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Safety of laser products —

Part 14: A user's guide

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British Standards

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TECHNICAL REPORT

IEC TR 60825-14

First edition
2004-02

Safety of laser products –

Part 14: A user's guide

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SAFETY OF LASER PRODUCTS –

Part 14: A user's guide

FOREWORD

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IEC 60825-14, which is a technical report, has been prepared by IEC technical committee 76: Optical radiation safety and laser equipment.

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

Enquiry draft	Report on voting
76/271/DTR	76/282/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.

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IEC consists of the following parts, under the general title *Safety of laser products*:

Part 1: Equipment classification, requirements and user's guide

Part 2: Safety of optical fibre communication systems

Part 3: Guidance for laser displays and shows

Part 4: Laser guards

Part 5: Manufacturer's checklist for IEC 60825-1

Part 6: Safety of products with optical sources, exclusively used for visible information transmission to the human eye

Part 7: Safety of products emitting infrared optical radiation, exclusively used for wireless 'free air' data transmission and surveillance

Part 8: Guidelines for the safe use of medical laser equipment

Part 9: Compilation of maximum permissible exposure to incoherent optical radiation

Part 10: Application guidelines and explanatory notes to IEC 60825-1

Part 12: Safety of free space optical communication systems used for transmission of information[1)]

Part 13: Measurements for classification of laser products[1)]

Part 14: A user's guide

The committee has decided that the contents of this publication will remain unchanged until 2007. At this date, the publication will be

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- withdrawn;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

[1)] To be published

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INTRODUCTION

To help in the use of this technical report, an outline of the topics that are covered within it is given below. The topics are presented in the order in which they would normally be considered as part of a laser safety programme.

– Safety responsibilities with regard to the operation of lasers and the need for appropriate training are covered in Clause 3.
– The meaning of the laser product classes and the assessment of laser exposure are covered in Clause 4.
– The determination of the maximum permissible exposure (MPE), and the concept of the hazard distance and hazard zone within which the MPE can be exceeded, are covered in Clause 5.
– Associated laser hazards (that is, hazards other than those of eye or skin exposure to the emitted laser beam) are covered in Clause 6.
– A three-stage process for evaluating risk (arising from both the laser radiation hazards discussed in Clauses 4 and 5, and the associated laser hazards discussed in Clause 6) is covered in Clause 7. These three stages are:
  1) the identification of all potentially injurious situations,
  2) the assessment of the risk arising from these situations and
  3) the determination of the necessary protective measures.
– The use of control measures for reducing the risk to an acceptable level is covered in Clause 8.
– The need to ensure the continuation over time of safe laser operation is covered in Clause 9.
– The reporting of laser-related hazardous incidents and the investigation of accidents is covered in Clause 10.
– The role of medical surveillance (eye examinations) is covered in Clause 11.
– Additional information on the use of interlock protection is given in Annex A.
– Examples of laser safety calculations are given in Annex B.
– An explanation of the biophysical effects of laser exposure to the eyes and skin is given in Annex C.

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SAFETY OF LASER PRODUCTS –

Part 14: A user's guide

1 Scope and object

This technical report provides guidance on best practice in the safe use of laser products that conform to IEC 60825-1. The terms "laser product" and "laser equipment" as used in this document also refer to any device, assembly or system, which is capable of emitting optical radiation produced by a process of stimulated emission. However, unlike IEC 60825-1, this document does not cover light-emitting diodes (LEDs).

Class 1 laser products normally pose no hazard and Class 2 laser products present only a minimal hazard. With these products, it is normally sufficient to follow the warnings on the product labels and the manufacturer’s instructions for safe use. Further protective measures as described in this document should not be necessary.

This document emphasizes evaluation of the risk from higher power lasers, but the users of the lower power lasers may benefit from the information contained. See Table 1 for an overview.

This technical report can be applied to the use of any product that incorporates a laser, whether or not it is sold or offered for sale. Therefore, it applies to specially constructed lasers (including experimental and prototype systems).

This technical report is intended to help laser users and their employers to understand the general principles of safety management (Clause 3), to identify the hazards that may be present (Clauses 4 to 6), to assess the risks of harm that may arise (Clause 7), and to set up and maintain appropriate control measures (Clauses 8 to 11).

Laser control measures vary widely. They depend on the type of laser equipment in use, the task or process being performed, the environment in which the equipment is used and the personnel who may be at risk of harm. Specific requirements for certain laser applications is given in other documents in the IEC 60825 series (see the Foreword or bibliography for the titles of these documents).

The terms “reasonably foreseeable” and “reasonably foreseeably” are used in this document in relation to certain specific events, situations or conditions. It is the responsibility of the person using this document to determine what is “reasonably foreseeable” and what might occur “reasonably foreseeably”, and to be able to defend, on the basis of risk-assessment criteria, any such judgements that are made.

Reference is made in this document to laser “users”. This should be taken to include persons having responsibility for safety in addition to those who actually work with or operate laser equipment.

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2 Terms and definitions

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

2.1
administrative control
safety measures of a non-engineering type such as key supervision, safety training of personnel, warning notices, countdown procedures, and range safety controls

2.2
alpha min
α min
See angular subtense (2.4)

2.3
angle of acceptance
γ
plane angle within which a detector will respond to optical radiation, usually measured in radians. This angle of acceptance may be controlled by apertures or optical elements in front of the detector

NOTE 1 The angle of acceptance is also sometimes referred to as the field of view.

NOTE 2 For evaluation of the photochemical hazard, a limiting measurement angle of acceptance, γ_p, is specified. The angle γ_p is biologically related to eye movements and is not dependent upon the angular subtense of the source. If the angular subtense of the source is smaller than the limiting angle of acceptance, the actual measurement angle of acceptance does not have to be limited. If the angular subtense of the source is larger than the specified limiting angle of acceptance, the angle of acceptance has to be limited and the source has to be scanned for hotspots. If the measurement angle of acceptance is not limited to the specified level, the hazard may be over-estimated.

2.4
angular subtense
α
angle subtended by an apparent source as viewed at a point in space

NOTE 1 In this standard, for classification, the angular subtense is determined at a point not less than 100 mm from the apparent source (or at the exit window or lens of the product if the apparent source is located at a distance greater than 100 mm within the window or lens). For an analysis of the maximum permissible exposure levels, the angular subtense is determined at the viewing distance from the apparent source but not less than 100 mm.

NOTE 2 The angular subtense of an apparent source is applicable in this part of IEC 60825 only in the wavelength range from 400 nm to 1 400 nm, the retinal hazard region.

NOTE 3 The angular subtense of the source should not be confused with the divergence of the beam.

2.5
aperture
any opening in the protective housing or other enclosure of a laser product through which laser radiation is emitted, thereby allowing human access to such radiation

2.5.1
aperture stop
opening serving to define the area over which radiation is measured

2.6
apparent source
real or virtual object that forms the smallest possible retinal image

NOTE This definition is used to determine the location of the apparent origin of laser radiation in the wavelength range of 400 nm to 1 400 nm, with the assumption of the apparent source being located in the eye's range of accommodation (≥100 mm). In the limit of vanishing divergence, i.e. in the case of an ideally collimated beam, the location of the apparent source goes to infinity.

The concept of an apparent source is used in the extended wavelength region 302,5 nm to 4 000 nm since focusing by conventional lenses might be possible in that region.

2.7
beam
laser radiation that may be characterized by direction, divergence, diameter or scan specifications

NOTE Scattered radiation from a non-specular reflection is not considered to be a beam.

2.8
beam attenuator
device which reduces the laser radiation to or below a specified level

2.9
beam diameter
$\boldsymbol{d_u}$
beam width
diameter of the smallest circle which contains *u* % of the total laser power (or energy). For the purpose of this standard d_{63} is used

NOTE In the case of a Gaussian beam, d_{63} corresponds to the point where the irradiance (radiant exposure) falls to 1/e of its central peak value.

2.10
beam divergence
far field plane angle of the cone defined by the beam diameter

NOTE 1 If the beam diameters at two points separated by a distance *r* are d_{63} and d'_{63}, the divergence is given by:

$$\varphi = 2 \arctan\left(\frac{d_{63} - d'_{63}}{2r}\right)$$

NOTE 2 SI unit: radian.

2.11
beam stop
device which terminates a laser beam path

2.12
Class 1 laser product
any laser product which does not permit human access to laser radiation in excess of the accessible emission limits of Class 1 for applicable wavelengths and emission durations

2.13
Class 1M laser product
any laser product in the wavelength range from 302,5 nm to 4 000 nm which does not permit human access to laser radiation in excess of the accessible emission limits of Class 1 for applicable wavelengths and emission durations, where the level of radiation is measured but is evaluated with smaller measurement apertures or at a greater distance from the apparent source than those used for Class 1 laser products

NOTE The output of a Class 1M product is therefore potentially hazardous when viewed using an optical instrument.

2.14
Class 2 laser product
any laser product, which does not permit human access to laser radiation in excess of the accessible emission limits of Class 2 for applicable wavelengths and emission durations

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2.15
Class 2M laser product
any laser product in the wavelength range from 400 nm to 700 nm which does not permit human access to laser radiation in excess of the accessible emission limits of Class 2 for applicable wavelengths and emission durations, where the level of radiation is measured but is evaluated with smaller measurement apertures or at a greater distance from the apparent source than those used for Class 2 laser products

NOTE The output of a Class 2M product is therefore potentially hazardous when viewed using an optical instrument.

2.16
Class 3R and Class 3B laser products
any laser product which permits human access to laser radiation in excess of the accessible emission limits of Class 1 and Class 2 as applicable, but which does not permit human access to laser radiation in excess of the accessible emission limits of Classes 3R and 3B (respectively) for any emission duration and wavelength

2.17
Class 4 laser product
any laser product which permits human access to laser radiation in excess of the accessible emission limits of Class 3B

2.18
collateral radiation
any electromagnetic radiation, within the wavelength range between 180 nm and 1 mm, except laser radiation, emitted by a laser product as a result of, or physically necessary for, the operation of a laser

2.19
collimated beam
"parallel" beam of radiation with very small angular divergence or convergence

2.20
continuous wave
CW
output of a laser which is operated in a continuous rather than pulsed mode. In this part of IEC 60825, a laser operating with a continuous output for a period equal to or greater than 0,25 s is regarded as a CW laser

2.21
defined beam path
an intended path of a laser beam within the laser product

2.22
diffuse reflection
change of the spatial distribution of a beam of radiation by scattering in many directions by a surface or medium.

NOTE 1 A perfect diffuser destroys all correlation between the directions of the incident and emergent radiation.

NOTE 2 This definition is different from IEV 845-04-47.

2.23
embedded laser product
laser product which, because of engineering features limiting the accessible emissions, has been assigned a class number lower than the inherent capability of the laser incorporated

NOTE The laser which is incorporated in the embedded laser product is called the embedded laser.

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2.24
emission duration
temporal duration of a pulse, of a train or series of pulses, or of continuous operation, during which human access to laser radiation could occur as a result of operation, maintenance or servicing of a laser product. For a train of pulses, this is the duration between the first half-peak power point of the leading pulse and the last half-peak power point of the trailing pulse

2.25
exposure duration
see exposure time (2.26).

2.26
exposure time
duration of a pulse, or series, or train of pulses or of continuous emission of laser radiation incident upon the human body. For a train of pulses, this is the duration between the first half-peak power point of the leading pulse and the last half-peak power point of the trailing pulse

2.27
extended source viewing
viewing conditions whereby the apparent source at a distance of 100 mm or more subtends an angle at the eye greater than the limiting angular subtense (α_{min})

NOTE Two extended source conditions are considered in this standard when considering retinal thermal injury hazards: intermediate source and large source, which are used to distinguish sources with angular subtenses, α, between α_{min} and α_{max} (intermediate sources), and greater than α_{max} (large sources).

Examples are viewing of some diffuse reflections and of some laser diode arrays.

2.28
fail safe
design consideration in which failure of a component does not increase the hazard. In the failure mode the system is rendered inoperative or non-hazardous

2.29
human access

a) capability of a part of the human body to meet hazardous laser radiation either as emitted from an aperture, or capability of a straight 12 mm diameter probe up to 80 mm long to intercept laser radiation of Class 2, 2M or 3R; or

b) for levels of laser radiation within a housing that exceed the limits in a), the capability for any part of the human body to meet hazardous laser radiation that can be reflected directly by any single introduced flat surface from the interior of the product through any opening in its protective housing

2.30
integrated radiance
integral of the radiance over a given exposure time expressed as radiant energy per unit area of a radiating surface per unit solid angle of emission (usually expressed as $J \cdot m^{-2} \cdot sr^{-1}$)

2.31
intrabeam viewing
all viewing conditions whereby the eye is exposed to the direct or specularly reflected laser beam in contrast, for example, to viewing of diffuse reflections

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2.32
irradiance
E
quotient of the radiant flux $d\Phi$ incident on an element of a surface by the area dA of that element:

$$E = \frac{d\Phi}{dA}$$

NOTE SI unit: watt per square metre ($W \cdot m^{-2}$).

2.33
laser
any device which can be made to produce or amplify electromagnetic radiation in the wavelength range from 180 nm to 1 mm primarily by the process of controlled stimulated emission.

NOTE This definition is different from IEV 845-04-39.

2.34
laser controlled area
area where the occupancy and activity of those within is subject to control and supervision for the purpose of protection from radiation hazards

2.35
laser energy source
any device intended for use in conjunction with a laser to supply energy for the excitation of electrons, ions, or molecules.

NOTE General energy sources such as electrical supply mains or batteries are not considered to constitute laser energy sources.

2.36
laser equipment
laser product – an assembly that is or contains a laser

2.37
laser product
any product or assembly of components which constitutes, incorporates or is intended to incorporate a laser or laser system, and which is not sold to another manufacturer for use as a component (or replacement for such component) of an electronic product

2.38
laser radiation
all electromagnetic radiation emitted by a laser product between 180 nm and 1 mm which is produced as a result of controlled stimulated emission

2.39
laser safety officer
one who is knowledgeable in the evaluation and control of laser hazards and has responsibility for oversight of the control of laser hazards

2.40
laser system
laser in combination with an appropriate laser energy source with or without additional incorporated components

2.41
limiting aperture
circular area over which irradiance and radiant exposure are averaged

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2.42
maintenance
performance of those adjustments or procedures specified in user information provided by the manufacturer with the laser product, which are to be performed by the user for the purpose of assuring the intended performance of the product. It does not include operation or service

2.43
maximum angular subtense
α max
value of angular subtense of the apparent source above which the MPEs are independent of the source size

2.44
maximum permissible exposure
MPE
that level of laser radiation to which, under normal circumstances, persons may be exposed without suffering adverse effects. The MPE levels represent the maximum level to which the eye or skin can be exposed without consequential injury immediately or after a long time and are related to the wavelength of the radiation, the pulse duration or exposure time, the tissue at risk and, for visible and near infra-red radiation in the range 400 nm to 1 400 nm, the size of the retinal image

NOTE 1 The values for maximum permissible exposure used in this document are those recommended by the International Commission on Non-Ionizing Radiation Protection, and are based on the current state of knowledge of threshold levels for laser injury.

NOTE 2 Annex B gives examples of the calculations of MPE levels.

2.45
minimum angular subtense
α min
value of angular subtense of the apparent source above which a source is considered an extended source

NOTE MPEs are independent of the source size for angular subtenses less than α_{min}.

2.46
nominal ocular hazard area
NOHA
area within which the beam irradiance or radiant exposure exceeds the appropriate corneal maximum permissible exposure (MPE), including the possibility of accidental misdirection of the laser beam

NOTE If the NOHA includes the possibility of viewing through optical aids, this is termed the "extended NOHA".

2.47
nominal ocular hazard distance
NOHD
distance at which the beam irradiance or radiant exposure equals the appropriate corneal maximum permissible exposure (MPE)

NOTE If the NOHD includes the possibility of optically-aided viewing, this is termed the "extended NOHD".

2.48
operation
performance of the laser product over the full range of its intended functions. It does not include maintenance or service

2.49
optical density
OD
logarithm to base ten of the reciprocal of the transmittance τ

Symbol: D $D = -\log_{10} \tau$

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2.50
photochemical hazard limit
MPE that was derived to protect persons against adverse photochemical effects

NOTE An example of such adverse effects is photoretinitis, a photochemical retinal injury from exposure to radiation in the wavelength range from 400 nm to 600 nm.

2.51
protective enclosure
physical means for preventing human exposure to laser radiation unless such access is necessary for the intended functions of the installation

2.52
protective housing
those portions of a laser product (including a product incorporating an embedded laser), which are designed to prevent human access to laser radiation in excess of the level required by the laser product's prescribed classification (generally installed by a manufacturer)

2.53
pulse duration
time increment measured between the half peak power points at the leading and trailing edges of a pulse

2.54
pulsed laser
laser which delivers its energy in the form of a single pulse or a train of pulses. In this part of IEC 60825, the duration of a pulse is less than 0,25 s

2.55
radiance
L
quantity defined by the formula

$$L = \frac{\mathrm{d}\Phi}{\mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}\Omega}$$

where

- $\mathrm{d}\Phi$ is the radiant flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $\mathrm{d}\Omega$ containing the given direction;
- $\mathrm{d}A$ is the area of a section of that beam containing the given point;
- θ is the angle between the normal to that section and the direction of the beam

NOTE 1 Unit: $W \cdot m^{-2} \cdot sr^{-1}$.

NOTE 2 This definition is a simplified version of IEV 845-01-34, sufficient for the purpose of this part. In cases of doubt, the IEV definition should be followed.

2.56
radiant energy
Q
time integral of the radiant flux over a given duration Δt

$$Q = \int_{\Delta t} \Phi \mathrm{d}t$$

NOTE SI unit: joule (J).

(IEV 845-01-27)

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2.57
radiant exposure
H
at a point on a surface, the radiant energy incident on an element of a surface divided by the area of that element

$$H = \frac{dQ}{dA} = \int E dt$$

NOTE SI unit: joule per square metre ($J \cdot m^{-2}$).

2.58
radiant power
radiant flux
Φ, P
power emitted, transferred, or received in the form of radiation

$$\Phi = \frac{dQ}{dt}$$

NOTE SI unit: watt (W).

2.59
reflectance
ρ
ratio of the reflected radiant power to the incident radiant power in the given conditions

NOTE SI unit: 1.

2.60
remote interlock connector
connector which permits the connection of external controls placed apart from other components of the laser product

2.61
safety interlock
automatic device associated with the protective housing of a laser product to prevent human access to Class 3 or Class 4 laser radiation when that portion of the housing is removed

2.62
service
performance of those procedures or adjustments described in the manufacturer's service instructions which may affect any aspect of the product's performance. It does not include maintenance or operation

2.63
single fault condition
any single fault that might occur in a product and the direct consequences of that fault

2.64
small source
source with an angular subtense α less than, or equal to, the minimum angular subtense α_{min}

2.65
specular reflection
reflection from a surface which maintains angular correlation between incident and reflected beams of radiation, as with reflections from a mirror

2.66
thermal hazard limit
MPE that was derived to protect persons against adverse thermal effects, as opposed to photochemical injury

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2.67
time base
emission duration to be considered for classification

2.68
tool
denotes a screwdriver, a coin, or other object which may be used to operate a screw or similar fixing means

2.69
transmittance
τ
ratio of the transmitted radiant flux to the incident flux in the given conditions

NOTE SI unit: 1.

2.70
visible radiation (light)
any optical radiation capable of causing a visual sensation directly

NOTE In this part of IEC 60825, this is taken to mean electromagnetic radiation for which the wavelength of the monochromatic components lies between 400 nm and 700 nm.

3 Administrative policies

3.1 Safety responsibilities

Safety responsibilities may be specified by national or local regulations. These specific responsibilities should be followed. However, in the absence of any specific legislation or regulations, the following are some general guides on responsibilities for the safe use of lasers.

Employers and employees, and all users of lasers (including students) and those supervising or overseeing them, have a role to play in maintaining a safe place of work and in ensuring that their activities do not present unacceptable levels of risk to themselves or to others.

In any place of work in which lasers are in use, it is the employer's responsibility to ensure that the risks to health arising from the use and reasonably foreseeable misuse of laser equipment are properly assessed. The employer must take all necessary steps to ensure that these risks are either eliminated or, where this is not reasonably practicable, reduced to an acceptably low level.

Wherever potentially hazardous lasers are in use, the employer (or any other person having overall responsibility) should establish a general policy for the safe management of these hazards, although specific safety tasks may be delegated to others. This policy, which should be an integral part of the organisation's overall safety policy, should require that all reasonably foreseeable hazards arising from laser use are identified and that steps are taken to control them so far as is reasonably practicable. Significant findings of this assessment should be documented and appropriate protective measures implemented wherever necessary to reduce the identified health and safety risks. The effectiveness of such protective measures should be reviewed regularly. These requirements for establishing a specific safety policy for lasers are not normally necessary where only laser products in Class 1 or Class 2 are in use, and may not always be necessary for laser products in Class 1M or Class 2M, but see Table 1 concerning protective control measures, 4.1.3 concerning embedded lasers and 4.2.2 concerning temporary visual effects.

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3.2 Competent persons

Where the employer or laser user is not able, without assistance, to properly determine the necessary safety arrangements and protective measures for eliminating or minimising the risks to health arising from the use of laser equipment, then the advice of a Competent Person should be sought. The Competent Person should have sufficient skill in, and knowledge and experience of, matters relevant to laser safety, and should provide appropriate assistance to the employer (or to the employer's delegated representative, or laser user) in hazard determination, risk assessment, and protective control and procedure provision.

The Competent Person need not be an employee of the organisation concerned, but may instead be an external adviser. The advice and assistance of a Competent Person is often only necessary temporarily, for example when first establishing appropriate protective control measures or when evaluating the risk prior to significant changes to procedures or equipment.

3.3 Laser Safety Officer

A Laser Safety Officer should be appointed in organisations in which Class 3B or Class 4 laser products are in use. The appointment of a Laser Safety Officer is also recommended where Class 1M and Class 2M laser products generating well-collimated beams are in use, and which could present a hazard if viewed through binoculars or telescopes at a considerable distance from the laser. (This can include the installation and servicing of embedded lasers where access may be gained to higher levels of laser radiation than is implied by the laser product’s class (see 4.1.3), or where the use of lasers of a lower class than 3B or 4 may nevertheless still introduce a significant risk, perhaps through the involvement of untrained people or because of the existence of associated laser hazards – see Clause 6.)

The Laser Safety Officer should take responsibility, on behalf of the employer, for the administration of day-to-day matters of laser safety. It is the employer's responsibility to ensure that the person appointed as Laser Safety Officer has sufficient competence and capability to perform this role satisfactorily. Suitable training should be provided if necessary.

The duties of the Laser Safety Officer should be agreed with the employer (or with the employer's delegated representative) and documented. These duties should be those necessary to ensure the continuing safe use of lasers within the organisation concerned, but are likely to include as a minimum:

a) being aware of and, if appropriate, maintaining records of, all potentially-hazardous laser products (including the identification, specification, class and purpose of the laser product; the location of the laser product; and any special requirements or restrictions relating to its use);
b) responsibility for monitoring compliance with the organisation's procedures for ensuring safe laser use, for maintaining appropriate written records, and for taking immediate and appropriate action in respect of any non-compliance or apparent inadequacy in such procedures.

Whether the Laser Safety Officer can authorise, or merely recommend to a person having such authority, the termination of unsafe practices and the implementation of corrective actions should be agreed and specified in the documented duties.

The role of Laser Safety Officer rarely needs to be a full-time appointment. Where a Competent Person (see 3.2) has been appointed and that person is an employee of the organisation concerned (often desirable in organisations having extensive and varied laser use), then the Competent Person may also be the Laser Safety Officer.

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In large organisations where there is extensive laser use, suitable employees may be appointed to act as local-area or departmental laser safety representatives in order to assist the Laser Safety Officer and to ensure, on behalf of the employer, safe laser use throughout the organisation. (The titles Laser Safety Officers and Senior Laser Safety Officer may be used, respectively, instead.) In such circumstances, regular liaison should be maintained between these people to ensure the consistent and effective overall management of the laser safety programme.

3.4 Information and training

All employees should, where relevant, be made aware of any hazards (including associated hazards; see Clause 6) to which they may be exposed during the use of laser equipment, and of the procedures necessary to ensure protection. Adequate warnings should be displayed. These warnings should include the laser hazard symbol shown in Figure 1 with appropriate wording. Sufficient instruction or training should be given in order that employees have the necessary understanding to avoid placing themselves and others at unacceptable risk. Safety training is especially important for those who work with Class 3B or Class 4 laser products.

Such instruction and training should be commensurate with the type of hazard and appropriate for the employees concerned. It should include, but need not be limited to:

a) the organisation's policy for safe laser use;

b) the risks of harm that could arise from the use and reasonably foreseeable misuse of the laser equipment;

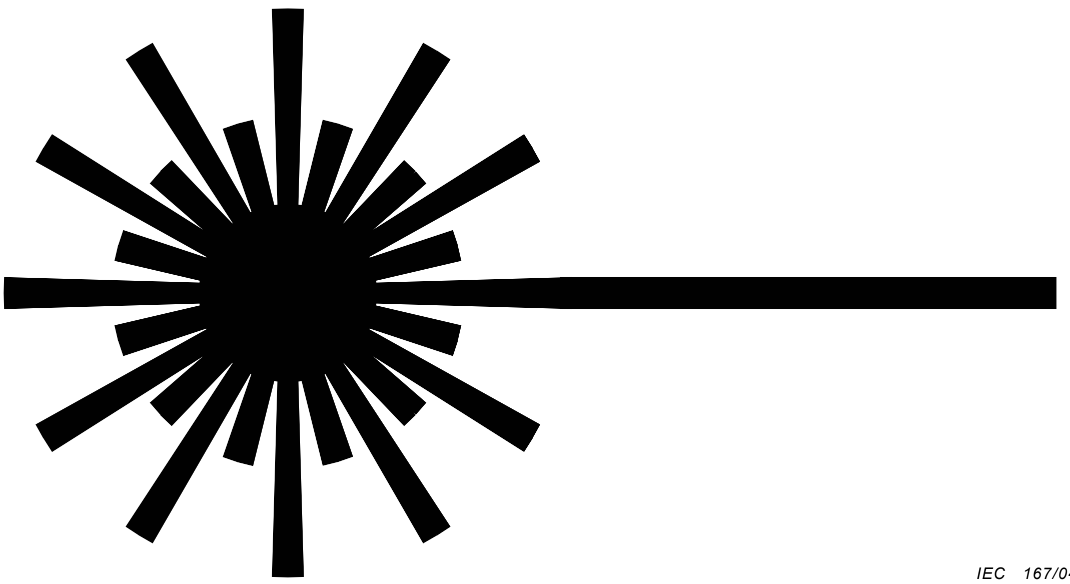
c) the meaning of displayed warning signs;

d) the correct use and operation of the laser equipment, and of associated equipment, including personal protective equipment (where applicable – see 8.4.5);

e) working procedures and local rules;

f) the procedures to be followed in the event of an actual or suspected accident or other safety-related incident.

Instruction and training should be completed prior to operating or working with laser products, and repeated as frequently as necessary in order to ensure continuing compliance with safety procedures. Records of training should be kept.



IEC 167/04

Figure 1 – Laser hazard symbol

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4 Laser radiation hazards

4.1 Laser products

4.1.1 Laser product classification

The class of a laser product gives an indication to the user of the potential of the accessible laser radiation for causing injury. All laser equipment, whether commercially produced or not, should therefore be classified in accordance with the provisions of IEC 60825-1, and labelled appropriately to inform the user of the class assigned. Classification of laser products is normally done by the manufacturer of the laser product, but where this is not the case (e.g., laser components, experimental or prototype systems), then the user should ensure that the effective class of the laser is determined based on the level of its accessible emission in accordance with IEC 60825-1.

If the user incorporates a laser into other equipment, then the complete equipment should itself be considered a laser product and be classified accordingly (see 4.1.3). In addition, it should be recognised that some or all of the original safety features of the incorporated laser product, including labelling, and which are intended to satisfy the manufacturing requirements specified in IEC 60825-1, may be inoperative, unusable or inaccessible because of the way in which the laser has been incorporated into the equipment. Where necessary to ensure safe operation, these safety features should be replicated or replaced.

4.1.2 Product classes

The classification of a laser gives an indication of its potential hazard. Laser product classification is based on the maximum level of laser radiation that is accessible during conditions of normal operation. Associated hazards (see Clause 6) that may also be present during use of the laser do not affect the laser classification.

The laser product classes are outlined below, together with a brief description of the protection requirements that should normally be satisfied for each product class. Except for Classes 2 and 2M, the emitted radiation may be visible or invisible. (For more complete details of classification, IEC 60825-1 should be consulted.)

a) **Class 1**

Laser products which are normally safe under reasonably foreseeable conditions of use, either because of the inherently low emission of the lasers themselves, or because they are totally enclosed and human access to higher levels of internal laser radiation is not possible during normal operation.

Protection requirements for Class 1: Ensure that the conditions for Class 1 operation are maintained (see 4.1.3). If access to levels of laser radiation in excess of the limits for Class 1 could occur, for example during servicing of an embedded laser product, or in the case of an expanded-beam laser by using external optics to reduce the size or divergence of the emitted beam then the protection requirements of the appropriate higher class apply.)

b) **Class 1M**

Laser products which exceed the permitted accessible emission limits for Class 1 but which, because of the geometrical spread of the emitted radiation, cannot cause harmful levels of exposure to the unaided eye. However, the safe limit for ocular exposure can be exceeded, and injury can occur, if magnifying viewing instruments are used. Such instruments include binoculars and telescopes in the case of large-diameter collimated beams, or magnifying lenses and microscopes in the case of highly divergent beams. Hazardous exposure can also occur if the dimensions of the laser beam (its diameter or divergence) are reduced by the use of optical components in the beam path.

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Protection requirements for Class 1M: Avoid the use of magnifying viewing aids or instruments (such as binoculars, telescopes, microscopes and magnifying lenses, but not spectacles or contact lenses). Avoid placing optical devices in the emitted beam that could cause the concentration of the laser radiation to be increased. Do not direct the beam into areas where other people may be present if there is a likelihood of the people in those areas using telescopes or binoculars to look directly into the beam.

c) **Class 2**

Laser products emitting low-levels of visible radiation (that is, at wavelengths between 400 nm and 700 nm) which are safe for the skin but which are not inherently safe for the eyes, but for which eye protection is normally afforded by natural aversion responses to bright light. Accidental eye exposure is therefore normally safe, although the natural aversion response can be overridden intentionally by deliberately staring into the beam, and can be influenced by taking alcohol or drugs.

Protection requirements for Class 2: Avoid staring into the beam (i.e. deliberate viewing of the laser source) or pointing the beam at other people.

d) **Class 2M**

Laser products emitting levels of visible radiation that exceed the permitted accessible emission limits for Class 2 but for which, because of the geometrical spread of the emitted radiation, protection of the unaided eye is normally afforded by natural aversion responses to bright light. However, the aversion response may not provide sufficient protection, and injury can occur, if magnifying viewing instruments are used. Such instruments include binoculars and telescopes in the case of large-diameter collimated beams, or magnifying lenses and microscopes in the case of highly divergent beams. Hazardous exposure can also occur if the dimensions of the laser beam (its diameter or divergence) are reduced by the use of optical components in the beam path.

Protection requirements for Class 2M: Avoid the use of magnifying viewing aids or instruments (such as binoculars, telescopes, microscopes and magnifying lenses, but not spectacles or contact lenses). Avoid placing optical devices in the emitted beam, which could cause the concentration of the laser radiation to be increased. Avoid staring into the beam (i.e. deliberate viewing of the laser source) or pointing the beam at other people.

e) **Class 3R**

Laser products having a level of accessible emission up to five times the limits for Class 1 (if invisible) or Class 2 (if visible). The maximum permissible exposure may be exceeded but the risk of injury is low.

Protection requirements for Class 3R: Prevent direct eye exposure to the beam or pointing the beam at other people.

f) **Class 3B**

Laser products having a level of accessible emission, which can be harmful to the eyes, whether magnifying viewing aids are used or not. Class 3B laser products can also be harmful to the skin at output levels approaching the upper limit of this class.

Protection requirements for Class 3B: Prevent eye (and in some cases skin) exposure to the beam. Guard against unintentional beam reflections.

g) **Class 4**

Laser products having a level of accessible emission, which can be harmful to both the eyes and the skin. Diffuse reflections of the laser radiation may also be hazardous. The laser emission can also be sufficient to ignite material, on which it impinges, and to generate harmful radiation or fume hazards by interaction with target materials.

Protection requirements for Class 4: Prevent eye and skin exposure to the beam, and to diffuse reflections (scattering) of the beam. Protect against beam interaction hazards such as fire and fume.

End use laser products in classes 2, 2M, 3R, 3B and 4 which are supplied in accordance with IEC 60825-1 will carry warning labels indicating the class and the basic precautions to be followed. Laser products in classes 1 and 1M may also carry labels, but at the discretion of the manufacturer, the required wording can instead be included in the user information.

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It is recommended that unlabelled lasers (including component lasers or user-modified systems) that are in regular use be appropriately labelled in accordance with the labelling requirements of IEC 60825-1.

In many applications where the laser products in use are no higher than Class 3R (i.e. they are Class 1, 1M, 2, 2M or 3R), the user may implement control measures based on the highest class of laser product in use without any need to undertake a detailed risk assessment or to evaluate possible levels of human exposure. These default control measures are summarised in Table 1 as a function of the laser class.

It may often be necessary, however, for a more detailed analysis to be undertaken in order to determine the protective measures that are appropriate. Such circumstances include:

– all uses of laser products in Class 3B or 4,
– the use of protective eyewear,
– reliance for protection on the concept of a minimum safe distance from the laser, and
– other situations where the controls specified in Table 1 may be inappropriate, insufficient or unreasonably restrictive given the actual degree of risk.

NOTE Many older laser products will be classified under the previous scheme of Classes 1, 2, 3A, 3B and 4. IEC 60825-1 may be used to determine the class that the product would be in under the current system of classification. The majority of laser products in classes 1, 2, and 4 will, however, be unaffected.

Table 1 – Default protective control measures for laser products

CLASS	PROTECTIVE CONTROL MEASURES These should be implemented unless a risk assessment justifying the adoption of alternative protective control measures has been undertaken.
1	No protective control measures are necessary under conditions of normal operation. (This may not be the case under conditions of maintenance or service.) In the case of embedded laser products containing a laser of higher power, follow instructions given on warning labels and supplied by the manufacturer. Special precautions may be needed for on-site servicing of embedded laser products (see 8.5).
1M	Prevent direct viewing of the laser source through magnifying viewing instruments, such as binoculars, telescopes, microscopes, optical sights or magnifying lenses, unless these incorporate adequate levels of protection[a]. Prevent the use of any external optics that could decrease the beam divergence or its diameter.
2	Do not stare into the beam. Do not direct the beam at other people or into areas where other people unconnected with the laser work might be present.
2M	Do not stare into the beam. Do not direct the beam at other people or into areas where other people unconnected with the laser work might be present. Ensure the beam is always terminated at a suitable non-specular (i.e. non mirror-like) surface. Prevent direct viewing of the laser source through magnifying viewing instruments, such as binoculars, telescopes, microscopes, optical sights or magnifying lenses, unless these incorporate adequate levels of protection[a]. Prevent the use of any external optics that could decrease the beam divergence or its diameter.
3R	Prevent direct eye exposure to the beam. Do not direct the beam at other people or into areas where other people unconnected with the laser work may be present.
3B and 4	Class 3B and Class 4 laser products should not be used without first carrying out a risk assessment to determine the protective control measures necessary to ensure safe operation. Where reasonably practicable, use engineering means, as specified in IEC 60825-1, to reduce the class of the laser to below Class 3B. (This will normally mean completely enclosing the laser radiation to form a Class 1 laser product.)
[a] The type of viewing instrument that could be hazardous may be indicated on the warning label or in the user information supplied by the manufacturer.	

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4.1.3 Embedded lasers

Since laser products are classified based on the level of laser radiation that is accessible during normal operation, a laser product of one class may contain an embedded (i.e. enclosed) laser of a higher class. This is most commonly encountered in the case of a product assigned to Class 1 but which incorporates an embedded laser that has been totally enclosed in a manner satisfying the manufacturing requirements of IEC 60825-1. Opening, removal or displacement of any part of an enclosure that is not designed to be opened, removed or displaced during operation may therefore give access to harmful levels of laser radiation. Procedures for the servicing of embedded lasers are discussed in 8.5.

Examples of Class 1 products that incorporate embedded lasers but have no accessible laser emission during normal operation include compact disc (CD) players, laser printers, and totally-enclosed industrial machining lasers. Examples of embedded laser products that have accessible laser emission include certain scanning lasers (such as bar code readers) where the rapidly moving beam may place the product in a lower class than would be the case for a stationary beam, and lasers employing various optical systems that expand or spread the emitted beam, thereby making it less hazardous.

IEC 60825-1 requires that, during operation for its intended function, the designated class of a laser product should be applicable under the maximum level of accessible emission and under all reasonably foreseeable single fault conditions. Some products, within any class other than Class 4, may incorporate a laser having accessible emission that is constrained within that class by the design of the electronic drive circuitry or by other means, even though the laser itself is capable of generating a level of emission that would place it in a higher class. Users of such products should therefore be aware that under a combination of fault conditions, or when used in a manner other than that intended by the manufacturer, higher levels of laser radiation can become accessible. The user should refer to the manufacturer's operating instructions in order to avoid exposure to potentially hazardous laser radiation.

4.1.4 Optical fibres

Optical fibres carrying laser radiation normally provide a complete enclosure of the radiation, and so prevent access to it. However, if a fibre is disconnected or a fibre break occurs, hazardous levels of laser exposure can be present.

Safety requirements specifically applicable to optical fibre communication systems are defined in IEC 60825-2. These requirements include the necessity for assessing the potential level of accessible laser emission from an optical fibre in terms of the *hazard level* (e.g., hazard level 1, 1M, 2, 2M, 3R, 3B or 4), equivalent to product class. The hazard level applies only to a particular location at which an interruption of the fibre might reasonably foreseeably occur, rather than to the complete system or installation as a whole. It is therefore possible that different locations at which access to fibre emission could occur within the same system may be assigned different hazard levels. This is not possible for product class, which is based on the highest level of accessible emission from a complete laser product.

4.1.5 Laser demonstrations and displays

Only Class 1, Class 2, or visible-beam Class 3R laser products should normally be used for demonstration, display, or entertainment purposes in unsupervised areas.

The use of other classes of laser products for such purposes should be permitted only:

1) after a risk assessment has been carried out to determine the protective control measures that are necessary;
2) when the laser operation is under the control of an experienced, well-trained operator, and/or when spectators are prevented from exposure to levels exceeding the applicable maximum permissible exposure (MPE).

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IEC 60825-3 gives specific guidance for laser displays and shows, although many countries have issued their own national guidelines.

4.2 Exposure to laser radiation

4.2.1 Maximum permissible exposure

One of the principal aims of a laser safety programme is to ensure that any exposure to laser radiation that might occur is within safe limits. It is therefore often necessary to assess the maximum level of exposure that could arise under all foreseeable conditions (as discussed in 4.3), and then to relate this to the maximum permissible exposure (the MPE, outlined below and explained in more detail in Clause 5).

NOTE The need to ensure that levels of exposure to laser radiation do not exceed the MPE is not applicable to the intentional exposure of a patient during medical treatment.

For any laser whose radiation emission is potentially hazardous (normally a laser of any class other than Class 1 or Class 2), protective measures may be necessary to ensure that reasonably foreseeable levels of human exposure to laser radiation cannot exceed the maximum permissible exposure (MPE). Wherever reasonably practicable, this should be done by total enclosure of the radiation and the complete elimination of the hazard at its source. Where this is not feasible, the necessary protective measures should be determined on the basis of a risk assessment as discussed in Clause 7. However, the levels of exposure that might arise and the conditions under which hazardous levels of exposure can occur should first be evaluated.

Values of MPE are given for eye and skin exposure in Tables 5, 6 and 7 as functions of the laser emission wavelength and exposure duration. They are discussed in more detail in Clause 5. The International Commission on Non-Ionising Radiation Protection (ICNIRP) develops these values. They are set below known damage thresholds and are based on the best available information. The MPE values should be used as guides in the control of exposure and should not be regarded as precisely defined dividing lines between safe and hazardous levels. Because exposure to laser radiation below the MPE can still be uncomfortable in certain circumstances and may cause secondary hazards (as explained below), exposure should in any case be kept as low as reasonably practicable.

4.2.2 Temporary visual effects

Visible emission from lasers can cause disturbing and potentially dangerous dazzle effects at exposure levels that are well below the maximum permissible exposure (see 4.2.1) and which therefore cause no direct physiological injury. This is especially so with laser classes 2, 2M and 3R (includes laser pointers and low-power alignment lasers). These should not therefore be directed, whether intentionally or unintentionally, at a person's eyes. This can startle and distract the exposed person, and can cause them to lose concentration, with particularly serious consequences if the person is performing a safety-critical task, such as driving or controlling machinery. It can also produce disturbing after-images, generate fear, and induce reactions such as watering eyes and headaches if the person believes that they might have suffered injury as a consequence of exposure. Persistent rubbing of the eyes in response to a perceived injury can also result in painful corneal abrasions.

4.3 Determining the level of laser exposure

4.3.1 The effective exposure

An assessment of laser exposure may be needed in order to determine the boundary of the laser hazard zone, or to specify the level of protection that is necessary (for example, with the use of laser protective eyewear or protective viewing windows).

The level of human exposure arising from a laser product should be determined at the positions at which it is reasonably foreseeable that a person might be located and where the highest levels of exposure can occur. This evaluation should take into account all reasonably foreseeable conditions of direct beam emission and beam reflection.

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This maximum anticipated level of exposure is not necessarily the same as that which would arise immediately adjacent to the emission aperture of the laser, although for persons who are in reasonably close proximity to a laser producing a collimated beam it will be.

For CW (continuous wave) lasers, the exposure will normally be expressed in terms of the incident irradiance, specified in units of watts per square metre. With pulsed lasers, both the average irradiance (in watts per square metre) and the radiant exposure due to a single pulse (and specified in joules per square metre) will usually need to be known. In assessing the level of exposure, careful attention must be made to the relevant limiting aperture (see 4.3.2) and where relevant, to the procedures for dealing with large (*extended*) laser sources (see 4.3.3 and 5.4). These considerations can mean that the value of the applicable exposure (called the *effective* exposure) that must be used for comparison with the MPE may not be the same as the exposure that would actually arise.

The main parameters that may be needed for exposure assessment are as follows:

- emission wavelength;
- beam dimensions at laser output;
- beam divergence and position of the beam waist;
- beam profile (power or energy distribution across the beam);
- maximum reasonably foreseeable exposure duration;
- minimum reasonably foreseeable exposure distance;
- angular subtense of apparent source (this is usually only needed for laser arrays and for the assessment of diffuse, i.e. non-specular, beam reflections, in order to determine the relevant exposure parameters and to calculate the value of the correction factor C6. In the case of single laser sources C6 normally has the value 1);
- for scanning beams, the scanning characteristics and scan geometry.

In addition, for continuous (CW) emission:

- beam power;

and for pulsed emission:

- pulse energy;
- pulse duration;
- pulse repetition frequency;
- pulse shape and pulse distribution in time (if complex).

Levels of exposure may be determined by physical measurement, or by calculation based on the emission parameters of the laser as specified by the manufacturer.

The profiles of most laser beams are non-uniform, and therefore the irradiance or radiant exposure arising from exposure to the beam will vary across the exposed area (in most cases having a maximum value at the centre of the beam). The MPE relates to the value of the exposure (irradiance or radiant exposure) when averaged over a circular area defined by the relevant limiting aperture, as defined in 4.3.2. For purposes of comparison with the MPE, therefore, an exposure is equivalent to the power (in the case of irradiance) or to the energy (in the case of radiant exposure) that is contained within the specified limiting aperture, divided by the area of the limiting aperture.

Where an exposure covers an area that is much larger than the limiting aperture, the maximum (normally on-axis) value of the irradiance or radiant exposure can be used.

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NOTE For circular beams having an approximately Gaussian profile, the on-axis value is equal to the total beam power or energy divided by the area of the beam determined on the basis of its 1/e diameter. This area contains 63 % of the total beam power or energy. The 1/e diameter is the diameter at which the beam irradiance, radiant exposure or radiant intensity has decreased to 1/e, or 0,37, of the peak, on-axis value. In many cases, however, the diameter of the beam will be specified by the manufacturer in terms of the $1/e^2$ value. The $1/e^2$ diameter is equal to the 1/e diameter multiplied by 1,4.

In other cases a more careful assessment of the total power or energy contained within the relevant limiting aperture may be necessary. For beams that are smaller than the relevant limiting aperture, the effective exposure (for purposes of comparison with the MPE) is the total power or energy of the beam divided by the area of the limiting aperture, not by the actual area of the beam.

4.3.2 Limiting apertures

An appropriate averaging aperture should be used for all measurements and calculations of exposure values. This is referred to as the limiting aperture, and is defined in terms of the diameter of a circular area over which the irradiance or radiant exposure is to be averaged. Values for the limiting apertures are shown in Table 2.

Table 2 – The diameter of the limiting aperture applicable to measurements of irradiance and radiant exposure (*t* is the exposure duration)

Spectral region nm	**Aperture diameter for**	
	Eye mm	**Skin** mm
180 to 400	1	3,5
≥ 400 to 1 400	7	3,5
≥ 1 400 to 10^5	1 for $t \le 0,35$ s $1,5\ t^{3/8}$ for $0,35\ \text{s} < t < 10$ s 3,5 for $t \ge 10$ s	3,5
≥ 10^5 to 10^6	11	11

For repetitively pulsed laser exposures within the spectral range between 1 400 nm and 10^5 nm, the 1 mm aperture is used for evaluating the ocular hazard from an individual pulse of duration no greater than 0,35 s, whereas the 3,5 mm aperture is applied for evaluating the MPE applicable to exposures longer than 10 s.

NOTE The values of ocular exposures in the wavelength range 400 nm to 1 400 nm are measured over a 7 mm diameter aperture (pupil). The MPE value is not to be adjusted to take into account smaller pupil diameters.

4.3.3 Angle of acceptance for the assessment of exposure from extended sources

The majority of single lasers represent “small” sources, since the angular subtense of the apparent source is less than α_{min} (1,5 mrad). Where the emission from such sources is within the retinal hazard region (i.e. between 400 nm and 1 400 nm), it can be focused by the eye to form an effective point image on the retina. This is not possible with larger apparent sources (often called *extended* sources), which, therefore, for a given level of exposure at the surface the eye, may be less hazardous. Extended-source exposure conditions may be applicable to diffuse reflections, laser arrays or laser products employing a diffuser, when these are viewed at a sufficiently close distance.

When determining the level of the effective exposure arising from an extended laser source (that is, any source subtending more than 1,5 mrad at the position at which the exposure is being assessed), the following angles of acceptance should be used. Any contribution to the exposure that is due to the source’s emission arising from outside the angle of acceptance should be excluded from the assessment of the effective exposure.

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The angular subtense of the apparent source is measured at the distance at which the exposure is being assessed, but not at a distance less than 100 mm. (The angular size of a source should not be confused with the divergence of its emission. To take the sun as an example, its angular size as viewed from the earth is only 0,5°, but the divergence of its emission is 360°.)

a) For the determination of the level of exposure to be evaluated against the photochemical MPEs in Table 6 (400 nm to 600 nm), the limiting angle of acceptance γ_p is

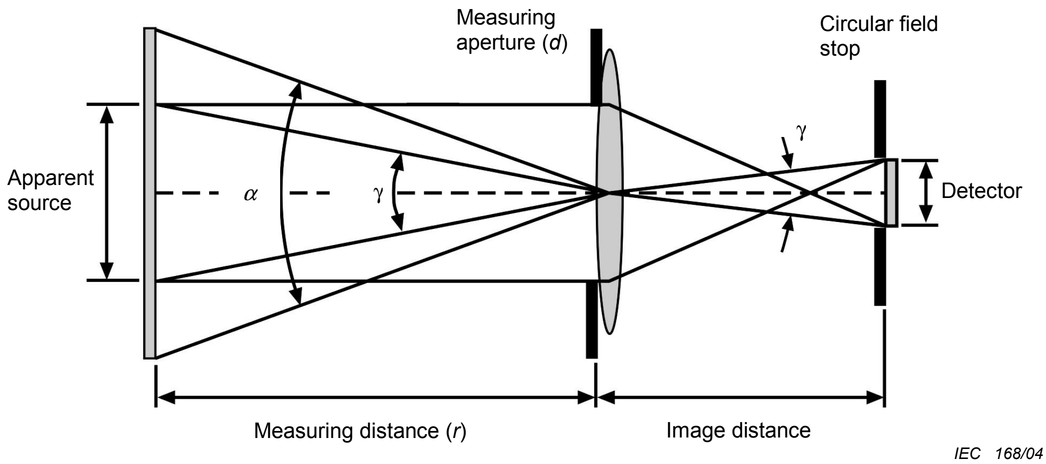
– for 10 s < $t \leq$ 100 s: γ_p = 11 mrad

– for 100 s < $t \leq 10^4$ s: $\gamma_p = 1{,}1\ t^{0,5}$ mrad

– for 10^4 s < $t \leq 3 \times 10^4$ s: γ_p = 110 mrad

If the angular subtense of the source α is larger than the specified limiting angle of acceptance γ_p, the angle of acceptance should not be larger than the values specified for γ_p. If the angular subtense α of the source is smaller than the specified limiting angle of acceptance γ_p, the angle of acceptance should fully encompass the source under consideration but otherwise need not be well defined (i.e. the angle of acceptance need not be restricted to γ_p).

NOTE For measurements of single small sources, where $\alpha < \gamma_p$, it will not be necessary to measure with a specific, well-defined, angle of acceptance. To obtain a well-defined angle of acceptance, the angle of acceptance can be defined by either imaging the source onto a field stop or by masking off the source – see Figure 2.



NOTE Above is an example of a measurement set-up providing a well-defined angle of acceptance by using a lens to image the apparent source onto the detector. This arrangement can be used where the apparent source is not directly accessible.

Figure 2a – Measurement set-up using a lens

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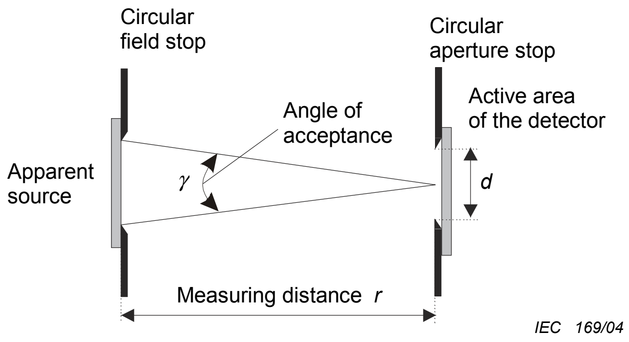

NOTE A measurement set-up using an aperture located at the apparent source to define the angle of acceptance of the detector.

Figure 2b – Direct measurement set-up

Figure 2 – Measurement set-ups

b) For the determination of the level of exposure to be evaluated against all MPEs given in Table 6 other than the retinal photochemical hazard limit, the angle of acceptance should fully encompass the source under consideration (i.e. the angle of acceptance shall be at least as large as the angular subtense of the source α). However, if $\alpha > \alpha_{max}$, in the wavelength range of 302,5 nm to 4 000 nm, the limiting angle of acceptance should not be larger than α_{max} (0,1 rad) for the thermal hazard limits. Within the wavelength range of 400 nm to 1 400 nm for thermal hazard limits, for the evaluation of an apparent source which consists of multiple points, the angle of acceptance shall be in the range of $\alpha_{min} \leq \gamma \leq \alpha_{max}$.

For the determination of the MPE for non-circular sources, the value of the angular subtense of a rectangular or linear source is determined by the arithmetic mean of the two angular dimensions of the source. Any angular dimension that is greater than α_{max} or less than α_{min} should be limited to α_{max} or α_{min} respectively, prior to calculating the mean. The retinal photochemical MPEs do not depend on the angular subtense of the source, and the exposure is determined using the angle of acceptance specified above in 4.3.3(a).

4.3.4 Use of binoculars

If a laser source is viewed through binoculars, then the increase in the effective exposure at the surface of the eye will be the smaller of either M^2 or $(D/d)^2$, where M is the angular magnification of the binoculars, D is the diameter of the objective (i.e. outer) lenses and d is the diameter of the relevant limiting aperture. (Binoculars are normally specified in the form M x D, e.g., 7 x 50.) Allowance can be made for transmission losses through the binoculars at the laser wavelength if this is known. Typical transmission percentages for binoculars are given below:

Wavelength	% Transmission
0,18-0,302 µm	<2%
0,302-0,4 µm	70%
0,4-0,7 µm	90%
0,7-2,8 µm	70%
2,8-10^3 µm	<2%

The angular subtense of an extended source viewed though the binoculars will be increased by a factor M.

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5 Determining the maximum permissible exposure (MPE)

5.1 General remarks

Levels of maximum permissible exposure, which are based on values developed by the International Commission on Non-Ionising Radiation Protection (ICNIRP), are given in Tables 5, 6 and 7 as functions of the emission wavelength and exposure duration. These tables should be used in conjunction with the correction factors given in Table 8.

Table 5 defines the MPE for the eye under conditions of direct exposure to a single laser beam (and in all other cases where the apparent angular subtense of the laser source does not exceed 1,5 mrad, see 4.3.3). For exposure of the eye to laser radiation at wavelengths between 400 nm and 1 400 nm (the retinal hazard region) to larger apparent sources than would be the case for the direct viewing of a single laser beam (that is, for certain multiple or extended sources that subtend an angle at the eye greater than 1,5 mrad), a relaxation (increase) in the MPE is possible. This is because the eye cannot focus such non-point sources onto a small spot on the retina, and therefore the maximum safe power or energy entering the eye is larger. These relaxed MPEs are given in Table 6.

Table 7 specifies values of the MPE for the skin.

The exposure duration used in determining the MPE from Tables 5, 6 and 7 should be based on the maximum duration of accidental exposure that could reasonably be expected to occur, taking into account the wavelength of laser emission and the conditions under which the laser might be used. Under worst-case conditions of accidental exposure, 100 s may be used as the maximum duration of exposure for laser radiation at wavelengths above 400 nm, and 30 000 s for wavelengths below 400 nm where longer-term photochemical effects may be initiated. This longer time-base is applicable in circumstances where repeated or prolonged exposure to ultraviolet radiation could occur without an immediate apparent effect, but is clearly not realistic in the case of direct accidental exposure to a high-power ultraviolet laser beam where immediate and obvious injury would be caused. For accidental exposure to visible laser radiation (400 nm – 700 nm) where purposeful staring is not intended or anticipated, the aversion response time of 0,25 s may be used.

Further consideration of the exposure duration is included in the discussion of risk assessment given in 7.3.

5.2 Repetitively pulsed or modulated lasers

Since there are only limited data on multiple pulse exposure criteria, caution must be used in the evaluation of exposure to repetitively pulsed radiation. The following methods should be used to determine the MPE to be applied to exposures to repetitively pulsed radiation.

The MPE for ocular exposure for wavelengths from 400 nm to 10^6 nm is determined by using the most restrictive of requirements a), b), and c). Requirement c) applies only to the thermal limits and not to the photochemical limits.

The MPE for ocular exposure for wavelengths less than 400 nm and the MPE for skin exposure are determined by using the most restrictive of requirements a) and b).

a) The exposure from any single pulse within a pulse train shall not exceed the MPE for a single pulse.

b) The average exposure for a pulse train of exposure duration T shall not exceed the MPE given in Tables 5, 6, and 7 for a single pulse of exposure duration T. (T is the duration used in the assessment of exposure as discussed in 4.1.)

c) The average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5.

NOTE 1 The exposures in a pulse train are to be averaged over the same emission duration that was used to determine N. Every averaged pulse exposure is to be compared to the reduced MPE_{train} as specified below:

$$MPE_{train} = MPE_{single} \times C_5^*$$

where

MPE_{train} is the MPE for any single pulse in the pulse train;

MPE_{single} is the MPE for a single pulse;

C_5 is the $N^{-1/4}$

N is the number of pulses expected in an exposure.

In some cases, this value may fall below the MPE that would apply for continuous exposure at the same peak power using the same exposure time. Under these circumstances, the MPE for continuous exposure may be used.

If pulses of variable amplitude are used, the assessment is made for pulses of each amplitude separately using requirement a), and for the whole train of pulses.

The maximum exposure duration for which requirement c) should be applied is T_2 in the wavelength range from 400 nm to 1 400 nm (as defined in Table 8) and 10 s for longer wavelengths. If multiple pulses appear within the period of T_i (see Table 3) they are counted as a single pulse to determine N and the radiant exposure of the individual pulses are added to be compared to the MPE of T_i, provided that all individual pulse durations are greater than 10^{-9} s.

NOTE 2 C_5 is only applicable to individual pulse durations shorter than 0,25 s.

NOTE 3 The exposure from any group of pulses (or sub-group of pulses in a train) delivered in any given time should not exceed the MPE for that time.

NOTE 4 In cases of varying pulse widths or pulse intervals, the total-on-time-pulse (TOTP) method may be used in place of requirement c). In this case, the MPE is determined by the duration of the TOTP, which is the sum of all pulse durations within the exposure duration or T_2, whichever is smaller. Pulses with durations less than T_i, are assigned pulse durations of T_i. If two or more pulses occur within a time duration of T_i, these pulse groups are assigned pulse durations of T_i. For comparison with the MPE for the corresponding duration, all individual pulse radiant exposures are added.

This method is equivalent to requirement c) when the average radiant exposure of pulses is compared to the MPE of a single pulse multiplied with C_5.

Table 3 – Duration T_i below which pulse groups are summed up

Wavelength	T_i
400 nm ≤ λ < 1 050 nm	18×10^{-6} s
1 050 nm ≤ λ < 1 400 nm	50×10^{-6} s
1 400 nm ≤ λ < 1 500 nm	10^{-3} s
1 500 nm ≤ λ < 1 800 nm	10 s
1 800 nm ≤ λ < 2 600 nm	10^{-3} s
2 600 nm ≤ λ ≤ 10^6 nm	10^{-7} s

5.3 Multiple wavelengths

When a laser emits radiation at several widely different wavelengths, or where pulses are superimposed upon a CW background, calculations of the hazard may be complex.

Exposures from several wavelengths should be assumed to have an additive effect on a proportional basis of spectral effectiveness according to the MPEs of Tables 5, 6 and 7 provided that:

a) the pulse width or exposure duration are within one order of magnitude, and
b) the spectral regions are shown as additive by the symbols (O) for ocular and (S) for skin exposure in the matrix of Table 4.

* C_5 is only applicable to pulse durations shorter than 0,25 s.

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Table 4 – Additivity of effects on eye (O) and skin (S) of radiation of different spectral regions

Spectral region [a]	UV-C and UV-B 180 nm to 315 nm	UV-A 315 nm to 400 nm	Visible and IR-A 400 nm to 1 400 nm	IR-B and IR-C 1 400 nm to 10^6 nm
UV-C and UV-B 180 nm to 315 nm	O S			
UV-A 315 nm to 400 nm		O S	S	O S
Visible and IR-A 400 nm to 1 400 nm		S	O [b] S	S
IR-B and IR-C 1 400 nm to 10^6 nm		O S	S	O S

[a] For definitions of spectral regions, see Table C1.

[b] Where ocular MPEs are being evaluated for time bases or exposure durations of 1 s or longer, then the additive photochemical effects (400 nm to 600 nm) and the additive thermal effects (400 nm to 1 400 nm) shall be assessed independently and the most restrictive value used.

Where the wavelengths radiated are not shown as additive, the hazards should be assessed separately. For wavelengths which are shown as additive, but when the pulse widths or exposure times are not within one order of magnitude, extreme caution is required (e.g., in the case of simultaneous exposure to pulsed and CW radiation).

5.4 Extended source MPEs

For exposures of the eyes to the emission from extended laser sources in the retinal hazard region (i.e. at wavelengths between 400 nm and 1 400 nm, see 4.3.3) the MPEs given in Table 6 should be used. It should be noted that in general, the angular subtense (α) of a source will decrease at increasing distances from the source, and the corresponding MPE may *increase*. (The angular subtense should be determined at the position at which the exposure is being evaluated.) This is particularly important when determining the hazard distance (e.g., the NOHD) of an extended source, since the MPE may not be constant, but can increase with distance until $\alpha = \alpha_{min}$. (α_{min} = 1,5 mrad.)

The thermal ocular hazard MPEs given in Table 6 are a function of the factor C_6. For a source subtending an angle larger than α_{max}, where α_{max} is equal to 100 mrad, C_6 has a constant value of 66,7 (i.e. $\alpha_{max}/\alpha_{min}$). For sources subtending an angle smaller than α_{min}, C_6 is equal to 1 and the MPEs given in Table 5 apply.

The correction factor C_6 is given by:

$C_6 = 1$ for $\alpha \leq \alpha_{min}$

$C_6 = \alpha/\alpha_{min}$ for $\alpha_{min} < \alpha \leq \alpha_{max}$

$C_6 = \alpha_{max}/\alpha_{min}$ for $\alpha > \alpha_{max}$

5.5 Hazard distance and hazard area

5.5.1 Nominal ocular hazard distance

In some laser applications, especially those involving divergent or scanning beams, long beam paths or diffuse beam reflections, it can be useful to know the distance over which the laser hazard might extend.

The distance at which the level of exposure has dropped to the level of the MPE (for the eye) is known as the nominal ocular hazard distance (NOHD). Beyond this distance there is no hazard to the unaided eye, although there may be a hazard if magnifying viewing aids are used.

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To take account of the possible use of magnifying aids, where this is reasonably foreseeable, the *extended* nominal ocular hazard distance can be used. This distance is determined on the basis of the increase in exposure (at the surface of the eye, within the relevant limiting aperture) that could arise through the use of magnifying instruments. The extended nominal ocular hazard distance (ENOHD) is therefore that distance beyond which magnifying instruments can be safely used. (See 4.3.4.)

Knowledge of the hazard distance can be especially useful in the case of divergent-beam lasers, where the hazard distance can be relatively short and the hazard therefore limited to the immediate vicinity of the laser aperture. It can also be important for collimated beams from lasers that are used over long distances, such as out-of-doors, where hazard distances can be considerable. Particular care needs to be taken with the out-door use of collimated-beam Class 1M and Class 2M laser products (that is, those with a large beam diameter that have exceeded the emission limit for Class 1 under condition 1 of the classification procedure specified in IEC 60825-1). Although these lasers present no hazard to the unaided eye, the distance over which the use of magnifying viewing aids could be hazardous may be very large. If the beam extends into public areas it cannot be assumed that magnifying aids such as binoculars will not be used.

Both the NOHD and ENOHD depend critically on the beam geometry as well as on the magnitude of the laser output. It can be possible, for example, to refocus or collimate the beam, even by means of an optical component positioned some distance from the source, and thereby increase both the NOHD and ENOHD.

In some applications it can be useful to determine the skin-hazard distance in an analogous manner to NOHD.

5.5.2 Nominal ocular hazard area

From knowledge of the NOHD and ENOHD, and of the way in which the laser is positioned and secured, and also of the circumstances of its use, it is possible to define an area or 3-dimensional space around the laser aperture within which exposure hazards can arise. This region, the hazard zone, is called the nominal ocular hazard area (NOHA) if it is based on the criterion for the NOHD, or the extended nominal ocular hazard area (ENOHA) if it is based on the ENOHD.

Because of the possible use of magnifying aids by people unconnected with the laser operation, especially where lasers are used out-of-doors, it is important to recognise that the laser hazard can extend over the full area of the ENOHA, and not just that of the NOHA. For outdoor applications, if the beam is terminated by the ground, a tree-line or other terrain features, the NOHD can not exceed the line of sight to this opaque feature.

Provided that access into the ENOHA can be restricted and reliably controlled, however, it is not always necessary to enclose the hazard area.

6 Associated hazards

6.1 Additional health hazards

The use of lasers can give rise to a number of associated hazards in addition to those arising from direct exposure of the eyes or skin to laser radiation. Associated hazards do not affect the laser classification, and so may be present with even Class 1 laser products. Some associated hazards, e.g., electric shock, can be life-threatening.

The control of associated hazards should normally be addressed by the manufacturer through appropriate design of the equipment and by written instructions for safe use supplied by the manufacturer to the user. Nevertheless, where such hazards cannot reasonably be completely eliminated through engineering design (as in the case of fume), or where the laser is being used for a purpose or in a manner other than that intended by the manufacturer, some responsibility for the control of these hazards will fall upon the user.

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A summary of some associated hazards is given below. Users should take all reasonable steps to investigate and ensure adequate protection from all hazards that may arise from their own use of laser equipment. Given the diversity of hazards that can be associated with laser use, only limited guidance can be given here, and users should refer to any national or regional requirements or regulations that may apply. Advice from Competent Persons who are experienced in areas other than laser radiation safety may be beneficial.

6.2 Hazards arising from the laser

6.2.1 Electricity

Many lasers utilise high voltages, and pulsed lasers frequently employ capacitors that can store significant amounts of electric charge. (This stored energy can remain even after the equipment has been disconnected from the electrical supply). The rating of the laser power supply usually greatly exceeds that of the emitted laser radiation. Under normal operating conditions laser equipment should be fully protected against the possibility of electric shock by the enclosure of all electrical terminals. During servicing, however, when this protection may be removed and any interlocks overridden, a serious hazardous condition may exist. In particular, precautions may need to be taken to ensure the removal of stored energy prior to commencement of servicing work.

6.2.2 Collateral radiation

Potentially hazardous levels of radiation other than laser radiation may be produced by the laser equipment, and by the plasma that can be generated by interaction of the laser beam with target materials. Such emissions can include x-rays, ultraviolet radiation (UV), visible light, infrared radiation (IR), microwave radiation and radio-frequency (RF) radiation. The principal potential sources of this collateral radiation are summarised below.

X-rays can be produced through the interaction of high-power laser beams with heavy metal targets and by high-voltage thermionic valves within the laser power supply.

Ultraviolet, visible and infrared emission can be produced from gas laser discharge tubes, by discharge lamps in optically pumped lasers, and by laser-induced plasmas.

Microwave and radio frequency radiation is produced in RF-excited lasers, and can be emitted by the equipment if not properly shielded.

6.2.3 Other laser radiation

Laser radiation can be emitted at wavelengths other than the principal emission wavelength in the case of certain lasers, especially where optical frequency-shifting techniques (e.g., frequency doubling), and optical pumping are used.

6.2.4 Hazardous substances

The material used as the active medium in many lasers (especially laser dyes and the gases used in excimer lasers) can be toxic and carcinogenic. The solvents used in many dye lasers have the ability to carry their solutes through the skin into the body. They may also be highly volatile and should not be inhaled. The liquids used in some optically active components (e.g., for Q-switching and frequency-doubling), as well as cleaning solutions and also other materials used in conjunction with the laser (e.g., zinc selenide lenses) may also be hazardous. Proper storage, handling and disposal precautions should be adopted.

6.2.5 Fume

Many applications of Class 4 lasers, especially in industrial materials processing and in laser surgery, can release hazardous particulate and gaseous by-products into the atmosphere through the interaction of the laser beam with the target material. These fume emissions may be toxic and noxious, and can produce hazardous effects even for short periods of exposure.

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The effects of fume vary considerably and depend principally on the material being processed, on the length of exposure, and on the fume concentration.

6.2.6 Noise

The discharge of capacitor banks within the laser power supply can generate noise levels high enough to cause ear damage. Ultrasonic emissions and repetitive noise from pulsed lasers can also be harmful. Some air-cooled lasers produce significant noise levels. Where excessive noise levels cannot be eliminated, ear protectors should be worn.

6.2.7 Mechanical hazards

Mechanical hazards can arise from the bulk of the laser equipment itself; including ancillary items such as gas cylinders, especially if the equipment is not properly secured or is moved manually. Trailing cables and water-circulation tubing can present a trip hazard. Cuts are possible from sharp objects, e.g., optical fibres. Beam delivery arms and robotic systems that move under remote control can cause serious injury. Large work-pieces (such as sheet metal) can present manual handling problems such as cuts, strain, and crush injuries.

6.2.8 Fire, explosion and thermal damage

The laser emission from high-power (Class 4) lasers can ignite target materials. These effects are enhanced in the oxygen-rich environment utilised in some laser processing applications.

Laser emission from even lower-class lasers, especially when concentrated over very small areas, can cause explosions in combustible gases or in high concentrations of airborne dust. Power levels above 35 mW emerging from a single mode optical fibre can be sufficient to cause combustion in such environments.

The high-pressure discharge lamps used in optically-pumped lasers, and other internal components such as capacitor banks, can explode. External beam-steering mirrors, which may have to dissipate considerable quantities of absorbed energy from incident high-power laser beams, can shatter.

Laser equipment can also present a fire hazard by virtue of the flammable components, plastic parts etc. contained within it, which can overheat or catch fire in the event of a fault within the equipment.

6.2.9 Heat and cold

The internal parts of some lasers may be hot, and the beam-steering mirrors used in conjunction with high-power processing lasers can reach high temperatures. In addition, cryogenic cooling is sometimes used with or in conjunction with laser equipment.

6.3 Hazards arising from the environment

6.3.1 Temperature and humidity

Excessive high or low ambient temperatures, or high levels of ambient humidity, can affect the performance of the laser equipment, including its in-built safety features, and can compromise safe operation. Condensation on optical components can affect beam transmission through the system.

6.3.2 Mechanical shock and vibration

These can affect the operation of the laser system, and can cause misalignment of the optical path, generating hazardous errant beams.

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6.3.3 Atmospheric affects

The beam from a high-power laser can ignite solvent vapour, dust, and inflammable gases present in the environment and arising from adjacent work activities or other causes. Such ignition may also cause explosions.

6.3.4 Electromagnetic and radio-frequency interference

Exposure to radiated electromagnetic, magnetic or electric fields, and high voltage pulses conducted down the supply or data cables can interfere with the performance of the laser equipment, including its in-built safety features or control circuits, and compromise safe operation.

6.3.5 Power supply interruption or fluctuation

Interruption or fluctuation of the electrical supply can affect the operation of the laser's safety system.

6.3.6 Computer software problems

Errors in computer programming, where part or all of the laser's operation and its protective systems are under software control, can cause serious and unpredictable hazards to arise without warning.

6.3.7 Ergonomic and human-factor considerations

Poor arrangement of the physical layout of the laser and its associated equipment, lack of space resulting in a cluttered environment and complex or difficult operating procedures can all increase the likelihood of accidents occurring. In addition, human factors, which arise from the interaction of an individual with their working environment, can greatly influence that individual's safety-related behaviour. These factors include:

– **personal aspects**, which cover the intellectual, mental and physical attributes of the individual, and include the person's work ability, as well as their perception of workplace risks and their attitude to safety;
– **job aspects**, which concern the tasks or functions that have to be performed, and the influence on human performance of the equipment that has to be used; and
– **organisational aspects**, which relate to the "safety culture" of the organisation concerned, and include the framework within which an individual has to work and the influences and pressures (real or imagined) that the individual may be under.

Human factors play some part in the majority of work-related accidents, and need to be addressed along with the control of the more specific physical hazards that can arise from the use of laser equipment.

6.4 Control of associated hazards

Any associated hazard that could reasonably be expected to exist during laser installation, operation, maintenance, service or disposal should be identified and adequately evaluated. The necessary protective control measures should then be determined on the basis of a risk assessment, as discussed in Clause 7, taking into account any relevant national or regional requirements that may apply.

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7 Evaluating risk

7.1 Hazards and risks

The control of hazards arising from the installation, operation, maintenance, service or disposal of laser equipment should be based on an assessment of the risk. A hazard is any physical condition, chemical or biological agent, which is capable of causing harm. Harm is normally understood to mean personal injury, but it can also include financial loss (e.g., damage to equipment or property, or loss of production time). There are hazards involved in all activities. In the context of laser equipment, laser radiation is a hazard, but there are also additional hazards that can be associated with laser use (e.g., electricity, fume, high-pressure gases), some of which are described in Clause 6.

In the context of risk assessment, risk is a combination of the likelihood of harm occurring and the severity of the harm that could be caused. Whenever there is a possibility of exposure to a hazard, there is also a risk of injury, but it is not always necessary or even possible to completely remove the risk. What is required is to reduce the risk during use (and also under reasonably foreseeable conditions of failure and misuse) to an acceptable level. The acceptable level will vary widely, depending upon the application and the circumstances of use, and so setting the level is a matter of judgement. In some cases it can be set by comparing the risk associated with the activity under consideration with similar risks in other activities.

The laser product class (see 4.1.2) is based on the maximum level of radiation to which human access is possible during normal conditions of operation. The product class gives a broad indication of the radiation hazard, and the default protective control measures given in Table 1 reflect this. Wider issues, including those of misuse and failure, however, affect the level of risk. The more detailed consideration of the likelihood and severity of injury that is required by risk assessment allow the user more scope for discretion in the selection of an appropriate mix of control measures. This is particularly useful in certain applications where the control measures summarised in Table 1 are inappropriate, insufficient or unreasonably restrictive.

Where practicable, an assessment of the risk associated with a particular laser process should be undertaken before purchase of the laser. This will ensure that the prospective user is fully aware of the safety implications, which may have a bearing on where the laser is to be located and how it is to be used. All the necessary preparations can then be made prior to the equipment's arrival.

The reduction of risk to acceptable levels is an iterative process. Various approaches to risk assessment are possible, but the essential steps involved are described below.

7.2 Risk assessment: Stage 1 – Identifying potentially injurious situations.

The most important part of a risk assessment is to consider every reasonably foreseeable injurious situation that could arise in the use of the laser equipment, including those of installation, normal operation, maintenance, service, and reasonably foreseeable misuse or failure. Account should be taken of any specific maintenance, adjustment or other tasks recommended by the manufacturer. The list of 'what could go wrong' can be derived by considering activities systematically, or randomly by 'brainstorming'.

Three key issues, which the user should focus on when listing potentially injurious situations are described in 7.2.1, 7.2.2, and 7.2.3.

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7.2.1 The hazards involved

It is important to consider the full range of possible hazards and the circumstances under which they might arise, taking into account the type of laser equipment (its class, the conditions under which hazardous exposure could occur, and the kind of injury that could result) and the task or process being performed. Although exposure to laser radiation poses the most obvious hazard, it is quite often not the only one. Clause 5 discusses many of the associated hazards that may be involved in the use of laser equipment. Any control measures already in place at the time of the risk assessment will effectively isolate some of these hazards (except, perhaps, during servicing). When drawing up the initial list, the extent to which such controls are taken into account (whether they be incorporated into the laser product by the manufacturer or already implemented in the laser installation) is a matter of judgement on the part of the user.

7.2.2 The laser environment

The laser environment covers

- the location of the laser equipment:
  e.g., inside a building within an enclosed and dedicated laser working area; inside within a more-widely accessible or open-plan working area; outside;
- the state of the working area from an equipment viewpoint:
  e.g., the influence on equipment of temperature, humidity, vibration, dust etc. and the possibility of disturbances or damage by collisions with persons or moving equipment;
- the state of the working area from a personnel viewpoint:
  e.g., spacious or cluttered; clean or dirty; well-lit or dark; ease of use and ease of operation of the laser and associated equipment; the simplicity or complexity of the task being performed;
- the level of access:
  e.g., localised restricted area within premises having no public access; unrestricted area within premises having no public access; public access areas.

7.2.3 The people at risk

Issues relating to persons at risk include the number of those at risk and their level of awareness, protection and training. The people at risk can include skilled and trained operators, service personnel, employees who may be unaware of the hazards, contractors, visitors, children and other members of the public who may not fully understand warning signs or appreciate the dangers involved.

7.3 Risk assessment: Stage 2 – Assessing risk for potentially injurious situations.

The two factors that make up the risk, namely likelihood of injury and severity of injury, can be considered separately for each item on the list of potentially injurious situations.

It can be quite difficult to quantify these factors, but it is often not necessary to do so. Indeed, it can sometimes become very apparent, after completing Stage 1 of the risk-assessment process, that an unacceptable risk exists and that steps need to be taken to eliminate or reduce it.

Guidance here concentrates on the laser beam, by way of example. Users will also have to consider the other, associated, hazards and the risks arising from those hazards.

Although both the likelihood and severity of injury are aspects of the overall risk, it is often more useful, and usually more important, because of uncertainties of the degree of harm that might be caused, to concentrate solely on the possibility that an exposure greater than the MPE might occur (regardless of the actual consequences). This is known as a deterministic risk assessment, and is the basis on which many risk assessments in laser safety are carried out.

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By placing the emphasis on an evaluation of the circumstances, conditions and events under which hazardous levels of exposure could occur, control measures (see 6.4) can be more readily linked to the need to ensure that those particular circumstances, conditions or events which could give rise to an injury (regardless of its severity) are unlikely to happen.

A more formal way of evaluating risk that can sometimes be appropriate is described in 7.3.1, 7.3.2, and 7.3.3.

7.3.1 Frequency

Place the likelihood of injury that could arise from each of the identified hazards into one of three categories, taking account of the frequency of exposure to the hazard, the duration of exposure to the hazard and the probability that, when exposed, the hazard cannot be avoided.

These categories are

- **likely**: will occur frequently;
- **possible**: can occur sometimes/occasionally;
- **improbable**: very unlikely to occur.

7.3.2 Severity

Place the severity of injury into one of three categories. (A fourth category could be added for damage to plant or environment.)

The suggested categories are

- **Minor**: slight inconvenience, may require first aid but full recovery quickly occurs;
- **Moderate**: more serious effect, longer recovery time, medical treatment likely to be necessary;
- **Major**: serious injury requiring urgent medical intervention, with the possibility of permanent disability (including loss of sight) or even death.

7.3.3 Resultant risk

Consider the resultant risk, and decide whether this is acceptable or not.

Important considerations are described in 7.3.3.1, 7.3.3.2, and 7.3.3.3.

7.3.3.1 Eyes or skin

a) The consequences of injury to the eyes are usually much more serious than equivalent injuries to the skin.
b) At any given level of exposure, large-area skin burns will be more serious than small-area burns.
c) Very high power lasers can cause extremely serious bodily injuries, possibly resulting in death.

7.3.3.2 Laser wavelength

a) There may be a risk of cumulative damage, even resulting in cancer, from repeated or prolonged exposure of the skin to ultraviolet radiation.
b) The eyes can be injured by exposure to laser radiation of sufficient power at any wavelength. (There is no "eye-safe" waveband.)
c) Even localised retinal injuries can lead to serious loss of vision.

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d) Superficial damage to the cornea may heal; injuries that penetrate deeper into the cornea will not.

e) Sudden and unexpected exposure of the eyes to visible laser radiation, even at levels well below the MPE, may distract and dazzle.

7.3.3.3 Duration of laser radiation exposure

The duration of exposure may be limited by speed of movement in response to pain, intense light, or to the sensation of heat. Photochemical injuries, however, do not in general produce an immediate sensation.

7.4 Risk assessment: Stage 3 – Selecting control measures

Where the level of risk is found to be unacceptable, then control measures must be introduced to reduce the risk to an acceptable level. These control measures are covered in Clause 8. In selecting appropriate controls, engineering controls, applied within the context of an established safety policy, should be given primary consideration as the means for reducing the risk of laser injury. Personal protective equipment should only be used as a last resort where a combination of engineering and administrative controls cannot reasonably provide a sufficient level of protection.

After control measures for reducing the risk have been determined, the risk assessment procedure outlined above should be repeated, and if necessary a further iteration carried out, until the risk from all potentially injurious situations has been reduced to an acceptable level. These iterations should be carried out before the proposed controls are implemented and the laser equipment is used, in order to confirm that once the control measures have been adopted the residual risk will be acceptable.

8 Control measures

8.1 General

Where a risk assessment (Clause 7) has shown that an unacceptable degree of risk exists, then protective control measures should be introduced. This applies to the use of all lasers, whether classified by the manufacturer, sold as an unclassified laser for incorporation into another product, or specially constructed for a particular use, experimentation or evaluation purpose. (A risk assessment will not normally be necessary for Class 1 and Class 2 laser products, although consideration should always be given to the possibility that an unusual or particular circumstance may require that special control measures be adopted.)

The feasibility of using a laser of a lower class should always be considered as the first option in controlling hazards. The need to use a hazardous laser should therefore be justified prior to purchase and use.

Where a laser product is used for purposes or in a manner other than those intended by the manufacturer, hazards can arise which require additional protective control measures to be implemented beyond those that may have been specified by the manufacturer.

Control measures should be considered under three headings, covering engineering controls, administrative controls and personal protective equipment. Wherever reasonably practicable, however, laser hazards should be eliminated completely at source by the use of engineering controls (e.g., by total enclosure of the beam).

– *Engineering controls* include features incorporated into the laser equipment and around the laser beam by the manufacturer or user, in particular the fixture of protective barriers and guards to prevent human access to laser radiation.

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– *Administrative controls* cover overall policy, procedural issues (the "local rules" governing laser use), and the use and display of hazard warning signs, training and instructions, assignment of responsibilities and prohibitions.
– *Personal protective equipment* is that protection worn by an individual. In the context of laser safety it refers primarily to the use of laser protective eyewear, but can also include items of special clothing (e.g., gloves and face-masks) to protect the skin, as well as respirators to protect against dust and fume and earplugs to protect against excessive noise.

Following the adoption of an overall policy governing laser use, engineering controls should be given primary consideration as the means for reducing the risk of laser-related injury. Administrative controls covering procedural issues and safe systems of work should then be considered. Personal protective equipment should only be used as a last resort where a combination of engineering and administrative controls cannot reasonably provide a sufficient level of protection. Where personal protective equipment is employed it should be supported with an adequate level of administrative control governing its use.

The reduction of risk to acceptable levels is an iterative process involving the identification of hazards associated with the use or reasonably foreseeable misuse of the laser equipment, (to include reasonably foreseeable failure modes), an evaluation of the risk of harm arising from exposure to these hazards, and the review of control measures that could reduce the risk.

Where more than one party is engaged in the design, specification and installation of laser equipment (this may involve, for example, the manufacturer of the laser itself, a separate company commissioned to supply and install associated equipment, and staff from the purchasing organisation), it is important that responsibilities for safety are clearly defined. It can be beneficial to agree in advance and in writing which party is taking responsibility for each specific safety aspect of the complete system, and to identify and clarify issues relating to overall system safety and safety compliance.

8.2 Hazard reduction

Consideration of the proposed use of a laser in relation to the level of risk may indicate that it is possible to achieve the intended purpose with a lesser degree of hazard (and consequent lower level of risk). This may be possible, for example, by reducing the laser emission, by increasing the beam diameter, or by using a different wavelength. The user should always ensure that the minimum degree of hazard commensurate with the intended application is achieved.

8.3 Enclosing the hazard

8.3.1 Beam enclosures

The use of enclosures to completely contain the laser beam should always be considered as a means of preventing human access to hazardous levels of laser radiation. Such enclosures include those intended to prevent the emission of laser radiation from the equipment, as well as those intended to prevent human access into areas where laser radiation might exist.

All enclosures need to be of appropriate material, robust, secure and fit for purpose in the context of their intended use and under the impact of their local environment.

Metal is universally applicable for constructing protective enclosures, and in some wavelength ranges glass or plastic materials may be used. The necessary properties of enclosure materials are adequate environmental stability (in particular, resistance to mechanical impact, heat and light) and sufficient optical density at the wavelength of the laser radiation. The walls of a room can, of course, be regarded as forming a protective enclosure if the need for personnel to be physically present in the laser environment can be eliminated.

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High-power Class 4 lasers, such as those used for cutting, welding and other forms of materials processing, present an additional enclosure problem by virtue of the ability of the laser beam to penetrate an opaque material through melting, burning, vaporisation or ablation. For guidance on assessing the suitability of materials of construction for high-power laser radiation the user should refer to IEC 60825-4. In general, enclosures must be sufficient to adequately contain the laser radiation that could impinge upon its inner surface for as long as necessary.

For all protective enclosures the means of preventing unintended or unauthorised removal of all or part of the enclosure, thereby gaining access to the laser radiation, is an important consideration (see 8.3.3: Interlock protection).

8.3.2 Viewing windows

While observation (viewing) windows can be employed to allow for inspection of the inside of a laser enclosure during laser operation, their use is not an ideal solution and the adoption of remote viewing (TV) systems should be considered as an alternative. Where viewing windows are used, they need to be fabricated of suitable material to permit viewing of the inside of the enclosure without compromising its protective properties.

The method of calculating the required optical density of the window material at the wavelength(s) of the laser radiation that is enclosed is the same as for laser protective eyewear (see 8.4.5.2), but the assessment of maximum foreseeable exposure will be different. In particular, since a viewing window is not worn, accidental exposure may be of much longer duration than is the case for eyewear. (See IEC 60825-4).

8.3.3 Interlock protection

8.3.3.1 Purpose of interlock protection

Access to a user-installed protective enclosure should be controlled by measures that are commensurate with the level of risk (see Table 9). Where there is a reasonably foreseeable risk of serious injury due to inadvertent, accidental, or even malicious opening or removal of part of the enclosure, a recommended solution is to control the laser hazard by engineering means (e.g., by use of a safety interlock) to prevent access or to terminate the laser emission. (See also 8.4.2 and Annex A.)

The guidelines for the user-installed interlocks given in the following paragraphs are intended as recommendations of good practice, but should not be construed as manufacturing requirements. (Manufacturing requirements for laser products are specified in IEC 60825-1.)

8.3.3.2 Design of interlock systems

For an interlock that performs a safety critical function it is recommended that the following criteria should be considered.

a) Mechanical switches should be of "positive break" design (see A.2.2). These have contacts that spring apart when the interlock switch is released, so preventing arcing or the risk of intermittent operation.

b) Proximity switches should be coded (that is, require two matched parts to be brought together) to prevent casual override.

c) Interlock systems should be so designed that a single fault in any part of the circuit does not lead to the loss of its protective function. The single fault should be detected before the system can be reset. (An example of a reasonably foreseeable single fault is a relay contact weld.)

d) Termination of laser emission achieved by interruption of the laser power supply should, in the case of pulsed lasers, be accompanied by the dumping of any residual energy that could give rise to further pulses. This is normally satisfied by the manufacturer in the design of the product.

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8.3.3.3 Resetting interlocks

It is good practice for interlock systems to be designed so that, after operation, the system can only be reset by a deliberate action (e.g., reset button).

Reset of the interlock system should then not be possible until all protective functions and protective devices are ready for operation and any fault has been rectified.

Resetting the interlock system should not itself restart the laser but should prepare the system to accept a start command.

8.3.3.4 Interlock override

Interlock systems that have provision for an override facility, so permitting access for servicing or other adjustment work, should meet the following requirements.

It should not be possible for the interlock to remain overridden when the enclosure has been reinstated. This requirement can be achieved, for example, by limiting the duration of override operation or by mechanical design of the override mechanism.

There should be a distinct visible or audible warning whenever the override is in operation.

Where interlocks can be overridden from outside a laser controlled area this should only be possible by means of a coded or key-operated switch to prevent activation of the override by unauthorised persons.

8.4 Hazard mitigation

8.4.1 Preventing access

Human access to a laser hazard should be prevented by engineering means as far as is reasonably practicable. Where this level of protection is not achieved, then human access to hazardous levels of laser radiation or to other laser hazards should be prevented to the extent that is reasonably practicable by appropriate use of barriers, beam tubes, and local enclosures, and by ensuring that access into the hazard area is limited to those persons for whom such access is necessary.

8.4.2 Laser controlled areas

A laser controlled area should be established wherever there is a reasonably foreseeable risk of harm arising from the use of laser equipment. At its simplest, a laser controlled area is an area within which laser beam hazards can exist and over which there is some level of effective hazard control. Such areas should be clearly delineated, and access to them limited to nominated persons who have received adequate safety training and to persons under their control.

The boundaries of a laser controlled area should enclose the hazards associated with the use of the laser under all reasonably foreseeable conditions of use (including reasonably foreseeable faults occurring with the laser or associated equipment, and reasonably foreseeable failures to follow correct procedures).

Warning signs should be clearly displayed on the outside of all laser controlled areas. Such signs should include the laser hazard symbol shown in Figure 1, and should indicate the type of hazard(s), the restrictions on access that are in force, and the precautions to be adopted on entry. It can also be useful to include the name of the person responsible for the area from whom further information can be obtained.

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Complete physical enclosure of the laser controlled area is often desirable, but may not always be necessary provided that a) access into the area is adequately controlled, and b) no unreasonable risk exists to persons outside the controlled area. Interlocking of the door or other entryways into laser controlled areas should be considered wherever significant hazards exist and where access cannot be adequately controlled by administrative means, and particularly where the use of personal protective equipment is required inside the laser area. If interlocks are fitted to an entryway, they may be connected to the remote interlock connector incorporated into Class 3B and Class 4 laser products in order to terminate laser emission when the interlock is activated by opening the entryway. Other means of using an interlock to terminate laser emission (e.g., by connecting it to the electrical supply to the laser or to a fail-safe beam shutter) may be used instead. An outline of various types of laser controlled area in relation to the laser class is given in Table 9.

Where entry into or exit from a controlled and interlock-protected laser area is necessary during laser use for reasonable operational reasons, then an interlock override may be fitted. (See 8.3.3.4.) Such a system is open to abuse, however, and can compromise the effectiveness of the laser controlled area by permitting the defeat, albeit temporarily, of a protective system An interlock-override facility should not be implemented, therefore, without considering carefully how it is likely to be used and how it could be misused.

If interruption of laser emission is unacceptable and an interlock override does not provide a satisfactory solution (e.g., in medical applications), then one option is to use fail-safe electromagnetic door locks having emergency door release buttons (accessible both inside and outside the laser controlled area) to release the door locks if operated.

Illuminated warning signs may be used on the outside of laser controlled areas to indicate when the laser is in use and the door interlocks (if fitted) are operational. These signs should clearly indicate when it is safe, and when it is not safe, to enter the area. (See A.2.5.)

The installation of conventional, red, emergency-stop buttons on the inside of laser areas to terminate hazardous laser emission in the event of an emergency should be considered in relation to other risks. Particular national requirements regarding the maintenance of a safe workplace may apply.

8.4.3 Local rules and procedures

Administrative controls should be implemented in the form of documented local rules and procedures. These may be drawn up specifically for the particular organisation, location or equipment concerned, or may be based on a suitable standard model. They should include:

a) description and purpose of the equipment or process;

b) the name and contact point of the Laser Safety Officer and of the person responsible for the laser equipment;

c) the names of personnel authorised to operate, maintain or service the laser equipment;

d) the procedures to be adopted for laser operation, maintenance and service (where relevant), and of all precautions to be followed, including, where applicable, the use of personal protection and the use and secure storage of laser control keys;

e) action to be taken in the event of specified equipment failure or other emergencies;

f) the incident reporting procedure and the action to be taken in the event of a suspected accident;

g) details of requirements, if any, for authorisation for hazardous operations, e.g., procedures for approval of servicing (permit to work).

Local rules should be reviewed regularly to ensure their continued relevance to requirements.

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8.4.4 Localised risk reduction

8.4.4.1 General precautions

Within all laser controlled areas, steps should be taken to reduce the risk of injury to persons authorised to work within them. These steps should include:

a) adequate training of all personnel involved;
b) sufficient levels of room illumination;
c) uncluttered environment and well-organised working layout;
d) secure control of laser operating keys;
e) the secure fixing of the laser and all components along the path of the beam;
f) safe method of beam alignment;
g) a beam stop at the end of the useful path of the laser beam, where appropriate;
h) use of the beam attenuator or beam stop fitted to Class 3B and Class 4 laser products to temporarily terminate laser emission whenever such emission is not required for short periods. Whenever laser emission is not required for longer periods, the laser should be turned off;
i) enclosure of as much of the beam as is reasonably practicable;
j) keeping the beam above or below eye level where practicable;
k) confinement of the beam within well-defined areas, which are as small as reasonably practicable (e.g., keeping the beam within the confines of an optical table; placing barriers preventing human access where an open beam crosses the floor);
l) the use of screens, blinds, or curtains to contain the laser radiation (see IEC 60825-4 for guidance on selection of suitable materials);
m) use of checklists where appropriate.

8.4.4.2 Specular reflection

Particular care should be taken to prevent the unintentional specular (i.e. mirror-like) reflection of laser radiation. Mirrors, lenses, and beam splitters should be rigidly mounted and should be subject to only controlled movements while the laser is emitting.

The specular reflection of radiation from Class 1M and Class 2M laser products from surfaces that may focus the beam can pose a hazard to the unaided eye. (Direct exposure to the emission from Class 1M and Class 2M laser products is not normally hazardous to the unaided eye.)

Reflecting surfaces that appear to be diffuse may actually reflect a considerable part of the radiation beam specularly, especially in the infrared spectral range. This may be potentially hazardous over longer distances than would be expected for purely (Lambertian) diffuse reflections.

Potentially hazardous specular reflections occur at all surfaces of transmissive optical components such as lenses, prisms, windows and beam splitters. Special care needs to be taken in the selection of optical components for Class 3B and Class 4 lasers and in maintaining the cleanliness of their surfaces.

Potentially hazardous radiation can also be transmitted through some reflective optical components such as mirrors (for example, infra-red radiation passing through a reflector of visible radiation).

Many surfaces become specularly reflecting at grazing incidence.

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8.4.5 Personal protection

8.4.5.1 Use of personal protective equipment (PPE)

PPE (such as laser protective eyewear) should be worn, where appropriate, by individuals working in laser controlled areas in order to provide protection against laser hazards. Such protection should, however, only be used where it is not reasonably practicable to ensure adequate protection by other means, preferably by total enclosure of the laser radiation, and where it has been ascertained that personal protective equipment is able to provide sufficient protection.

Where personal protective equipment has been deemed to be an appropriate method of risk reduction, its use should be compulsory and not left as a matter of individual choice.PPE should ideally be issued on a person-by-person basis, and for hygiene reasons should be properly cleaned by an appropriate method before reuse by another person. Additional national requirements covering the design, specification and use of PPE may exist.

Special requirements apply in Europe covering the specification, marking and testing of laser eye protection, using the concept of protective (rather than optical) density, which takes into account the ability of the protection to withstand the incident laser radiation (ref EN 207 and EN 208).

8.4.5.2 Specifying eye protection

Eye protection can be in the form of spectacles (having frames which rest on the ears) or goggles (secured by a band around the head). Such protection incorporates optical filters to reduce the transmission of laser radiation to the eye, and may be employed as a protective measure within a laser controlled area. Total beam enclosure combined where necessary with the use of remote viewing (e.g., television) systems should, however, always be considered first as an alternative to reliance on personal eye protection.

8.4.5.2.1 Eye protection should only be used if all of the following conditions are satisfied.

a) There exists a non-trivial risk of injury arising from the accidental exposure of the eyes to levels of laser radiation above the MPE.

b) There is no serious co-existent risk of skin injury arising from laser exposure (but see 8.4.5.3). Such a risk is likely to exist where high levels of filter density would be necessary to protect the eyes.

c) It is not reasonably practicable to ensure adequate protection entirely by the use of engineering and/or administrative controls.

d) The protective eyewear has the necessary performance specification with regard to:

   1) the reduction in the maximum reasonably foreseeable laser exposure to safe levels,

   2) the capability of the eyewear for withstanding the maximum reasonably foreseeable laser exposure long enough for corrective action to be taken to terminate exposure, and

   3) the ability of the wearer to be able to use the eyewear without discomfort and without any significant degradation in vision.

8.4.5.2.2 When choosing appropriate eyewear the following should be considered:

a) the wavelength of operation. Laser eyewear utilises filter materials to provide protection over certain defined wavelength ranges. Use of the incorrect eyewear will usually mean that insufficient protection is provided;

b) the reasonably foreseeable worst-case effective exposure (determined in accordance with Clause 3), expressed in terms of either the incident irradiance ($W \cdot m^{-2}$) or the incident radiant exposure ($J \cdot m^{-2}$);

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c) the applicable value of the ocular MPE (determined in accordance with Clause 4), and specified in the same units as the effective exposure;

d) the actual exposure and the beam diameter (these parameters enable the ability of the eyewear to withstand the incident laser radiation to be established);

e) the optical density D_λ of the eyewear at the laser wavelength. The optical density should be sufficient to reduce the transmitted radiation to below the MPE applicable for the maximum reasonably foreseeable exposure time. The value of D_λ required to give the minimum necessary level of eye protection can be calculated from the formula:

$$D_\lambda = \log_{10}[(\textit{maximum reasonably foreseeable exposure})/(\mathrm{MPE})]$$

8.4.5.2.3 Other important factors include:

a) visible light transmission, and the ability to see warning lights or other indicators through the filters;

b) general design, comfort, ventilation, peripheral vision, and provision for spectacle correction (either by using goggle-style protectors which fit over normal spectacles, or protective spectacles which incorporate the wearer's own optical correction);

c) degradation or modification of the absorbing material of the filter, including radiation-induced transparency;

d) mechanical strength of materials and resistance to shock;

e) any relevant national requirements or regulations.

8.4.5.2.4 Eyewear should be permanently marked to indicate:

a) the operating wavelength;

b) the optical density at the operating wavelength.

8.4.5.2.5 Other eyewear considerations include the following.

a) Any limitation on the maximum level of laser exposure to which the eyewear should be subjected (due to the possibility of damage to the filter material at high levels of exposure) should also be known.

b) Where different kinds of protective eyewear are in use it can be helpful to use colour-coding or other means to link each pair with its particular laser.

c) For work with visible laser emission it can sometimes be desirable to be able to see the laser beam for alignment purposes or other operational reasons. In this case the eye protective filters should be specified on the basis of reducing an accidental exposure to the equivalent of Class 2, where protection is afforded by the natural aversion response. This is done by using a time base of 0,25 s for defining the MPE in the equation given above for D_λ.

d) Protective eyewear is designed to protect against accidental exposure to laser radiation. It should not be used to protect against deliberate exposure or the intentional viewing of a laser beam. Protective eyewear should be checked periodically for signs of wear or damage. The date of checking should be recorded and the eyewear replaced when necessary. Protective eyewear should also be examined for suitability on each occasion prior to use.

e) At high incident power or energy levels, absorption of the incident radiation in the filter material can result in severe stress build-up and sudden failure of the filter. For this reason, protective eyewear, which has been subjected to a single incident of accidental exposure at a high level of exposure, should be replaced.

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8.4.5.3 Protective clothing

In some cases it may be necessary to provide other protective clothing for work in laser controlled areas. This is most likely to take the form of masks or gloves, but may very occasionally require the use of whole body protection.

Such protection should be considered wherever a risk assessment has shown that a serious risk of harm (in addition to any hazard to the eyes) exists (see Clause 7), although in such circumstances complete enclosure of the hazard should always be the preferred solution.

8.5 Equipment servicing

8.5.1 Increased risks during laser equipment servicing

Laser products are classified on the basis of the level of laser radiation accessible during operation. Maintenance and servicing, on the other hand, may require removal of protective covers, disabling of the product's protective features and/or a significant change to the performance of the laser product, thereby increasing the risk of injury. Additional hazards (e.g., electrical) may also be present. Servicing and maintenance operations may require a higher level of safety training than is necessary for normal operation.

Before service operations are undertaken a separate risk assessment should be undertaken. A record should be kept of all servicing operations and any resulting changes to the performance of the laser product.

The servicing of embedded lasers can greatly increase the risk of a laser radiation injury. Servicing includes beam alignment and other adjustment operations, and the likelihood of creating errant laser beams (that is, beams pointing in unexpected directions) is greatly increased. In order to carry out servicing in a safe manner it is often necessary to set up a temporary laser controlled area around the laser equipment (see below), and to implement procedures and safeguards (e.g., a systematic method for beam alignment) appropriate to the increased level of risk. Manufacturers are required to provide advice on safe procedures during servicing, upon request.

8.5.2 Temporary laser controlled areas

A temporary laser controlled area should be established whenever conditions allowing human access to hazardous levels of laser radiation are created temporarily (e.g., during servicing), and where persons who are unauthorised, unaware of the presence of the laser hazard and/or are not appropriately trained or supervised in the necessary safety procedures could be present.

The guidance for temporary controlled areas is the same as for laser controlled areas in general (see 8.4.2). Although the normal requirement for engineering control of access may be difficult to achieve, administrative controls can have increased effectiveness when restriction of access is only temporary. If safe access to the area is not controlled by engineering means, then appropriate warning and prohibited entry signs should be posted at the points of entry to the area. In certain circumstances it may be desirable in addition to have another person present to enforce the temporary access restrictions.

8.5.3 Controls during servicing

In establishing control measures during equipment servicing, where there is an increased risk of laser radiation injury, particular consideration should be given to the following:

a) reducing the level of emission to the maximum necessary;

b) limiting the range of movement of beam steering components to reduce uncertainty in beam position during alignment;

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c) first checking beam alignment close to the laser and then progressively further away, to minimise the uncertainty in beam position;

d) placing large area beam stops behind target screens during beam alignment to stop the laser beam in the event that it misses the target;

e) providing beam visualising alignment aids (e.g., cameras, fluorescent or heat sensitive screens and viewers). These should also be used in the case of visible laser beams where there is the added benefit of countering the strong temptation to remove protective eyewear in order to clearly see the beam;

f) provision of comfortable laser safety eyewear, suitable for use over prolonged periods, where adequate protection by other means is not feasible;

g) providing an engineering means for the transfer of control of the laser beam (e.g., a hand-held hold-to-fire device) where two or more persons are involved in servicing, in particular where a person remote from the laser might otherwise call to the other to fire the laser;

h) using non-reflective coatings or diffusely-reflecting surfaces on tools, and requiring the removal or covering of jewellery, watches, etc. by those in the controlled area, in order to minimise stray reflections.

8.5.4 Visiting service engineers

If an outside agency (e.g., the laser equipment supplier) is engaged to conduct the servicing of the laser equipment, then a permit-to-work procedure should be adopted for handing the equipment over to the service engineer and accepting it back fully-restored to normal operation when the work is completed. Written procedures should be used to achieve this. Verification of safety interlock restoration should be part of the release of the equipment to the user.

A risk assessment of the service operation is required, even if the service engineer has complete control of the work. Responsibility for establishing a temporary laser controlled area prior to starting service activities, if such an area is required, may be determined by contractual arrangement. If no such contractual arrangement exists, then responsibility should be taken by the laser user to ensure that necessary servicing controls are put in place.

9 Maintenance of safe operation

Regular monitoring of laser working areas should be carried out, and such monitoring recorded, to ensure that the control procedures that have been adopted remain effective and that the conditions for achieving acceptable risk remain satisfied. Protective procedures should be modified whenever necessary to ensure continuing safe use. The results of investigations into safety incidents and suspected accidents (see Clause 10) should be used to re-appraise the effectiveness and adequacy of the control procedures.

Circumstances that could indicate an urgent need for reassessing risk and for reviewing protective procedures and controls include the following.

a) modifications to, or relocation or replacement of, the laser equipment;

b) changed conditions of use;

c) changes to the environment in which the laser equipment is used;

d) changes to the personnel who could have access to the laser equipment or who could be exposed to laser hazards;

e) indications of *any* reduction in compliance with safety procedures.

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10 Incident reporting and accident investigation

In the event of an actual or suspected hazardous exposure to laser radiation or other laser hazard (an accident), or a possible failure of a protective measure which could have led to an accident (an incident), laser emission should be terminated immediately. The incident should be reported to the management of the facility where the incident occurred.

Where an accident has or is suspected to have occurred, medical attention should be sought as necessary. In the event of an apparent or suspected injury to the eye, a medical examination by a qualified ophthalmologist should be carried out within 24 h of the event. It is useful to have a summary of the laser beam characteristics to accompany the casualty and assist the ophthalmologist. In all cases where a hazardous exposure is suspected, a full investigation to ascertain the circumstances surrounding the event and the likely magnitude of the exposure should be undertaken, and the conclusions of this investigation documented. In the case of an accident, the reason for the possible failure should be determined, and any necessary changes to the system of protective controls should be introduced before re-use of the laser.

11 Medical surveillance

Routine ophthalmic examinations of employees working with laser equipment have no value as part of a health surveillance programme. Ophthalmic examinations are sometimes carried out for other (e.g., medico-legal) reasons. Some of the investigative procedures used are themselves hazardous, and these should therefore only be carried out when medically advisable, and not used for routine screening.

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Table 5 – Maximum permissible exposure (MPE) at the cornea for direct exposure to laser radiation

<table>
<tr><th rowspan="2">Wavelength
λ in nm</th><th colspan="10">Exposure time t in seconds (s)</th></tr>
<tr><th>10^{-13} to 10^{-11}</th><th>10^{-11} to 10^{-9}</th><th>10^{-9} to 10^{-7}</th><th>10^{-7} to $1,8 \times 10^{-5}$</th><th>$1,8 \times 10^{-5}$ to 5×10^{-5}</th><th>5×10^{-5} to 1×10^{-3}</th><th>1×10^{-3} to 10</th><th>10 to 10^2</th><th>10^2 to 10^4</th><th>10^3 to 3×10^4</th></tr>
<tr><td>180 to 302,5</td><td colspan="2" rowspan="3">3×10^{10} W·m^{-2}</td><td colspan="8">30 J·m^{-2}</td></tr>
<tr><td>302,5 to 315</td><td colspan="5">($t \le T_1$)
C_1 J·m^{-2}
C_2 J·m^{-2}
($t > T_1$)</td><td colspan="3">C_2 J·m^{-2}</td></tr>
<tr><td>315 to 400</td><td colspan="5">C_1 J·m^{-2}</td><td colspan="2">10^4 J m^{-2}</td><td>10 W m^{-2}</td></tr>
<tr><td>400 to 450 [a]</td><td rowspan="3">$1,5 \times 10^{-4}$ J·m^{-2}</td><td rowspan="3">$2,7 \times 10^4$ $t^{0,75}$ J·m^{-2}</td><td colspan="2" rowspan="3">5×10^{-3} J·m^{-2}</td><td colspan="3" rowspan="3">18 $t^{0,75}$ J·m^{-2}</td><td>100 J·m^{-2}</td><td colspan="2" rowspan="2">C_3 W·m^{-2}</td></tr>
<tr><td>450 to 500 [a]</td><td>100 C_3 J·m^{-2}
and [b]
10 W·m^{-2}</td></tr>
<tr><td>500 to 700 [a]</td><td colspan="3">10 W·m^{-2}</td></tr>
<tr><td>700 to 1 050 [a]</td><td>$1,5 \times 10^{-4}$ C_4 J·m^{-2}</td><td>$2,7 \times 10^4$ $t^{0,75}$ C_4 J·m^{-2}</td><td colspan="2">5×10^{-3} C_4 J·m^{-2}</td><td colspan="3">18 $t^{0,75}$ C_4 J·m^{-2}</td><td colspan="3" rowspan="2">10 C_4 C_7 W·m^{-2}</td></tr>
<tr><td>1 050 to 1 400 [a]</td><td>$1,5 \times 10^{-3}$ C_7 J·m^{-2}</td><td>$2,7 \times 10^5$ $t^{0,75}$ C_7 J·m^{-2}</td><td colspan="3">5×10^{-2} C_7 J·m^{-2}</td><td colspan="2">90 $t^{0,75}$ C_7 J·m^{-2}</td></tr>
<tr><td>1 400 to 1 500</td><td colspan="2">10^{12} W·m^{-2}</td><td colspan="4">10^3 J·m^{-2}</td><td>5 600 $t^{0,25}$ J·m^{-2}</td><td colspan="3" rowspan="4">1 000 W·m^{-2}</td></tr>
<tr><td>1 500 to 1 800</td><td colspan="2">10^{13} W·m^{-2}</td><td colspan="5">10^4 J·m^{-2}</td></tr>
<tr><td>1 800 to 2 600</td><td colspan="2">10^{12} W·m^{-2}</td><td colspan="4">10^3 J· m^{-2}</td><td>5 600 $t^{0,25}$J·m^{-2}</td></tr>
<tr><td>2 600 to 10^6</td><td colspan="2">10^{11} W·m^{-2}</td><td>100 J·m^{-2}</td><td colspan="4">5 600 $t^{0,25}$ J·m^{-2}</td></tr>
</table>

NOTE 1 For correction factors and units, see Table 8.

NOTE 2 The MPEs for exposure times below 10^{-9} s and for wavelengths less than 400 nm and greater than 1 400 nm have been derived by calculating the equivalent irradiance from the radiant exposure limits at 10^{-9} s. The MPEs for exposure times below 10^{-13} s at all wavelengths are set to be equal to the equivalent irradiance values of the MPEs at 10^{-13} s.

[a] The MPEs given in this table for the wavelength range 400 to 1 400 nm (the retinal hazard region) apply to apparent source sizes no greater than 1,5 mrad. (This covers the direct viewing of most single laser sources.) Increased limits that are applicable to larger sources (such as certain multiple sources or diffuse reflections) are given in Table 6.

[b] In the wavelength range between 450 nm and 500 nm, dual limits apply for exposure durations from 10 to 100 s and the exposure must not exceed either limit applicable.

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Table 6 – Maximum permissible exposure (MPE) at the cornea for direct exposure to laser radiation from extended sources in the wavelength range from 400 nm to 1 400 nm (retinal hazard region)

Wavelength λ in nm	Exposure time t in seconds (s)								
	10^{-13} to 10^{-11}	**10^{-11} to 10^{-9}**	**10^{-9} to $1,8 \times 10^{-5}$**	**$1,8 \times 10^{-5}$ to 5×10^{-5}**	**5×10^{-5} to 10**		**10 to 10^2**	**10^2 to 10^4**	**10^4 to 3×10^4**
400 to 700 [a]	$1,5 \times 10^{-4}$ C_6 J·m^{-2}	$2,7 \times 10^4$ $t^{0,75}$ C_6 J·m^{-2}	5×10^{-3} C_6 J·m^{-2}	18 $t^{0,75}$ C_6 J·m^{-2}		400 to 600 nm [a]	Retinal photochemical hazard		
							100 C_3 J·m^{-2} using γ_p = 11 mrad	1 C_3 W·m^{-2} using γ_p = 1,1 $t^{0,5}$ mrad	1 C_3 W·m^{-2} using γ_p = 110 mrad
							AND		
						400 to 700 nm [a]	Retinal thermal hazard		
							($t \le T_2$) 18 $t^{0,75}$ C_6 J·m^{-2}		($t > T_2$) 18 C_6 $T_2^{-0,25}$ W·m^{-2}
700 to 1 050	$1,5 \times 10^{-4}$ C_4 C_6 J·m^{-2}	$2,7 \times 10^4$ $t^{0,75}$ C_4 C_6 J·m^{-2}	5×10^{-3} C_4 C_6 J·m^{-2}	18 $t^{0,75}$ C_4 C_6 J·m^{-2}			($t \le T_2$) 18 $t^{0,75}$ C_4 C_6 C_7 J·m^{-2}		($t > T_2$) 18 C_4 C_6 C_7 $T_2^{-0,25}$ W·m^{-2}
1 050 to 1 400	$1,5 \times 10^{-3}$ C_6 C_7 J·m^{-2}	$2,7 \times 10^5$ $t^{0,75}$ C_6 C_7 J·m^{-2}	5×10^{-2} C_6 C_7 J·m^{-2}		90 $t^{0,75}$ C_6 C_7 J·m^{-2}				

NOTE 1 For correction factors and units see Table 8.

NOTE 2 The angle γ_p is the limiting angle of acceptance for the measuring instrument.

[a] In the wavelength range between 400 nm and 600 nm, dual limits apply and the exposure must not exceed either limit applicable. Normally photochemical hazard limits only apply for exposure durations greater than 10 s; however, for wavelengths between 400 nm and 484 nm and for apparent source sizes between greater than 1,5 mrad and up to 82 mrad, the photochemical hazard limit of 100 C_3 J m^{-2} shall be applied for exposures greater than or equal to 1 s.

Table 7 – Maximum permissible exposure (MPE) of skin to laser radiation

Wavelength λ in nm	Exposure time *t in seconds (*s)					
	$<10^{-9}$	10^{-9} to 10^{-7}	10^{-7} to 10^{-3}	10^{-3} to 10	10 to 10^{3}	10^{3} to 3×10^{4}
180 to 302,5	3×10^{10} W·m^{-2}			30 J·m^{-2}		
302,5 to 315		C_1 J·m^{-2} ($t > T_1$)		C_2 J·m^{-2} ($t > T_1$)	C_2 J·m^{-2}	
315 to 400		C_1 J·m^{-2}			10^{4} J·m^{-2}	10 W·m^{-2}
400 to 700	2×10^{11} W·m^{-2}	200 J·m^{-2}		$1,1\times10^{4}\ t^{0,25}$ J·m^{-2}	2 000 W·m^{-2}	
700 to 1 400	$2\times10^{11}\ C_4$ W·m^{-2}	200 C_4 J·m^{-2}		$1,1\times10^{4}\ C_4\ t^{0,25}$ J·m^{-2}	2 000 C_4 W·m^{-2}	
1 400 to 1 500	10^{12} W·m^{-2}	10^{3} J·m^{-2}		5 600 $t^{0,25}$ J·m^{-2}	1 000 W·m^{-2} [a]	
1 500 to 1 800	10^{13} W·m^{-2}	10^{4} J·m^{-2}				
1 800 to 2 600	10^{12} W·m^{-2}	10^{3} J·m^{-2}		5 600 $t^{0,25}$ J·m^{-2}		
2 600 to 10^{6}	10^{11} W·m^{-2}	100 J·m^{-2}	5 600 $t^{0,25}$ J·m^{-2}			

NOTE 1 For correction factors and units see Table 8.

NOTE 2 There is only limited evidence about effects for exposures of less than 10^{-9} s. The MPEs for these exposure times have been derived by maintaining the irradiance applying at 10^{-9} s.

[a] For exposed skin areas greater than 0,1 m^2, the MPE is reduced to 100 W·m^{-2}. Between 0,01 m^2 and 0,1 m^2, the MPE varies inversely proportional to the irradiated skin area.

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Table 8 – Correction factors for MPEs

Parameter	Spectral region nm
$C_1 = 5{,}6 \times 10^3\ t^{0{,}25}$	302,5 to 400
$T_1 = 10^{0{,}8(\lambda - 295)} \times 10^{-15}$ s	302,5 to 315
$C_2 = 10^{0{,}2(\lambda - 295)}$	302,5 to 315
$T_2 = 10 \times 10^{[(\alpha - \alpha min)/98{,}5]}$ s[a]	400 to 1 400
$C_3 = 1{,}0$	400 to 450
$C_3 = 10^{0{,}02(\lambda - 450)}$	450 to 600
$C_4 = 10^{0{,}002(\lambda - 700)}$	700 to 1 050
$C_4 = 5$	1 050 to 1 400
$C_5 = N^{-1/4}$ [b]	400 to 10^6
$C_6 = 1$ for $\alpha \le \alpha_{min}$	400 to 1 400
$C_6 = \alpha/\alpha_{min}$ for $\alpha_{min} < \alpha \le \alpha_{max}$	400 to 1 400
$C_6 = \alpha_{max}/\alpha_{min} = 66{,}7$ for $\alpha > \alpha_{max}$ [d]	400 to 1 400
$C_7 = 1$	700 to 1 150
$C_7 = 10^{0{,}018(\lambda - 1150)}$	1 150 to 1 200
$C_7 = 8$	1 200 to 1 400

[a] T_2 = 10 s for α < 1,5 mrad and T_2 = 100 s for α > 100 mrad

[b] C_5 is only applicable to pulse durations shorter than 0,25 s

[c] C_6 is only applicable to pulsed lasers and to CW lasers where thermal injury dominates

[d] The limiting angle of acceptance γ shall be equal to α_{max}

α_{min} = 1,5 mrad

α_{max} = 100 mrad

N is the number of pulses contained within the applicable duration (see 5.2)

NOTE 1 There is only limited evidence about effects for exposures of less than 10^{-9} s for wavelengths less than 400 nm and greater than 1 400 nm.

NOTE 2 Correction factors C_1 to C_7 and breakpoints T_1 and T_2 used in Tables 5 to 7 are defined in the following expressions.

NOTE 3 See Table 2 for limiting apertures.

NOTE 4 In the formulae in Tables 5 to 7 and in these notes, the wavelength has to be expressed in nanometres, the emission duration t has to be expressed in seconds, and α has to be expressed in milliradians

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Table 9 – Laser controlled areas

Laser class	Nature of hazard	Example of controlled area	Outline of protective control measures
Class 1 Class 2	Minimal (N.B. Embedded lasers may present associated hazards.)	Unrestricted i.e., a designated laser area is not normally required.	Follow warnings on labels and manufacturer's instructions for safe use.
Divergent-beam Class 1M Divergent-beam Class 2M (i.e. products that have failed Class 1 or Class 2 under Condition 2)	Localised eye hazard if optical viewing instruments such as eye loupes are used.	Localised Can be open-plan, if effective procedural control is exercised over the immediate area around the laser.	Training recommended. Prevent use of eye-loupes and other magnifiers in vicinity of the laser. Prevent re-focusing or collimation of the beam.
Collimated-beam Class 1M Collimated-beam Class 2M (i.e. products that have failed Class 1 or Class 2 under Condition 1)	Long range eye hazard if optical viewing instruments such as binoculars or telescopes are used.	Enclosed or open-plan Access to the ENOHA to be controlled by procedural means, i.e. by the use of signs, instructions and training. Where open-plan, public access into the ENOHA must be prevented.	Training required. LSO recommended. Prevent use of telescopes and binoculars. Prevent re-focusing of the beam.
Class 3R	Low-level eye hazard.	Unrestricted i.e. safety depends on responsible use.	Training recommended. Prevent direct eye exposure.
Class 3B	Eye hazard. Possible skin hazard at higher levels of class.	Enclosed and interlock-protected i.e. access controlled by engineering means.	Training and LSO required. Ensure key security. Enclose as much of beam as possible, using complete enclosure where feasible. Implement safe systems of work. Use PPE if exposure risk is unavoidable.
Class 4	Eye and skin hazard. Possible fire and fume hazards.	Enclosed and interlock-protected i.e., access controlled by engineering means.	Training and LSO required. Ensure key security. Enclose as much of beam as possible, using complete enclosure where feasible. Implement safe systems of work. Use PPE if exposure risk is unavoidable. Protect against associated hazards (e.g., fire, fume).
NOTE This table covers the normal operation of lasers (i.e. not maintenance or servicing) and is intended only as a guide to laser controlled areas. A risk assessment may indicate that a laser of a given class should be placed in a higher or lower category of controlled area, or that a different system of protective controls is necessary in order to adequately reduce the risk.			

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Annex A
(informative)

Examples of interlock systems for laser controlled areas

NOTE This annex gives information on the range of possibilities available for engineering control of laser hazards using interlock systems. It is intended for those who may be unfamiliar with their use, but it should not preclude the implementation of alternative solutions that may give a satisfactory level of protection in a given set of circumstances. The full set of facilities described here is given for illustrative purposes; not all are necessarily required for a given installation.

A.1 Introduction

Interlock systems can be used to terminate laser emission whenever a door giving access into a laser controlled area is opened.

There are many different ways to configure an interlock system, depending on the particular requirements, but they all fall into two basic categories; locking and non-locking. These are shown in Figures A.1 to A.3. Not all of the elements are always necessary, but they are shown here for completeness.

A.2 Common elements

A.2.1 Interlock control system

An interlock control system should be of fail-safe design such that it maintains its protective function in the event of a component failure. (An example of component failure is relay contact weld.) The system should also have a reset button so that once the interlock has been tripped (by opening the door), it needs a deliberate action to restart laser emission (rather than by simply re-closing the door). Note, however, that the remote interlock connector specified by IEC 60825-1 for all Class 3B and Class 4 laser products, and which may be used for linking to door switches, is not required to have a re-set mechanism, and so it is suggested that users consider installing their own.

A.2.2 Door interlock switches

Mechanical switches are generally the simplest. They should be of a "positive break" design (i.e. the contacts spring apart by the action of opening the door) to prevent the contacts sticking or welding. Magnetic or other proximity switches are useful on sliding doors or where a high degree of hygiene is required. These switches should be coded (i.e. the two parts designed to operate as a unique pair) to avoid casual override, and should be of a design that eliminates the possibility of contact weld.

A.2.3 Override switches

An interlock override facility, permitting temporary defeat of the interlock protection by authorised persons, should only be installed if its use is justifiable and safety is not compromised (see 8.4.2). It is also essential to ensure that laser emission cannot emerge through the open doorway while the override is in operation.

Where an override system is adopted, a non-secure switch, such as a push-button type, will normally be adequate for use on the inside of the room. If override switches are to be placed outside the room as well (which will be essential if the room may be left unoccupied while the laser is running), it is sensible to use a key switch, keypad or coded magnetic card to control access. The override itself should be fail-safe and time-limited, independently of the switches, so that it will not remain in continuous use even if the override switch fails in the "on" position.

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A.2.4 Shutter

Where a beam shutter is used to terminate laser emission rather than by switching off the laser power supply, it should be of fail-safe design such that it will always remain in the closed position when the shutter power is off, and also be capable of withstanding the incident laser beam without damage.

A.2.5 Illuminated warning sign

This can be a useful administrative control, especially when the non-locking type of system is being used, helping to avoid unnecessary interruptions of laser emission. In order to do this effectively the sign must be appropriately connected so that it only indicates "on" when the laser is being operated. Manually-operated illuminated signs are not usually satisfactory.

A.2.6 Non-locking interlock system (see Figure A.2)

These are the most common types of interlock system. They perform a safety function by shutting down the laser emission in the event of someone opening the door, and they should be designed to prevent restart until all doors are closed. An override can be used to allow authorised personnel to enter and leave the hazardous area without interruption of the laser (but see A.2.3), while illuminated warning signs can be used to indicate the status of the laser at all access doors. One means of terminating laser emission is to interrupt the power supply, although this may have implications for the performance of the laser (e.g. by affecting its stability and accelerating component failure), except where relatively low power diode lasers are in use. It is therefore often rejected for reasons of practicality. (If adequate procedural controls have been implemented, however, the inadvertent operation of an interlock through unauthorised access ought to be an extremely rare event.) An alternative method is by the use of a fail-safe shutter that interrupts the laser beam (see A.2.4).

A.2.7 Emergency stop switch

If an emergency stop button to terminate laser emission is not already easily accessible from all parts of the room, one or more emergency stop buttons should be included in the system.

A.2.8 Locking interlock systems (see Figure A.3)

These systems physically prevent unauthorised access into a laser area and therefore eliminate unwanted interruptions to laser emission. Manual locking of a laboratory door is, however, not acceptable, since a person may become trapped inside in the event of an accident. Even keeping keys outside the room does not solve the problem since they may go missing at the crucial time, or in the event of a fire be hard to find. A locking system must be fail-safe, shutting down the laser and allowing access to the room in the event of power failure or when emergency access is required. This can be achieved by the use of key-coded or magnetic card operated electronic locks, provided that a clear and obvious override facility allowing emergency access is available that can be operated by anyone and does not require a key, code or swipe card. It can also be accomplished by the use of fail-safe door strikes to lock the doors (see A.2.9), which can similarly be opened in an emergency. The laser should still be interlocked by the use of a shutter or directly into the power supply, to terminate laser emission when emergency access is gained. Door interlock switches can still be used to ensure that start-up cannot occur while a door is open, and to instigate shutdown if a door is left open beyond the allowed override time.

A.2.9 Electric locks (door strikes)

Fail-safe electric locks can be fitted which hold the door in the closed position when energised, so preventing unauthorised entry. (Conventional key-operated locks should not be used.) These devices are fitted to the doorframe, and cover the door latch when energised. (The latch is not connected to, and cannot be operated by, the door handles.) This allows the door to shut when the strike is energised but not to open. When the strike is not energised the door can simply be pushed or pulled open.

Emergency stop switches should be fitted outside each door wherever a locking system is used to allow entry in the event of an emergency. On the inside of each door a push-button override switch will always allow exit and may be considered adequate, although at least one easily accessible emergency stop button should be fitted inside the room. When pressed, the emergency stop switch will render the situation safe by simultaneously shutting down the laser beam and de-energising the door strikes, thus allowing exit.

Purpose of an interlock system

Walls and doors contain the hazard within the laser controlled area.

An interlock system connected to the doors and which is operative when the hazard is present restricts access to those personnel who are trained, authorised and suitably equipped.

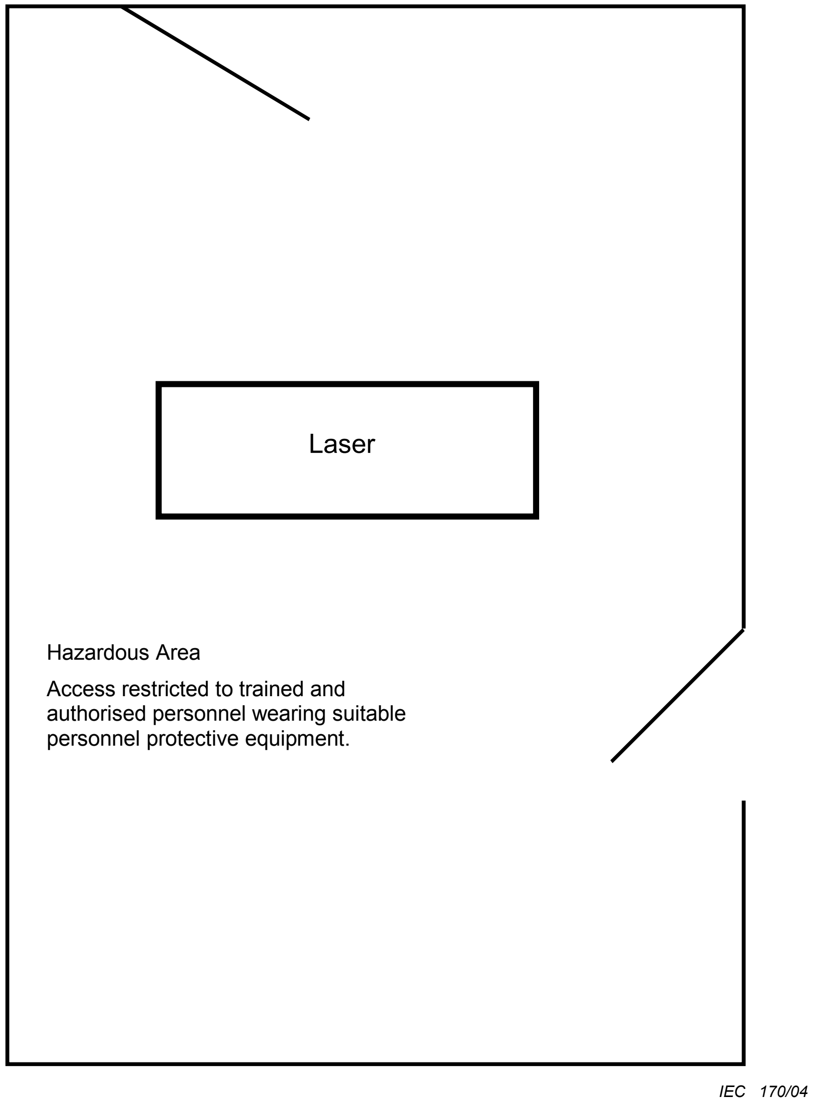

Figure A.1 – Purpose of an interlock system

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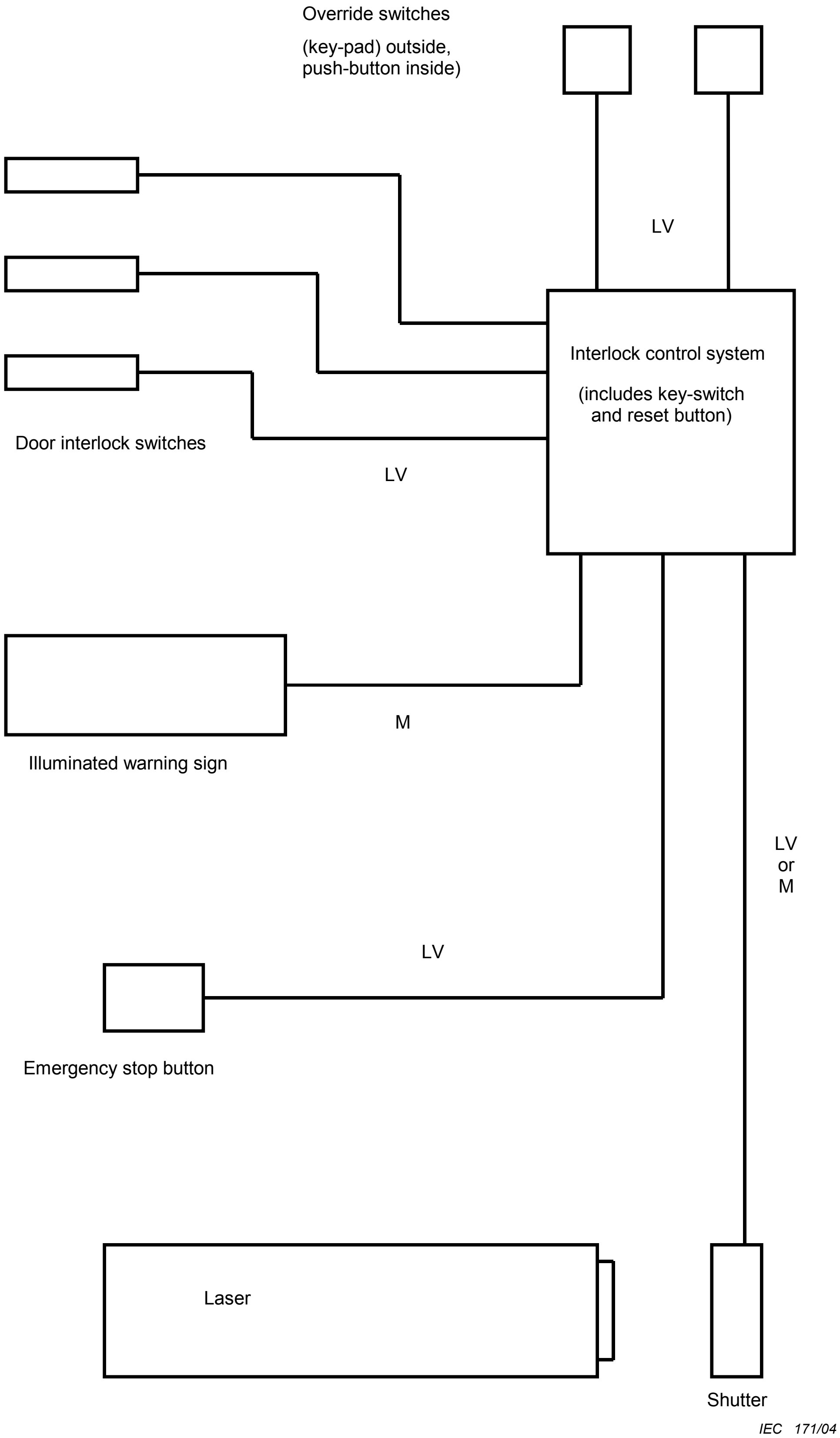
Non-locking interlock system



Key
LV = Low voltage
M = Mains

Figure A.2 – Non-locking interlock system

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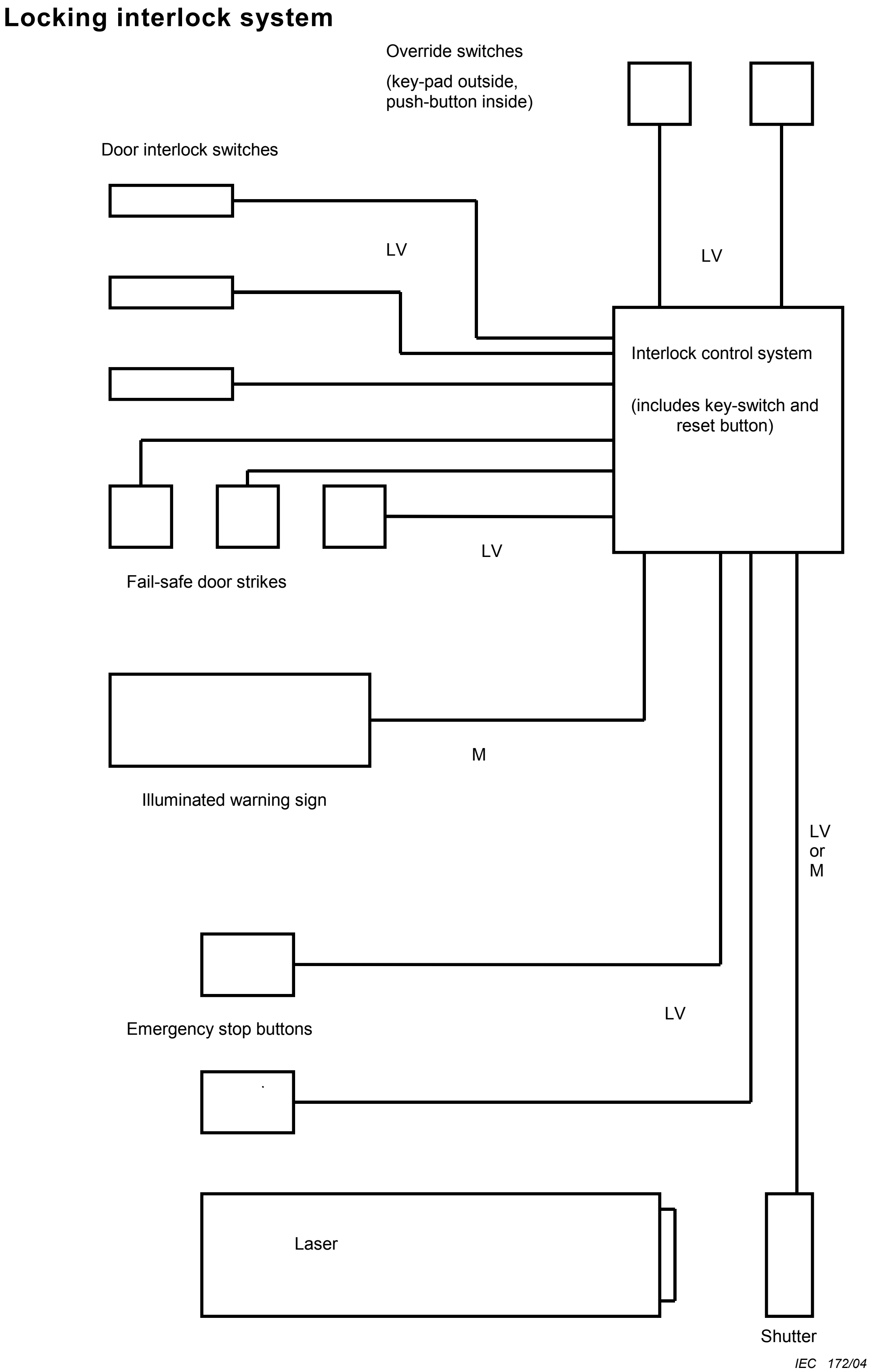

Key
LV = Low voltage

M = Mains

Figure A.3 – Locking interlock system

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Annex B
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Examples of calculations

B.1 Introduction

This annex provides a selection of worked examples using additional information and formulae provided in IEC TR 60825-10, *Application guidelines and explanatory notes to IEC 60825-1*. The determination of maximum permissible exposure (MPE) is introduced in B.3 with examples for small source viewing of CW or single pulse laser output in B.4, and repetitively pulsed systems in B.5. The determination of nominal ocular hazard distance (NOHD) for small sources is covered in B.6 and for extended sources in B.7. Calculation of the optical density of laser eye protectors is presented in B.8, and a multiple small source calculation is provided in B.9.

B.2 Symbols used in the examples of this annex:

Symbol	Unit	Definition
a	m	Diameter of the emergent laser beam.
α	rad	The angle subtended by an apparent source (or a diffuse reflection) as viewed at a point in space.
α_f	rad	Angle at the eye subtending the apparent source of radiation at a distance of r_f = 100 mm.
α_{min}	rad	Minimum angle subtended by a source for which the extended source criterion applies.
α_{max}	rad	The value of angular subtense of the apparent source above which the MPEs are independent of the source size. (α_{max} = 0,1 rad)
$C_1, C_2, \ldots, C_7$	no units	Correction factors (see Table 8)
d_u	m	Diameter of the smallest circle at a specified distance, r, from the apparent source that contains u % of the total laser power (or energy). In the case of a Gaussian beam, d_{63} corresponds to the points where the irradiance (or radiant exposure) falls to 1/e of its central peak value.
D_e	m	Diameter of the exit pupil of an optical system.
D_o	m	Diameter of the objective of an optical system.
η	no units	Fraction of the total laser power (or energy) collected through a specified aperture located at a specified distance, r, from the apparent source.
F	Hz	Pulse repetition frequency.
G	no units	Square root of the ratio of retinal irradiance or radiant exposure received by an optically aided eye to that received by an unaided eye.
H	$J \cdot m^{-2}$	Radiant exposure or
E	$W \cdot m^{-2}$	irradiance at a specified distance, r, from the apparent source.
H_o	$J \cdot m^{-2}$	Emergent beam radiant exposure or
E_o	$W \cdot m^{-2}$	irradiance at zero distance from the apparent source.

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Symbol	Unit	Definition
k	no units	Mode structure factor with values ranging from k = 1 for beams having Gaussian profiles to k = 2,5 for beams of unknown mode structure.
L_p	$J \cdot m^{-2} \cdot sr^{-1}$	Integrated radiance of an extended source.
λ	nm	Wavelength of laser radiation.
M	no units	Magnification of an optical instrument.
H_{MPE} or E_{MPE}	$J \cdot m^{-2}$ $W \cdot m^{-2}$	Maximum permissible exposure
μ	m^{-1}	Atmospheric attenuation coefficient at a specified wavelength.
N	no units	Number of pulses contained within an exposure duration
NA	no units	Numerical aperture of a laser source.
NA_m	no units	Numerical aperture of a microscope objective
NOHD	m	Nominal ocular hazard distance.
OD	no units	Optical (transmittance) density defined as the logarithm to base 10 of the reciprocal of the transmittance (see also IEV 845-04-66; symbol *D* is not used here to avoid confusion with diameters).
P_o	W	Total radiant power (radiant flux) of a CW laser, or average radiant power of a repetitively pulsed laser.
P_p	W	Radiant power within a pulse of a pulsed laser.
ϕ	rad	Divergence angle of an emergent laser beam.
π	no units	The numerical constant 3,142.
Q	J	Total radiant energy of a pulsed laser.
r	m	Distance from the apparent source to the viewer, measurement aperture, or diffuse target.
r_1	m	Distance from the laser target to the viewer or measurement aperture.
$r_{1,max}$	m	Maximum distance from the laser target to the viewer where extended source viewing conditions apply.
t	s	Time duration of a single laser pulse.
T	s	Total exposure duration of a train of pulses.
T_1, T_2	s	Time breakpoints (see Table 8).

B.3 Maximum permissible exposure (MPE) – Introduction

The maximum permissible exposure is defined in 2.47 as the maximum level of laser radiation to which living tissues (persons) may be exposed without suffering consequential injury either immediately after exposure, or later in time. Maximum permissible exposure values are set below known hazard levels. However, the MPE values should be regarded as guides for safe exposure, rather than as sharp dividing lines between safe and unsafe levels of exposure.

The MPE values are dependent upon:

- wavelength of the radiation;
- exposure time or pulse duration;
- spectrum of wavelengths, when the tissue is exposed to more than one wavelength;

- nature of the tissue exposed, and
- angular subtense of the source (which determines the size of the retinal image) in the wavelength range from 400 nm to 1 400 nm.

The examples presented in this annex illustrate the calculation procedures for intrabeam viewing, for diffuse reflections and extended sources, and for pulsed or modulated exposures. The selection of an exposure time may be obvious as in the case of a single pulse laser or a CW or repetitively pulsed laser operating in the visible wavelength range 400 nm to 700 nm when the aversion response of 0,25 s may be used for an ocular exposure. Repetitively pulsed or CW lasers operating at wavelengths outside the visible range will often require a Laser Safety Officer to make a value judgement of the likely exposure time.

NOTE Tables 5 and 6 provide MPE values for ocular exposures while Table 7 provides MPE values for skin exposures.

The examples show step-by-step calculation procedures for typical wavelengths and other exposure parameters. The user may then adapt these procedures to a specific situation when calculation of the MPE is necessary.

B.4 Maximum permissible exposure (MPE) – Single small source

Small source viewing occurs when the angular subtense of the source is ≤ α_{min}. The following four examples illustrate the calculation procedures for single, small source viewing conditions, to CW or single pulse laser output.

Example B.4.1

Calculate the MPE for a helium-cadmium laser, λ = 325 nm, with an emission duration of 0,1 s.

Solution:

The applicable MPE value can be found in Table 5, at the intersection of the wavelength range from 315 nm to 400 nm and exposure duration column 1×10^{-3} s to 10 s, the MPE is found to be equal to C_1 J·m^{-2}. C_1 can be calculated from the formula given in Table 8.

$$C_1 = 5{,}6 \times 10^3 \times t^{0{,}25}$$

$$H_{MPE} = 5{,}6 \times 10^3 \times 0{,}1^{0{,}25} = 3{,}15 \times 10^3 \text{ J·m}^{-2}$$

To obtain the MPE in terms of irradiance divide by the exposure duration t,

$$E_{MPE} = H_{MPE}/t = 3{,}15 \times 10^3 / 0{,}1 = 3{,}15 \times 10^4 \text{ W·m}^{-2}$$

Example B.4.2

Determine the maximum permissible single pulse exposure for a pulsed ruby laser, λ = 694 nm, with an exposure duration of 10^{-3} s.

Solution:

In Table 5, the MPE is found at the intersection of the wavelength range from 400 nm to 700 nm and exposure duration $t = 5 \times 10^{-5}$ s to 10^{-3} s. The MPE value is,

$$H_{MPE} = 18 \times t^{0{,}75} \text{ J·m}^{-2}$$

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Thus,

$$H_{MPE} = 18 \times (10^{-3})^{0,75} = 0,10 \text{ J·m}^{-2}$$

Example B.4.3

What is the MPE for a single-pulse of a gallium-arsenide laser, λ = 905 nm, with a 100 ns pulse width?

Solution:

In Table 5, the MPE is found at the intersection of the wavelength range from 700 nm to 1 050 nm and exposure duration $t = 10^{-7}$ s to $1,8 \times 10^{-5}$ s. The MPE expressed as a radiant exposure is given by:

$$H_{MPE} = 5 \times 10^{-3} \times C_4 \text{ J·m}^{-2}$$

The coefficient C_4 can be calculated from the formula given in Table 8:

$$C_4 = 10^{0,002(\lambda-700)} = 2,57$$

Thus,

$$H_{MPE} = 5 \times 10^{-3} \times 2,57 = 12,9 \times 10^{-3} \text{ J·m}^{-2}$$

Example B4.4

Calculate the MPE for a continuous wave helium-neon (He-Ne) laser, λ = 633 nm.

Solution:

As the laser is operating in the visible part of the spectrum and intentional viewing is not intended, an exposure duration limited by the aversion response to T = 0,25 s will be used. The MPE values can be found in Table 5 at the intersection of the wavelength range from 400 nm to 700 nm and exposure duration column 1×10^{-3} s to 10 s. The MPE expressed as a radiant exposure is given by:

$$H_{MPE} = 18 \times t^{0,75} \text{ J·m}^{-2}$$

$$H_{MPE} = 18 \times (0,25)^{0,75} = 6,36 \text{ J·m}^{-2}$$

To obtain the MPE in terms of irradiance divide by the exposure duration t = 0,25 s, therefore,

$$E_{MPE} = 25 \text{ W·m}^{-2}$$

B.5 Maximum permissible exposure (MPE) – Repetitively pulsed systems

The rules applying to exposures from repetitively pulsed laser products (or exposures from scanning laser systems) are set out in 4.2. IEC TR 60825-10 provides a flow chart detailing the steps involved in calculating the MPE for a repetitively pulsed laser.

Example B.5.1

Determine the small-source MPE for accidental, direct ocular exposure to the radiation from an argon laser (λ = 488 nm) operating at a pulse repetition frequency of F = 1 MHz with a pulse duration of $t = 10^{-8}$ s.

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Solution:

As the laser is operating in the visible part of the spectrum and intentional viewing is not intended, an exposure duration limited by the aversion response to T = 0,25 s will be used. If intentional viewing of radiation in the wavelength range 400 nm to 600 nm is intended for exposure durations of 1 s or more, then the photochemical ocular limit should be evaluated, in addition to the thermal limit, and the most restrictive gives the applicable MPE.

Subclause 5.2 includes three criteria that must be considered, and the most restrictive one applies to this evaluation.

From 5.2a), the exposure from any single-pulse shall not exceed the single-pulse MPE. Thus, the radiant exposure for the time period of 10^{-8} s from Table 5 is

$$H_{\text{single}} = 5 \times 10^{-3}\ \text{J·m}^{-2}$$

From 5.2b), the average exposure for a pulse train of exposure duration T shall not exceed the MPE for a single pulse of exposure duration T. For the total 0,25 s exposure duration, Table 5 limits the radiant exposure to

$$H_{\text{T}} = 18\ t^{0,75}\ \text{J·m}^{-2} = 18 \times (0,25)^{0,75} = 6,36\ \text{J·m}^{-2}$$

Since there are $N = 2,5 \times 10^5$ pulses in the 0,25 s period, the average irradiance criteria results in a single pulse radiant exposure of

$$H_{\text{single-avg}} = H_{\text{T}}/N = 6,36/2,5 \times 10^5 = 2,55 \times 10^{-5}\ \text{J·m}^{-2}$$

From 5.2c), the average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5 (where $C_5 = N^{-1/4}$). The maximum exposure duration for which requirement c) should be applied is T_2 in the wavelength range 400 nm to 1 400 nm, where T_2 = 10 s for $\alpha \leq \alpha_{\text{min}}$.

Since the laser is operating at a high repetition rate, NOTE 3 to 5.2c) is applicable. This requires that, if multiple pulses appear within the period of T_{i} (see Table 3 for $T_{\text{i}} = 18 \times 10^{-6}$ s) they are counted as a single pulse to determine N and the radiant exposure of the individual pulses is added and compared to the MPE of T_{i}. Hence, the effective pulse repetition frequency is:

$$F_{\text{E}} = 1/T_{\text{i}} = 1/(18 \times 10^{-6}) = 55,56\ \text{kHz}$$

The MPE for a pulse of duration T_{i} is given in Table 5 as 5×10^{-3} J·m^{-2}.

The effective number of pulses in 0,25 s is:

$$N_{\text{E}} = T \times F_{\text{E}} = 0,25 \times 55,56 \times 10^3 = 1,39 \times 10^4$$

For $N_{\text{E}} = 1,39 \times 10^4$ pulses each of duration T_{i} in the 0,25 s period the radiant exposure under this criteria would be:

$$H_{\text{train}} = H_{\text{single-eff}} \times (N_{\text{E}})^{-1/4} = 5 \times 10^{-3}\ (1,39 \times 10^4)^{-1/4} = 4,6 \times 10^{-4}\ \text{J·m}^{-2}$$

Conditions 5.2a) and 5.2b) are applicable to a pulse of energy Q while condition 5.2c) is applicable to a pulse of energy = $Q \times T_{\text{i}} \times F = 18 \times Q$. Hence, dividing H_{train} by 18 (to give $2,55 \times 10^{-5}$ J·m^{-2}) enables the three MPEs calculated from5.2 to be compared. In this example criteria5.2b) and5.2c), which are equal, are the most restrictive; the single-pulse MPE for this system would be $2,55 \times 10^{-5}$ J·m^{-2}.

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Example B.5.2

Determine the intrabeam MPE for direct ocular exposure to the radiation from an Nd:YAG laser (λ = 1 064 nm) operating at a frequency of F = 20 Hz with a pulse width of t = 1 ms.

Solution:

As the laser does not operate in the visible part of the spectrum, protection is not afforded by the aversion response. A reasonable estimate of a hazardous chance exposure time can be taken as 10 s. For this time period, the total number of pulses is:

$$N = T \times F = 10 \times 20 = 200$$

Subclause 5.2 includes three criteria that must be considered, and the most restrictive one applies to this evaluation.

From 5.2a), the exposure from any single pulse shall not exceed the single pulse MPE. Since the beam is emitted from a small source the MPE is determined from Table 5 and the value of C_7 = 1 at a wavelength of 1 064 nm from Table 8. Thus the radiant exposure from Table 5 for the time period of 1 ms is:

$$H_{\text{single}} = 90\ t^{0,75}\ C_7\ \text{J·m}^{-2} = 90 \times 0{,}001^{0,75} \times 1 = 0{,}506\ \text{J·m}^{-2}$$

From 5.2b), the average exposure for a pulse train of exposure duration T shall not exceed the MPE for a single pulse of exposure duration T. For the 10 s duration (the total exposure time), Table 5 limits the radiant exposure to:

$$H_{\text{T}} = 90\ t^{0,75}\ C_7\ \text{J·m}^{-2} = 90 \times 10^{0,75} \times 1 = 506\ \text{J·m}^{-2}$$

Since there are N = 200 pulses in the 10 s period, the average irradiance criteria results in a single pulse radiant exposure of:

$$H_{\text{single.avg}} = \frac{H_{\text{T}}}{N} = \frac{506}{200} = 2{,}53\ \text{J} \cdot \text{m}^{-2}$$

From 5.2c), the average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5 (where $C_5 = N^{-1/4}$). For the N = 200 pulses in the 10 s period, the radiant exposure under this criteria would be:

$$H_{\text{train}} = H_{\text{single}} \times N^{-0,25} = 0{,}506 \times (200)^{-0,25} = 0{,}135\ \text{J·m}^{-2}$$

Since the limit from the repetitive pulse criteria of 5.2c) is the most restrictive, the single pulse MPE for this system would be 0,135 J·m^{-2}. The MPE could also be expressed in terms of irradiance for the duration of each pulse as:

$$E_{\text{MPE}} = \frac{H_{\text{train}}}{t} = \frac{0{,}135\text{J} \cdot \text{m}^{-2}}{10^{-3}\ \text{s}} = 135\ \text{W} \cdot \text{m}^{-2}$$

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B.6 Nominal ocular hazard distance (NOHD)

As explained in 5.5 the NOHD represents that range at which, under ideal conditions, the irradiance and the radiant exposure fall below the appropriate MPE.

The irradiance at a distance *r* from a laser source is given by (see IEC TR 60825-10):

$$E = \frac{4P_o e^{-\mu r}}{\pi (a + r\phi)^2} \qquad \text{(B.1)}$$

NOTE a and ϕ are measured at the 1/e points of the beam profile, when the beam profile is assumed to be Gaussian. In practice only gas lasers produce beams having Gaussian profiles, most solid state lasers having distinctly non-regular multi-mode beam structures, and in this latter case the following formula should be used:

$$L = \frac{I e^{-\mu r}}{r^2}$$

where I = radiant intensity ($W \cdot sr^{-1}$).

If I is not known and cannot be measured, the value for P_o in Equation (B.1) above can be increased by 2,5 for laser systems known to have a multi-mode beam structure. In IEC TR 60825-10 the symbol k is used to account for beams of unknown mode structure and has values ranging from k= 1 for beams having Gaussian profiles to k = 2,5 for beams of unknown mode structure.

The term $e^{-\mu r}$ accounts for losses due to atmospheric attenuation and may be neglected for most purposes. Simplifying Equation (B.1) and accounting for the k factor gives:

$$E = \frac{4 k P_o}{\pi (a + r\phi)^2} \qquad \text{(B.2)}$$

When E is replaced with E_{MPE}, r becomes the NOHD and the expression can be solved for NOHD:

$$NOHD = \frac{1}{\phi}\sqrt{\frac{4 \times k \times P_o}{\pi \times E_{MPE}}} - \frac{a}{\phi} \qquad \text{(B.3)}$$

or

$$NOHD = \frac{1}{\phi}\sqrt{\frac{4 \times k \times Q}{\pi \times H_{MPE}}} - \frac{a}{\phi} \qquad \text{(B.4)}$$

where Q is the energy per pulse and H_{MPE} is the MPE per pulse expressed as a radiant exposure.

If the effects of atmospheric attenuation are to be included, a simple solution to Equation (B.1) in terms of r is not readily available. A reliable estimate for μ, the atmospheric attenuation coefficient, can be obtained from the following formula:

$$\mu = 10^{-3} \times \frac{3{,}91}{V} \times \left(\frac{550}{\lambda}\right)^A \text{ m}^{-1} \qquad \text{(B.5)}$$

where

$A = 0{,}585\ V^{0{,}33}$,

V is the visual range in km, and

λ is the wavelength in nm (400 nm < λ < 2000 nm).

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Use of optical viewing aids

Where viewing aids (telescopes, binoculars, etc.) are used to view a source of laser radiation, it is necessary to extend the NOHD to account for the increase in radiation entering the eye.

The radiation entering the eye from a laser viewed through a pair of binoculars is increased by an optical gain factor *G*. The following recommendations are provided in IEC TR 60825-10.

a) For 400 nm ≤ λ < 1 400 nm where the pupil is overfilled,

$$G = \tau \cdot M^2 \qquad \text{(B.6)}$$

or, where the output beam is smaller than the pupil,

$$G = \frac{\tau \cdot D_0{}^2}{49} \qquad \text{(B.7)}$$

Use whichever is the smaller, where

τ is the transmission coefficient at the appropriate wavelength (= 1 if unknown),

M is the magnification of the viewing aid, and

D_o is the diameter of the objective lens in mm.

(b) For 320 nm ≤ λ< 400 nm and 1 400 nm ≤ λ < 4 500 nm

$$G = \tau \cdot M^2$$

In this region the radiation is absorbed before reaching the retina.

(c) For λ < 320 nm and λ > 4 500 nm

In this region the radiation is unlikely to be transmitted through the viewing aid.

The extended NOHD now becomes

$$ENOHD = \frac{1}{\phi}\sqrt{\frac{4 \times k \times G \times Q}{\pi \times H_{\text{MPE}}}} - \frac{a}{\phi} \qquad \text{(B.8)}$$

Unless provided with special laser attenuating filters or unless the actual transmission of the viewing optics is known at the laser wavelength, no allowance should be made for transmission losses in viewing optics, as many devices have a high transmittance (>0,8) extending well into the infrared region of the spectrum above 2 000 nm.

NOTE The output from Class 1, Class 1M, Class 2, Class 2M and Class 3R laser products may be viewed via a diffusing screen or non-specular target through magnifying optics, provided that the criteria for unaided viewing of extended sources are satisfied and that the radiation is within the band 400 nm to 1 400 nm.

Two useful flow charts are provided in IEC TR 60825-10 as an aid to calculating NOHDs of CW and repetitively pulsed laser products emitting one or more wavelengths and ENOHDs when viewing optics are in use.

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Example B.6.1

A laser with a Gaussian beam profile (k = 1) has an output of 4 W, a beam divergence of 0,7 mrad and an exit beam diameter of 1 mm. If the appropriate MPE is 10 W·m^{-2}, calculate the NOHD, assuming negligible atmospheric attenuation.

Solution:

Substituting in Equation (B.3) gives:

$$NOHD = \frac{1}{0{,}7\times 10^{-3}}\sqrt{\frac{4\times 4}{\pi\times 10}} - \frac{1\times 10^{-3}}{0{,}7\times 10^{-3}} = 1\,019 - 1{,}4 = 1018 \text{ m} = 1{,}02 \text{ km}$$

Example B.6.2

Beam expanding optics are fitted to the laser in the previous example which reduces the beam divergence to 0,1 mrad and increases the beam diameter to 7 mm. Calculate the NOHD.

Solution:

The new NOHD is:

$$NOHD = \frac{1}{0{,}1\times 10^{-3}}\sqrt{\frac{4\times 4}{\pi\times 10}} - \frac{7\times 10^{-3}}{0{,}1\times 10^{-3}} = 7\,136 - 70 = 7\,066 \text{ m} = 7{,}07 \text{ km}$$

Note the importance of beam divergence in determining the NOHD.

Example B.6.3

The laser in example B.4.2 operates at 550 nm. Calculate the modified NOHD, assuming a visual range of 10 km.

Solution:

The atmospheric attenuation coefficient, μ, is obtained using Equation (B.5):

$$\mu = 10^{-3}\times\frac{3{,}91}{10}\times\left(\frac{550}{550}\right)^{1{,}25} = 3{,}91\times 10^{-4}\,\text{m}^{-1}$$

The modified NOHD can now be obtained from Equation (B.3) by including the atmospheric attenuation term:

$$NOHD = \frac{1}{\phi}\sqrt{\frac{4\times k\times P_o e^{-\mu r}}{\pi\times E_{MPE}}} - \frac{a}{\phi}$$

and solving iteratively (for r = $NOHD$) gives

$$NOHD = \frac{1}{0{,}1\times 10^{-3}}\sqrt{\frac{4\times 4\times e^{(-3{,}91\times 10^{-4}\times r)}}{\pi\times 10}} - \frac{7\times 10^{-3}}{0{,}1\times 10^{-3}} = 3{,}52 \text{ km}$$

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Example B.6.4

A surveying helium-neon (He-Ne) laser (λ = 633 nm) of output power 3 mW emits a beam of initial diameter 13 mm, which expands to 18 mm at a distance of 50 m from the laser:

a) How long is it safe to view the laser directly from a distance of 60 m?

b) What is the minimum distance for safe direct viewing of this laser for a period of 3 minutes?

Solution:

a) The output power $P_o = 3 \times 10^{-3}$ W, and the initial beam diameter a = 0,013 m. The beam divergence is therefore

$$\phi = \frac{0{,}018 - 0{,}013}{50} \text{ rad} = 10^{-4} \text{ rad}$$

Assuming the laser has a Gaussian beam profile (k = 1) then the irradiance at a range r can be determined using Equation (B.2), namely,

$$E = \frac{4\,P_o}{\pi\,(a + r\,\phi)^2}$$

thus,

$$E = \frac{4 \times 3 \times 10^{-3}}{\pi\,(0{,}013 + 60 \times 10^{-4})^2} = 10{,}58 \text{ W} \cdot \text{m}^{-2}$$

For an exposure duration between 10 s and 3×10^4 s, the appropriate MPE is given in Table 5 as

$$E_{MPE} = 10 \text{ W·m}^{-2}$$

Since this is less than the beam irradiance at 60 m the exposure duration will be less than 10 s. Table 5 shows for exposure durations in the range 1 x 10^{-3} s to 10 s the appropriate MPE is

$$H_{MPE} = 18\ t^{0{,}75} \text{ J·m}^{-2}$$

which is equivalent to

$$E_{MPE} = 18\ t^{-0{,}25} \text{ W·m}^{-2}$$

Thus, the maximum exposure duration is obtained by equating this value of E_{MPE} to 10,58 W·m^{-2} and solving for t.

$$18\ t^{-0{,}25} = 10{,}58 \text{ W·m}^{-2}$$

Thus $$t = \left(\frac{10{,}58}{18}\right)^{-4} = 8{,}38 \text{ s}$$

b) The minimum range for safe viewing can be obtained by solving Equation (B.3) for the nominal ocular hazard distance (NOHD). In this case, the exposure duration t = 180 s (3 min) and Table 5 gives E_{MPE} = 10 W·m^{-2}:

$$NOHD = \frac{1}{0{,}1 \times 10^{-3}} \sqrt{\frac{4 \times 3 \times 10^{-3}}{\pi \times 10}} - \frac{13 \times 10^{-3}}{0{,}1 \times 10^{-3}} = 65{,}4 \text{ m}$$

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Example B.6.5

A hand-held infrared laser surveying instrument has the following characteristics.

– Wavelength (λ)	903 nm
– Pulse repetition frequency (F)	300 Hz
– Peak power per pulse (P_p)	30 W
– Energy per pulse (Q)	600 nJ
– Beam divergence (ϕ)	10 mrad
– Effective exit aperture diameter (a)	55 mm

Assuming the laser has a Gaussian beam profile, assess the NOHD for this instrument

a) for viewing by the unaided eye, and

b) when using 8 × 50 binoculars.

Solution:

a) Unaided eye condition

From the laser specification, the pulse width is given by $t_p = Q/P_p = (6 \times 10^{-7})/30 = 20$ ns. In this example, it is assumed that the subtense α is less than α_{min}. If there is no intentional viewing, the exposure time to be used is 100 s; during this time the number of pulses is:

$$N = F \times t = 300 \text{ Hz} \times 100 \text{ s} = 3 \times 10^4$$

The intrabeam MPE is taken as the most restrictive calculated from the application of 5.2.

Single-pulse assessment (condition5.2a))

Table 5 gives the single-pulse MPE for this radiation with the exposure time of 20 ns, as:

$$H_{MPE} = 5 \times 10^{-3}\ C_4 \text{ J·m}^{-2}$$

where $C_4 = 10^{0,002(903-700)} = 2{,}55$, hence:

$$H_{MPE} = 5 \times 10^{-3} \text{ x } 2{,}55 = 1{,}275 \times 10^{-2} \text{ J·m}^{-2}$$

Average irradiance assessment (condition 5.2b))

The MPE for exposure duration of 100 s is obtained from Table 5. Since $\alpha \leq 1{,}5$ mrad T_2 = 10 s, therefore the condition $t > T_2$ applies:

$$E_{MPE,\ avg} = 10\ C_4\ C_7 \text{ W·m}^{-2}$$

where $C_4 = 2{,}55$ and $C_7 = 1$. Since the pulse repetition frequency is 300 Hz the average MPE per pulse is

$$H_{MPE,average} = \frac{E_{MPE,avg}}{F} = \frac{10 \times 2{,}55 \times 1}{300} = 8{,}5 \times 10^{-2} \text{ J} \cdot \text{m}^{-2}$$

Multiple-pulse assessment (condition 5.2c))

The average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5 (where $C_5 = N^{-1/4}$). The maximum exposure duration for which requirement c) should be applied is T_2 in the wavelength range 400 nm to 1 400 nm, where T_2 = 10 s for $\alpha \leq \alpha_{min}$. Hence:

$$H_{MPE,\ single} = H_{MPE} = 5 \times 10^{-3} \times 2{,}55 = 1{,}275 \times 10^{-2} \text{ J·m}^{-2}$$

$$H_{MPE,\ train} = H_{MPE,\ single}\ N^{-1/4} = 1{,}275 \times 10^{-2} \times (10 \times 300)^{-1/4} \text{ J·m}^{-2}$$

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$$H_{\text{MPE, train}} = 0{,}135 \times 1{,}275 \times 10^{-2} = 1{,}72 \times 10^{-3}\ \text{J·m}^{-2}$$

The conclusion is that condition 5.2c) produces the most restrictive MPE per pulse and therefore $H_{\text{MPE}} = 1{,}72 \times 10^{-3}$ J·m^{-2} for intrabeam viewing. Substituting this value of MPE into Equation (B.4) gives,

$$NOHD = \frac{1}{0{,}01}\sqrt{\frac{4 \times 600 \times 10^{-9}}{\pi \times 1{,}72 \times 10^{-3}}} - \frac{0{,}055}{0{,}01} = 2{,}11 - 5{,}5 = -3{,}39\ \text{m}$$

Because this result is negative, the laser product is safe for viewing by the unaided eye at any distance. Therefore, for this laser product when only viewing by the unaided eye is involved, the appropriate NOHD is zero.

b) Binocular viewing condition

The optical gain factor, G, of the binoculars is determined from Equations (B.6) and (B.7) with the smaller of the two values being substituted in Equation (B.8) to give ENOHD.

Assuming that there is no attenuation through the optics ($\tau = 1$) then Equation (B.6) gives $G = M^2 = 8^2 = 64$, and Equation (B.7) gives $G = D_0^2/49 = 50^2/49 = 51$. Thus substituting $G = 51$ in Equation (B.8) gives,

$$ENOHD = \frac{1}{0{,}01}\sqrt{\frac{4 \times 51 \times 600 \times 10^{-9}}{\pi \times 1{,}72 \times 10^{-3}}} - \frac{0{,}055}{0{,}01} = 9{,}6\ \text{m}$$

It is consequently hazardous for this laser product to be viewed with 8 x 50 binoculars at distances of less than 9,6 m.

Example B.6.6

A neodymium-glass Q-switched laser rangefinder has the following characteristics.

– Wavelength (λ)	1 060 nm
– Peak power per pulse P_p	1,5 MW
– Energy per pulse Q_p	45 mJ
– Pulse repetition rate (F)	12 per minute
– Exit aperture beam diameter (a)	10 mm
– Beam divergence angle (ϕ)	1 mrad

Determine:

a) the NOHD for the unaided eye,

b) the NOHD for the unaided eye when a 10 % transmission filter is fitted to the output aperture of the rangefinder, and

c) the NOHD for intrabeam viewing when 50 mm diameter optics is used.

Neglect the effects of beam attenuation or refractive focusing due to atmospheric transmission.

Solution:

a) The pulse width t_p can be calculated from the condition $P_p \times t_p = Q_p$ by $1{,}5 \times 10^6 \times t_p = 45 \times 10^{-3}$ giving $t_p = 30$ ns (i.e. $10^{-9} < t_p < 5 \times 10^{-5}$ s). The pulse repetition frequency F is 12/60 = 0,2 Hz.

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In this example, it is assumed that $\alpha \leq \alpha_{min}$. If there is no intentional viewing, the exposure duration to be used is 100 s; during this time, the number of pulses is

$$N = F \times t = 0{,}2 \text{ Hz} \times 100 \text{ s} = 20$$

The intrabeam MPE is taken as the most restrictive calculated from the application of 5.2.

Single-pulse assessment (condition 5.2a))

From Table 5, the MPE for a single-pulse exposure from this laser is

$$H_{MPE} = 5 \times 10^{-2}\ C_7 \text{ J·m}^{-2}$$

where from Table 8 C_7 = 1, therefore

$$H_{MPE,\ single} = 5 \times 10^{-2} \text{ J·m}^{-2}$$

Average irradiance assessment (condition 5.2b))

From Table 5, the MPE for the exposure duration of 100 s is

$$H_{MPE} = 90 \times t^{0{,}75}\ C_6\ C_7 \text{ J·m}^{-2}$$

where C_7 = 1. There are 20 pulses in 100 s, therefore the average MPE per pulse is

$$H_{MPE,\ average} = \frac{90 \times 100^{0{,}75}}{20} = 142 \text{ J} \cdot \text{m}^{-2}$$

Multiple-pulse assessment (condition 5.2c))

The maximum exposure duration for which requirement c) should be applied is T_2 in the wavelength range 400 nm to 1 400 nm, where T_2 = 10 s for $\alpha \leq \alpha_{min}$. Therefore, the correction factor $N^{-1/4} = (10 \times 0{,}2)^{-1/4} = 0{,}84$ is used to calculate $H_{MPE,\ train}$:

$$H_{MPE,\ train} = H_{MPE,\ single}\ N^{-1/4} = 5 \times 10^{-2} \times 0{,}84 = 4{,}2 \times 10^{-2} \text{ J·m}^{-2}$$

The conclusion is that condition 5.2c) produces the most restrictive MPE per pulse and therefore $H_{MPE} = 4{,}2 \times 10^{-2}$ J·m^{-2} for intrabeam viewing. Substitute this value of MPE in Equation (B.4) and because the mode structure of this solid-state laser is not specified, the pulse energy should be increased by the factor k = 2,5. Therefore,

$$NOHD = \frac{1}{\phi}\sqrt{\frac{4 \times 2{,}5 \times Q}{\pi \times H_{MPE,train}}} - \frac{a}{\phi}$$

$$NOHD = \frac{1}{10^{-3}}\sqrt{\frac{4 \times 2{,}5 \times 45 \times 10^{-3}}{\pi \times 4{,}2 \times 10^{-2}}} - \frac{10^{-2}}{10^{-3}} = 1837 \text{ m}$$

The NOHD for the rangefinder is therefore 1,84 km.

b) If a 10 % transmission filter is fitted to the output aperture of the rangefinder, the NOHD is reduced. In this case, using the previous equation for NOHD the energy per pulse must be modified by the factor 0,1, to take into account the effect of the 10 % filter. The modified NOHD is therefore given by

$$NOHD = \frac{1}{10^{-3}}\sqrt{\frac{4 \times 2{,}5 \times 0{,}1 \times 45 \times 10^{-3}}{\pi \times 4{,}2 \times 10^{-2}}} - \frac{10^{-2}}{10^{-3}} = 574 \text{ m}$$

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c) When 50 mm diameter collecting optics are involved in the intrabeam viewing of this laser, the NOHD is increased because of the optical gain factor G of the viewing optics which can be determined from Equation (B.7) and substituted in Equation (B.8) to give ENOHD. From Equation (B.7) assuming $\tau = 1$, $G = 50^2/49 = 51$ and from Equation (B.8),

$$ENOHD = \frac{1}{10^{-3}}\sqrt{\frac{4 \times 2{,}5 \times 51 \times 45 \times 10^{-3}}{\pi \times 4{,}2 \times 10^{-2}}} - \frac{10^{-2}}{10^{-3}} = 13{,}18\ \text{km}$$

Thus, in view of the very short pulse duration for this laser, while a telescopic system is used, even the briefest exposure of the eye to the laser radiation may be hazardous at distances less than 13,18 km from the laser.

B.7 Diffuse reflections and extended sources

Examples of extended source viewing are:

a) Laser radiation within the wavelength range 400 nm to 1 400 nm when it is reflected from a diffusing surface (apparent source).

b) The image formed on the retina of the eye by the diffuse reflection is larger than a certain minimum value of the retinal image, determined by the limiting angular subtense α_{min}, where α_{min} is equal to 1,5 mrad and is measured at a distance of no less than 100 mm from the apparent source (see 5.4)).

IEC 60825-10 identifies three distinct regions for viewing of a diffuse reflection. Consider a diffuse reflection source with a spot diameter D then α_{min} is associated with a range r_{max} (= D/α_{min}) beyond which small source viewing conditions exist. This defines one of the three regions for viewing of a diffuse reflection. A second region exists where the subtended angle is ≥ α_{max} = 0,1 rad corresponding to a range of r_{min} (= D/α_{max}). Between r_{min} and r_{max} is a transition zone between very large retinal image conditions and small source viewing conditions. TR 60825-10 presents a flow chart that greatly aids the calculation of hazard ranges, however, before proceeding beyond box 2 of this flow chart check that r_{max} ≥ 100 mm; if not, go to box 7A or 7B of the flow chart depending on the units of MPE. Similarly, check that r_{min} ≥ 100 mm; if not, go to box 5A or 5B of the flow chart depending on the units of MPE.

Example B.7.1

The radiation from a Q-switched Nd:YAG laser (λ = 1 064 nm, $t = 10^{-8}$ s) is expanded to form a beam 2 cm in diameter before being reflected from a perfect diffuser.

a) What is the range over which extended source viewing conditions exist?

b) What is the MPE at a distance of 2,5 m from the diffuser?

Solution:

The angular subtense is defined by the equation:

$$\alpha = 2\ \text{arctan}\frac{d_{63}}{2r_1} \simeq \frac{d_{63}}{r_1}$$

where d_{63} is the diameter of the laser beam at the diffusing target.

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a) In the limiting case $\alpha = \alpha_{min}$ and, therefore,

$$r_{1,max} = \frac{d_{63}}{\alpha_{min}}$$

For this example

$$r_{1,max} = \frac{0{,}02\ \text{m}}{1{,}5 \times 10^{-3}\ \text{rad}} = 13{,}3\ \text{m}$$

At distances greater than $r_{1,max}$ = 13 m, small source viewing conditions exist.

The small source MPE for the specified exposure duration is given by (see Table 5):

$$H_{MPE} = 5 \times 10^{-2} \times C_7\ \text{J·m}^{-2}$$

where C_7 = 1 for λ = 1 064 nm (see Table 8).

Thus,

$$H_{MPE} = 5 \times 10^{-2} \times 1\ \text{J·m}^{-2} = 5 \times 10^{-2}\ \text{J·m}^{-2}$$

b) At distances less than $r_{1,max}$ = 13 m, extended source viewing conditions exist.

The MPE for the specified exposure duration is given by (see Table 6):

$$H_{MPE} = 5 \times 10^{-2} \times C_6 \times C_7\ \text{J·m}^{-2}$$

where as before C_7 = 1 and $C_6 = \alpha/\alpha_{min}$ for $\alpha_{min} < \alpha \leq \alpha_{max}$ (where α_{max} = 0,1 rad).

At the distance of r_1 = 2,5 m,

$$\alpha = \frac{d_{63}}{r_1} = \frac{0{,}020\ \text{m}}{2{,}5\ \text{m}} = 8 \times 10^{-3}\ \text{rad}$$

and

$$C_6 = \frac{\alpha}{\alpha_{min}} = \frac{8{,}0 \times 10^{-3}\ \text{rad}}{1{,}5 \times 10^{-3}\ \text{rad}} = 5{,}33$$

Hence, the MPE for viewing of the extended source at 2,5 m is,

$$H_{MPE} = 5 \times 10^{-2} \times 5{,}33 \times 1\ \text{J·m}^{-2} = 0{,}27\ \text{J·m}^{-2}$$

Example B.7.2

Find the maximum radiant energy from the laser in example B.7.1 permitting non-hazardous viewing of the output reflected from a perfect diffuser located less than 0,2 m from the observer's eye.

Solution:

At distances less than 0,20 m, the viewing conditions are such that the acceptance angle α is greater than α_{max} = 0,1 rad:

$$\alpha = \frac{d_{63}}{r_1} = \frac{0{,}020\ \text{m}}{0{,}20\ \text{m}} = 0{,}10\ \text{rad}$$

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The incident beam radiant exposure capable of producing a hazardous diffuse reflection under this extended source viewing condition can be obtained by first expressing the diffuse reflection MPE as an integrated radiance. This is accomplished by dividing the diffuse reflection MPE expressed as a radiant exposure by the solid angle formed by the maximum angle of acceptance. Where the maximum angle of acceptance, α_{max}, is 0,1 rad corresponding to a solid angle, Ω, given by $\Omega \approx \pi\ (\alpha_{max}/2)^2 = 7{,}85 \times 10^{-3}$ sr

and the diffuse reflection MPE expressed as an integrated radiance is

$$L_{MPE} = (C_6/\Omega) \times H_{MPE,\ small\ source} = (66{,}66/7{,}85 \times 10^{-3}) \times H_{MPE,\ small\ source}$$

$$L_{MPE} = 8{,}5 \times 10^3 \times H_{MPE,\ small\ source}\ \mathrm{J{\cdot}m^{-2}{\cdot}sr^{-1}}$$

The integrated radiance MPE for this problem is obtained by substituting the small source MPE obtained in example B.5.2:

$$L_{MPE} = 8{,}5 \times 10^3 \times 5{,}0 \times 10^{-2}\ \mathrm{J{\cdot}m^{-2}{\cdot}sr^{-1}} = 425\ \mathrm{J{\cdot}m^{-2}{\cdot}sr^{-1}}$$

The integrated radiance of the diffuse reflection is related to the incident beam radiant exposure at the target through the expression:

$$H = \pi \times L_p$$

Hence, the radiant exposure sufficient to produce a hazardous reflection from a 100 % reflectance, white diffuse target is

$$H_{MPE} = \pi\ \mathrm{sr} \times L_{MPE}\ \mathrm{J{\cdot}m^{-2}{\cdot}sr^{-1}} = 1{,}34 \times 10^3\ \mathrm{J{\cdot}m^{-2}}$$

Finally, assuming that the radiant energy is uniformly distributed over the area of the target beam spot, A, the radiant energy sufficient to produce a hazardous reflection is

$$Q_{MPE} = H_{MPE} \times A = H_{MPE} \times (\pi/4) \times d_{63}^2 = 1{,}34 \times 10^3 \times (\pi/4) \times 0{,}02^2 = 0{,}42\ \mathrm{J}$$

Example B.7.3

Calculate the minimum safe viewing distance normal to a perfect diffusing screen if the output from the laser in example B.5.2 is focused on the screen.

Solution:

In this situation, the radiation is reflected hemispherically outward from the focal point on the diffuse Lambertian target; therefore, small source viewing conditions apply. At a distance r_1 from a Lambertian source, the radiant exposure is given by:

$$H = \left(\frac{Q\cos\theta}{\pi r_1^2}\right)$$

where θ is the viewing angle with respect to the normal to the surface.

The nominal ocular hazard distance, NOHD, for a Lambertian source is obtained from the small source radiant exposure MPE as follows:

$$NOHD = \sqrt{\frac{Q\cos\theta}{\pi H_{MPE,\ small\ source.}}}$$

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The maximum radiant energy output of the laser obtained in the previous example is 0,42 J, and the specified viewing angle is $\theta = 0$ rad. Assuming that the target is also perfectly reflecting, the minimum safe viewing distance is,

$$NOHD = \sqrt{\frac{0,42 \times \cos(0)}{\pi \times 0,05}} = 1,6\ \text{m}$$

B.8 Eye protection

The optical density D_λ of protective eyewear at the laser wavelength should be sufficient to reduce the transmitted radiation to below the MPE applicable for the maximum reasonably foreseeable exposure time (see 8.4.5.2.2). The value of D_λ required to give the necessary level of eye protection can be calculated from either Equation B.9) or Equation (B.10) where,

$$D_\lambda = \log_{10}\left(\frac{E_o}{MPE}\right) \qquad \text{(B.9)}$$

when E_o is the maximum expected irradiance at the unprotected eye and the MPE is expressed as an irradiance or where,

$$D_\lambda = \log_{10}\left(\frac{H_o}{MPE}\right) \qquad \text{(B.10)}$$

when H_o is the maximum expected radiant exposure at the unprotected eye and the MPE is expressed as a radiant exposure.

Example B.8.1

Determine the optical density of protective eyewear for the operator of the laser rangefinder specified in example B.6.6.

Solution:

The MPE per pulse for a 100 s exposure was calculated in example B.6.6 as $4,2 \times 10^{-2}$ J·m^{-2}. The radiant exposure experienced by a person directly in front of the laser is given by:

$$H_o = \left(\frac{4 \times k \times Q}{\pi \times d_{63}^2}\right)$$

where d_{63} is specified as 10 mm, Q = 45 mJ and k = 2,5 because the mode structure is unknown, hence H_o = 1432 J·m^{-2} and the optical density is given by Equation (B.10) as:

$$D_\lambda = \log_{10}\left(\frac{1432}{4,2 \times 10^{-2}}\right) = 4,53$$

Usually in the interests of safety this would be rounded up to the next integer value and an optical density of 5 would be specified.

Example B.8.2

Determine the optical density of protective eyewear for the operator of the laser rangefinder specified in example B.6.1.

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Solution:

The MPE is specified as 10 W·m^{-2}. The irradiance experienced by a person directly in front of the laser is given by:

$$E_o = \left(\frac{4 \times k \times P}{\pi \times d_{63}^2}\right)$$

where d_{63} is specified as 1 mm, P = 4 W and as specified in example B.6.1 k = 1. Since the beam diameter of 1 mm is less than the limiting aperture of 7 mm (Table 2) at the emission wavelength (specified as 550 nm in example B.6.3), then the irradiance is calculated using the limiting aperture and not the actual beam diameter, hence E_o = 1,04 x 10^5 W·m^{-2} and the optical density is given by Equation (B.9) as:

$$D_\lambda = \log_{10}\left(\frac{1{,}04 \times 10^5}{10}\right) = 4{,}0$$

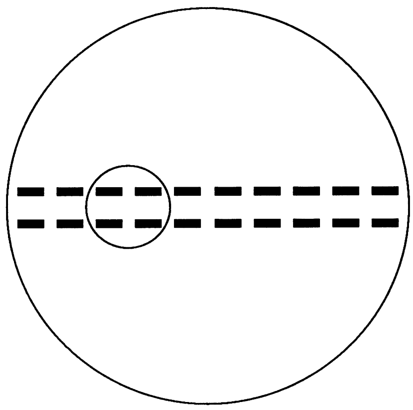
An optical density of 4 would be specified.

B.9 Multiple small sources

Example B.9.1: Complex laser diode array source

Find the MPE applicable to intrabeam viewing for a 10 s exposure at a distance of 1 m from a complex GaAs (905 nm) laser diode array source. The source consists of two rows of 10 diodes each that are mounted behind collimating optics. The source has an output power of 6 W and a pulse repetition frequency F of 12 kHz. The pulse duration is 80 ns. The exit aperture (collimating lens) is 5 cm in diameter and the emergent beam diameter is 3,5 cm at the 1/e peak irradiance points (i.e., a 3,5 cm circular measurement aperture would collect 63 % of the beam power). The axial beam irradiance (average) at a distance of 1 m is 3,6 × 10^3 W·m^{-2}. The beam divergence is 25 mrad horizontally by 3 mrad vertically, and at a distance of 1 m from the exit aperture, the beam size is approximately 3,0 cm by 3,8 cm, respectively.

An intrabeam photograph (using infrared film) taken at a distance of 1 m from the exit aperture reveals that each diode subtends a projected line image 2,2 mrad long and less than 0,5 mrad across. Each diode is separated by an angle of 3,0 mrad centre-to-centre, and the two rows are separated by an angle of 2,3 mrad (see Figure B.1). Using an infrared image converter with an OD 4 filter to reduce glare, it is revealed that these angular separations are constant from all viewing distances between 10 cm and 2 m. [2)]



IEC 173/04

Figure B.1 – Laser diode array with two groupings

2) This behavior is explained in Chapter 15 of Sliney and Wolbarsht, *Safety with Lasers and other Optical Sources*, New York: Plenum Publishing Co., 1980.

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Solution:

The MPE applicable to the laser diode array is the most restrictive MPE resulting from an evaluation of each individual source and each possible grouping of the array of diodes. However, the evaluation can be greatly simplified by using the conservative assumption that all the radiant power originates from a single point source. This would always overstate the hazard, and if it did not result in overly restrictive control measures, the more complex analysis of the extended source would not have to be performed.

The determination of the applicable (most restrictive) MPE requires a trial-and-error approach, since the MPE for a single diode, two adjacent diodes, a group of three or four, etc., and the entire array is to be calculated, recognizing that in each case the power or energy is averaged over the angular subtense α applicable to that grouping. It is useful to draw a map of the source to study different combinations of diodes (see Figure B.1). The total number of pulses N in a 10 s exposure is 120 000.

The single pulse MPE for the multiple-pulse assessment is given by (using Table 6 for an 80 ns pulse) the following:

$$H_{\mathrm{MPE,train}} = C_5 \times 5 \times 10^{-3}\ C_4 C_6\ \mathrm{J{\cdot}m^{-2}}.$$
$$= 120\ 000^{-0,25} \times 5 \times 10^{-3} \times 2{,}57\ C_6\ \mathrm{J{\cdot}m^{-2}}$$
$$= 6{,}9 \times 10^{-4}\ C_6\ \mathrm{J{\cdot}m^{-2}}$$

In order to compare the single pulse MPE with the average irradiance of the beam, it is convenient to express the above MPE (expressed in terms of radiant exposure) as an irradiance averaged over F pulses per second as follows:

$$E_{\mathrm{MPE,train,F}} = H_{\mathrm{MPE,train}} \times F$$
$$= 6{,}9 \times 10^{-4}\ C_6\ \mathrm{J{\cdot}m^{-2}} \times 1{,}2 \times 10^4\ \mathrm{Hz}$$
$$= 8{,}28\ C_6\ \mathrm{W{\cdot}m^{-2}}$$

The single pulse MPE for the average power assessment is given by the following (using Table 6 for a 10 s exposure):

$$H_{\mathrm{MPE,avg}} = 18 \times t^{0,75}\ C_4\ C_6\ \mathrm{J{\cdot}m^{-2}}$$
$$= 18 \times 10^{0,75} \times 2{,}57\ C_6\ \mathrm{J{\cdot}m^{-2}}$$
$$= 260 \times C_6\ \mathrm{J{\cdot}m^{-2}}$$

The above MPE, expressed as a radiant exposure, can also be expressed as an irradiance averaged over the 10 s exposure as follows:

$$E_{\mathrm{MPE,avg}} = H_{\mathrm{MPE,avg}}/t$$
$$= 260 \times C_6\ \mathrm{J{\cdot}m^{-2}}\ /(10\ \mathrm{s})$$
$$= 26 \times C_6\ \mathrm{W{\cdot}m^{-2}}$$

Since C_6 depends only on the angular subtense of the diode group, it has the same value in the equations for $E_{\mathrm{MPE,train,F}}$ and $E_{\mathrm{MPE,avg}}$. Consequently, for this example $E_{\mathrm{MPE,train,F}}$ is always the most restrictive.

Single-diode group

The individual diodes subtend angles of 0,5 mrad (vertical) and 2,2 mrad (horizontal). The MPE for rectangular sources is determined by the arithmetic mean of the two angular subtenses. As stated in 3.3.3, before determining the mean, any angular subtense less than 1,5 mrad or greater than 100 mrad should be replaced by 1,5 mrad or 100 mrad, respectively. Therefore, the mean is as follows:

$$(1,5 + 2,2)/2 \text{ mrad} = 1,85 \text{ mrad}$$

This value is greater than 1,5 mrad, thus the individual diode is considered to be an extended source and the correction factor is C_6 = 1,85/1,5 = 1,23. The applicable MPE is as follows:

$$E_{\text{MPE,diode}} = E_{\text{MPE,train,F}} = 8,28 \times 1,23 = 10,2 \text{ W}\cdot\text{m}^{-2}$$

This MPE is not applicable to the total irradiance, but rather the irradiance of each single diode. Assuming that all diodes have the same power emission, this MPE has to be compared with the total irradiance divided by the number of diodes, i.e. 20.

$$E_{\text{diode}} = E_{\text{total}} /20 = 3\ 600/20 = 180 \text{ W}\cdot\text{m}^{-2}$$

This MPE is exceeded at a distance of 1 m by a factor of 180/10,2 = 17,6

Horizontal two-diode group

A plausible group of the array to consider is two horizontally adjacent diodes subtending angles of 0,5 mrad (vertical) by 5,2 mrad (horizontal). Replacing 0,5 mrad by 1,5 mrad as stated in 4.3.3, the arithmetic mean of the two angular dimensions is (1,5 + 5,2)/2 mrad = 3,35 mrad. The correction factor is C_6 = 3,35/1,5 = 2,23 and the applicable MPE is as follows:

$$E_{\text{MPE,hor,two}} = E_{\text{MPE,train,F}} = 8,28 \times 2,23 = 18,5 \text{ W}\cdot\text{m}^{-2}$$

Since the irradiance of this grouping is twice the irradiance of the single diode, this MPE has to be compared with the following:

$$E_{\text{two}} = E_{\text{diode}} \times 2 = 180 \times 2 = 360 \text{ W}\cdot\text{m}^{-2}.$$

At a distance of 1 m, the hazard factor is 360/18,5 = 19,5. Hence, this grouping of two diodes produces a greater hazard factor (i.e. a more conservative MPE) than the single-diode group.

Vertical two-diode group

Another sub-unit of the array to consider is two vertical diodes subtending angles of 2,8 mrad (vertical) by 2,2 mrad (horizontal). The arithmetic mean of the two angular dimensions is 2,5 mrad. Hence the correction factor is C_6 = 2,5/1,5 = 1,67. The applicable MPE is as follows:

$$E_{\text{MPE,vert,two}} = E_{\text{MPE,train,F}} = 8,28 \times 1,67 = 13,8 \text{ W}\cdot\text{m}^{-2}$$

The irradiance of this grouping is twice the irradiance of the single diode. Hence, this MPE has to be compared with the following:

$$E_{\text{two}} = E_{\text{diode}} \times 2 = 180 \times 2 = 360 \text{ W}\cdot\text{m}^{-2}$$

At a distance of 1 m, the hazard factor is 360/13,8 = 26,1. Hence, this grouping produces a greater hazard factor than the previous one.

Four-diode group

Another plausible sub-unit of the array to consider is four adjacent diodes (2 by 2) subtending angles of 2,8 mrad (vertical) by 5,2 mrad (horizontal). The arithmetic mean of the two angular dimensions is 4 mrad. Hence, the correction factor is C_6 = 4/1,5 = 2,67. The applicable MPE is as follows:

$$E_{\text{MPE,four}} = E_{\text{MPE,train,F}} = 8,28 \times 2,67 = 22,1 \text{ W}\cdot\text{m}^{-2}$$

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Since the irradiance of this grouping is four times the irradiance of the single diode, this MPE has to be compared with the following:

$$E_{four} = E_{diode} \times 4 = 180 \times 4 = 720 \text{ W·m}^{-2}$$

At a distance of 1 m, the hazard factor is 720/22,1 = 32,5. This grouping produces a hazard factor greater than all the previous ones.

One row of 10 diodes

Another interesting grouping to evaluate is one entire row of 10 diodes subtending angles of 0,5 mrad (vertical) and 29,2 mrad (horizontal). Replacing 0,5 mrad by 1,5 mrad, as stated in 4.3.3, the arithmetic mean of the two angular dimensions is (1,5 + 29,2)/2 mrad = 15,3 mrad. Hence the correction factor is C_6 = 15,3/1,5 = 10,2.

$$E_{MPE,ten} = E_{MPE,train,F} = 8{,}28 \times 10{,}2 = 84{,}5 \text{ W·m}^{-2}$$

Since this grouping contains 10 diodes, this MPE has to be compared with the following:

$$E_{ten} = E_{diode} \text{ x } 10 = 180 \text{ x } 10 = 1\,800 \text{ W·m}^{-2}$$

At a distance of 1 m, the hazard factor is 1 800/84,5 = 21,3.

20-diode group

The last grouping to be considered in this example is an evaluation of the entire array of 20 diodes. Since the diodes are arranged in two adjacent rows, the vertical angular subtense is identical to that in the four-diode group, i.e. 2,8 mrad, and the horizontal angular subtense is 29,2 mrad. The average is 16 mrad, the correction factor is C_6 = 16/1,5 = 10,7 and the applicable MPE is as follows:

$$E_{MPE,twenty} = E_{MPE,train,F} = 8{,}28 \times 10{,}7 = 88{,}3 \text{ W·m}^{-2}$$

At a distance of 1 m, the hazard factor is 3 600/88,3 = 40,7. This is the largest hazard factor found in this example.

It can be shown by calculations that other groups, such as three horizontally adjacent diodes, six adjacent diodes (2 × 3), etc., give hazard factors smaller than 40,7. Therefore, 40,7 is the hazard factor to be used to evaluate the hazard of this array.

Additional remarks

It is important to note that in other situations the limiting case could be obtained from a grouping of a part of the source, not by the group of the entire source. For example, we can consider another array constituted by twenty diodes arranged in two rows of 10 diodes each, with the same angular dimensions of the diodes and the same vertical distances as in the example described above, but with a horizontal centre-to-centre distance of 6 mrad.

In this new situation, the angular subtense that is to be used for the entire array is (2,8 + 56,2)/2 mrad = 29,5 mrad, and the most restrictive MPE is given by $E_{MPE,train,F}$. Hence, the correction factor C_6 = 29,5/1,5 = 19,7 and the applicable MPE is as follows:

$$E_{MPE,twenty} = E_{MPE,train,F} = 8{,}28 \times 19{,}7 = 163 \text{ W·m}^{-2}$$

The hazard factor of the entire array is 3 600/163 = 22,1.

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Thus, C_6 = 11,5/1,5 = 7,67. The angular subtense of this group is (2,8 + 20,2)/2 = 11,5. Thus, C_6 = 11,5/11 = 1,05. Hence, the applicable MPE is as follows:

$$E_{\mathrm{MPE,eight}} = E_{\mathrm{MPE,train,F}} = 8{,}28 \times 7{,}67 = 63{,}5\ \mathrm{W{\cdot}m^{-2}}$$

This value should be compared with the following:

$$E_{\mathrm{eight}} = E_{\mathrm{diode}} \times 8 = 180 \times 8 = 1\,440\ \mathrm{W{\cdot}m^{-2}}$$

The hazard factor of this grouping is 1 440/63,5 = 22,7. Since 22,7 is the greatest value, it is to be considered as the hazard factor for this array.

The fact that the whole array gives a hazard factor smaller than the hazard factor of the eight-diode group does not mean that the whole array, i.e. the assembly of 20 diodes, is less hazardous than the assembly of eight diodes. The meaning of this apparently strange result is that, in this specific case, the correct evaluation of the hazard is not obtained by considering the 20 diodes as one uniform source subtending an angular subtense of 29,5 mrad, but is given by the analysis of the parts that form the array itself. This is due to the fact that the whole source is not uniform.

Required optical density

To protect the viewer at a distance of 1 m, an attenuation factor of 40,7 would be required in a protective filter. An optical density of 1,7 corresponds to an attenuation factor of 50 and would provide adequate protection from this laser at a distance of 1 m.

In general, it is also necessary to ensure that the filter can withstand the level of radiation power because, although the filter may have a sufficient optical density, it might be damaged by the radiation, and thus lose its capability to protect.

Using the simplistic approach of a point source approximation instead of the group calculations, the MPE for the entire array would be equal to 8,28 $\mathrm{W{\cdot}m^{-2}}$. Thus, at a distance of 1 m, the point source approximation results in the irradiance exceeding the MPE by 3 600/8,28 = 435 times, requiring an OD of log 435 = 2,64 or more. Notice that the point source approximation results in the hazard being estimated at more than four times the hazard obtained by the more accurate approach of grouping diodes.

Use of an optical device

Normal telescopes and binoculars cannot focus objects at a distance of 1 m. However, for the purpose of this example, the use of a 3×-power device to view the laser at 1 m is considered. This requires the following additional analysis.

The aperture of this device is 21 mm, smaller than the dimensions of the beam. Therefore, the power is increased by a factor of 3^2 = 9. The angular dimensions of the array are increased by a factor of 3 due to the magnification of the 3×-power device. Hence, it is necessary to perform the calculation as previously reported, but taking into consideration new values for the angular dimensions and the power of each grouping.

Since the measurement method requires a maximum acceptance angle of α_{max} = 100 mrad to collect the radiation (see 4.3.3)), when one of the two angular dimensions of the grouping, e.g., the horizontal one (indicated by α_{hor}), is greater than α_{max}, the power of the grouping should be reduced to a factor of $\alpha_{\mathrm{max}}/\alpha_{\mathrm{hor}}$, to exclude the part of the source which is outside the acceptance angle. Furthermore, any angular subtense should be limited to α_{max} before determining the arithmetic mean to be used for the calculation of C_6, as stated in 4.3.3. However in this specific example, all the angular subtenses are less than α_{max}.

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Considering the aided viewing with this optical device, the analysis of the different diode groups shows that the highest value of the hazard factor is given by the group of the whole array of 20 diodes. This value is 122, requiring an additional optical density of log 122 = 2,1.

It should be noted that in other situations the evaluation is simpler when the source is uniform, when the beam is larger than the aperture of the 3×-power optical device and when the angular subtenses of each grouping (the whole array included) are between α_{min} and α_{max} for both the aided and unaided viewing. In fact, in this case the optics would collect about nine times as much power, but the source would appear three times larger. Hence, since the factor C_6 is three times greater, the hazard produced by this optical device should be three times the hazard of the unaided viewing.

In this specific case, even if the source is not uniform, the hazard factor is about three times the hazard factor for unaided viewing. However, in other cases, the results could be very different.

Assuming the binoculars have a transmission of about 70 % at this wavelength, supplying 0,15 of this additional optical density,, the necessary optical density with 3×-power optics is: OD = 2,1 – 0,15 = 1,95. Thus, an OD of 1,95 or more would provide protection for both aided and unaided direct intra-beam viewing at a distance of 1 m from the exit aperture.

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Annex C
(informative)

Biophysical considerations

C.1 Anatomy of the eye

See Figure C.1.

C.1.1 Figure C.1(A)

Diagram of the external features of a left eye. The gap between the overlying lids limits the field-of-view (FOV) of the eye to an almond shape. The main features of the front of the eye are labelled, and dotted lines and arrowheads relate them to the section through the eye.

C.1.2 Figure C.1(B)

A diagrammatic horizontal section of a left eye. The eye is divided into two parts, the front or anterior chamber which is bounded by the cornea, the iris, and the lens and the back or posterior eye cup which is bounded by the retina and contains the gel-like vitreous humor.

C.1.3 Figure C.1(C)

The inside of an intact eye seen through an ophthalmoscope. This instrument directs a beam of light through the pupil and illuminates the inside of the eye and so allows it to be seen. The picture so viewed is referred to as the fundus. It looks reddish, but the major retinal vessels can be clearly seen. Other prominent features are the whitish optic disc, and the fovea. The fovea is a small depression in the retinal surface, which may be more pigmented than the surrounding retina and is the area of most acute vision. The fovea is the centre of the macula; the macula is responsible for detailed vision.

C.1.4 Figure C.1(D)

The structure of the retina as seen in the cut surface of Figure C.1(B) but magnified approximately 320 times larger than life. The retina consists of a series of layers of nerve cells, which overlie the photosensitive rod and cone cells; i.e. light falling on the retinal surface has to pass through the layers of nerve cells before it reaches the photosensitive cells. Underneath the layer of rods and cones is a layer called the pigment epithelium, which contains a brownish black pigment called melanin; and beneath this is a layer of fine blood vessels, the choriocapillaris. The final absorbing layer is the choroid, which contains both pigmented cells and blood vessels.

C.1.5 Figure C.1(E)

The structure of the foveal region magnified approximately 150 times. Here only cones are present. The nerve cells are displaced radially away from this area of most acute vision. The macular pigment, which absorbs strongly from 400 nm to 500 nm, is located in the fibre layer of Henle.

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C.2 The effects of laser radiation on biological tissue

The mechanism by which laser radiation induces damage is similar for all biological systems and may involve interactions of heat, thermoacoustic transients, photochemical processes, and non-linear effects. The degree to which any of these mechanisms is responsible for damage may be related to certain physical parameters of the irradiating source, the most important of which are wavelength, pulse duration, image size, irradiance, and radiant exposure.

In general terms, in supra-threshold exposures the predominating mechanism is broadly related to the pulse duration of the exposure. Thus, in order of increasing pulse duration, the predominant effects in the following time domains are: nanosecond and sub-nanosecond exposures, acoustic transients and non-linear effects; from 1 ms to several seconds, thermal effects, and, in excess of 10 s, photochemical effects.

Laser radiation is distinguished from most other known types of radiation by its beam collimation. This, together with an initial high energy content, results in excessive amounts of energy being transmitted to biological tissues. The primary event in any type of laser radiation damage to a biological system is the absorption of optical radiation by that system. Absorption occurs at an atomic or molecular level and is a wavelength specific process. Thus, it is the wavelength that determines which tissue a particular laser is liable to damage.

Thermal effects. When sufficient radiant energy has been absorbed by a system its component molecules experience an increased vibration, and this is an increase in heat content. Most laser damage is due to the heating of the absorbing tissue or tissues. This thermal damage is usually confined to a limited area extending to either side of the laser energy absorbing site, and centred on the irradiating beam. Cells within this area show burn characteristics, and tissue damage primarily results from denaturation of protein. As indicated above, the occurrence of secondary damage mechanisms in laser impacts can be related to the time course of the tissue heating reaction which is directly related to the pulse duration (Figure C.2) and the period of cooling. Thermochemical reactions occur during both the heating and cooling period, giving rise to a spot-size dependence of thermal injury. If a CW or long-pulse laser impulse is directed onto a tissue, then because of conduction, the area of the biological tissue experiencing a raised temperature is progressively increased. This spreading thermal front results in an increasing damage zone as more and more cells are raised above their thermal tolerance. The beam image size is also of great importance, as the degree of peripheral spread due to conduction is a function of the size as well as the temperature of the initial area of tissue heating. This type of thermal lesion is commonly seen on exposure to CW or long pulsed lasers, but also occurs with short pulses. For irradiated spot sizes of the order of 1 mm to 2 mm or less, the radial heat flow leads to a spot-size dependence of injury.

Photochemical effects. On the other hand, damaging effects can be the direct result of specific molecular absorption of a given light. This process is created by absorption of given light energy. Rather than releasing the energy, however, the species undergoes a chemical reaction unique to its excited state. This photochemical reaction is believed to be responsible for damage at low levels of exposure. By this mechanism, some biological tissues such as the skin, the lens of the eye, and in particular the retina may show irreversible changes induced by prolonged exposure to moderate levels of UV radiation and short-wavelength light. Such photochemically induced changes may result in damage to a system if the duration of irradiation is excessive, or if shorter exposures are repeated over prolonged periods. Some of the photochemical reactions initiated by laser exposure may be abnormal, or exaggerations of normal processes. Photochemical reactions generally follow the Law of Bunsen and Roscoe, and for durations of the order of 1 h to 3 h or less (where repair mechanisms come into play), the threshold expressed as a radiant exposure is constant over a wide range of exposure durations. The spot-size dependence, as occurs with thermal effects due to heat diffusion, does not exist.

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Non-linear effects. Short-pulsed high peak-power (i.e., Q-switched or mode-locked) lasers may give rise to tissue damage with a different combination of induction mechanisms. Energy is delivered to the biological target in a very short time and hence a high irradiance is produced. The target tissues experience such a rapid rise in temperature, that the liquid components of their cells are converted to gas. In most cases, these phase changes are so rapid that they are explosive and the cells rupture. The pressure transients may result from thermal expansion and both may also result in shearing damage to tissues remote from the absorbing layers by bulk physical displacement. At sub-nanosecond exposures, self-focusing of the ocular media further concentrates laser energy from a collimated beam and further lowers the threshold between approximately 10 ps and 1 ns. Furthermore, other non-linear optical mechanisms appear to play a role in retinal injury in the sub-nanosecond region.

All of the above-described damage mechanisms have been shown to operate in the retina, and are reflected in the breakpoints or changes of slope in the safe exposure levels described in this standard.

Table C.1 – Summary of pathological effects associated with excessive exposure to light

<table>
<tr><th>CIE Spectral region [a]</th><th>Eye</th><th colspan="2">Skin</th></tr>
<tr><td>Ultra-violet C
(180 nm to 280 nm)</td><td rowspan="2">Photokeratitis</td><td rowspan="2">Erythema (sunburn)
Accelerated skin ageing process
Increased pigmentation</td><td rowspan="2"></td></tr>
<tr><td>Ultra-violet B
(280 nm to 315 nm)</td></tr>
<tr><td>Ultra-violet A
(315 nm to 400 nm)</td><td>Photochemical cataract</td><td rowspan="2">Pigment darkening
Photosensitive reactions</td><td rowspan="5">Skin burn</td></tr>
<tr><td>Visible
(400 nm to 780 nm)</td><td>Photochemical and thermal retinal injury</td></tr>
<tr><td>Infra-red A
(780 nm to 1 400 nm)</td><td>Cataract, retinal burn</td><td rowspan="3"></td></tr>
<tr><td>Infra-red B
(1,4 μm to 3,0 μm)</td><td>Aqueous flare, cataract, corneal burn</td></tr>
<tr><td>Infra-red C
(3,0 μm to 1 mm)</td><td>Corneal burn only</td></tr>
<tr><td colspan="4">[a] The spectral regions defined by the CIE are short-hand notations useful in describing biological effects and may not agree perfectly with spectral breakpoints in the MPE tables.</td></tr>
</table>

C.2.1 Hazards to the eye

A brief description of the anatomy of the eye is given in Clause C.1. The eye is specially adapted to receive and transduce optical radiation. The absorption properties of the eye with respect to radiations of different wavelengths are shown in Figure C.2 and the associated pathologies caused by excessive exposures are summarized in Table C.1. Thus, lasers emitting ultra-violet and far infra-red radiation represent a corneal hazard while systems emitting visible and near infra-red wavelengths will be transmitted to the retina.

Visible and near infra-red lasers are a special hazard to the eye because the very properties necessary for the eye to be an effective transducer of light result in high radiant exposure being presented to highly pigmented tissues. The increase in irradiance from the cornea to the retina is approximately the ratio of the pupil area to that of the retinal image. This increase arises because the light, which has entered the pupil, is focused to a "point" on the retina. The pupil is a variable aperture but the diameter may be as large as 7 mm when maximally dilated in the young eye. The retinal image corresponding to such a pupil may be between 10 μm and 20 μm in diameter. With intra-ocular scattering and corneal aberrations considered, the increase in irradiance between the cornea and the retina is of the order of 2×10^5.

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If an increase of 2×10^5 is assumed, a 50 W·m^{-2} beam on the cornea becomes 1×10^7 W·m^{-2} on the retina. In this standard, a 7 mm pupil is considered as a limiting aperture as this is a worst-case condition and is derived from figures obtained from the young eye where pupillary diameters of this order have been measured. An exception to the assumption of a 7 mm pupil was applied in the derivation of exposure limits to protect against photoretinitis whilst viewing bright visible (400 nm to 700 nm) laser sources for periods in excess of 10 s. In this latter situation, a 3 mm pupil was assumed as a worst-case condition; however, a 7 mm irradiance averaging aperture for measurement was still considered appropriate due to physiological movements of the pupil in space.

If an intense beam of laser light is brought to a focus on the retina only a small fraction of the light (up to 5 %) will be absorbed by the visual pigments in the rods and cones. Most of the light will be absorbed by the pigment called melanin contained in the pigment epithelium. (In the macular region some energy in the 400 nm to 500 nm range will be absorbed by the yellow macular pigment.) The absorbed energy will cause local heating and will burn both the pigment epithelium and the adjacent light sensitive rods and cones. This burn or lesion may result in a loss of vision. Photochemical injuries, although non-thermal, are also localized in the pigment epithelium.

Depending on the magnitude of the exposure, such a loss of vision may or may not be permanent. A visual decrement will usually be noted subjectively by an exposed individual only when the central or foveal region of the macula is involved. The fovea, the pit in the centre of the macula, is the most important part of the retina as it is responsible for sharpest vision. It is the portion of the retina that is used "to look right at something". This visual angle subtended by the fovea is approximately equal to that subtended by the moon. If this region is damaged, the decrement may appear initially as a blurred white spot obscuring the central area of vision; however, within two or more weeks, it may change to a black spot. Ultimately, the victim may cease to be aware of this blind spot (scotoma) during normal vision. However, it can be revealed immediately on looking at an empty visual scene such as a blank sheet of white paper. Peripheral lesions will only be registered subjectively when gross retinal damage has occurred. Small peripheral lesions will pass unnoticed and may not even be detected during a systematic eye examination.

In the wavelength range from 400 nm to 1 400 nm, the greatest hazard is retinal damage. The cornea, aqueous humor, lens, and vitreous humor are transparent for radiation of these wavelengths. In the case of a well-collimated beam, the hazard is virtually independent of the distance between the source of radiation and the eye, because the retinal image is assumed to be a diffraction-limited spot of around 10 µm to 20 µm diameter. In this case, assuming thermal equilibrium, the retinal zone of hazard is determined by the limiting angular subtense α_{min}, which generally corresponds to retinal spot of approximately 25 µm in diameter.

In the case of an extended source, the hazard varies with the viewing distance between the source and the eye, because whilst the instantaneous retinal irradiance only depends on the source's radiance and on the lens characteristics of the eye, thermal diffusion of energy from larger retinal images is less efficient, leading to a retinal spot-size dependence for thermal injury which does not exist for photochemical injury (dominating only in the 400 nm to 600 nm spectral region). In addition, eye movements further spread the absorbed energy for CW laser exposures, leading to different dependencies of risk for differing retinal image sizes.

In the derivation of limits for ocular exposure in the retinal hazard region, correction factors for eye movements were only applied for viewing durations exceeding 10 s. Although physiological eye movements known as saccades do spread the absorbed energy in minimal retinal images (of the order of 25 µm or less) within the 0,1 s to 10 s time regime, the limits provide a desired added safety factor for this viewing condition. At 0,25 s, the mean retinal spot illuminated is approximately 50 µm. By 10 s, the illuminated retinal zone becomes approximately 75 µm and the added safety factor for the minimal image condition becomes 1,7 over a stabilized eye, with the spot-size dependence taken into account. By 100 s, it is rare to achieve an illuminated zone (measured at 50 % points) as small as 135 µm leading to an additional safety factor of 2-3 or more for the minimal image condition.

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The data from eye-movement studies and retinal thermal injury studies were combined to derive a break-point in viewing time T_2 at which eye movements compensated for the increased theoretical risk of thermal injury for increased retinal exposure durations if the eye were immobilized. Because the thermal injury threshold expressed as radiant power entering the eye decreases as the exposure duration t raised to the –0,25 power (i.e. a reduction of only 44 % per tenfold increase in duration), only moderate increases in the exposed retinal area will compensate for the increased risk for longer viewing times. The ever-increasing retinal area of irradiation resulting from greater eye movements with increased viewing time takes longer to compensate for the reduced impact of thermal diffusion in larger extended sources. Thus, for increasing angular subtense α, the break-point T_2 increases from 10 s for small sources to 100 s for larger sources. Beyond 100 s there is no further increase in risk of thermal injury for small and intermediate size images. The specification of limits and measuring conditions attempt to follow these variables with some simplification leading to a conservative determination of risk. It is conservatively assumed that retinal thermal injury thresholds vary inversely with retinal image size (stabilized) between approximately 25 µm to 1 mm (corresponding to angular sizes of 1 µm to 59 mrad), whilst beyond 1,7 mm (corresponding to angular sizes greater than 100 mrad), there is no spot-sized dependence.

For photochemically induced retinal injury there is no spot size dependence for a stabilized image. Unlike thermal injury mechanism, the thresholds for photochemical injury are highly wavelength dependent and are exposure dose dependent, i.e. the thresholds decrease inversely with the lengthening of exposure time. Studies of photochemical retinal injury from welding arcs subtending angles of the order of 1 mrad to 1,5 mrad showed typical lesion sizes of the order of 185 µm to 200 µm (corresponding to visual angles of 11 mrad to 12 mrad), clearly showing the influence of eye movements during fixation; these and other studies of eye movements during fixation led to the derivation of MPEs to protect against photochemical retinal injury. These studies also led to MPE irradiance to be specified as being averaged over 11 mrad for exposure durations between 10 s and 100 s. Hence, sources with an angular subtense α less than 11 mrad were treated equally with "point-type" sources, and the concept of α_{min} was extended to CW laser viewing. This approach was not strictly correct, as an irradiance measurement of an 11-mrad source is not equivalent to irradiance averaging over a field of view (γ) of 11 mrad unless the source had a rectangular ("top-hat") radiance distribution. Hence, in this edition of the standard, distinction is made between angular subtense of a source and irradiance averaging for photochemical MPE values. For viewing times in excess of approximately 30 s to 60 s, the saccadic eye motion during fixation is generally overtaken by behavioral movements determined by visual task, and it is quite unreasonable to assume that a light source would be imaged solely in the fovea for durations longer than 100 s. For this reason, the angle of acceptance γ_p is increased linearly with the square-root of t. The minimal angular subtense α_{min} correctly remains at the reference angle of 1,5 mrad for all exposure durations used in thermal retinal hazard evaluation. However, for photochemical retinal hazard assessment, the concept is actually different, as the angle γ_p is a linear angle of acceptance for the measurement of irradiance, and this is important to apply only for extended sources greater than approximately 11 mrad.

Viewing distance. In the case of a "point-type", diverging-beam source, the hazard increases with decreasing distance between the beam waist and the eye. The reason is that, with decreasing distance, the collected power increases, while the size of the retinal image can be assumed to remain nearly diffraction-limited for true laser sources down to a distance as close as 100 mm (due to the accommodation capabilities of the eye). The greatest hazard occurs at the shortest accommodation distance. With further reduced distance, the hazard to the unaided eye is also reduced, as there is a rapid growth of the retinal image and a corresponding reduction of the irradiance, even though more power may be collected. To simulate the risk of optically aided viewing of a collimated beam with binoculars or a telescope, the closest distance of approach of 2 m with a 50-mm aperture was assumed based upon the closest distance for clear viewing.

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For the purpose of this technical report, the shortest accommodation distance of the human eye is set to 100 mm at all wavelengths from 400 nm to 1 400 nm. This was chosen as a compromise, because all but a few young people and very few myopics cannot accommodate their eyes to distances of less than 100 mm. This distance may be used for the measurement of irradiance in the case of intrabeam viewing.

For wavelengths of less than 400 nm or more than 1 400 nm, the greatest hazard is damage to the lens or the cornea. Depending on the wavelength, optical radiation is absorbed preferentially or exclusively by the cornea or the lens (see Table C.1). For diverging-beam sources (extended or point-type) of these wavelengths, short distances between the source and the eye should be avoided.

In the wavelength range from 1 500 nm to 2 600 nm, radiation penetrates into the aqueous humor. The heating effect is therefore dissipated over a greater volume of the eye, and the MPEs are increased for exposures less than 10 s. The greatest increase in the MPEs occurs for very short pulse durations and within the wavelength range of 1 500 nm to 1 800 nm where the absorbing volume is greatest. At times greater than 10 s, heat conduction redistributes the thermal energy so that the impact of the penetration depth is no longer significant.

C.2.2 Skin hazards

In general terms, the skin can tolerate a great deal more exposure to laser beam energy than can the eye. The biological effect of irradiation of skin by lasers operating in the visible (400 nm to 700 nm) and infra-red (greater than 700 nm) spectral regions may vary from a mild erythema to severe blisters. An ashen charring is prevalent in tissues of high surface absorption following exposure to very short-pulsed, high-peak power lasers. This may not be followed by erythema.

The pigmentation, ulceration, and scarring of the skin and damage of underlying organs may occur from extremely high irradiance. Latent or cumulative effects of laser radiation have not been found prevalent. However, some limited research has suggested that under special conditions, small regions of human tissue may be sensitized by repeating local exposures with the result that the exposure level for minimal reaction is changed and the reactions in the tissues are more severe for such low-level exposure.

In the wavelength range 1 500 nm to 2 600 nm, biological threshold studies indicate that the risk of skin injury follows a similar pattern to that of the eye. For exposures up to 10 s, the MPE is increased within this spectral range.

C.3 MPEs and irradiance averaging

In this standard, the maximum permissible exposure (MPE) values recommended by the ICNIRP have been adopted. The irradiance-averaging apertures (measurement apertures) recommended by the ICNIRP were adopted, or an additional safety factor applied by IEC TC 76.

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Table C.2 – Explanation of measurement apertures applied to the MPEs

Spectral band λ	**Exposure time** t	**Aperture diameter**	**Comments and rationale for aperture diameter**
180 nm to 400 nm	$t < 3 \cdot 10^4$ s	1 mm	Scatter in corneal epithelium and in stratum corneum leads to 1 mm; assumption of no movement of exposed tissue for continuous exposure conditions is applied by IEC. However, ICNIRP recommends 3,5 mm for lengthy exposures due to eye movements.
400 nm to 600 nm photochemical	$t > 10$ s	3 mm in derivation of MPE, but 7 mm used for measurements	Lateral motion of 3-mm diameter pupil in space to produce 7-mm aperture averaging for CW exposures applicable for photochemical injury mechanism
400 nm to 1 400 nm thermal	All times t	7 mm	Diameter of dilated pupil and lateral motion in CW exposures
$\lambda > 1\,400$ nm	$t < 0,35$ s	1 mm	Thermal diffusion in stratum corneum and epithelial tissues
$\lambda > 1\,400$ nm	$0,35 \text{ s} < t < 10$ s $t > 10$ s	$1,5 \cdot t^{3/8}$ mm 3,5 mm	Greater thermal diffusion and movement of target tissue relative to beam after 0,35 s
$10^5 \leq \lambda \leq 10^6$ nm	All t	11 mm	Aperture to be greater than diffraction limit (i.e., approximately 10×) for accurate measurements

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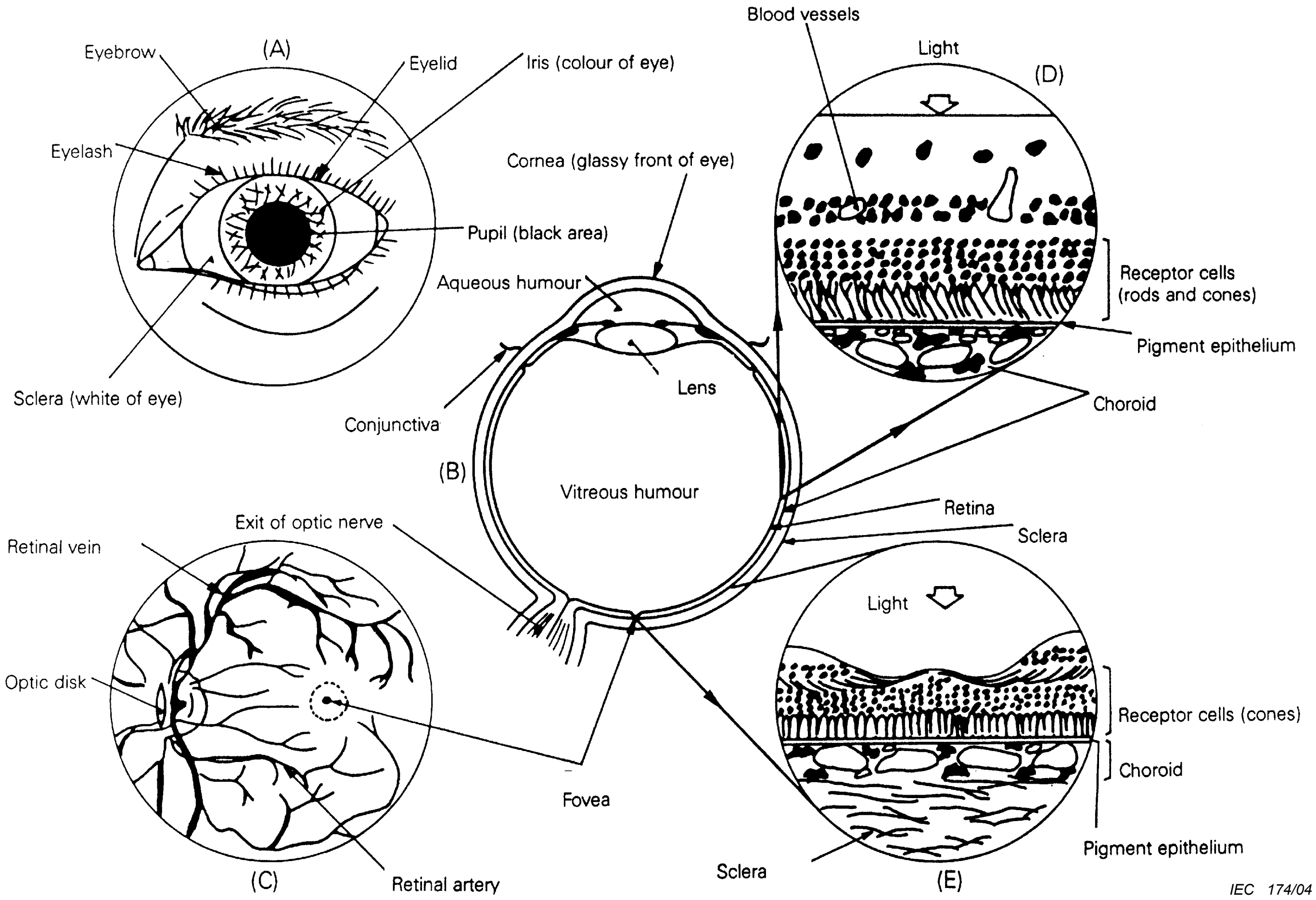

Figure C.1 – Anatomy of the eye

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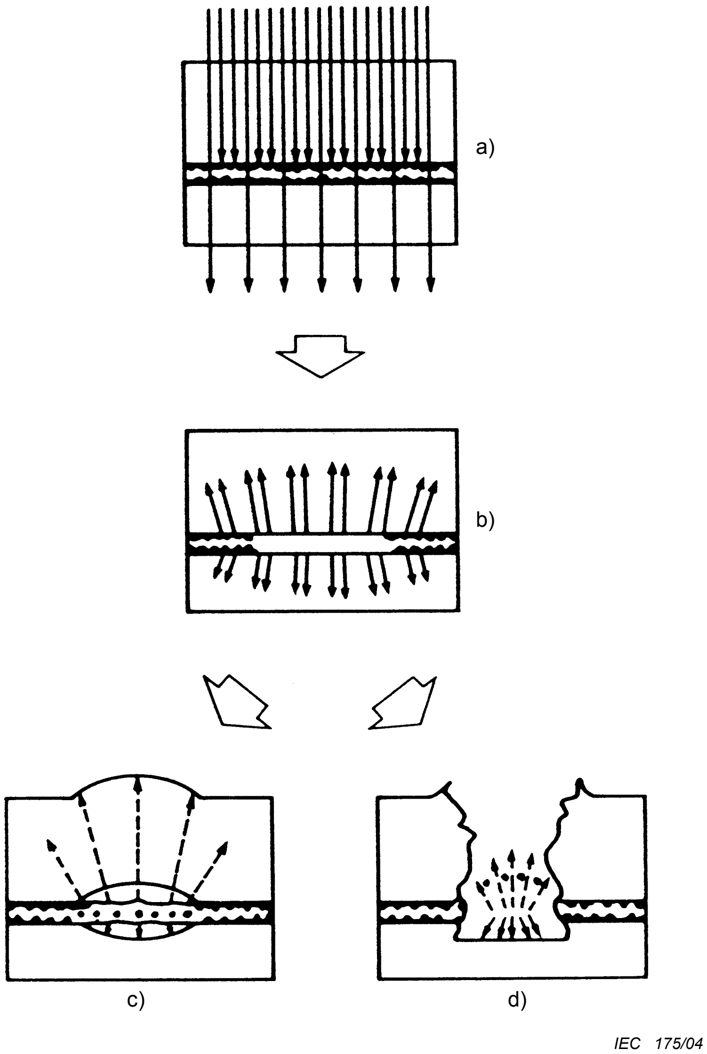

a) Laser energy is absorbed by the system.

b) The absorbed energy produces heat which is conducted to surrounding tissues.

c) In long-pulse or CW lasers the persistence of the thermal front gives rise to a progressively enlarging lesion.

d) In short-pulse lasers the high power density gives rise to explosive rupture of cells and damage by physical displacement.

Figure C.2 – Diagram of laser-induced damage in biological systems

C.4 Reference documents

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IEC 60825-9, *Safety of laser products – Part 9: Compilation of maximum permissible exposure to incoherent optical radiation*

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