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Optics and optical instruments — Lasers and laser-related equipment — Lifetime of lasers

Optique et instruments d'optique — Lasers et équipements associés aux lasers — Durée de vie des lasers

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 17526 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

Introduction

There are many different types of lasers with very different attributes and very different areas of application; not all types of lasers can be treated by the same means and measures to characterize and specify their longterm behaviour and lifetime.

This International Standard covers many types of laser, but not all methods and procedures can be applied to all types.

There are lasers, primarily laser diodes in the lower power range, which are produced in large quantities and which allow the performance of lifetime tests on large quantities to gain results on a statistically significant level. In this case and if more than approximately 50 lasers are used for testing, lifetime predictions using informative annex B of IEC 61751:1998, may be applied alternatively to this International Standard.

High-power lasers are manufactured in low quantities and lifetime tests cannot be carried out on statistically significant sample sizes.

There are types of laser of which the main components cannot be repaired, e.g. sealed-tube gas lasers or semiconductor lasers. There are others that can easily be repaired, e.g. CO_2 lasers. The former class may be characterized by "lifetime", the latter more appropriately characterized by "meantime to failure".

Optics and optical instruments — Lasers and laser-related equipment — Lifetime of lasers

1 Scope

This International Standard covers terms and definitions as well as test methods and evaluation procedures to characterize, estimate and predict the longterm behaviour of various types of lasers.

This International Standard defines terms for the lifetime of lasers and specifies test procedures and fundamental aspects for the determination of lifetime. It applies for all types of lasers for which lifetime is a critical issue, including diode lasers except those used in telecommunications.

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.

ISO 11145:2001, *Optics and optical instruments — Lasers and laser-related equipment — Vocabulary and symbols*

ISO 11554:2003, *Optics and optical instruments — Lasers and laser-related equipment — Test methods for laser beam power, energy and temporal characteristics*

IEC 60050-191:1990, *International Electrotechnical Vocabulary. Chapter 191: Dependability and quality of service*

IEC 61703:2001, *Mathematical expressions for reliability, availability, maintainability and maintenance support terms*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 and the following apply.

NOTE For simplicity, in all following parts of this International Standard the term “power” refers to cw or repetitive-cw mode, whereas “energy“ refers to pulse and quasi-cw mode.

3.1 Modes of operation

NOTE 1 The following modes of operation define the temporal and pulsed characteristics of the laser.

NOTE 2 There might be modes of operation that are not covered by the subsequent classification. These modes should be described in detail in the test report.

3.1.1
cw-mode
mode where the laser emits radiation continuously over periods of time longer than or equal to 0,25 s

3.1.2
repetitive cw-mode
mode in which the laser is operated in cw-mode but repetitively switched on and off more than once per minute

3.1.3
pulsed mode
mode in which the laser delivers its energy in the form of a single pulse or a train of pulses

NOTE 1 The duration of a pulse is shorter than 0,25 s.

NOTE 2 The subsequently defined modes of operation (3.1.4 to 3.1.7) are special cases of pulsed mode.

3.1.4
pulse train mode
mode in which the laser emits at least 100 subsequent radiation pulses (pulse duration $< 0{,}25$ s) at a continuous pulse repetition rate

3.1.5
single pulse mode
mode in which the laser emits single pulses at low repetition rate, i.e. the laser medium has reached its equilibrium state between subsequent pulses

NOTE The laser is considered to be in its state of equilibrium, if each pulse is identical to the first pulse after switch-on of the laser in all characteristics that are relevant for the intended application.

3.1.6
burst pulse mode
mode in which a pulsed laser beam emitting at a fixed pulse repetition rate f_P is repetitively switched on and off, where each burst contains at least two pulses and the time interval between two bursts is at least 2 × the inverse of the pulse repetition rate

3.1.7
quasi-cw-mode
mode in which the duration of the laser radiation is so long that the laser active material has reached its optical but not its thermal equilibrium

NOTE For some laser types (especially diode lasers and diode laser based devices) this operation mode is relevant.

3.2 Operating conditions

NOTE 1 In the following definitions different modes of long-term operation are defined under which a lifetime test is performed.

NOTE 2 For simplicity, in the subsequent clauses, only the term “laser” is used, although the respective definitions and methods might also refer to laser devices, laser units, laser modules, etc. in accordance with 3.4.

3.2.1
automatic pump power control mode
APPC-mode
mode in which the laser is operated at a constant, automatically controlled pump power (energy) with all other operating conditions (e.g. temperature) being kept constant

NOTE For optically pumped lasers, e.g. solid-state lasers, the operating current for the arc lamps or pump diodes is adjusted to compensate for degradation of the pump source.

3.2.2
automatic current control mode
ACC-mode
mode in which the laser is operated at constant, automatically controlled operation current with all other operating conditions (e.g. temperature) being kept constant

NOTE ACC-mode is only applicable for lasers with current-controlled output power, e.g. arc lamp pumped solid-state-lasers, some types of gas lasers or diode lasers. For certain types of lasers, an automatic voltage control mode (AVC-mode) may also be applied.

3.2.3
automatic power control mode
APC-mode
mode in which the laser is operated at constant automatic controlled optical output power (energy) by adjusting the pump power (energy) (e.g. operation current or optical pump power) with all other operating conditions (e.g. temperature) being kept constant

3.2.4
user selected mode
mode in which the laser is operated at constant user-accessible settings

NOTE Examples of the parameters to be held on a constant level are: the current of the exciting discharge of a gas laser, the current of the flashlamp of a solid state laser, the current of a diode laser, pump power or pump energy.

3.3 Lifetime related terms

3.3.1
time to failure
TTF
total time duration of operating time of an item, from the instant it is first put in an up state, until failure or from the instant of restoration until next failure

[IEC 60050-191-10-02:1990]

NOTE If time to failure refers to a significant component or subsystem of the laser, this should be stated with the TTF-statement.

3.3.2
mean time to failure
MTTF
expectation of the time to failure

[IEC 60050-191-12-07:1990]

3.3.3
availability
ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided

NOTE 1 This ability depends on the combined aspects of the reliability performance, the maintainability performance and the maintenance support performance.

NOTE 2 Required external resources, other than maintenance resources do not affect the availability performance of the item.

NOTE 3 In French, the term "disponibilité" is also used in the sense of "instantaneous availability".

[IEC 60050-191-02-05:1990]

NOTE 4 See also IEC 61703:2001, subclause 6.3.10.

3.3.4
degradation
decrease of the performance of a laser during time of operation when tested at constant operating and environmental conditions

3.3.5
power degradation
gradual decrease of the optical output power of a laser during time of operation when tested at constant operating and environmental conditions

NOTE Occasional discontinuities (< 10 % power drop) as e.g. caused by failures of small parts of a laser can be included.

3.3.6
(power) degradation rate
ratio of decrease of the laser output power (energy) to operation duration under constant test conditions

NOTE If the laser is tested in automatic pump power control mode (APPC-mode) or in automatic current control mode (ACC-mode) the degradation rate is measured as the ratio of the power decrease between time t_1 and t_2 (P_1 and P_2, respectively) $P_2 - P_1$ and the time interval $\Delta t = t_2 - t_1$:

$$\frac{\Delta P}{\Delta t} = \frac{P_2 - P_1}{t_2 - t_1}$$

For pulsed lasers the power P is replaced by the energy E

$$\frac{\Delta E}{\Delta t} = \frac{E_2 - E_1}{t_2 - t_1}$$

If the laser is tested in automatic power control mode (APC-mode) the degradation rate is measured as the ratio of the pump power P_{pump} increase between time t_1 and t_2 ($P_{\text{pump},1}$ and $P_{\text{pump},2}$, respectively) $P_{\text{pump},2} - P_{\text{pump},1}$ and the time interval $\Delta t = t_2 - t_1$

$$\frac{\Delta P_{\text{pump}}}{\Delta t} = -\frac{P_{\text{pump},2} - P_{\text{pump},1}}{t_2 - t_1}$$

For pulsed lasers that are pumped in pulsed mode the pump power P_{pump} is replaced by the pump energy E_{pump}.

For certain types of lasers, e.g. gas lasers or diode lasers, the pump power is essentially proportional to the operating current I. Therefore the pump power P_{pump} can be replaced by the operating current I in the formula in those cases:

$$\frac{\Delta I}{\Delta t} = -\frac{I_2 - I_1}{t_2 - t_1}$$

3.3.7
end of life
EOL
duration after which the laser does not fulfil its output power specifications for the first time

3.3.7.1
end of life for ACC- or APPC mode
$\tau^{\text{ACC}}{}_{\text{EOL},\alpha}$ **or** $\tau^{\text{APPC}}{}_{\text{EOL},\alpha}$
⟨ACC- or APPC-mode⟩ duration $\tau^{\text{ACC}}{}_{\text{EOL},\alpha}$ or $\tau^{\text{APPC}}{}_{\text{EOL},\alpha}$ after which the power has dropped to α % of the initial power P_0 [= $P(t = 0)$]:

$$P(\tau^{\text{ACC}}{}_{\text{EOL},\alpha}) = (\alpha/100\ \%)\ P_0 \text{ or } P(\tau^{\text{APPC}}{}_{\text{EOL},\alpha}) = (\alpha/100\ \%)\ P_0\text{, respectively}$$

NOTE For high power diode lasers α = 80 % is frequently used. For low power diode lasers α = 50 % is common. The manufacturer/furnisher should specify the value α in the technical documentation.

3.3.7.2
end of life for APC mode
$\tau^{APC}{}_{EOL,\alpha}$
⟨APC-mode⟩ duration $\tau^{APC}{}_{EOL,\alpha}$ after which the pump power P_{pump} has to be increased by (100 – α)/α of the initial pump power $P_{pump,0}$ above the (initial) threshold pump power $P_{th,0}$:

$$P_{pump}\left(\tau^{APC}{}_{EOL,\alpha}\right) = P_{pump,0} + \frac{100\,\% - \alpha}{\alpha}\left[P_{pump,0} - P_{th,0}\right]$$

NOTE 1 For current-controlled lasers (ref. 3.2.2) the pump power is replaced by the operating current I and consequently

$$I\left(\tau^{APC}{}_{EOL,\alpha}\right) = I_0 + \frac{100\,\% - \alpha}{\alpha}\left[I_0 - I_{th,0}\right]$$

NOTE 2 This EOL-definition ensures comparability with ACC-mode lifetimes for diode lasers (see [1, 2]) provided that threshold current and slope efficiency show identical long-term behaviour in APC- and ACC mode.

NOTE 3 For high power diode lasers α = 80 % is frequently used. For low power diode lasers α = 50 % is common. The manufacturer/furnisher should specify the value α in the technical documentation.

3.4 Types and classification

For this International Standard the general definitions of ISO 11145:2001, Figure 1, concerning “laser” apply. Additionally to the classification given in ISO 11145 the following classification is used:

NOTE A laser unit may consist of different lasers or laser devices. (Examples are lasers that are pumped by other lasers, oscillator-amplifier configurations and multi laser modules.)

3.4.1
multi-laser module
two or more lasers or laser devices which are combined into one unit by the manufacturer and cannot be separated by the user

3.4.2
laser source
laser radiation source including all devices that are essential for its operation, excluding electrical power supplies and controller and external cooling equipment (e.g. water chiller)

NOTE Unlike a "Laser device" as shown in Figure 1 of ISO 11145:2001 a laser source includes the "Laser" and essential "Beam-guiding devices", but no "Supply".

3.5 Others

3.5.1
burn-in
procedure applied by the manufacturer to a laser or a significant component of a laser, where the laser or the component is operated and tested at manufacturer-defined operating conditions

NOTE Frequently, a burn-in procedure is part of the manufacturer”s quality assurance programme.

3.5.2
screening
selection procedure applied by the laser manufacturer according to specific attributes or parameters

NOTE A burn-in procedure is one possible type of screening procedure.

NOTE A burn-in procedure is one possible type of a screening procedure.

3.5.3
sudden failure
instantaneous (sudden) power drop below the EOL-criterion of a laser

4 Symbols and abbreviated terms

4.1 Symbols

Symbol	Unit	Definition
$\Delta I/\Delta t$	A/h	degradation rate in APC-mode for current-controlled lasers
$\Delta P/\Delta t$	W/h	degradation rate in APPC- or ACC-mode
$\Delta P_{\text{pump}}/\Delta t$	W/h	degradation rate in APC-mode
α	%	percentage parameter that determines the EOL-criterion
τ_{EOL}	h	duration until the “end of life”-criterion is reached
$\tau^{\text{ACC}}{}_{\text{EOL},\alpha}$	h	lifetime in automatic current control mode (ACC-mode)
$\tau^{\text{APC}}{}_{\text{EOL},\alpha}$	h	lifetime in automatic power control mode (APC-mode)
$\tau^{\text{APPC}}{}_{\text{EOL},\alpha}$	h	lifetime in automatic pump power control mode (APPC-mode)

4.2 Abbreviated terms

Abbreviation	Definition
ACC	automatic current control (driving current and all other operation parameters are kept fixed)
APC	automatic power control (pump power adapted to maintain constant optical output power, all other operation parameters are kept fixed)
APPC	automatic pump power control (pump power and all other operation parameters are kept fixed)
EOL	end of life

5 Test methods

5.1 General

Test methods and evaluation procedures are applicable to all types of lasers as defined in 3.4 and Figure 1 of ISO 11145:2001. Lifetime tests can be performed on different parts of a laser unit and therefore it shall be clearly stated in the test report on which part of the laser the test has been performed and for which parts of the laser the results are valid.

Routine maintenance and service according to the manufacturer′s prescriptions shall be carried out according to schedule and shall be stated in the test report.

Measurements of the optical power (energy) shall be performed in accordance with ISO 11554.

Generally, identical high-power lasers, large multi-laser modules and large laser sources cannot be manufactured in very large quantities and lifetime tests in many cases will be based on small sample sizes, which makes statistical predictions and extrapolations difficult.

For most types of laser not only the optical output power (energy) but also other parameters and attributes [e.g. power (energy) distribution, farfield characteristics, beam parameter product, beam positional stability, spectral behaviour] are important. The relevance of these parameters is strongly influenced by the application of the laser. The long-term stability of these other parameters can be taken into account by a proper selection of the lifetime testing equipment. The definition of sudden failure may be applied accordingly.

5.2 Selection of lasers for lifetime testing

A sample of randomly selected lasers shall be taken from the standard production process. Any burn-in or other screening procedure that extends beyond procedures that are applied to all (regular) qualified lasers is not allowed.

5.3 Lifetime test in APPC- and ACC-mode

A sample (see 5.2) of lasers is operated at constant pump power (cw- or repetitive cw-mode) or constant pump energy (pulsed or quasi-cw mode) through the entire test and the emitted output power (energy) is recorded either continuously or at regular time intervals. The pump power shall be kept constant to within ± 2 %.

For current-controlled lasers constant pump power is achieved by operating in automatic current control (ACC-) mode.

For diode lasers the voltage drop across the laser shall also be recorded.

NOTE From voltage and current the (electrical) input power can be calculated and in conjunction with the (optical) output power the efficiency can be calculated and the emission wavelength shift due to enhanced dissipating heat can be estimated.

If the data are not acquired continuously but at distinct time intervals only, the interval between successive measurements shall be short enough to ensure that the power degradation between these measurements is within 2 %. The measuring intervals shall be shorter than 1/30 of the (intended) test duration.

It shall be ensured that the repeatability of the detector system used is better than ± 0,5 % throughout the whole test.

The temperature of the laser under test shall be kept constant during the lifetime test within the requirements for stable operation of the laser as given by the manufacturer. All other environmental conditions, e.g. humidity and cleanness of the ambient atmosphere should be kept constant and controlled.

Interruptions of the test, e.g. for maintenance purposes, shall be documented and stated in the test report.

5.4 Lifetime test at APC-mode

A sample (see 5.2) of lasers is operated at constant optical output power (energy) through the entire test by adjusting the pump power or the operating current. If the output power is not monitored continuously or the pump power/operating current is not adjusted instantaneously by means of a closed loop, an output power variation of up to ± 2 % is acceptable and the pump power/current may be adjusted stepwise to keep the output power within the ± 2 % interval. Time and pump power/operating current values of a stepwise adjustment shall be recorded and stated in the test report.

For diode lasers the voltage drop across the laser shall also be recorded.

NOTE From voltage and current the (electrical) input power can be calculated and in conjunction with the (optical) output power the efficiency can be calculated and the emission wavelength shift due to enhanced dissipating heat can be estimated.

The pump power/operating current and the output power (energy) are recorded either continuously or at regular time intervals.

If the data are acquired at distinct time intervals only, the interval between successive measurements shall be short enough to ensure that the power variation between the measurements is within 2 %. The measuring intervals shall be shorter than 1/30 of the (intended) test duration.

It shall be ensured that the repeatability of the detector system used is better than ± 0,5 % throughout the whole test.

The temperature of the laser under test during the lifetime test shall be kept constant within the requirements for stable operation of the laser as given by the manufacturer. All other environmental conditions, e.g. humidity and cleanness of the ambient atmosphere should be kept constant and controlled.

Interruptions of the test, e.g. for maintenance purposes, shall be documented and stated in the test report.

5.5 Lifetime tests at limited aperture

If the power density distribution or the farfield characteristics (divergence) are of importance the lifetime test shall be performed by measuring the output power within a limited solid angle by setting a well-defined set of apertures between the laser and the power detector. The set of apertures limits the detection angle of the power detector.

If the aperture and/or detector are/is removed from the laser during the lifetime test, special care shall be taken to ensure the proper alignment of the aperture(s) with respect to the beam axis. At the beginning of the lifetime test the required positioning accuracy of the aperture(s) and detector shall be determined.

For each of the three orthogonal directions [along beam axis (z-axis) and laterally (x- and y-axes)] the aperture is moved until the power behind the aperture has decreased by 10 %. The respective linear shifts are recorded. The reproducibility in positioning the aperture(s) and detector with respect to the laser shall be better than 1/5 of the determined shifts.

An analogue procedure shall be applied for the angular positioning.

Lifetime tests at limited aperture can be performed either in APPC-/ACC- as well as in APC-mode.

6 Evaluation and extrapolation

For all types of lifetime tests (in APPC-, ACC- and APC-mode), the recorded values are plotted vs. operating time. If sudden failures occur during the test, they shall be listed in the test report and identified in the plot.

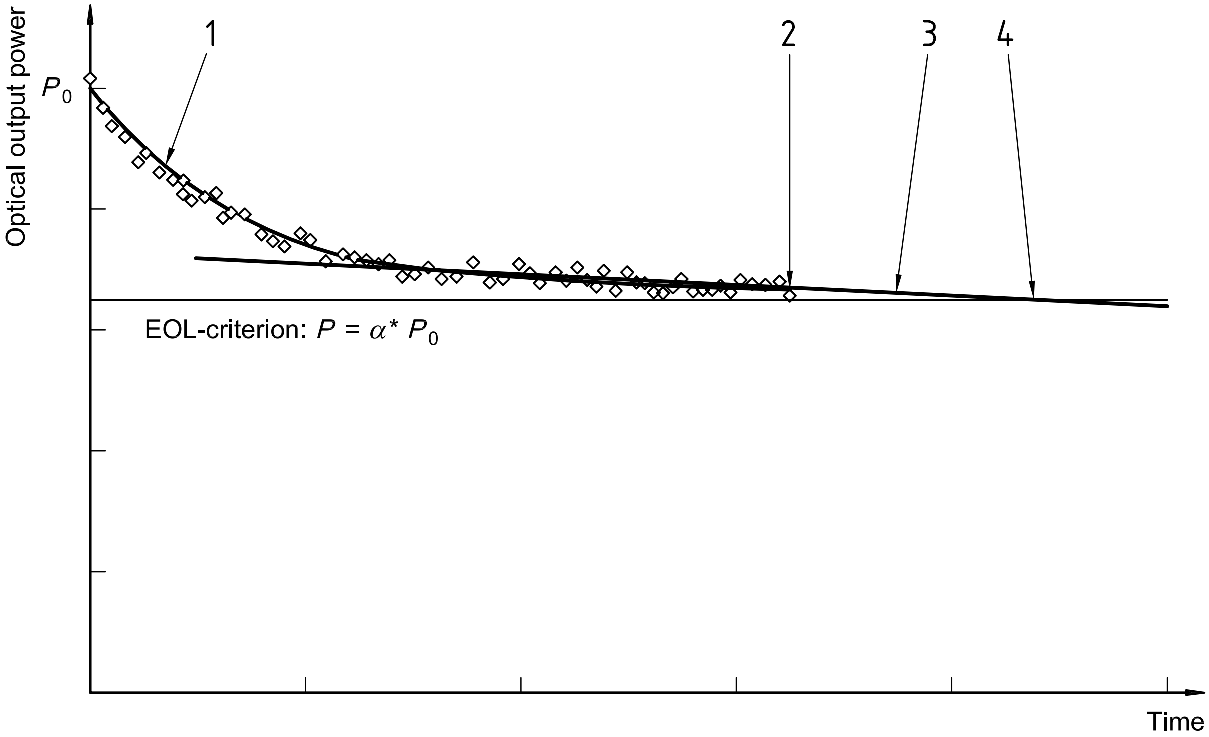
From the test curves the degradation rate $\Delta P/\Delta t$ or $\Delta P_{\text{pump}}/\Delta t$ or $\Delta I/\Delta t$ respectively is determined. In general, the degradation rate is not constant but a function of time.

NOTE Frequently, lasers show a larger degradation rate at the beginning, which tends to settle to a nearly constant value. This initial test period of enhanced degradation is not considered for extrapolations.

From the final part of the actual performed test the lifetime $\tau^{\text{APPC}}{}_{\text{EOL},\alpha}$, $\tau^{\text{ACC}}{}_{\text{EOL},\alpha}$ or $\tau^{\text{APC}}{}_{\text{EOL},\alpha}$ is determined by linear extrapolation: The recorded test data are extended by a straight line until the EOL-criterion is reached. The linear extrapolation shall be based at least on the final 2/3 (i.e. 67 %) of the performed test and the degradation rate during this period shall be constant to within ± 10 %.

If, from the recorded test curves a non-linear degradation is assumed i.e. a curve of higher polynomial order, this can be checked by a log-log plot of the recorded values vs. operating time. The highest order of the polynomial is determined by the slope of the log-log plot.

If a higher order polynomial degradation can clearly be derived from a log-log plot, a polynominal fit can be used for extrapolation and determination to the lifetime $\tau^{\text{APPC}}{}_{\text{EOL},\alpha}$, $\tau^{\text{ACC}}{}_{\text{EOL},\alpha}$ or $\tau^{\text{APC}}{}_{\text{EOL}}$. The order of the polynomial function and the coefficients shall be stated in the test report. Relevant standards to assure the confidence of the results of extrapolation shall be followed (e.g. ISO 16269-7). See Figure 1.



Key

1 initial period of higher degradation

2 end of test

3 linear extrapolation

4 τ_{EOL}

Figure 1 — Example of a lifetime test plot in APPC- or ACC-mode, assuming linear degradation at the final part of the test

Extrapolation is allowed only up to n-times of the actual performed test duration, which is considered to follow linear degradation according to definition. If the EOL-criterion is not reached within that time, a definite lifetime $\tau_{EOL,\alpha}$ cannot be determined, but it shall only be stated that the lifetime is longer than n-times the test duration.

The permitted extent of extrapolation, n, is determined by the number of lasers that have been tested and the variation in the respective final linear degradation rates. See Table 1.

Table 1 — Permitted extent of extrapolation

Number of test lasers	Standard deviation of the degradation rate	Permitted extrapolation extend n
5 to 10	5 % to 10 %	3
5 to 10	$<$ 5 %	5
$>$ 10	5 % to 10 %	5
$>$ 10	$<$ 5 %	7

The extrapolation to achieve lifetime data is only valid for those lasers that reach a constant (variation $\leqslant$ 10 %) degradation rate during the test duration, so that a linear fit is reasonable. All other lasers need to perform the complete time span to achieve a lifetime result.

7 Test report

The test results shall be recorded and shall include the following information. Additionally, the test report shall be accompanied by test plots similar to Figure 1.

a) General information:

   1) test has been performed in accordance with ISO 17526:2003;

   2) date of test;

   3) name and address of test organization;

   4) name of individual performing the test;

b) Information concerning the tested laser:

   1) laser type;

   2) manufacturer;

   3) manufacturer's model designation;

   4) serial number;

c) Test conditions:

   1) laser wavelength(s) tested at

   @ temperature in K (diode laser cooling fluid) (only applicable for diode lasers)

   2) operating mode (cw or pulsed)

   3) laser parameter settings (those which are applicable):

      i) output power or energy;

      ii) current or energy input;

      iii) pulse energy;

      iv) pulse duration;

      v) pulse repetition rate;

   4) mode structure;

   5) polarization;

   6) environmental conditions;

d) Information concerning testing and evaluation:

   1) test method used;

   2) detector and sampling system;

      i) response time of the detector system (if pertinent);

      ii) trigger delay of sampling (if pertinent);

      iii) measuring time interval (if pertinent);

3) beam forming optics and attenuating method;

   i) type of attenuator;

   ii) type of beam splitter;

   iii) type of focusing element;

4) other optical components and devices used for the test (polarizer, monochromator, etc.);

5) other relevant parameters or characteristics of the test which have to be chosen (aperture setting, reference plane, reference axis, laboratory system);

e) Test results:

(Lifetime plots similar to Figure 1 should be included in the test report.)

Number of sudden failures:.......................... test time elapsed before failure(s): .... h

Interruption due to maintenance: time of interruption: .... h

description of maintenance: ....

type of extrapolation and coefficients, if a non-linear extrapolation is used.

<u>APPC-/ACC-mode:</u>

Total degradation during test period τ:

$(\Delta P)_t$: .... W standard deviation:.. %

Final degradation rate:

mean value $\langle \Delta P/\Delta t \rangle$: .... W/h standard deviation:.. %

percentage parameter α: .... %

lifetime: mean value $\tau^{ACC}{}_{EOL,\alpha}$ or $\tau^{APPC}{}_{EOL,\alpha}$ ....h standard deviation: .... h

<u>APC-mode:</u>

Total degradation during test period τ:

$(\Delta I)_t$: .... A standard deviation:.. %

Final degradation rate:

mean value $\langle \Delta I/\Delta t \rangle$: .... A/h standard deviation:.. %

percentage parameter α: .... %

lifetime: mean value $\tau^{APC}{}_{EOL,\alpha}$: .... h standard deviation: ....h

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