIC ACTIVE COMPONENTS AND DEVICES –
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FOREWORD

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IEC 61751-2, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices of IEC technical committee 86: Fibre optics, based on the Standard IEC 61751 prepared by subcommittee 47C: Optoelectronic, display and imaging devices, of IEC technical committee 47: Semiconductor devices.

The field of this technical report will henceforth be placed under the responsibility of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/833/DTR	86C/847/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of IEC 62752 series, under the general title *Fibre optic active components and devices – Reliability standards*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

The laser modules covered by this technical report are purchased by a system supplier (SS) to be inserted in equipments which in turn are supplied/sold to a system operator (SO), for example, a telecommunications company (see definitions in Clause 3).

For the system operator to act as an informed buyer, knowledge of the potential risks posed by the use of critical components is required.

Optoelectronic component technology is continuing to develop. Consequently, during product development phases, many failure mechanisms in laser modules have been identified. These failure mechanisms, if undetected, could result in very short laser lifetime in system use.

FIBRE OPTIC ACTIVE COMPONENTS AND DEVICES – RELIABILITY STANDARDS –

Part 2: Laser module degradation

1 Scope

This technical report deals with reliability assessment of laser modules used for telecommunication guidance on testing, use of failure criteria and reliability predictions is provided.

This technical report provides guidance on:

– the testing that a system supplier should ensure is in a place prior to procurement of a laser module from a laser module manufacturer;

– a range of activities expected of a system supplier to verify a laser module manufacturer's reliability claims.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60068-2-1: *Environmental testing – Part 2-1: Tests. Tests A: Cold*

IEC 60068-2-14: *Environmental testing – Part 2-14: Tests. Test N: Change of temperature*

IEC 60747-1: *Semiconductor devices Part 1: General*

IEC 60749-1: *Semiconductor devices – Mechanical and climatic test methods Part 1: General*

ISO 9000: *Quality management systems – Fundamentals and vocabulary*

MIL-STD-883G: *Test method standard, microcircuits*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
laser module
packaged assembly containing a laser diode with/without photodiode

NOTE The module may also include a cooler and temperature sensor to enable laser temperature to be controlled and monitored. The optical output is normally via an optical fibre pigtail.

3.2
submount
substrate upon which a laser is mounted for assembly into the subcarrier

3.3
subcarrier
substrate upon which a laser diode and/or photodiode may be mounted for assembly into the laser module

NOTE Components on submounts are also subject to qualification testing.

3.4
laser module manufacturer (LMM)
manufacturer of laser modules who provides devices meeting the requirements of the relevant detail specification (DS) and the customer's reliability requirements

3.5
system supplier (SS)
manufacturer of telecommunications/data transmission equipment containing optoelectronic semiconductor lasers, i.e. laser module customer

3.6
system operator (SO)
network operator of telecommunications/data transmission equipment containing optoelectronic semiconductor lasers in the transmission path

NOTE The system may also be part of other more extensive systems, for example telecommunications, rail, road vehicles, aerospace or weapons.

3.7
capability qualifying components (CQC)
components selected to represent critical stages of the process and limiting or boundary characteristics of mechanical and electro-optic design.

4 Laser diode and laser module failure mechanisms

4.1 General

Much of the published laser reliability data (and also reliability data from laser manufacturers) is from the service life testing of laser chips bonded onto submounts or special headers. The results usually show increasing threshold or operating currents leading to eventual failure. However, other laser characteristics can also degrade and should be monitored during life testing, for example, light-output spectrum.

Practical laser transmitters, as used in fibre transmission systems, contain several other important piece parts and components that are also vulnerable to failure. For example, reduced fibre output power, due to instability in the fibre to laser chip alignment, is a significant failure mechanism in laser modules. Less information is available on the stability of the output from receptacle packages.

Various kinds of laser module have been used in fibre transmission systems. An example structure for laser module is shown in Figure 1 in which the laser chip is mounted on a submount within a dual-in-line package with a fibre pigtail. The temperature of the laser submount is often controlled using a TEC, with a thermistor as a temperature sensor. Some distributed feedback laser modules for use in high bit-rate optical fibre systems also contain optical isolators to prevent reflected optical power from adversely affecting the laser operation. Advanced modules containing integrated circuits for some control functions are also available.

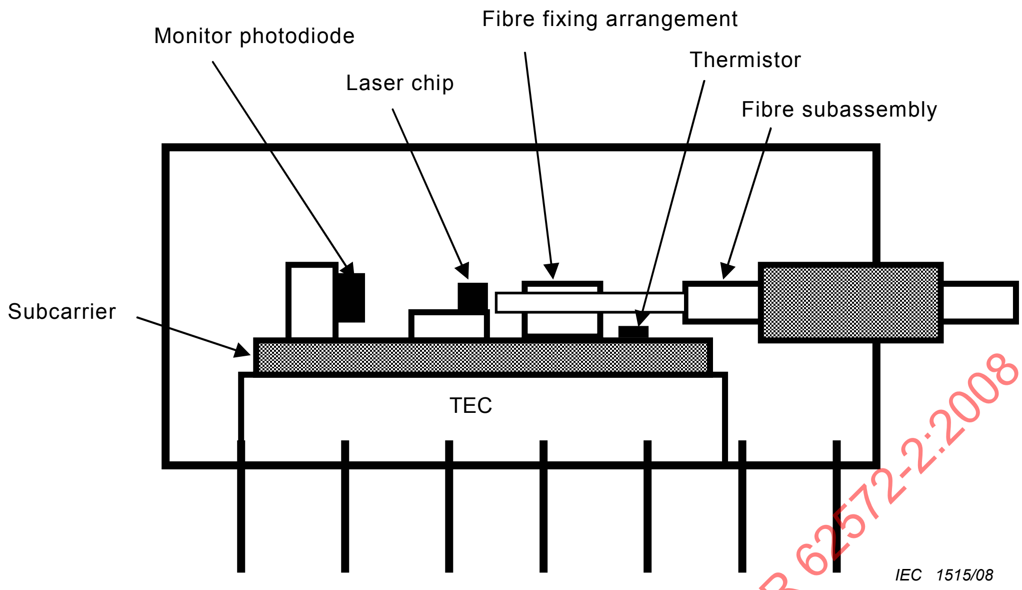

Figure 1 – An example of cross-section for laser module

4.2 Description of the main failure mechanisms which affect laser diodes and laser modules

4.2.1 Laser diodes

Two typical cross-sections through a ridge waveguide and a buried heterostructure type InGaAsP/InP laser are shown in Figure 2. A wide range of failure mechanisms has been identified in laser diodes associated with material defects in the semiconductor material, facet degradation, both p and n-side metallizations and with the bond to the heatsink. These failure mechanisms are discussed in more detail below.

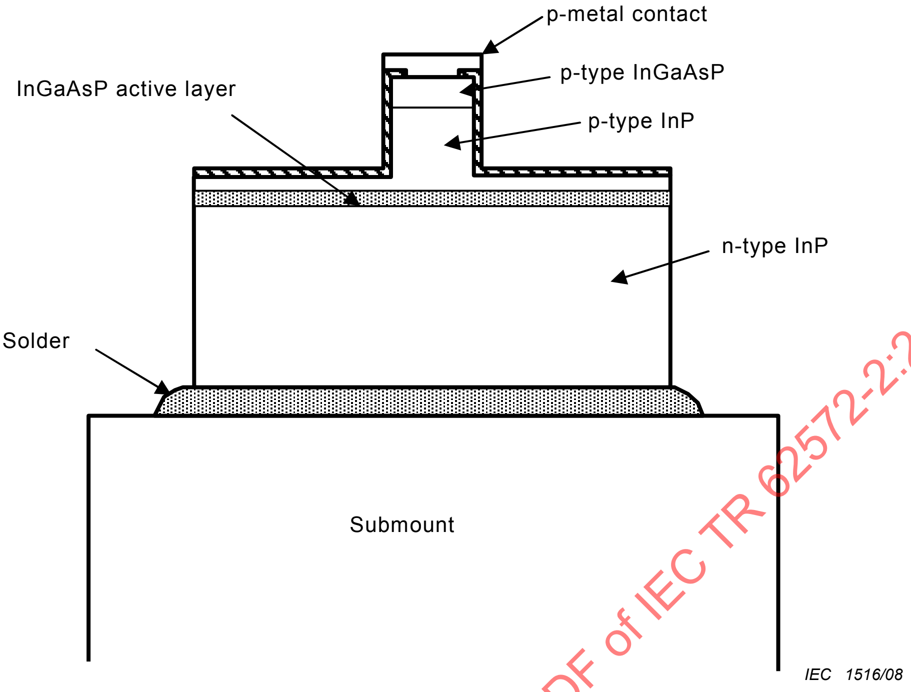

Figure 2a – Ridge waveguide type

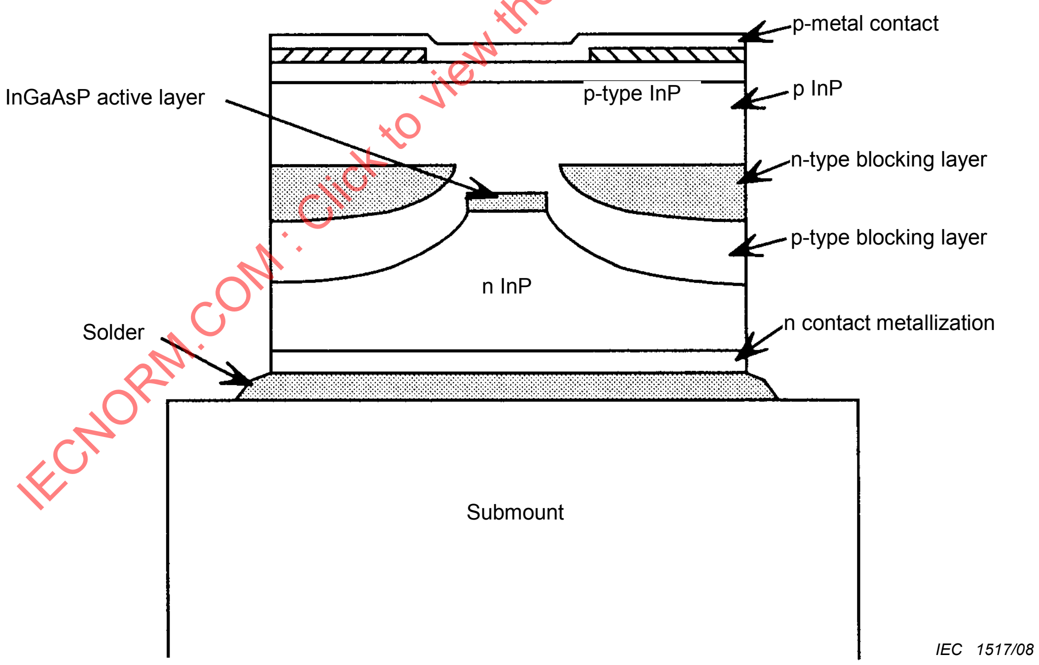

Figure 2b – Buried heterostructure type

Figure 2 – Cross-section through a typical heterostructure laser (bonded section side up)

a) Degradation due to the growth of material defects

A common cause of rapid failure in early lasers was the growth of dark line defects (DLDs) and dark spot defects (DSDs) – network of dislocations leading to localized regions of strong non-radiative recombination, and hence increased threshold currents or even complete loss of light output. The defects could be observed as dark lines or spots when the electroluminescence topograph of the light emitting region through the substrate of laser is monitored and the cathode-luminescence or electron-beam-induced current (EBIC) topograph is observed in a scanning-electron-microscope. They were a particular problem in early GaAlAs/GaAs (850 nm) lasers, in which they were associated with defects threading up through the epitaxial layers from the substrate. Networks and microloops of dislocation grow due to non-radiative-recombination-enhanced defect motion. Another type of defect growth is accelerated by mechanical stress within the laser, for example caused by bonding. The difference of the two types of dislocation can be distinguished by the growth direction, <100> equivalent direction: non-radiative recombination and <110> equivalent direction: mechanical stress. Here, <100> and <110> indicates the crystal axes of the cubic semiconductor crystal. Penetration of copper from the laser submount has also been seen to contribute to the growth of arrays of dark spot defects when copper is used without any cover metal. In 1 300-nm- and 1 550-nm-band lasers fabricated from the InGaAsP/InP material system, dislocation networks mainly grow as a result of mechanical stress introduced by thermal expansion mismatch between semiconductor and electrode metal, between laser chip and heat sink, etc. Schematic diagrams of DSD and DLDs are shown in Figure 3.

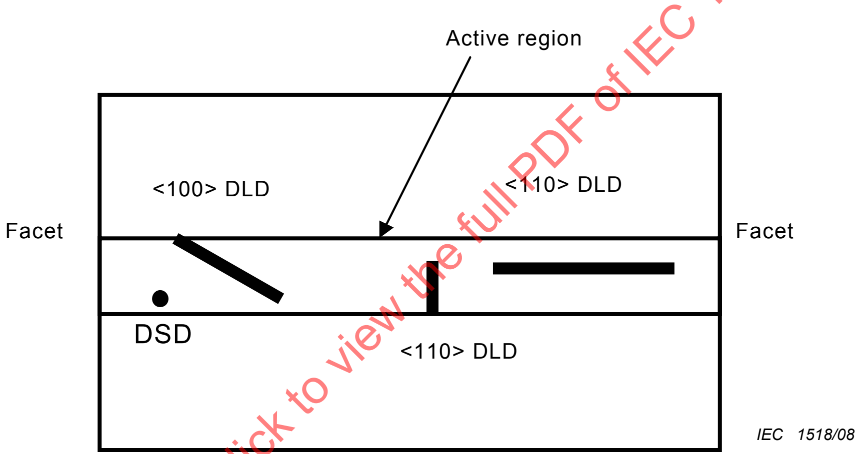

Figure 3 – Schematic diagram of DSD and DLDs viewed from the direction perpendicular to the (001) substrate

In strained quantum well lasers, a large amount of the mechanical shear stress exists within the quantum well layers. If the total thickness of well layers is comparable to the critical thickness of the strained quantum well structure or more, dislocation grows due to mechanical stress.

Rapid failures due to DLDs and DSDs have largely been eliminated by the use of low-defect density substrates and greatly improved epitaxial material growth and structure with low mechanical stress. A rigorous burn-in screen can effectively remove any individual lasers which may still suffer from this problem. Although rapid failures due to material problems have largely been eliminated, lasers in general still show gradual long-term degradation under normal operating conditions, leading to a slow rise in threshold current or change in efficiency. The manner in which degradation occurs is dependent on the laser structure, and the rate (and hence the laser lifetime) is very dependent on the quality of the material growth and on batch-to-batch processing variations.

In buried heterostructure (BH) lasers, defects tend to grow along the side walls of the active layer which are exposed to atmosphere before the growth of the blocking layers. These defects lead to increased non-radiative recombination and hence to an increase in threshold current. In InGaAsP/InP lasers, the slope efficiency is generally unchanged (at a given current). Two stages of degradation have been reported, a rapid first stage which saturates, followed by a much lower rate of long-term degradation. A short period of high temperature and current stress, applied as a burn-in, will saturate the first stage degradation. The user should therefore only observe the gradual long-term increase in threshold or operating current.

With ridge waveguide lasers, the active layer is not cut during processing, with the result that sidewalls are not exposed to atmosphere during overgrowth. Ridge lasers do not in general therefore exhibit the two-stage degradation exhibited by BH lasers, but tend only to show gradual degradation after an initial settling down period.

The cause of the gradual long-term increase in threshold current, which continues after any first stage has saturated, is not clearly understood, but is thought to be associated with the accumulation or generation of point defects within the active region which give rise to increased non-radiative recombination. In BH InGaAsP/InP lasers, the gradual long-term increase in threshold current is mainly caused by the increase in the defects along the sidewalls of the active layer.

b) Blocking layer leakage

Increased leakage currents in the blocking layers of buried heterostructure lasers have been reported leading to increased threshold currents. However, blocking layer degradation is not a general problem.

c) Facet degradation

Laser facets are vulnerable to catastrophic damage (COD) due to high-optical power output induced by high-current transients, and even slight transient damage has been shown to lead to increased degradation rates in GaAlAs/GaAs lasers, and hence reduced laser lifetimes. InGaAsP/InP lasers are generally somewhat less sensitive to facet damage than GaAlAs/GaAs lasers. The facets of all types of lasers can be damaged by handling during assembly.

Oxidation of the facet, leading to increased threshold currents, was observed to be a problem in early GaAlAs/GaAs (850 nm) lasers and strained quantum well InGaAs/GaAs (980 nm) lasers, but was largely suppressed by the use of coatings such as Al_2O_3.

InGaAsP/InP lasers are far less vulnerable to this problem and, under normal operation, facet degradation is generally insignificant.

Contamination within a laser package can lead to build-up of contaminates (for example carbon, chlorine, copper) along the line of the active region on the facets and hence to reduced light output. This contamination on the facet also absorbs the emitted light and leads to catastrophic damage, if the absorption is large, for example, hydrocarbon on the facet of InGaAs/GaAs lasers used for pumping Er-doped fibre amplifier.

d) Laser metallization and bonding

A common cause of failure in early GaAlAs/GaAs lasers was increased thermal impedance due to the formation of indium/gold intermetallics in the laser die bond. This was due to the use of indium solder in conjunction with gold layer metallization or gold-plated submounts. This problem can be minimized by careful control of gold layer thickness, but operation of lasers with this bonding system at temperatures greater than 50 °C is still risky. Indium solder is no longer widely used for InGaAsP/InP lasers, but is often required for GaAlAs/GaAs lasers where a low-stress solder is essential.

Laser failures have been seen to be due to metal penetration into the active layer, including gold from metallization and copper submounts. Effective barrier metals are therefore essential in both lasers and submounts, for example TiPtAu for laser p-side metallizations and for submounts formed with silicon, ceramics, etc.

Sudden laser failures have been observed because of short-circuits of whisker growth, but these can be eliminated by the corrected choice of solder. Solders having high melting points, such as AuSn (80:20), can give reliable bonds for InGaAsP/InP lasers.

e) Electrical surge and ESD

Most lasers which failed during handling or measuring are influenced by electrical surge or ESD. The weakest part in a laser is destroyed under the electrical surge or ESD. Lasers to which damage is introduced by the ESD and surge tend to show a large degradation rate under long term operation even if no failure is observed during handling or measuring. The endurance level of the surge and ESD gradually decreases during operation. In forward surge, COD occurs in short wavelength lasers such as GaAlAs/GaAs lasers and melting of semiconductor between the metal and semiconductor interface in long wavelength lasers such as InGaAsP/InP lasers. In reverse surge, destruction of the pn-junction is common.

f) Change in laser characteristics

The slow degradation described above leads to various changes in lasing characteristics because of increasing threshold current, decreasing slope efficiency, heat generation at degraded or deteriorated point, etc. in addition to decreasing power under constant current operation and increasing current under constant power operation (or constant monitor PD current). Those changes are lasing wavelength change, lasing instability, optical noise increase, etc. The magnitude of the characteristic changes varies widely with properties of laser material.

The lasing wavelength change is critical in optical fibre systems employing dense wavelength-division-multiplexing (DWDM) techniques. This wavelength change is influenced from refractive index change in laser cavity, band-filling effect, and Joule heating. Refractive index reduction and band-filling effect shortens lasing wavelength, and Joule heating lengthens lasing wavelength through refractive index increase and band-gap shrinkage. The refractive index reduction and the band-filling are introduced by increasing in injected carrier density within laser cavity. The lasing wavelength change is governed with these factors under degradation, and the band-filling and the band-gap shrinkage are dominant in FP laser and refractive index change which determines effective grating pitch of grating is dominant in distributed feedback (DFB) laser. The wavelength is lengthened under degradation if additional Joule heating is dominant. This case is often observed under constant power operation because operating current increases to keep output power constant. If the additional Joule heating is ignored, the lasing wavelength is shortened under degradation. From the material viewpoint, InGaAsP/InP lasers tend to show more stable characteristics under the degradation when compared with AlGaAs/GaAs lasers because laser cavity degradation, which means optical absorption increase due to DSD and DLD generation, and so forth, occurs very slowly in InGaAsP and InP material.

4.2.2 Monitor photodiode

Several kinds of photodiode are used as back-facet monitors in the laser module. For 850 nm operation, silicon pin photodetectors are used, and for long wavelengths either germanium or III-V pin detectors can be used. There are two-main types of InGaAs/InP photodiode available, having either a mesa or a planar structure.

The dominant cause of failure in photodiodes is increased dark (leakage) current. Mesa structures, which have an exposed p-n junction at the surface, are particularly vulnerable to increased surface leakage. An improvement in the stability of the mesa pin can be obtained by the use of an organic passivation or dielectric film coating, but the best reliability is normally achieved by planar devices.

4.2.3 TEC and thermistor

TEC is constructed from a series of p and n doped bismuth telluride elements soldered to copper bus bars within a sandwich of ceramic plates. They are relatively fragile devices and vulnerable to mechanical stresses arising from mounting them within the package and from thermal mismatch with other package materials. Diffusion of metal ions into the elements from the solder or metallization can lead to loss of cooling efficiency, and metallurgical reactions in solders can lead to weakened joints and cracked elements.

Changes in the thermistor resistance can occur due to reactions within the metallization and solder. Increased laser drive currents then follow as the laser submount is controlled at a higher temperature than intended.

4.2.4 Packaging and optical fibre

A critical alignment is required between the fibre tip and laser facet in order to maintain a constant light output from the fibre pigtail. For lasers coupled to single-mode fibres, alignment is required to within a micrometre, unless lenses are used to reduce the alignment tolerance.

Some very early failures have been observed in laser module service life tests due to fibre alignment instability and consequent loss of fibre light output. Failures due to dislocation between laser and fibre have also been observed during temperature cycling testing. Temperature cycling testing can also reveal vulnerability to fibre breaks due to shrinkage of the fibre pigtail. As with other hermetic packages, a dry inert gas atmosphere is required within the package to avoid problems such as metallization corrosion. Therefore, hermeticity and gas analysis testing are required. Contamination, for example residual chlorine from solvent residues, resulting from inadequate cleaning can exacerbate corrosion problems.

5 Guidance on testing

5.1 Service life tests – General

To demonstrate the long-term stability of laser modules, accelerated ageing is required. Thermally accelerated testing is the most widely used method of providing component reliability data in a test of reasonable duration, and is also appropriate for laser diodes and photodiodes.

For thermal overstress, the relationship between lifetime and temperature is derived from the Arrhenius relationship:

$$t_1/t_2 = \exp\,[(E_a/k)(1/T_1 - 1/T_2)] \qquad (1)$$

where

t_1 and t_2 are the lifetimes at temperatures T_1 and T_2 respectively;

k is Boltzmann's constant;

T_1 and T_2 are absolute temperatures, in degrees Kelvin;

E_a is the activation energy for the failure mechanism.

In order to obtain an estimate of the reliability of laser modules, life testing of the laser diodes is not sufficient. Many kinds of failure mechanisms which cause field failures are associated with packaging and therefore life tests as well as environmental testing of complete modules are essential. The results of life tests of laser diodes on submounts, monitor photodiodes, or other included components, provide necessary supporting data on the reliability of the key active devices. As a matter of fact, on such components, life tests can be performed over a wider temperature range without the limitations imposed by packaging materials. Such life testing is most readily performed by the component manufacturer. However, the laser customer system supplier should perform an independent test of complete modules (sample size > 10 per test). To obtain valid results, all life test components have to be representative of the standard production processes, including burn-in and screening tests (where appropriate, see DS).

5.2 Scale of testing

The scale of reliability testing will be dependent on the system requirements and system operator application and, in particular, the failure rate (or lifetime) and the confidence level required. The sample size selected should enable the total failure rate (wear-out + random failure rate) to be determined with sufficient accuracy for the system construction. To demonstrate a low total failure rate to a high level of confidence, accumulated component hours on many hundreds of components may be required (see Clause 6). Field data and water validation and burn-in results may be used to life test results to give increased confidence. Periodic testing on a smaller sample size is required to ensure that predictions remain valid.

5.3 Screening of components (including burn-in)

The screening test should be designed by the laser module manufacturer specifically for his particular technology. Any approach based on similarity to that which is performed by other manufacturers, is good for comparison purposes, but can be ineffective in achieving the actual screening goal. This is particularly true for fibre optic components whose technology is not yet mature and varies significantly from supplier to supplier.

Where a manufacturer can demonstrate component and process stability, screening procedures may be revised.

5.3.1 Laser diodes

With a laser diode, either on a submount or in an appropriate submodule without fibre, the stress applied is a combination of temperature and optical power or driving current. Probably the most widely used screening procedure is the so-called APC burn-in (automatic power control), where the optical power is kept constant by means of a photodiode with a feedback circuit. Another widely used procedure is the ACC burn-in (automatic current control) where high current and high temperature are applied. A short ACC test is not expected to reduce device lifetime, and is therefore ideal for screening.

For most current laser technologies, a two-step burn-in should be used, during which laser degradation is measured, see Table 1.

Table 1 – Example of laser diode screening and burn-in conditions

Conditions	Step 1 [a] ACC	Step 2 [b] APC
Temperature	100 °C minimum [c]	$T_{op\ max}$
Duration (h) [d]	96 h	96 h
Failure criterion [e]	$\Delta I_{th}/I_{tho} > x$ %	$\Delta I_{th}/I_{tho} > y$ %, $< x$ %

[a] Step 1 laser diode burn-in should be sufficiently rigorous to achieve saturated initial degradation.

[b] Step 2 is sometimes performed with the laser diode in its final package (module). Parameters other than threshold current can also be monitored, but an important requirement is that the rate of degradation in step 2 is significantly less than that in step 1 and commensurate with the requirements of the DS.

[c] For some buried heterostructure (BH) type lasers, high-temperature ageing may introduce different degradation mechanisms when compared with the mechanisms observed under relatively lower temperature operating conditions. Therefore, the step 1 burn-in temperature may be set below 100 °C for these BH type lasers.

[d] Duration will depend on temperature.

[e] The necessary failure criteria x % and y % will depend on the behaviour of the particular laser technology, and in particular on initial saturable degradation.

Examples of ACC conditions are 100 °C, 150 mA for 96 h or 125 °C, 100 mA for 24 h. A widely used APC condition is 70 °C with the laser operating at its maximum rated power.

5.3.2 Monitor photodiode

Monitor photodiodes are in laser modules to control the optical power by means of external feedback. Because high performance is not required of them in terms of speed and sensitivity, they are normally large area pin diodes based on Si for 800 nm to 900 nm and on InGaAs for 1 300 nm to 1 550 nm.

A standard burn-in for pin photodiodes is the so-called HTRB (high-temperature reverse bias) carried out at fixed reverse bias (for example V_r = 0,8 of the specified breakdown voltage or I_r at the breakdown point) at very high temperature (125 °C to 200 °C). Again, parameter stabilization is important, especially as these devices are sensitive to surface contamination, possibly induced during manufacturing.

Table 2 – Example of monitor photodiode screening conditions

Bias conditions	V_r = 0,8 breakdown (specified)
Temperature	125 °C to 200 °C
Duration	48 h to 96 h
Failure criterion	$\Delta I_r/I_{ro}$ > 100 %

5.3.3 Other components of the laser module

Other parts have to have adequate reliability.

Here is a list of the components that could be screened prior to assembly:

a) TEC (thermoelectric cooler): power cycling;

b) active components: high-temperature, reverse bias;

c) optical components: insertion loss repeatability.

The thermoelectric cooler can be especially important, as its influence on short-term reliability is not clear.

6 Guidance on the use of failure criteria during testing

The failure criteria that should be applied during testing of laser diodes, photodiodes and laser modules should be stated in the detail specification (DS). The criteria are dependent on the application and should be agreed between the system supplier and laser module manufacturer, both in terms of the parameters that are specified and also the values of these parameters which are defined as failure criteria. Similarly, measurement methods and conditions will depend on the application and device specifications.

Most endurance or environmental tests that can be performed on laser modules or devices on submounts will produce parametric changes rather than complete failures. Parametric changes, for example laser threshold current, lasing wavelength, or fibre output power, therefore, have to be extrapolated to determine when specification failures will occur. An exception to this general observation is the photodiode where failures of dark current specification limit can readily be obtained during high-temperature life tests on discrete devices.

Parameters which are generally measured at frequent intervals during life tests to allow life-times to be determined (by extrapolation if necessary) are given in Table 3. Certain parameters may be omitted if measurement techniques degrade life test data.

Table 4 gives examples of additional failure criteria.

Table 5 provides suggested failure criteria for laser modules after temperature cycling testing. Variations of the following parameters and values given in Tables 3, 4 and 5 are acceptable where it can be shown to be necessary to meet a particular system requirement. The criteria should be stated in the (DS).

Table 3 – Example of life test failure criteria

Devices	Parameters	Failure criteria	Measurement conditions
Laser diode	Threshold current or operating current	50 % increase* or 10 mA increase if I_{th} <20 mA	25 °C or life test temperature
	Slope efficiency	10 % change*	25 °C or life test temperature
	Forward voltage	10 % change*	25 °C or life test temperature
	Kinks in L/I curve	Kink-free within 1,2 × P_{nom} (linearity change ≤10 %)*	$T_{op\ min}$, 25 °C, $T_{op\ max}$
	Wavelength	See DS and application	See DS
Photodiode	Dark current	USL or 10 nA increase*	25 °C
Laser module	Laser threshold or operating current	50 % increase* or 10 mA increase if I_{th} <20 mA	25 °C or Life test temperature
	Fibre output power	10 % change*	Life test temperature I_{mon} set to initial value
	Kinks in L/I curve	Kink-free within 1,2 × P_{nom} (linearity change ≤10 %)*	$T_{op\ min}$, 25 °C, $T_{op\ max}$
	Wavelength	See DS and application	See DS
	Tracking ratio (I_{mon}/P_{fibre})	<LSL ≥ USL	$T_{op\ min}$ – $T_{op\ max}$ at rated power level
	Photodiode dark current	USL or 10 nA increase*	25 °C
	Thermistor resistance	5 % change*	25 °C or submount life test temperature T_s
	TEC current	±10 % change*	To maintain constant ΔT during life test
	TEC voltage	±10 % change*	

* Change of pre- and post- test values in the DS. See Figure 4.

NOTE 1 Additional parameters should be measured at the start and finish of the life tests, and periodically during long life tests, provided these measurements do not degrade the life test data. Some of these measurements can be readily made, for example, light/current (L/I) and current/voltage (I/V), but others are relatively time-consuming and may not be performed on all life tests/samples (to be specified in the DS). Examples of parameters are given in Table 4. Other parameters which are required for specified system applications (for example coherent or linear systems) include optical noise, light output linearity, chirp and spectral linewidth. This list is not exhaustive.

NOTE 2 Measurements which are susceptible to reflected optical power (for example spectral performance and noise should be made with the laser module terminated with a return loss representative of the system application (to be specified in the DS).

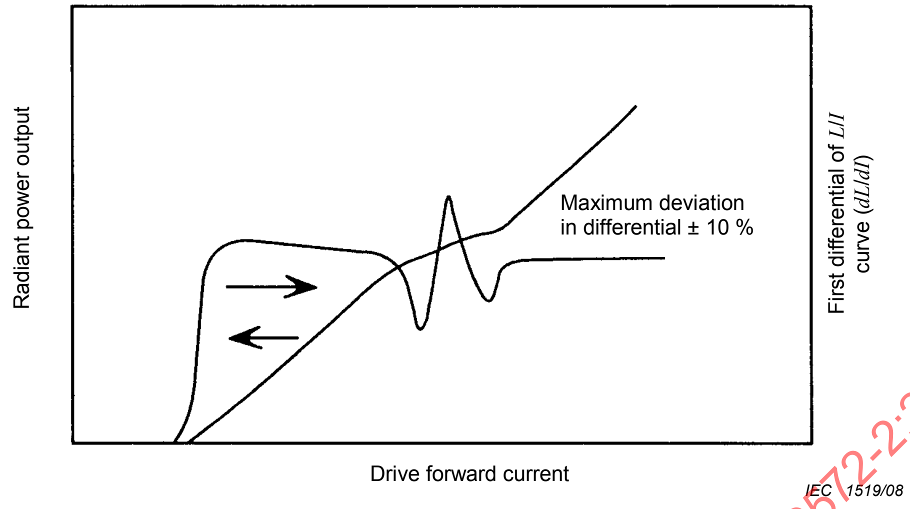

Figure 4a – Kinks in radiant power – forward current (*L*/*I*) curve

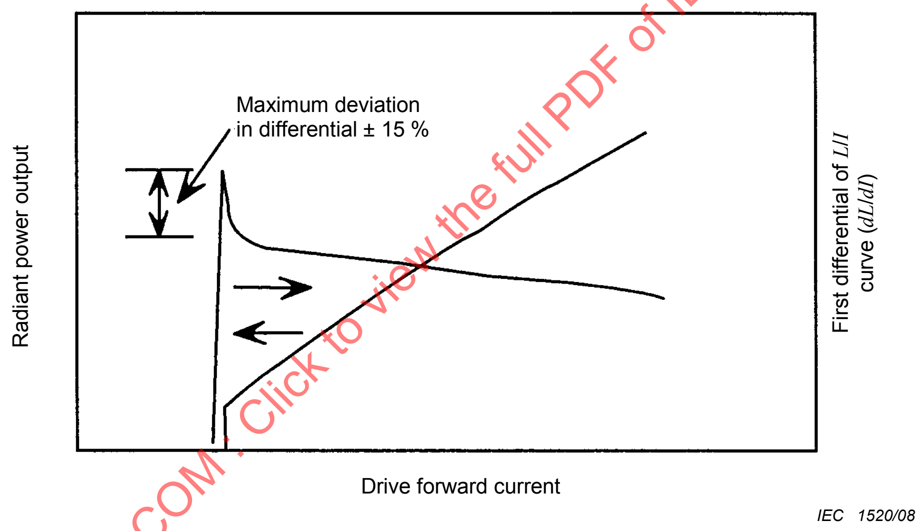

Figure 4b – Snap-on of radiant power output

Figure 4 – Non-linearities in laser-current characteristics

Table 4 – Example of additional failure criteria for laser module service life tests

Parameters	Failure criteria	Measurement conditions
Peak wavelength operating at system modulation conditions	<LSL, ≥ USL	$T_{op\ min}$, 25 °C, $T_{op\ max}$ Laser-modulated at system modulation conditions
Spectral width (RMS) operating at system modulation conditions	USL	$T_{op\ min}$, 25 °C, $T_{op\ max}$ Laser-modulated at system modulation conditions
Side-mode suppression operating at system modulation conditions	LSL	$T_{op\ min}$, 25 °C, $T_{op\ max}$ Laser-modulated at system modulation conditions
Snap-on* (from first differential L/I curve)	≥15 % first differential L/I curve	$T_{op\ min}$, 25 °C, $T_{op\ max}$
Kink in L/I*	10 %**	$T_{op\ min}$, 25 °C, $T_{op\ max}$ I_F < max and/or $P_{o\ max}$
Reverse bias leakage	Manufacturers' recommended maximum	25 °C
*See Figure 4. **The numerical aperture for the collection of the light from the laser facet may significantly affect the ability to detect kinks in the light-current curves. Measurement on unpackaged laser diodes (on submounts) should be made into a numerical aperture representative of that of the optical fibre in the final package.		

Table 5 – Example of failure criteria for laser modules after temperature cycling testing and high-temperature storage testing

Parameters	Failure criteria	Measurement conditions
Laser threshold	10 % increase*	T_s = 25 °C
Fibre output power	1 dB change*	T_s = 25 °C, I_{mon} constant
Photodiode dark current	10 mA increase*	T_s = 25 °C, T_s = $T_{op\ min}$
Thermistor resistance	5 % change*	T_s = 25 °C
TEC current	±10 % change*	To maintain constant Δt_s from start of test
TEC voltage	±10 % change* See Table 3	To maintain constant Δt_s from start of test
*Change of pre- and post-test values except for laser threshold where I_{th} <30 mA the criteria is 3 mA maximum.		
NOTE Modules should remain hermetic after the temperature cycling test.		

7 Guidance on reliability predictions

7.1 Lifetime predictions

The stress that can be applied to laser modules during a life test is often insufficient to cause either parametric or catastrophic failures during the test. However, parametric variations can be monitored during the life test and predictions of the times to failure (TTF) of individual devices can be extrapolated as described below.

a) Extrapolation of laser threshold or operating current

Almost all lasers exhibit a gradual increase in threshold current (and hence in the driving current required for a given light output) during life testing and normal operation. The life-times of individual lasers can then be predicted by extrapolating the increase in current to some pre-determined failure criteria (for example, Iop 50 % increase). A widely used model, well adapted to life data, is the relation:

$$(I - I_o)/I_o = At^n \qquad (2)$$

where

I is the operating current (or threshold current);

I_o is the operating current, initial value;

t is the time;

A and n are constant.

Although a linear extrapolation (n = 1) is often used for simplicity, in general the exponent, n, has a value less than unity, for example 0,5. Allowances for initial changes may be necessary to enable long-term degradation trends to be modelled more accurately. Alternative models to Equation (2) are acceptable, provided that they give a significantly better fit to presented data.

Using this relationship, the distribution of lifetimes at the life test temperature can be obtained. With well-manufactured and screened lasers, a life test duration of several thousand hours will be required to obtain sufficient degradation for a good prediction of lifetime to be made.

b) Changes in laser module fibre output power

Laser modules are usually operated with the laser drive current controlled to maintain a constant monitor photodiode output. Under such conditions, any changes in alignment of the optical fibre/laser facet will result in changes in the fibre output power. The changes in fibre output power from laser transmitter modules is also usually very gradual, although very rapid failures have been observed.

Extrapolation of the changes observed during life test is therefore usually required. A simple linear extrapolation is often applied, but the best fit to the fibre movement can result in non-linear changes in light output.

c) Temperature dependence of lifetime

For discrete components such as laser diodes or photodiodes, the Arrhenius relationship (Equation (1)) can readily be used to describe the temperature dependence of the component lifetime and hence to estimate the lifetime at the normal operating temperature. The median life (time for 50 % wearout failure) at each life test temperature can be used in the estimation of the activation energy.

The Arrhenius relationship indicates that, to obtain failures in a conveniently short life test, a high test temperature should be used. However, with laser diodes and modules care shall be taken that the lifetime predictions made from high temperature tests are valid. At high temperatures, there is a risk that failure will occur due to a high activation energy mechanism, whereas at lower, activation energy mechanism might dominate. For example, failures associated with metallization and bonding often have high activation energies (>0,7 eV), whereas laser chip degradation can have lower activation energy.

Care should therefore be taken when extrapolating the results of high-temperature life tests to normal operating temperatures. Some laser modules contain organic or plastic materials (for example photodiode passivations or fibre coatings), or low melting point solders, which limit the upper temperature at which testing can be performed.

Caution is needed when assuming that an activation energy obtained in high operating temperature life tests is applicable to normal operating temperatures. Analysis of life test data and failure analysis of degraded components can show whether the same failure mechanism is causing failures over the life test temperature range. The distribution of lifetimes should be the same at all life test temperatures if only a single failure mechanism is present. A long-term (10 000 h) life test at a relatively low (for example 50 °C) temperature can give confidence that results of high-temperature life tests are relevant to normal operation.

d) Current dependence of lifetime

In addition to the temperature dependence of lifetime, the lifetime is influenced from injected current. The lifetime is ordinarily shortened as injected current (density) increases and inversely proportional to I^m, (I: current, m: constant, 1-2). It is therefore favourable that the temperature dependence of lifetime is estimated at the same current under constant current operation. Under constant output power operation, a constant current operation is impossible because the operating current varies with ambient temperature and output power level. This current dependence results in a variety of test data for lifetime. BH interface and electrode degradation are enhanced by injected current (density), although the rate is low for lasers used in optical fibre systems.

e) Interpretation of life test results on laser transmitter modules

This is more complex due to

1) the different stresses experienced by the various constituent components during the life tests;
2) a number of different activation energies that need to be used in the estimation of the module lifetime under normal operating conditions.

If a value for the activation energy is not available from life test data, one is often assumed (a default value should be agreed with the customer and ONS). Caution should be taken when interpreting lifetime predictions based on assumed values of activation energy.

Table 6 – Recommended values of activation energy for lifetime predictions (when an experimentally determined value is not available, i.e. default values)

Component/failure mechanism	Activation energy eV	Acceleration factor from T_{op} 70 °C to 25 °C
1) Wear out failures on laser diodes:		
a) buried heterostructure	0,5	13
b) buried crescent	0,3	4,6
c) ridge waveguide	0,3	4,6
Laser module fibre stability	0,7	36
Photodiode dark current	0,7	36
2) Random failures		
All components	0,35	6

7.2 Failure rate prediction

The variation of failure rate with time can be represented in simplified and generalized form by the “bathtub curve” shown in Figure 5. Optoelectronic components, and particularly lasers, are vulnerable to early failures, and the early failure rate can be high if burn-in and screening are not adequate. During the useful life, where randomly occurring failures dominate, the failure rate is assumed constant. The failure rate then begins to increase again as general wear-out failure mechanism causes failures. With devices, wearout failure may have a significant effect on the system failure rate, as the devices useful life may be less than the expected system lifetime. The total failure rate is given by the sum of the wear-out and the random failure rate.

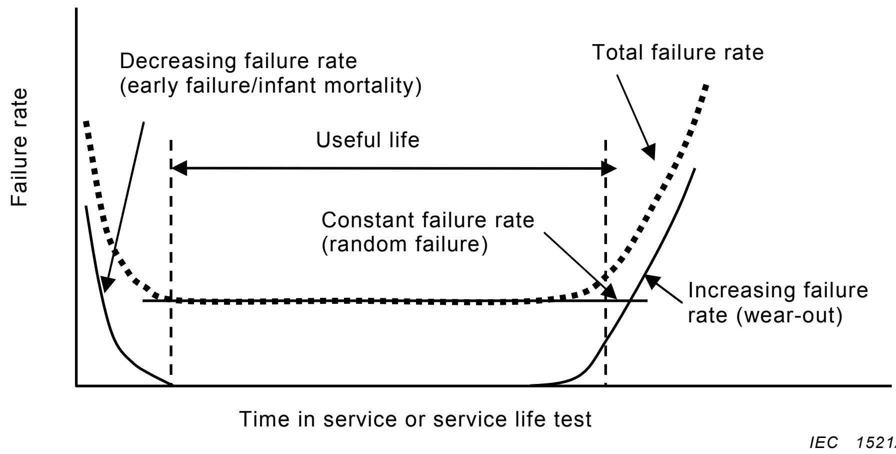

Figure 5 – "Bathtub" failure rate curve

a) Component failure rate due to wear-out

Both log-normal and Weibull distribution have been used to describe the distribution of laser and detector lifetimes. An example of a log-normal plot of laser lifetimes is shown in Figure 6. It can be seen that there is a significant spread in lifetimes and it can be shown that the failure rate due to wear-out is not constant. Simply describing the lifetime by the commonly used term "mean time to failure (MTTF)" is therefore not sufficient, and two parameters, the median life (time for 50 % wear-out failure) and the dispersion (which gives a measure of the spread in lifetimes) are required to allow the failure rate to be determined as a function of time. The dispersion, sigma (σ), is equal to $\log_e(t_{50}/t_{16})$, where t_{50} is the median life and t_{16} is the time for about 16 % failures.

The variation of the failure rate with time is very dependent on the value of the dispersion. To illustrate this point, Figure 7 shows the failure rate as a function of time for components having a log-normal lifetime distribution with a median life of 10^6 h and values of dispersion in the range 0,5 to 2,0. From the viewpoint of system maintenance after starting service, the dispersion calculated from the slope in the log-normal distribution of laser failure rate (see Figure 6) is important. If the dispersion is large (gently slope in the log-normal distribution in Figure 6), many failures occur within a service term of system even though the median life is beyond the service term. This results in a large failure rate.

The wear-out failure rate for components having a log-normal lifetime distribution can be determined using Goldthwaite curves if the median life and dispersion are known.

The estimated median life and the dispersion should be assessed from the viewpoint of sample size, because the values are correct when the size is infinite or very large. Reliability testing on finite samples will not give identical results and introduce an uncertainty to the value. The uncertainty is related to a confidence level indicating a probability that the true value is included in a certain range. The confidence level is usually expressed by a value between 0 % and 100 %. The values of $(t_{mp}/t_{mh})^{1/\sigma}$ are indicated in Table 7, where t_{mp} is the median life, t_{mh} and σ are the median life and the dispersion estimated from life test data. The median life, t_{mp}, is, therefore, calculated by using Table 7 at a certain confidence level.

For simplicity, a system operator may only wish to know the time at which a given percentage of failures will occur, or alternatively, the percentage of failures which will occur during the system lifetime. Both these values can be estimated from the distribution of lifetime (as in the example shown in Figure 6).

The failure rate at other temperatures can be calculated using the activation energy for the lifetime temperature dependence, see 5.1, Equation (1).

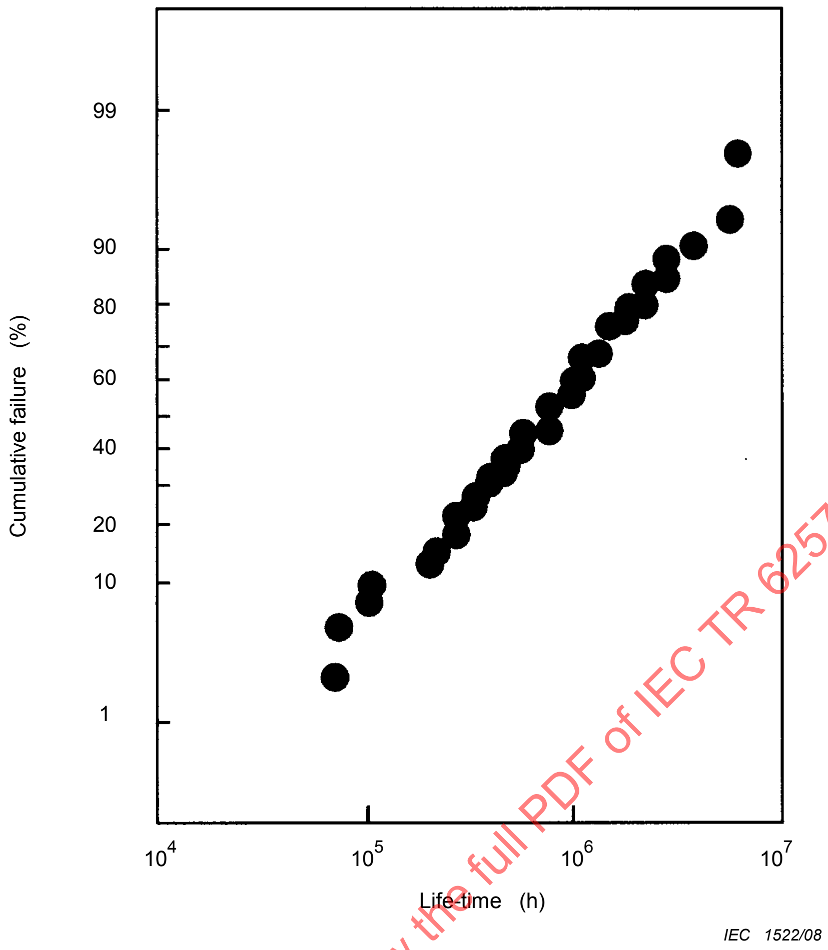

Figure 6 – Example of cumulative failure plot showing log-normal distribution of laser failure rate. The sample number tested is 33.

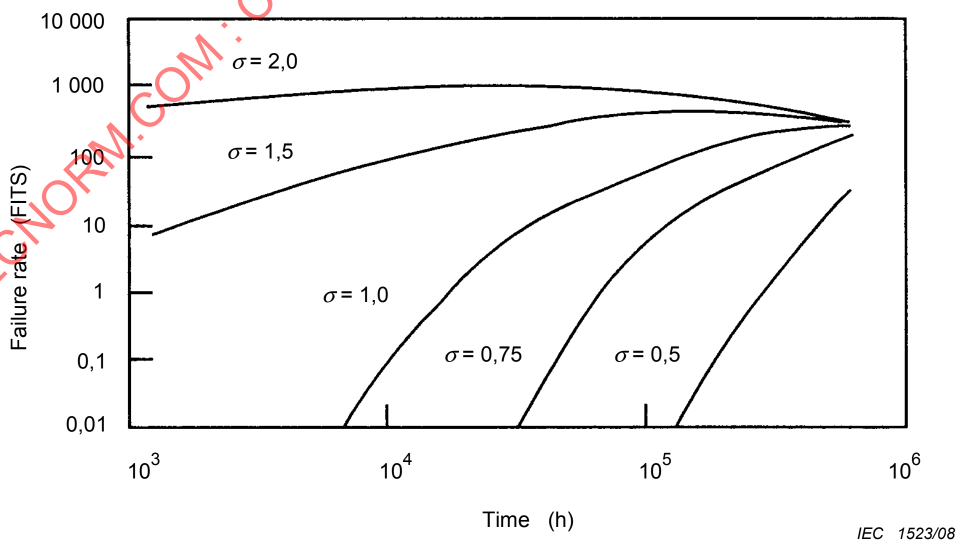

Figure 7 – Calculate failure rates as a function of service term for components having a log-normal lifetime distribution with a median life of 10^6 h and dispersion in the range 0,5 to 2,0

b) Random failure rate