INTERNATIONAL STANDARD

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Laser and laser-related equipment — Determination of laser-induced damage threshold of optical surfaces —

Part 1: 1-on-1 test

Lasers et équipements associés aux lasers — Détermination du seuil d'endommagement provoqué par laser sur les surfaces optiques —

Partie 1: Essai 1 sur 1

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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.

Attention is drawn to the possibility that some of the elements of this part of ISO 11254 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 11254-1 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

ISO 11254 consists of the following parts, under the general title *Laser and laser-related equipment — Determination of laser-induced damage threshold of optical surfaces*:

— *Part 1: 1-on-1 test*

— *Part 2: S-on-1 test*

Annexes A, B and C of this part of ISO 11254 are for information only.

Introduction

Optical components can be damaged by laser irradiation of sufficiently high energy or power. At any specified laser irradiation level, the probability for laser damage is usually higher for the surface of a component than for the bulk. Thus the limiting value of an optical component is usually given by the damage threshold of its surface.

This part of ISO 11254 describes a standard procedure for determining the laser-induced damage threshold (LIDT) of optical surfaces, both coated and uncoated. The procedure has been promulgated in order to provide a method for obtaining consistent measurement results, which may be rapidly and accurately compared among different testing laboratories. In order to simplify the comparison of laser-damage measurement facilities, laser groups are defined in this part of ISO 11254.

This part of ISO 11254 is applicable to single-shot testing only (1-on-1 tests). For multi-shot testing (S-on-1) refer to ISO 11254-2.

Laser and laser-related equipment — Determination of laser-induced damage threshold of optical surfaces —

Part 1: **1-on-1 test**

1 Scope

This part of ISO 11254 specifies a test method for determining the single-shot laser radiation-induced damage threshold (LIDT) of optical surfaces.

This test procedure is applicable to all combinations of different laser wavelengths and pulse lengths. However comparison of laser damage threshold data may be misleading unless the measurements have been carried out at identical wavelengths, pulse lengths and beam diameters.

Application of this part of ISO 11254 is provisionally restricted to irreversible damage of optical surfaces.

NOTE Examples of units and scaling of laser-induced damage thresholds are given in annex C.

WARNING — The extrapolation of damage data can lead to inaccurate or wrong calculated results and to an overestimation of the LIDT. In the case of toxic materials (e.g. ZnSe, GaAs, CdTe, ThF_4, chalcogenides, Be, Cr, Ni) this could lead to severe health hazards.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 11254. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 11254 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 10110-7:1996, *Optics and optical instruments — Preparation of drawings for optical elements and systems — Part 7: Surface imperfection tolerances*.

ISO 11145:1994, *Optics and optical instruments — Lasers and laser-related equipment — Vocabulary and symbols.*

3 Terms and definitions

For the purposes of this part of ISO 11254, the terms and definitions given in ISO 11145 and the following apply.

3.1
surface damage
any permanent laser radiation-induced change of the surface characteristics of the specimen which can be observed by an inspection technique described within this part of ISO 11254

3.2
1-on-1 test
test programme that uses one shot of laser radiation on each unexposed site on the specimen surface

3.3
threshold
highest quantity of laser radiation incident upon the optical surface for which the extrapolated probability of damage is zero

NOTE The quantity of laser radiation may be expressed as energy density H_{max} or power density E_{max} (see annex C).

3.4
target plane
plane tangential to the surface of the specimen at the point of intersection of the test laser beam axis with the surface of the specimen

3.5
effective area
$A_{\text{T,eff}}$
ratio of power [pulse energy] to maximum power [energy] density

NOTE 1 For spatial beam profiling perpendicular to the direction of beam propagation and angles of incidence differing from 0 rad, the cosine of the angle of incidence is included in the calculation of the effective area. In this case, the effective area may be approximated by the following formulae:

$$A_{\text{T,eff}} = \frac{Q}{H_{\text{max}}\cos(\alpha)} \tag{1}$$

$$A_{\text{T,eff}} = \frac{P}{E_{\text{max}}\cos(\alpha)} \tag{2}$$

NOTE 2 For the special case of a circular flat-top beam profile with diameter d_{100}, the effective area is given by:

$$A_{\text{T,eff}} = \frac{Q}{H_{\text{max}}} = \frac{H_{\text{max}}\pi d_{100}^2}{4H_{\text{max}}} = \frac{1}{4}\pi d_{100}^2 \tag{3}$$

For a focused Gaussian beam (circular beam) with a beam diameter $d_{86,5}$, the effective area is given by:

$$A_{\text{T,eff}} = \frac{Q}{H_{\text{max}}} = \frac{H_{\text{max}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{e}^{-8\frac{x^2+y^2}{d_{86,5}^2}}\,\mathrm{d}x\mathrm{d}y}{H_{\text{max}}} = 2\pi\int_0^{\infty} e^{-\frac{8r^2}{d_{86,5}^2}}\,r\mathrm{d}r = \frac{1}{8}\pi d_{86,5}^2 \tag{4}$$

With the definition of the second moment of the energy density distribution function $H(x,y,z)$ at the location z,

$$\sigma^2(z) = \frac{\int_0^{\infty}\int_0^{2\pi} r^2 H(r,\varphi) r \,\mathrm{d}r\,\mathrm{d}\varphi}{\int_0^{\infty}\int_0^{2\pi} H(r,\varphi) r \,\mathrm{d}r\,\mathrm{d}\varphi} \tag{5}$$

and the definition of the beam diameter d_σ as a function of the second moment

$$d_\sigma(z) = 2\sqrt{2}\sigma(z) \tag{6}$$

the effective area can be expressed in the following forms:

a) flat-top beam: $$A_{\mathrm{T,eff}} = \frac{1}{4}\pi d_{100}^2 = \frac{1}{4}\pi d_{\sigma}^2 = 2\pi\sigma^2; \quad d_{100} = d_{\sigma} \tag{7}$$

b) Gaussian beam: $$A_{\mathrm{T,eff}} = \frac{1}{8}\pi d_{86,5}^2 = \frac{1}{8}\pi d_{\sigma}^2 = \pi\sigma^2; \quad d_{86,5} = d_{\sigma} \tag{8}$$

3.6
effective beam diameter
$d_{\mathrm{T,eff}}$
double the square root of the effective area divided by the factor pi

$$d_{\mathrm{T,eff}} = 2\sqrt{\frac{A_{\mathrm{T,eff}}}{\pi}} \tag{9}$$

3.7
effective pulse duration
ratio of total pulse energy to maximum pulse power

4 Symbols and units

Table 1 — Symbols and units of measurement

Symbol	Unit	Term
λ	nm	wavelength
α	rad	angle of incidence
p		degree of polarization
d_{T}	mm	beam diameter in the target plane
$d_{\mathrm{T,eff}}$	mm	effective beam diameter in target plane
$A_{\mathrm{T,eff}}$	cm^2	effective area in the target plane
t_{H}	ns, µs, s	pulse duration
t_{eff}	ns, µs, s	effective pulse duration (see 6.2.6.2)
Q	J	pulse energy
P_{pk}	W	peak pulse power
P	W	power
H_{max}	$\mathrm{J/cm}^2$	maximum energy density
E_{max}	$\mathrm{W/cm}^2$	maximum power density
H_{th}	$\mathrm{J/cm}^2$	threshold energy density
E_{th}	$\mathrm{W/cm}^2$	threshold power density
F_{th}	W/cm	threshold linear power density
N_{TS}		total number of sites for the test

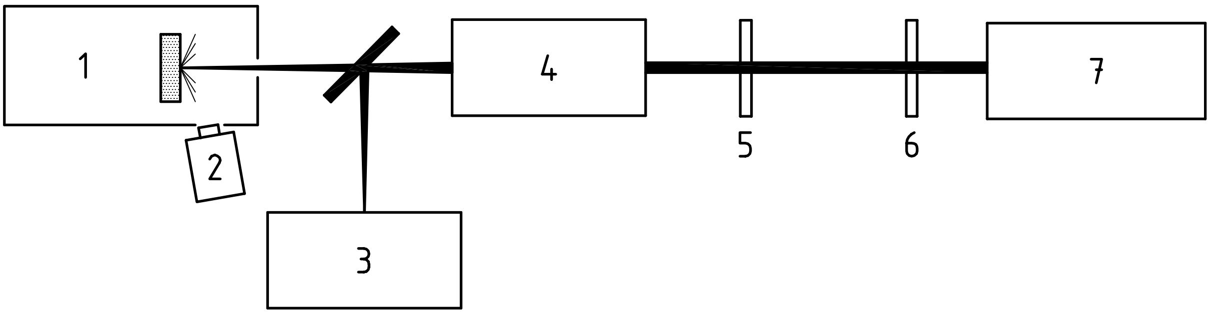
5 Sampling

Either a functional component or a witness specimen shall be tested. If a witness specimen is tested, the substrate material and surface finish shall be the same as for the component, and the witness specimen shall be coated in the same coating run as the component. The coating run number and date shall be identified for the test component.

6 Test method

6.1 Principle

The basic approach to laser damage testing is shown in Figure 1. The output of a well-characterized stable laser is set to the desired energy or power with a variable attenuator, and delivered to the specimen located at or near the focus of a focussing system. The use of a focussing system permits the generation of destructive energy densities or power densities at the test specimen.



Key

1 Sample compartment
2 On-line damage detector
3 Beam diagnostic
4 Focussing system
5 Waveplate
6 Variable attenuator
7 Laser system

Figure 1 — Basic approach to 1-on-1 laser damage testing

The specimen is mounted in a manipulator which is used to position different test sites in the beam and set the angle of incidence. The polarization state is set with an appropriate waveplate. The incident laser beam is sampled with a beamsplitter which directs a portion of the beam to a diagnostic unit. The beam diagnostic unit permits simultaneous determination of the total pulse energy and the spatial and temporal profiles.

Microscopic examination of the testing site before and after irradiation is used to detect damage.

The specimen is positioned at different non-overlapping test sites in reference to the beam, and irradiated at different energy densities or power densities. From these data the damage threshold can be determined.

This procedure is applicable to testing with all laser systems, irrespective of pulse length and wavelength. Pulse durations widely used in industrial and scientific applications are summarized and grouped in Table 2.

Table 2 — Laser groups

Group	Description	Pulse duration
1	very short pulse	1 ns to 3 ns
2	short pulse	10 ns to 30 ns
3	medium pulse	1 µs to 3 µs
4	long pulse	200 µs to 1000 µs
5		pulse length to be specified
6	cw	1 s
NOTE Damage thresholds of pulsed lasers (Groups 1 to 4) are usually expressed in units of energy density (J/cm^2). The pulse duration of the test laser shall be documented in the test report. Group 6: Damage thresholds of continuous-wave (cw) lasers are usually expressed in units of linear power density (W/cm). Power density refers to the average power during the irradiation time. Examples for units of laser-induced damage thresholds are described in annex C.		

6.2 Apparatus

6.2.1 Laser, delivering pulses with a reproducible near-Gaussian or near-flat-top spatial profile.

The temporal profile of the pulses is monitored during the measurement. For the different laser groups, the maximum allowable variations of the pulse parameters are compiled in Table 3. As a minimum specification of a laser system of Group 5, the pulse-to-pulse variation of the maximum power density shall be less than ± 20 %. Stability criteria for the beam parameters shall be determined and documented in an error budget.

Table 3 — Maximum percentage variation of laser parameters and corresponding percentage variation of maximum pulse power density E_{max}

Laser group	Pulse energy Q	Average power P_{av}	Pulse duration τ_{eff}	Effective area $A_{T,eff}$	Power density E_{max}
1	± 5	—	± 10	± 10	± 15
2	± 5	—	± 5	± 6	± 10
3	± 5	—	± 5	± 6	± 10
4	± 5	—	± 5	± 6	± 10
6	—	± 5	—	± 6	± 20

6.2.2 Variable attenuator and beam delivery system

The laser output shall be attenuated to the required level with an external variable attenuator that is free of drifts in transmissivity and imaging properties.

The beam delivery system and the attenuator shall not affect the properties of the laser beam in a manner inconsistent with the tolerances given in 6.2.1. In particular, the polarization state of the laser beam shall not be altered by the beam delivery system.

6.2.3 Focussing system

The arrangement of the focussing system should be adapted to the special requirements of the laser system and to the intended beam profile in the target plane. The specific arrangement and the parameters of the focussing system shall be documented in the test report. The specifications of the active area and the energy density shall be referred to the location of the test surface.

For Gaussian beams, it is advisable to select an aperture of the focussing system which amounts to not less than three times the beam diameter at the entrance of the focussing system. A minimum effective *f*-number of 50 and a beam diameter in the target plane of not less than 0,8 mm are recommended. The target plane should be located at or near the focal waist formed by the focussing system. For Groups 3 to 6, the beam diameter may be reduced depending on the power density necessary, but should not be smaller than 0,2 mm. In such cases the effective *f*-number may be reduced below a value of 50.

For near-flat-top laser beams, it is advisable to position the test surface in the image plane of the focussing system with a focal length > 0,2 m that forms an image of a suitable aperture in the optical path.

Coherence effects in specimens with parallel surfaces can occur and affect the measurement. These effects shall be eliminated by appropriate techniques, such as wedging or tilting of the specimen. The application of a highly converging beam is also a practical method for removing coherence effects in the specimen.

6.2.4 Specimen holder

The test station shall be equipped with a manipulator which allows for a precise placement of the test sites on the specimen with an accuracy sufficient for the specimen size.

6.2.5 Damage-detection microscope, to inspect the surface before and after the test.

The investigations shall be made with an incident light microscope having Nomarski-type differential interference contrast. A magnification in the range from 100× to 150× shall be used.

NOTE 1 For routine inspection and objective measurement of laser damage, an image analyser may be attached to the microscope.

NOTE 2 An appropriate on-line damage detection system may be installed for evaluating the state of the surface under test or for switching off the laser in long-pulse and cw damage-measurement facilities to avoid catastrophic damage of the specimen. For on-line detection, any appropriate technique may be used. Techniques suited to this purpose are for instance on-line microscopic techniques in conjunction with image analysers, photoacoustic and photothermal detection, as well as scatter measurements using a separate laser or radiation from the damaging laser. A typical set-up for an on-line scatter measurement system is described in ISO 11254-2.

6.2.6 Beam diagnostics

6.2.6.1 Measurement of total pulse energy and power

The diagnostic package shall be equipped with a calibrated detector to measure the pulse energy or beam power delivered to the target plane. This instrument shall be traceable to a national standard with an absolute uncertainty of ± 5 % or better.

6.2.6.2 Temporal profile analysis

The diagnostic package shall include suitable instrumentation for analysing the temporal profile of the laser to determine the pulse duration. The temporal profile shall be integrated to determine the ratio of total pulse energy Q to maximum pulse power P_{pk}. This ratio is called the effective pulse duration t_{eff}:

$$t_{eff} = \frac{Q}{P_{pk}} = \frac{\int_0^\infty P(t)\, dt}{P_{pk}} \tag{10}$$

For pulsed lasers (Groups 1 to 4), upper limits for the temporal resolution of the pulse duration measurement are defined in Table 4. For Group 6 lasers, the temporal stability of the output shall be determined with a resolution of less than 10 ms. For lasers not included in Table 4, the upper limit of the temporal resolution shall not exceed 10 % of the effective pulse duration.

Table 4 — Upper limits for the temporal resolution of the pulse duration measurement

Group	Temporal resolution
1	100 ps
2	1 ns
3	100 ns
4	10 µs

6.2.6.3 Spatial profile

In all cases, the spatial profile shall be analysed in the target plane or an equivalent plane. The diagnostic package shall be equipped with instrumentation to measure the two-dimensional spatial profile with a spatial resolution of 1,5 % of the beam diameter or better.

The maximum energy density or power density of the beam shall be determined as follows:

The two-dimensional profile shall be integrated to determine the ratio of total pulse energy Q to maximum energy density H_{max} or the ratio of power P to maximum power density E_{max}, respectively. The effective area $A_{T,eff}$ is deduced from the formulae:

$$A_{T,eff} = \frac{Q}{H_{max}} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(x,y)\, dx\, dy}{H_{max}} \tag{11}$$

$$A_{T,eff} = \frac{P}{E_{max}} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y)\, dx\, dy}{E_{max}} \tag{12}$$

The maximum energy density H_{max} is given by

$$H_{max} = \frac{Q}{A_{T,eff}} \tag{13}$$

The maximum power density E_{max} is given by

$$E_{max} = \frac{H_{max}}{t_{eff}} \tag{14}$$

The maximum power density E_{max} is given by

$$E_{max} = \frac{P}{A_{T,eff}} \tag{15}$$

The testing equipment shall be characterized by the following parameters:

a) wavelength, λ;

b) angle of incidence, α;

c) degree of polarization, p;

d) beam diameter in the target plane, d_T;

e) effective beam diameter in the target plane, $d_{T,eff}$;

f) pulse duration, t_H;

g) effective pulse duration, t_{eff};

h) (minimum) number of sites tested at each energy density value;

i) total number of sites per test, N_{TS}.

6.3 Preparation of test specimens

Wavelength, angle of incidence and polarization of the laser radiation as used in the test shall be in accordance with the specifications by the manufacturer for normal use. If ranges are given for the values of these parameters, an arbitrary combination of wavelength, angle of incidence and polarization within these ranges may be used.

Carry out storage, cleaning and preparation of the specimens in accordance with the specimen specifications provided by the manufacturer for normal use.

In the absence of manufacturer-specified instructions, use the following procedure.

a) Store the specimen at less than 50 % relative humidity for 24 h prior to testing. Handle the specimen by the non-optical surfaces only.

b) Before testing, carry out a microscopic evaluation of surface quality and cleanliness in accordance with ISO 10110-7 using a Nomarski/darkfield microscope at 150× magnification or higher.

c) If contaminants are seen on the specimen, the surface shall be cleaned. The cleaning procedure shall be documented. If the contaminants are not removable, document them by photographic and/or electronic means before testing.

d) Inspect the test site for dust particles during irradiation. The test environment shall be clean, filtered air of less than 50 % relative humidity and shall be documented.

e) The test sites shall be in a defined and reproducible arrangement. Refer the test grid to fixed reference points on the specimen. It is acceptable to make marks at known locations on the specimen as reference points only after testing is completed and before the specimen is removed from the specimen positioner.

NOTE It is usually possible to use one or more large damage spots as reference points, rather than potentially contaminating the surface of the specimen. This is preferable if there is any likelihood of having to make further tests on the specimen.

6.4 Procedure

A number of test sites are positioned into the beam and irradiated at different energy densities or power densities. From this data, the damage threshold can be determined. Test a minimum of 10 sites for each energy-density or power-density increment. The range of pulse energies or beam powers employed shall be sufficiently broad to include points of zero damage frequency, as well as points of 100 % damage probability.

7 Evaluation

Damage threshold data are obtained by the damage-probability method. Expose a minimum of ten sites to one pulse energy (or beam power) and record the fraction of sites which are damaged. Repeat this procedure for other pulse energies or beam powers to develop a plot of damage probability versus energy or power. An example is shown in Figure 2. Linear extrapolation of the damage probability data to zero damage probability yields the threshold energy. Convert the threshold value to the appropriate threshold energy density H_{th} or threshold power density E_{th} as described in 6.2.6.3.

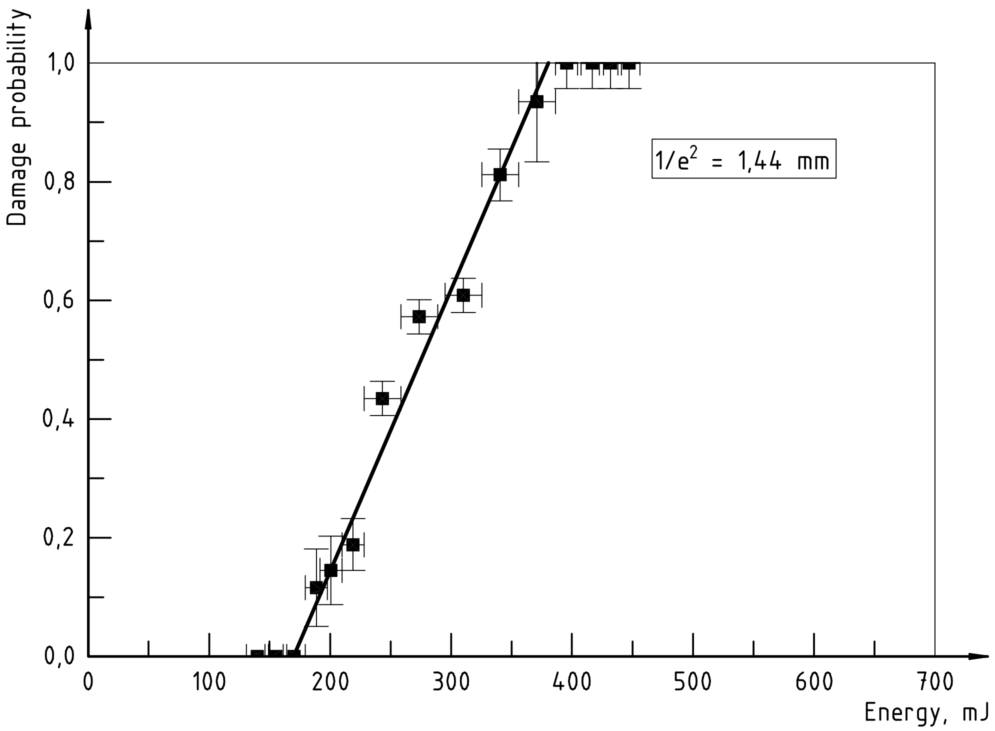


Figure 2 — Diagram for the determination of the damage threshold from experimental data
(damage to KBr windows, 50 pieces, ∅ 40 mm, BMFT 315-5691 ATT 2249 A/8)

In the case of a laser system with a high pulse-to-pulse energy variation, it is permissible to expose the specimen to arbitrary pulse energies and to sort the data with respect to appropriate energy intervals after the experiment. A minimum of ten sites shall be tested within one energy interval.

NOTE For an efficient measurement procedure with maximum accuracy for a given number of sites, an appropriate example is described in annex B.

8 Accuracy

Prepare a calibration error budget to determine the overall measurement accuracy. Variations in the total energy or beam power, spatial profile, and temporal profile shall be included in the error budget.

An example for Group 3 lasers is given in Table 5. Similar formats are appropriate for other laser groups.

Table 5 — Error budget for a Group 3 laser-damage testing facility

Random variations:	
Pulse-to-pulse energy stability	± 3 %
Pulse-to-pulse spatial profile stability	± 5 %
Pulse-to-pulse temporal profile stability	± 5 %
Systematic variations:	
Calorimeter calibration	± 3 %
Calorimeter-energy monitor correlation	± 2 %
Overall energy density measurement reproducibility	± 5,8 %
Overall energy density measurement uncertainty	± 6,8 %
Overall power density measurement reproducibility	± 7,7 %
Overall power density measurement uncertainty	± 8,5 %

9 Test report

To guarantee a reliable in-process documentation, each specimen tested is assigned a unique run number, which accompanies it through the test process from initial receipt to submission of the final report. All pertinent information pertaining to test station configurations, source calibration, cleaning, microscopic inspections, exposure parameters, raw data and reduced test results shall be traceable to this run number. This data shall be retained by the test laboratory as a primary permanent reference.

For the purpose of documentation and presentation of measured data, the test report shall include the following information.

a) Information on the testing institute

1) name and address of the testing institute;

2) date of testing;

3) name of the operator.

b) Information on the specimen

1) type of the specimen (part or witness);

2) manufacturer of the specimen;

3) specifications of the manufacturer for storage, cleaning, and preconditioning;

4) specifications of the manufacturer for normal use (wavelength, pulse duration, polarization, angle of incidence, purpose);

5) part identification number, date of production.

c) Information on the test (test specifications)

1) test equipment used including focussing system and beam f-number;

2) laser parameters according to 6.2.6.3 a) to h);

3) diagrams of the spatial and temporal profile of the laser beam;

4) error budget (see Table 5);

5) arrangement of the testing sites on the specimen;

6) damage detection method;

7) methods for storage, cleaning and preconditioning;

8) test environment.

d) Information on the result

1) Nomarski micrograph of a typical damaged testing site; a pulse energy or beam power in the range between 20 % and 80 % damage probability shall be chosen;

2) diagram according to clause 7;

3) result of the test, given as H_{th} or E_{th} or F_{th};

4) total number of sites for the test, N_{TS}.

It is recommended that a test report containing the test specifications and the test results be written and supplied to the customer. An example is given in annex A.

Annex A
(informative)

Test report example

Laser-induced Damage Threshold, 1-on-1 test

(ISO 11254-1)

Testing Institute

Testing Institute:	Xaa Xaaaaa Xaaaaaaaaa xaa XX Xaaaa XXXX-XXXX Xaaaaa XX (Xaa. Xaa. Xaaaaaa)
Tester/Date	X. Xaaaaaaaa / 1994-02-28

Specimen

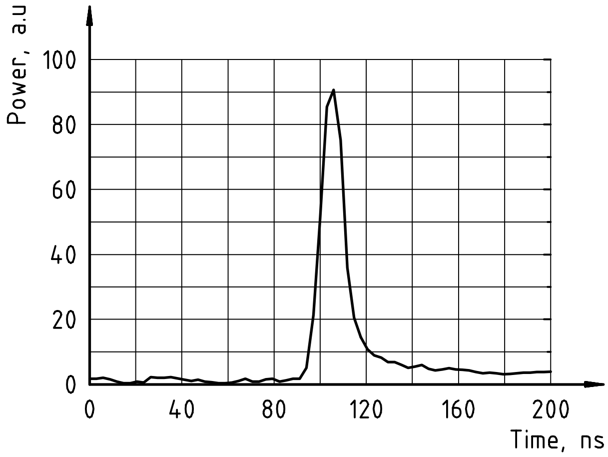
Type of Specimen:	original part, HR at 1064 nm on BK7 glass
Manufacturer:	Xaa Xaaaaa XaaAXaaaaa xaa XX Xaaaa XXXX-XXXX Xaaaaa XX (Xaa. Xaa. Xaaaaaa)
Storage, Cleaning:	No special requirements
Specification:	Highly reflective mirror, R > 99,5 % at 1064 nm, 0 rad angle of incidence, standard coating for normal use
Part identification:	
Date of production:	Coating Run #1187 of 1993-05-31

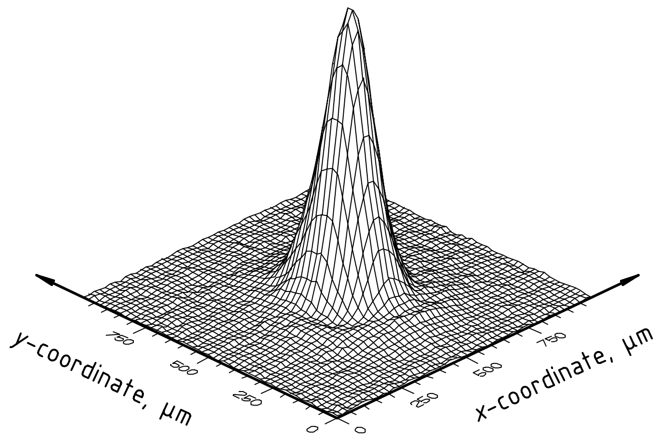
Test Specification

Pulsed Nd:YAG-laser consisting of an electro-optically Q-switched oscillator and an optically isolated amplifier stage. Single transversal and longitudinal mode operation. Focussing by a biconvex lens with a beam f-number of 300.

Laser parameters:

Wavelength	1064 nm
Angle of incidence	0 rad
Polarization state	linear
Minimum time between two shots	5 s
Effective beam diameter in target plane	0,34 mm
Pulse duration	12 ns (Group 2)
Effective pulse duration	12,7 ns





Error budget:

a) random variations:

pulse-to-pulse energy stability	± 3 %
pulse-to-pulse spatial profile stability	± 5 %
pulse-to-pulse temporal profile stability	± 8 %

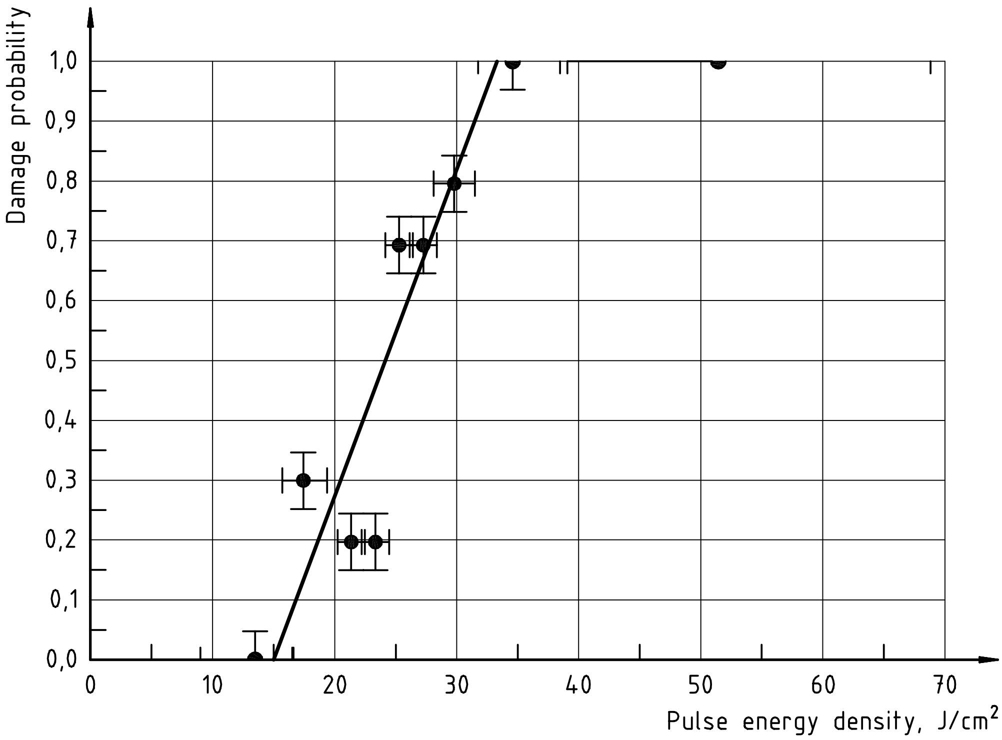
b) systematic variations:

calorimeter calibration	± 5 %
calorimeter-energy monitor correlation	± 2 %
overall energy density measurement reproducibility	± 12,2 %
overall energy density measurement uncertainty	± 10,4 %

Test procedure:

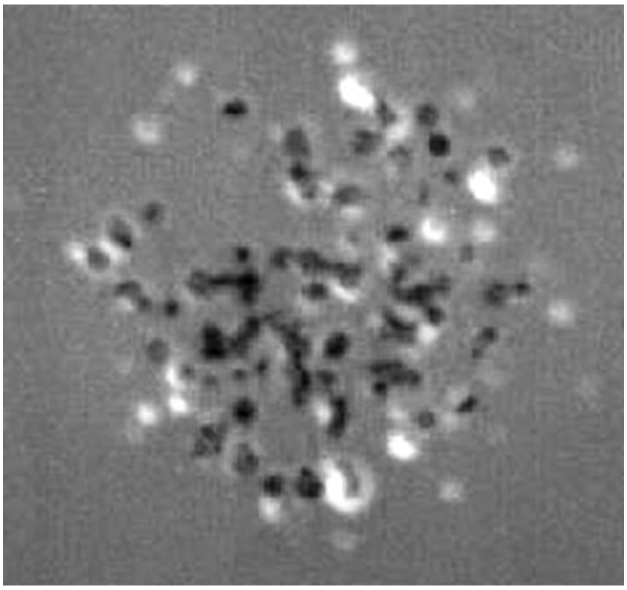
Number of shots per specimen:	25
Arrangement of test sites:	5 × 5 matrix
Minimum distance between sites:	3 mm
Number of specimens tested:	5
Total number of sites for the test:	125
Damage detection:	on-line scatter measurement, on-line image processor
Storage of the specimen:	manufacturer box, normal room conditions
Test environment:	clean filtered air
Cleaning:	dust off with dry nitrogen

Test Result

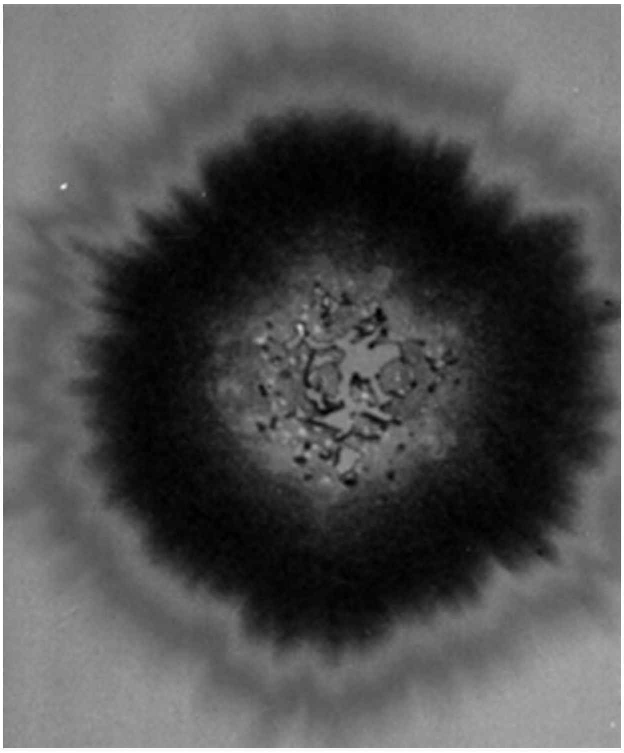


Damage Probability Plot (13 EU 0077, EU 226)

Damage threshold 15,1 J



Nomarski micrograph for
an energy density of 19 J/cm^2



Nomarski micrograph for
an energy density of 30 J/cm^2

Comment: Damage induced by inclusions in the coating. Contribution of absorption-induced damage for higher energy density levels.

Annex B
(informative)

Example of a measurement procedure

B.1 General

This annex describes an example of a measurement procedure (J. W. Arenberg). The basic structure of the procedure consists of three steps.

In the first initialization step, the fundamental parameters of the test are calculated or defined. The initialization may also include a binary search routine for an estimation of the actual damage threshold and for a determination of the energy density intervals for testing. In the initialization procedure, the fundamental test parameters are specified on the basis of the intended application and information available from former tests of samples of similar design and materials.

In the second step, the optic is interrogated and the data collected.

In the final step, the data collected is analysed and an estimate of the damage threshold and its uncertainty are calculated.

B.2 Initialization of the measurement procedure

B.2.1 Total number of test sites, n_{total}

From the area A_{optic} of the sample available for the damage test, the beam diameter $d_{T,eff}$ and the separation of test sites in terms of laser spot size d_{sep}, the total number n_{total} of test sites can be determined. If a rectangular array of test sites is assumed, the total number of sites is determined by:

$$n_{total} = \frac{4A_{optic}}{(d_{sep}d_{T,eff})^2} \tag{B.1}$$

In case of an arrangement of the test sites according to a hexagonal close-packed (HCP) structure, a factor of $2/\sqrt{3}$ has to be introduced in equation (B.1):

$$n_{total} = \frac{8A_{optic}}{\sqrt{3}(d_{sep}d_{T,eff})^2} \tag{B.2}$$

In this HCP-arrangement, all next-neighbour test sites are $d_{sep} \cdot d_{T,eff}$ apart. As minimum conditions for the damage frequency method, the value of n_{total} should exceed 75 shots, and d_{sep} should range between 1,25 and 5 for a beam with a Gaussian spatial distribution.

B.2.2 n_{steps}, Probability resolution, P_{res}, Number of damage sites, n_{sites}

Figure B.1 is used to determine the values of the probability resolution, P_{res} and the number of sites to be damaged per fluence level, n_{sites}, for a given value of n_{total}. For a given value of n_{total}, the range of possible values of P_{res} and n_{sites} can be seen by following the contour for the value of n_{total} from left to right. For a sufficiently large value of n_{total} there is a large number of possible values for P_{res} and n_{sites} allowing a great flexibility in the design of the test. For smaller values of n_{total}, the choices in design are more limited.

If there is history or suspicion of a tail of low probability, then the tester should opt for the smallest acceptable value of P_{res}. This will ensure, to the extent possible, that such a low probability tail is seen by the interrogation protocol. If there is no history or concern over a low probability tail, then preferred selection would be for the largest value of n_{sites} possible. The choice of a large value of n_{sites} leads to the most precise determination of the damage-probability allowed-for area available to test [see equation (B.5)].

After the selection of P_{res}, Figure B.2 is used to determine the number of fluence levels used in the test, n_{steps}. The curve in Figure B.2 is directly read to determine n_{steps}, the number of fluence steps.

EXAMPLE Selection of n_{sites} and P_{res}.

Consider a test with 200 sites. The n_{sites} contour for 200 allows for values of n_{sites} from 1 to 5 and corresponding values of P_{res} from approximately 0,06 to 0,15. If there is concern over a low probability tail, then the lower values of P_{res}, which allows for more fluence levels to be interrogated, is recommended. If this concern is not present, then a higher value for P_{res} is the preferred choice, because of increased precision in measuring of the damage probability.

B.2.3 Top and bottom energy density levels, H_{top} and H_{bottom}

The top and bottom energy density levels, H_{top} and H_{bottom}, can be estimated by historical data available from previous damage tests on comparable specimens. The value H_{top} corresponds to an energy density value with approximately 60 % damage probability. The value for H_{bottom} is near, but above, the estimated threshold. If historical data are not available, the values H_{top} and H_{bottom} can be determined by a binary search routine, which is performed on the actual test area. A minimum number of 15 test sites should be used for this binary search routine. For large test areas with n_{total} >150, it is permissible to employ a fraction of 0,1 n_{total} sites for this initial binary search.

B.2.4 Resolution of energy density, δH

The energy density resolution is defined by

$$\delta H = \frac{H_{top} - H_{bottom}}{n_{steps}} \tag{B.3}$$

where n_{steps} has been determined in step B.2.2.

B.3 Testing routine

The algorithm for the irradiation sequence of the specimen is illustrated in Figure B.3. The initial energy density level H_1 is H_{top}. After interrogation of the first site, the state of damage is detected and recorded. The variables $n^{D}{}_{i}$ and $n^{ND}{}_{i}$ are counting variables for the number of sites damaged and not damaged, respectively, at the selected energy density level H_i. Irradiation of the sample at the i^{th} level continues until at least 12 sites have been interrogated and $n^{D}{}_{i} = n_{sites}$ or $n^{ND}{}_{i} = 3/P_{res}$ without observation of a single damage site. When the irradiation is complete at the i^{th} level and n_{sites} sites have been damaged, the energy density level is decreased by the decrement δH. If $3/P_{res}$ shots at H_i are taken without observation of a single damage site, the energy density level for the next value of i is increased by the increment 0,5 δH and δH for each level thereafter. This procedure is repeated until the test area is exhausted.

B.4 Evaluation of the test

The final step of the algorithm consists of an evaluation procedure of the data stored during the test routine, as discussed below.

For the determination of the damage threshold and the uncertainty in the result of the test, a linear extrapolation of the measured damage probabilities is performed. For each energy density level H_i the observed damage probability P_i is calculated by the equation:

$$P_i = \frac{n_i^{\mathrm{D}}}{n_i^{\mathrm{D}} + n_i^{\mathrm{ND}}} \tag{B.4}$$

where $n^{\mathrm{D}}{}_i + n^{\mathrm{ND}}{}_i$ is the total number of sites exposed to achieve $n^{\mathrm{D}}{}_i$ damaged sites. The uncertainty for each point i in the data set is estimated using:

$$\sigma_i = \begin{cases} \sqrt{\dfrac{n^{\mathrm{ND}}}{n_i^{\mathrm{D}}(n_i^{\mathrm{D}} + n_i^{\mathrm{ND}})} + \varepsilon_F^2} & \text{when } n^{\mathrm{D}} > 0 \\ \sqrt{\varepsilon_F^2} & \text{when } n^{\mathrm{D}} = 0 \end{cases} \tag{B.5}$$

where ε_F is the fractional uncertainty in the measured energy density.

The slope, m, and intercept, b, of the weighted linear fit to the measured damage probability curve is calculated using:

$$m = \frac{1}{\Delta}\left[\left(\sum_i \frac{1}{\sigma_i^2}\right)\left(\sum_i \frac{P_i H_i}{\sigma_i^2}\right) - \left(\sum_i \frac{H_i}{\sigma_i^2}\right)\left(\sum_i \frac{P_i}{\sigma_i^2}\right)\right] \tag{B.6}$$

where

$$\Delta = \left(\sum_i \frac{1}{\sigma_i^2}\right)\left(\sum_i \frac{H_i^2}{\sigma_i^2}\right) - \left(\sum_i \frac{H_i}{\sigma_i^2}\right)^2 \tag{B.7}$$

and

$$b = \frac{1}{\Delta}\left[\left(\sum_i \frac{H_i^2}{\sigma_i^2}\right)\left(\sum_i \frac{P_i}{\sigma_i^2}\right) - \left(\sum_i \frac{H_i}{\sigma_i^2}\right)\left(\sum_i \frac{P_i H_i}{\sigma_i^2}\right)\right] \tag{B.8}$$

The damage threshold is determined by the expression:

$$H_{\mathrm{TH}} = -\frac{b}{m} \tag{B.9}$$

The calculated threshold should be both positive and less than or equal to the lowest observed energy density causing damage. If the value of H_{TH} is not positive, the reported threshold should be given as the lowest observed energy density causing damage. Further, if any additional test sites are available, a binary search for the threshold should be conducted with highest energy density in this search being the lowest energy density corresponding to damage seen in the measurement.

The uncertainty in the threshold is determined using:

$$\sigma_{\text{Th}} = \frac{1}{m^2}\sqrt{b^2\sigma_m^2 + m^2\sigma_b^2} \tag{B.10}$$

where

$$\sigma_b = \sqrt{\frac{1}{\Delta}\sum\frac{H_i^2}{\sigma_i^2}} \tag{B.11}$$

and

$$\sigma_m = \sqrt{\frac{1}{\Delta}\sum\frac{1}{\sigma_i^2}} \tag{B.12}$$

The lower limit of the estimated threshold $H_{\text{Th}} - \sigma_{\text{Th}}$ should be positive and less than or equal to the lowest observed energy density causing damage. If either of these conditions is not fulfilled for the lower limit, then it should be replaced with 0.

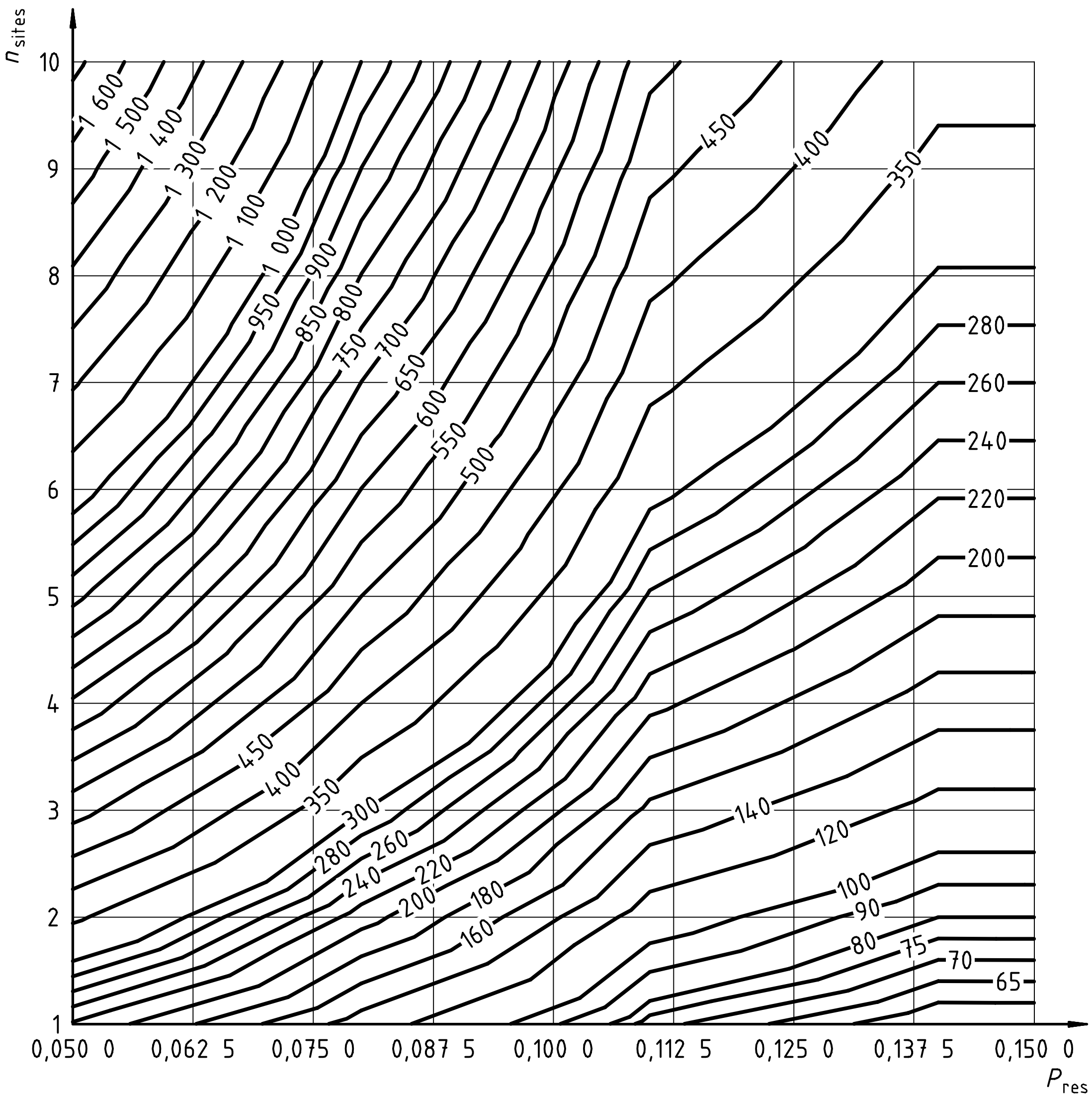


Figure B.1 — Contour plot of n_{total}

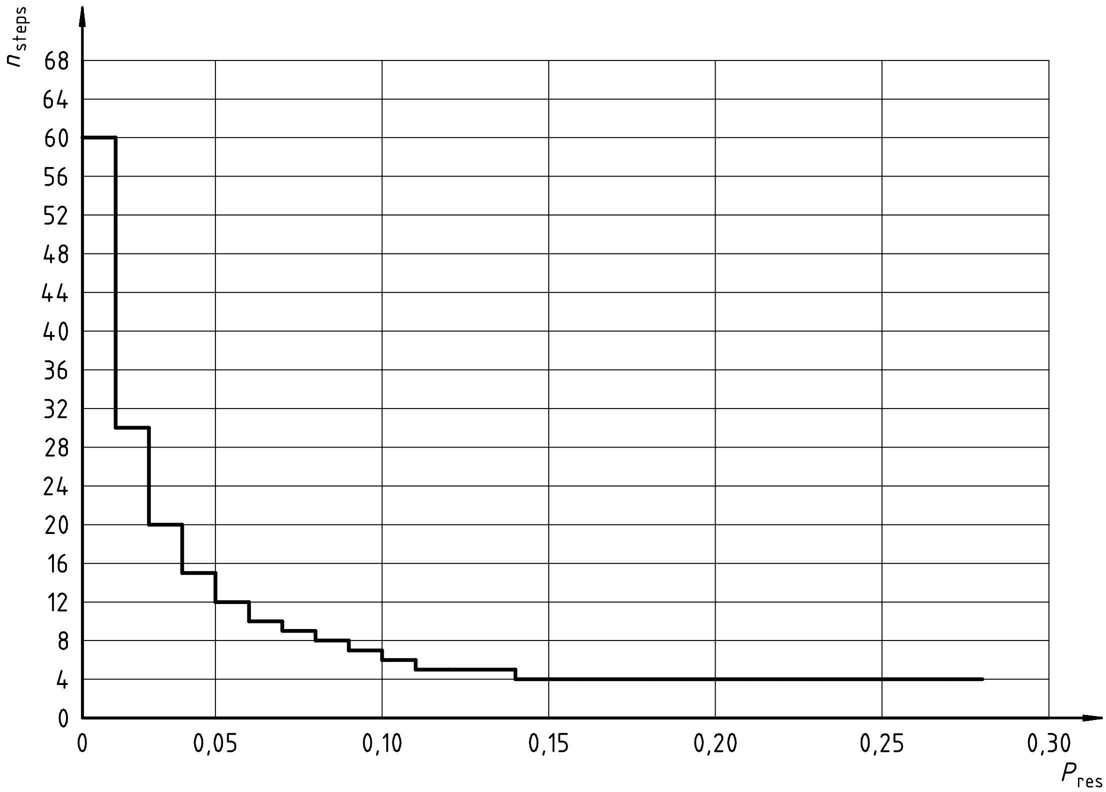


Figure B.2 — Plot of P_{res} versus n_{steps}

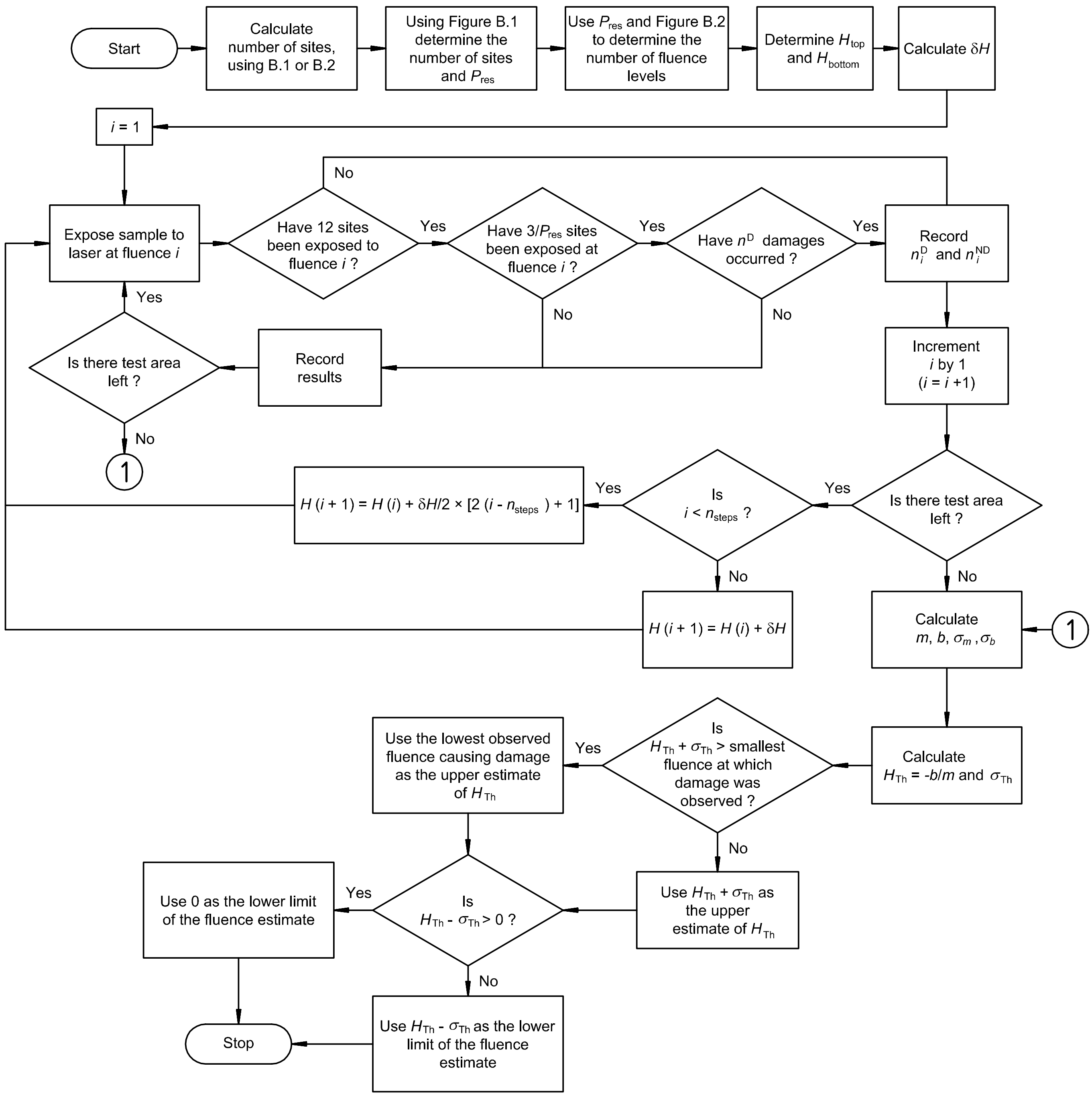


Figure B.3 — Test flow

Annex C
(informative)

Units and scaling of laser-induced damage thresholds

C.1 General

It is the purpose of this annex to inform the user of potential dangers in scaling results of a damage threshold measurement when applied to different conditions.

Excluding environmental conditions, damage is a function of material properties and the laser parameters, in particular wavelength, spot size and irradiation duration. Scaling broadly falls into three groups, depending on the component properties.

For pulsed laser irradiation in insulators, the laser-induced damage threshold correlates with dielectric breakdown. The laser-induced damage thresholds in this case are usually reported in units of watts per square centimetre (W/cm^2). Where dielectric breakdown is the dominant mechanism, there are four regimes in which the scaling laws with respect to pulse duration are different. In this case, a statement of laser-induced damage threshold shall specifically state wavelength, spot size and pulse duration.

For absorbing and semi-transmitting materials and coatings, where the laser pulses are short with respect to the thermal diffusion time, the laser-induced damage threshold is driven by the energy density level, units of joules per square centimetre (J/cm^2). For those materials subjected to longer pulses, there is significant flow of heat out of the vicinity of the laser spot; the key parameter is peak power, which is expressed in watts (W).

For very long pulses or cw-operation, for all materials, the LIDT is thermally dominated, and scales with linear power density, whose units are watts per centimetre (W/cm).

C.2 Example of incorrect scaling

This clause describes the pitfalls of an incorrect scaling and the potential dangers therein. This specific case deals with a mirror made of beryllium (Be-mirror). With a spot diameter of 0,33 mm, the maximum safe operating power is determined to be 56 W. If this result is scaled using the power density as a variable to a beam size of 5 mm diameter, the safe operating power is calculated to be 12,76 kW. When the LIDT is scaled in terms of the linear power density, the safe operating power is calculated to be 0,85 kW. The estimate of safe operating power obtained by scaling in power density is 15 times greater than the estimate derived from scaling in linear power density. If the Be-mirror were to be exposed to a laser with a spot diameter of 5 mm and 12,76 kW it would surely melt, causing an extreme safety problem.

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