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TECHNICAL REPORT

colour inside

Safety of laser products –
Part 14: A user's guide

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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IEC TR 60825-14 has been prepared by IEC technical committee 76: Optical radiation safety and laser equipment. It is a Technical Report.

This second edition cancels and replaces the first edition published in 2004. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) incorporates changes made in IEC 60825-1:2014;
b) adds information to users of laser equipment on administrative controls to ensure safety in the workplace, including the training and appointment of people to specific laser safety management roles;
c) updates an approach to risk assessment;
d) includes updated guidance on the management of incidents and accidents;
e) includes updated guidance on medical surveillance for laser workers;
f) includes revised examples of calculations.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
76/661/DTR	76/693/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts of the IEC 60825 series, published under the general title *Safety of laser products*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

To help in the use of this document, 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 4.
- The meaning of the laser product classes and the assessment of laser exposure are covered in Clause 5.
- 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 6.
- Associated laser hazards (that is, hazards other than those of eye or skin exposure to the emitted laser beam) are covered in Clause 7.
- A three-stage process for evaluating risk (arising from both the laser radiation hazards discussed in Clause 5 and Clause 6, and the associated laser hazards discussed in Clause 7) is covered in Clause 8. These three stages are
  1) the identification of 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 9.
- The need to ensure the continuation over time of safe laser operation is covered in Clause 10.
- The reporting of laser-related hazardous incidents and the investigation of accidents is covered in Clause 11 and Clause 12.
- The role of medical surveillance (eye examinations) is covered in Clause 13.
- 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.

SAFETY OF LASER PRODUCTS –

Part 14: A user's guide

1 Scope

This document provides guidance on best practices 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 that is capable of emitting optical radiation produced by a process of stimulated emission.

Class 1 laser products normally pose no beam hazard and Class 2 and Class 3R laser products present only a minimal beam hazard. With these products, it is normally sufficient to follow the warnings on the product labels and the manufacturer's instructions for safe use. It is unlikely that further protective measures as described in this document will be necessary.

This document emphasizes evaluation of the risk from higher power lasers, but the users of the lower power lasers can benefit from the information provided.

This document 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 document is intended to help laser users and their employers to understand the general principles of safety management, to identify the hazards that can be present, to assess the risks of harm that can arise, and to set up and maintain appropriate control measures. Although the guidance given in this document is aimed principally at organizations (whether private, corporate or public), where systems of safety management would be expected to be in place, it can be applied by anyone using lasers.

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 are at risk of harm. Specific requirements for certain laser applications are given in other documents in the IEC 60825 series.

The terms "reasonably foreseeable" and "reasonably foreseen" 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 occurrences might be "reasonably foreseen", 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 includes persons having responsibility for safety in addition to those who actually work with or operate laser equipment.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60825-1:2014, *Safety of laser products – Part 1: Equipment classification and requirements*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60825-1:2014 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

– IEC Electropedia: available at http://www.electropedia.org/
– ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
control measure
precaution adopted to reduce the risk of harm occurring

Note 1 to entry: Control measures include engineering controls (safety features incorporated into the laser equipment), administrative controls (documented policies, operating procedures, safety training, etc.) and personnel protection (safety equipment including eye protection that is worn by individuals).

3.1.2
laser equipment
laser product
assembly that is a laser or contains a laser

3.1.3
optical density
OD
$D(\lambda)$
logarithm to base ten of the reciprocal of the transmittance τ

$$D(\lambda) = -\log_{10} \tau$$

3.1.4
protective enclosure
physical means for preventing human exposure to laser radiation unless such access is necessary for the intended functions of the installation

3.2 Symbols

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_{min} = 1,5 mrad).
α_{max}	rad	The value of angular subtense of the apparent source above which the MPEs are independent of the source size (α_{max} = 5 mrad to 100 mrad, see Table 10).
$C_1, C_2, \ldots, C_7$	no units	Correction factors (see Table 9).
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.
$D(\lambda)$	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	Unit	Definition
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 E	$J{\cdot}m^{-2}$ $W{\cdot}m^{-2}$	Radiant exposure or irradiance at a specified distance, r, from the apparent source.
H_o E_o	$J{\cdot}m^{-2}$ $W{\cdot}m^{-2}$	Emergent beam radiant exposure or irradiance at zero distance from the apparent source.
k	no units	Irradiance averaging 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
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.
R_{NOH}	m	Nominal ocular hazard distance.
$R_{NOH,E}$	m	Extended nominal ocular hazard distance.
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 10).

4 Administrative policies

4.1 Safety responsibilities

Safety responsibilities may be specified by national or local regulations. 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 (environment) 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 needs to 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 organization'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, Class 1C, Class 2, or Class 3R 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, 5.1.3 concerning embedded lasers and 5.2.2 concerning transient visual effects.

4.2 Competent Person

Where the employer or laser user is not able, without assistance, to properly determine the necessary safety arrangements and protective measures for eliminating or minimizing 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, relating particularly to the specific technical area within which advice is being sought, 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 (often termed the Laser Protection Adviser (4.5.1) when considering laser beam hazards) need not be an employee of the organization 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.

4.3 Laser Safety Officer

A Laser Safety Officer (LSO) should be appointed in organizations 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 5.1.3), 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 7.)

The Laser Safety Officer should be authorized to act on behalf of the employer and take responsibility, on behalf of that 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 the technical understanding, competence and capability that are necessary to perform the duties required. Appropriate training and sufficient resources should be provided to support the Laser Safety Officer in this role.

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 organization concerned, but are likely to include as a minimum:

– being aware of and, if appropriate, maintaining records of all potentially-hazardous laser products (including the classifications, specifications, and purposes of the laser products; the locations of the laser products; and any special requirements or restrictions relating to their uses);
– responsibility for monitoring compliance with the organization'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 authorize, 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 4.2) has been appointed and that person is an employee of the organization concerned (often desirable in organizations having extensive and varied laser use), then the Competent Person may also be the Laser Safety Officer.

In large organizations where there is extensive laser use or in higher risk applications, suitable employees may be appointed to assist the Laser Safety Officer by being tasked to manage day to day safety of a particular activity or by being given more local responsibility for specific laser areas. In such circumstances, regular liaison should be maintained between all those involved to ensure the consistent and effective management of laser safety throughout the organization.

4.4 Information and training

All employees should, where relevant, be made aware of any hazards (including associated hazards; see Clause 7) 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 3 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, the following:

a) the organization'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 9.4.5);

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.

4.5 Levels of competence

4.5.1 Laser Protection Adviser

Where an employer is not competent to undertake without assistance the necessary duties with regard to laser safety, a Competent Person, having sufficient skill, knowledge and experience, should be appointed to advise the employer in these matters and to provide assistance in the establishment of the organization's laser safety policy and in the implementation of the required arrangements. Such a person, called a Laser Protection Adviser, may be an employee of the organization concerned or an external adviser.

The employer should ensure that all relevant information relating to the use or intended use of the laser equipment is made available to the Laser Protection Adviser, and that the Laser Protection Adviser is given sufficient time and resources to enable him or her to undertake the necessary tasks effectively, having regard to the size of the organization, the risks to which employees may be exposed, and the distribution of those risks throughout the organization.

Many larger organizations undertaking extensive and varied laser work may find it convenient to retain professional laser safety skills in-house and to combine the role of the Laser Safety Officer with that of the Laser Protection Adviser in one employee.

In other circumstances, however, the Laser Safety Officer need not be the Laser Protection Adviser, since it is neither necessary nor appropriate for a high level of expertise in laser safety to be retained in-house where such expertise cannot be utilized on a regular basis. In such cases the employer, or on their behalf the Laser Safety Officer, should seek the guidance of an external Laser Protection Adviser whenever necessary.

Any person acting as a Laser Protection Adviser should have sufficient knowledge, understanding, competence and experience in relevant matters of laser safety, particularly with regard to the following:

– the provisions and applicability of relevant safety standards and national regulations;
– the type of laser equipment in use;
– the particular application or working environment concerned;
– the hazards that may be present;
– hazard evaluation and risk assessment procedures;
– safety management;
– the selection, specification and proper use of hazard controls;
– the safety training requirements of relevant personnel;
– the drafting of safe working procedures.

4.5.2 Laser Safety Officer

Every organization within which laser equipment of Class 3B or Class 4 is in use should appoint an internal Laser Safety Officer to take administrative responsibility on behalf of the employer for overseeing laser safety. Certain lower class embedded laser products contain lasers Class 3B or Class 4 emission levels that may produce hazardous accessible emissions under some conditions of use, e.g. during servicing, and could therefore also necessitate the appointment of a Laser Safety Officer. The appointment of a Laser Safety Officer is also recommended where Class 1M or 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. In some instances, it may be appropriate to appoint a Laser Safety Officer where lower power (3R and below) visible laser beams are being used in a high-risk environment, e.g. roadside construction sites, where persons are performing safety critical tasks, and there is the potential for interference with vision.

The Laser Safety Officer should ensure that adequate controls for minimizing health risks arising from the use of laser equipment are in place, that regular monitoring of laser hazards and of the effectiveness of control measures is carried out, and that records of such monitoring are maintained.

Overall responsibility for laser safety remains with the employer, who should ensure that the person appointed as the Laser Safety Officer has the capability, knowledge and understanding, as well the resources needed, to undertake these tasks effectively. Within the limits of the mandate from the employer the Laser Safety Officer bears the responsibility for the safety control actions, both engineering and administrative.

Within large organizations having extensive laser use, a more continuous (day to day) laser safety presence is beneficial, so it can often be helpful to appoint area or departmental laser safety representatives to assist the Laser Safety Officer and to provide more local support to laser users.

The standard of competence necessary for a Laser Safety Officer is that they should:

- know that optical radiation encompasses visible light and invisible infrared and ultraviolet radiation, that it is designated in terms of wavelength, and that it differs from ionizing radiation;
- know the basic characteristics (spatial, spectral and temporal) of laser emission;
- understand the appropriate quantities and units in which laser emission is specified;
- know of the existence of relevant laser safety standards and national regulations affecting laser use;
- understand the concept of laser hazard Classes 1, 1C, 1M, 2, 2M, 3R, 3B and 4, and the meaning of laser warning labels;
- know the type(s) of laser equipment in use within the organization concerned and understand its intended purpose;
- know the waveband(s) and wavelength(s) of emission of the laser equipment in use;
- know the tissue(s) at risk from laser beam exposure, and in the case of laser emission within the retinal hazard region (wavelengths between 400 nm and 1 400 nm) understand the focusing effects of the eye;
- appreciate the severity of harm that can occur from laser beam exposure;
- know the approximate area around the laser(s) within which hazardous exposure levels may arise under different circumstances of use;
- understand the nature and extent of other hazards that may arise from the use of the laser equipment, including
  - mechanical hazards,
  - electrical hazards,
  - noise and vibration hazards,
  - thermal hazards,
  - fire and explosion hazards,
  - chemical hazards;
  - biological hazards including laser fume or plume, and

  - radiation hazards, in addition to those due to laser emission;
- understand the control procedures that are necessary to eliminate the risk of harm occurring or to reduce this risk to an acceptable level, including the proper use of warning signs and controlled areas;
- understand the essential requirements of occupational health and safety and the general principles of good safety management;
- understand the need to establish, document and implement safe working procedures (covering normal operation, adjustment work, and the occurrence of unplanned events, including accidents);
- have sufficient technical understanding and management ability to be able to take administrative responsibility, on behalf of the employer, for overseeing, regular monitoring, and the continuous control of laser hazards within the organization, having due regard to the type(s) of laser(s) in use, the specific nature of the laser application(s), the people involved in the work, and the kind(s) of working environment(s) concerned;
- know how to respond to laser-related accidents and to other incidents where safety could be compromised;
- know how to seek, and be able to act on, the specialist advice of a Laser Protection Adviser whenever necessary.

4.5.3 Laser Safety Supervisor

One or more Laser Safety Supervisors may be appointed to manage the day-to-day safe operation of the laser(s). They would be expected to have a higher level of competency than the laser user but have access to the Laser Safety Officer and/or Laser Safety Adviser when necessary. The duties of the Laser Safety Supervisor should be agreed in writing but are likely to include ensuring that any safety systems are in place and procedures complied with. The Laser Safety Supervisor is likely to be directly involved with the laser work.

4.5.4 Laser user

Those who use, work with, or who are placed in control of laser equipment of Class 1M, 2M, 3R, 3B or 4 should be sufficiently competent in the operation and use of the equipment, and in addition should:

- understand the general nature of laser radiation,
- know the health hazards that can arise from the use of the laser equipment, the tissues of the body which are at risk, and the severity of harm which can result,
- understand the meaning of the warning labels appropriate to the class(es) of laser being used,
- understand the proper use of hazard control procedures including, where appropriate, the need for personal protection,
- be aware of the need for any additional precautions that may be necessary when undertaking nonroutine activities, such as adjustment work,
- be familiar with the organization's procedures and policy governing laser use, including emergency action and accident reporting procedures.

4.5.5 Awareness for other persons

Persons who are not themselves involved in using or working with laser equipment, but who nevertheless have some responsibility for laser equipment of Class 1M, 2M, 3R, 3B or 4, for those who use it, or for general health and safety matters within the organization, should have some understanding of the general issues of laser safety. Such persons could include, for example, supervisors, managers, safety officers, occupational health and safety staff, auxiliary staff required to enter a laser hazard area as part of their duties, e.g. cleaners, security, general maintenance, etc., and employee representatives. They should appreciate in general terms the extent and function of laser equipment within the organization, and in addition should:

– understand the general nature of laser radiation and laser radiation hazards,
– have a knowledge of the classification scheme for lasers and the meaning of laser warning signs,
– appreciate the extent of laser use within the organization, and its intended purpose,
– be familiar with the organization's policies regarding laser safety,
– know the particular hazards arising from the use of laser equipment within the organization and be aware of the control measures that are in place,
– know restrictions on access to any laser controlled area and the meaning of access restriction signs,
– have good knowledge of the safety infrastructure.

4.6 Training requirements

Training in laser safety, and also in associated issues of occupational safety and health, should be given to employees whenever necessary in order to provide them with sufficient skills, knowledge and understanding to ensure that laser equipment is safely used and that the organization's laser safety policies are effectively and continuously implemented.

Training should be suitable, sufficient and comprehensible, taking into account the experience, capabilities and educational level of the employees being trained. Refresher training should also be given at reasonable intervals to ensure that an adequate level of safety awareness and competence is maintained.

Any suitable method of training can be used, and may be by means of one, or a combination of any, of the following:

– a short course given internally from the organization's own resources;
– a short course given internally by an external trainer;
– attendance at an externally-run off-site course;
– the use of computer-aided learning packages;
– self-teaching through books, etc. and remote learning by correspondence;
– work experience and informal one-to-one training.

In the case of a person seeking to become a Laser Protection Adviser, a single short course or period of study is not normally sufficient to develop adequate competence for this role. A high-level of capability combined with considerable experience in the relevant area of laser application is needed.

4.7 Accreditation

There are currently no internationally recognized schemes for accrediting laser safety courses, or for approving individuals and organizations able to provide training services or safety advice. In determining the suitability of particular training courses or training providers for Laser Protection Advisers, employers should use their own judgement, using this document as a guide, but could also take account of any recommendations given by a third party. Personnel need to be qualified, competent and current for the agreed duties.

NOTE National certification or accreditation schemes are available in some countries.

Trainers should have knowledge exceeding the level of training being taught, e.g. Laser Safety Officers are unlikely be suitably qualified to train equivalent Laser Safety Officers until they have experience or a higher level of skill than the role they are training.

5 Laser radiation hazards

5.1 Laser products

5.1.1 Laser product classification

The class of a laser product gives a broad 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 5.1.2). In addition, it should be recognized that some or all of the original safety features of the incorporated laser product, including labelling, may be inoperative, unusable or inaccessible. Where necessary to ensure safe operation, these safety features should be replicated or replaced.

5.1.2 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, including reasonably foreseeable single fault conditions. Associated hazards (also referred to as non-beam hazards) (see Clause 7) that may also be present during use of the laser do not affect the laser classification. During the maintenance or servicing of embedded laser products, access may be gained to higher levels of radiation than is indicated by the class of the product.

NOTE 1 See IEC 60825-1: 2014, 6.2.1

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 all reasonably foreseeable conditions of operation, 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 5.1.3). 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 if the emitted laser beam is modified, such as by using external optics to reduce the size or divergence of the emitted beam in a manner that could increase its hazard, then the protection requirements of the appropriate higher class apply.)

b) Class 1C

Laser products that are intended to be used in direct contact with the skin of a person. Ocular hazard is prevented by one or more engineering means which only permit exposure when the applicator is in contact with the skin. The MPE for the skin may be exceeded, depending on the intended purpose of the product.

Protection requirements for Class 1C: These products should have adequate engineering controls to protect the eyes from laser radiation. However, modification or defeat of safety features may result in hazardous exposure to laser radiation. Repeated exposure of the same area of the skin may cause injury.

c) 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. Hazardous exposure can also occur if the dimensions of the laser beam are reduced by the use of optical components in the beam path.

Protection requirements for Class 1M: Avoid the use of magnifying viewing aids or instruments (such as binoculars or telescopes, but not spectacles or contact lenses). Avoid placing optical devices in the emitted beam that could decrease the beam diameter. 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.

NOTE 2 In the case of optical fibre communication systems assessed under IEC 60825-2 using hazard levels instead of the product classes specified in IEC 60825-1, an ocular hazard might be introduced in the case of hazard level 1M by the use of magnifiers to view the fibre end face.

d) 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. Laser beams from Class 2 laser products may cause distraction, dazzle, flash blindness or after images, especially under low ambient light levels.

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.

e) 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. Hazardous exposure can also occur if the dimensions of the laser beam are reduced by the use of optical components in the beam path. Laser beams from Class 2M laser products may cause distraction, dazzle, flash blindness or after images, especially under low ambient light levels.

Protection requirements for Class 2M: Avoid the use of magnifying viewing aids or instruments (such as binoculars or telescopes, but not spectacles or contact lenses). Avoid placing optical devices in the emitted beam that could decrease the beam diameter. Avoid staring into the beam (i.e. deliberate viewing of the laser source) or pointing the beam at other people.

NOTE 3 In the case of optical fibre communication systems assessed under IEC 60825-2 using hazard levels instead of the product classes specified in IEC 60825-1, the ocular hazard in the case of hazard level 2M might be increased by the use of magnifiers to view the fibre end face such that the aversion response cannot provide sufficient protection.

f) 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. Laser beams within the wavelength range 400 nm to 700 nm from Class 3R laser products may cause distraction, dazzle, flash blindness or after images, especially under low ambient light levels. The natural aversion response for exposure to bright light for the case of visible radiation and the response to heating of the cornea for far infrared radiation reduce the risk of eye injury.

Protection requirements for Class 3R: Prevent direct eye exposure to the beam or pointing the beam at other people. Consider conducting a risk assessment that takes into account the actual use and the operational environment, particularly in low ambient light conditions.

g) Class 3B

Laser products having a level of accessible emission, which can be harmful to the eyes for any direct intrabeam exposure (including specular reflection), even for exposure durations shorter than the aversion response time, 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.

h) 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 1C, 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 Class 1 and Class 1M may also carry labels, but at the discretion of the manufacturer, the required wording can instead be included in the printed user information supplied with the product. 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, 1C, 1M, 2, 2M or 3R), are used in a way where the accessible emissions do not exceed 3R (e.g. Class 1M or 2M cannot be viewed through telescopic optics) and are used in an implicitly low risk environment, 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 summarized 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.

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, or reasonably foreseeable misuse.) 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 9.5).
1C	No special precautions are required to protect the eye during normal operation because the product should have effective engineering controls. Repeated exposure of the same site on the skin is not advised. Products should have effective engineering controls to prevent use of the applicator on the face where the eye may be at risk of exposure to optical radiation in excess of the appropriate maximum permissible exposure level.
1M	Prevent direct viewing of the laser source through magnifying viewing instruments, such as binoculars or telescopes, unless these incorporate adequate levels of protection.[a] Prevent the use of any external optics that could decrease the diameter. 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 9.5).
2	Do not stare into the beam. Do not look into the laser or 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. 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 9.5).
2M	Do not stare into the beam. Do not look into the laser or 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 or telescopes, unless these incorporate adequate levels of protection.[a] Prevent the use of any external optics that could decrease the beam diameter. 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 9.5).
3R	Prevent direct eye exposure to the beam. Do not look into the laser or direct the beam at other people or into areas where other people unconnected with the laser work may be present. Ensure the beam is always terminated at a suitable non-specular (i.e. non mirror-like) surface. 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 9.5).
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. Ensure the beam is always terminated at a suitable non-specular (i.e. non mirror-like) surface. Where reasonably practicable, use engineering means, as specified in IEC 60825-1, to reduce the effective class of the laser system 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.

5.1.3 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. However, Class 2 and Class 3R products may also contain lasers of a higher class. 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 9.5.

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 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.

5.1.4 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 optical fibre communication system may be assigned different hazard levels. (This is in contrast to the class of a laser product, which is based on the highest level of accessible emission that could arise during normal operation from any part of the product. The class allocated applies to the complete product.)

Safety requirements for the use of optical fibres to deliver laser radiation in applications other than communication systems, for example in materials processing applications, need to consider the risk of the laser radiation becoming accessible and how such risk can be managed.

5.1.5 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, or when spectators are prevented from exposure to levels exceeding the applicable maximum permissible exposure (MPE).

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

5.1.6 Consumer laser products

Laser products intended to be used by people who are unlikely to have been trained in safe laser use should normally be restricted to Class 1, Class 1C or Class 2. Class 1M, Class 2M and Class 3R lasers may be incorporated into consumer products where the application is justified and where adequate instructions for safe use are supplied with the product. Such instructions should be appropriate for the intended user. Class 3B and Class 4 laser products are not recommended for use as consumer products.

5.2 Exposure to laser radiation

5.2.1 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 5.3), and then to relate this to the maximum permissible exposure (the MPE, outlined below and explained in more detail in Clause 6).

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 8. 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 Table 4 to Table 8 as functions of the laser emission wavelength and exposure duration. They are discussed in more detail in Clause 6. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) develops these values. They are set below known damage thresholds and are based on the best available information. The MPE can be regarded as the level above which there should be safety control. The MPE should not be used as a guide above which one would necessarily expect an injury. 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.

5.2.2 Transient visual effects

The classification of a laser product relates to the relative risk of permanent tissue damage and the potential for causing injury. But even with laser products in Classes 1 and 2, where the risk of injury is very low or non-existent, visual discomfort such as disability and discomfort glare ("dazzle"), and flash-blindness or after images, can occur from direct viewing of laser radiation in the visible spectrum. These transient visual effects can give rise to secondary risks, particularly under low ambient light conditions. They may therefore have indirect implications on general safety, resulting from temporary disturbance of vision or from startle reactions. Such visual disturbances could be of particular concern if experienced while performing safety-critical operations such as working with machines or at height, with high voltages or driving/flying. In some jurisdictions the misuse of intense, visible (e.g. green) laser pointers has been banned (or prevented by legal action).

Such sudden and unexpected visual disturbances can also generate fear and can 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 may result in painful corneal abrasions.

5.3 Determining the level of laser exposure

5.3.1 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.

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 needs to be paid to the relevant limiting aperture (see 5.3.2) and, where relevant, to the procedures for dealing with large (extended) laser sources (see 5.3.3 and 6.4). These considerations can mean that the value of the applicable exposure (called the effective exposure) that needs to 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 C_6. In the case of single laser sources, C_6 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 5.3.2. 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.

NOTE For circular beams having an approximately Gaussian profile, the on-axis value of the irradiance or radiant exposure 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 d_{63} 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.

5.3.2 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 time of the relevant exposure, either pulse duration or total exposure)

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 $t \leq 0{,}35$ s $1{,}5\ t^{3/8}$ for $0{,}35\ s < t < 10$ s 3,5 for $t \geq 10$ 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 adjusted to take into account smaller pupil diameters.

5.3.3 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 of 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 an angle 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.

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 subtense of a source should not be confused with the divergence of its emission. To take the sun as an example, its angular subtense as viewed from earth is only 8,7 mrad (0,5°), but the divergence of its emission is 2π rad (360°).

a) For the determination of the level of exposure to be evaluated against the photochemical MPEs in Table 5 (400 nm to 600 nm), the limiting angle of acceptance γ_{ph} is

   – for 10 s < t ≤ 100 s: γ_{ph} = 11 mrad

   – for 100 s < t ≤ 10^4 s: γ_{ph} = 1,1 $t^{0,5}$ mrad

   – for 10^4 s < t ≤ 3 × 10^4 s: γ_{ph} = 110 mrad

   If the angular subtense of the source is larger than the specified limiting angle of acceptance γ_{ph}, the angle of acceptance should not be larger than the values specified for γ_{ph}. If the angular subtense of the source is smaller than the specified limiting angle of acceptance γ_{ph}, 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_{ph}).

   NOTE For measurements of single small sources, where the angular subtense of the source is smaller than γ_{ph}, 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 1a and 1b. For measurements of extended sources where the angular subtense of the source is larger than γ_{ph} using an angle of acceptance that is larger than the source results in an over-restrictive exposure level, but can be used as a simplified assessment.

   Figure 1a 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 field stop in front of the detector. This arrangement can be used where the apparent source is not directly accessible.

   Figure 1b is an example of a measurement set-up providing a well-defined angle of acceptance by placing the field stop at the source. This arrangement can be used where the source is directly accessible.

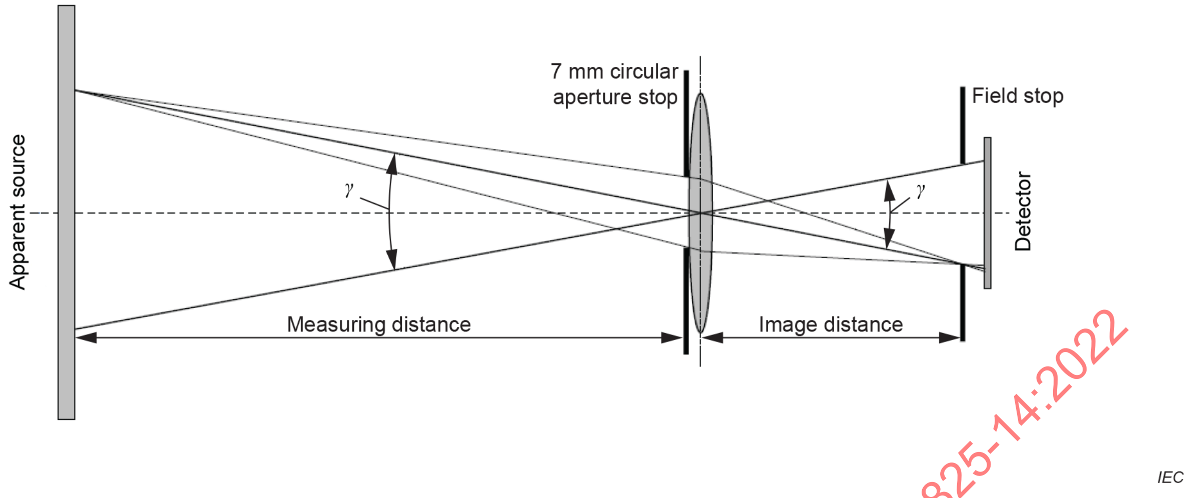


Figure 1a – Measurement set-up using a lens to image the apparent source onto a field stop

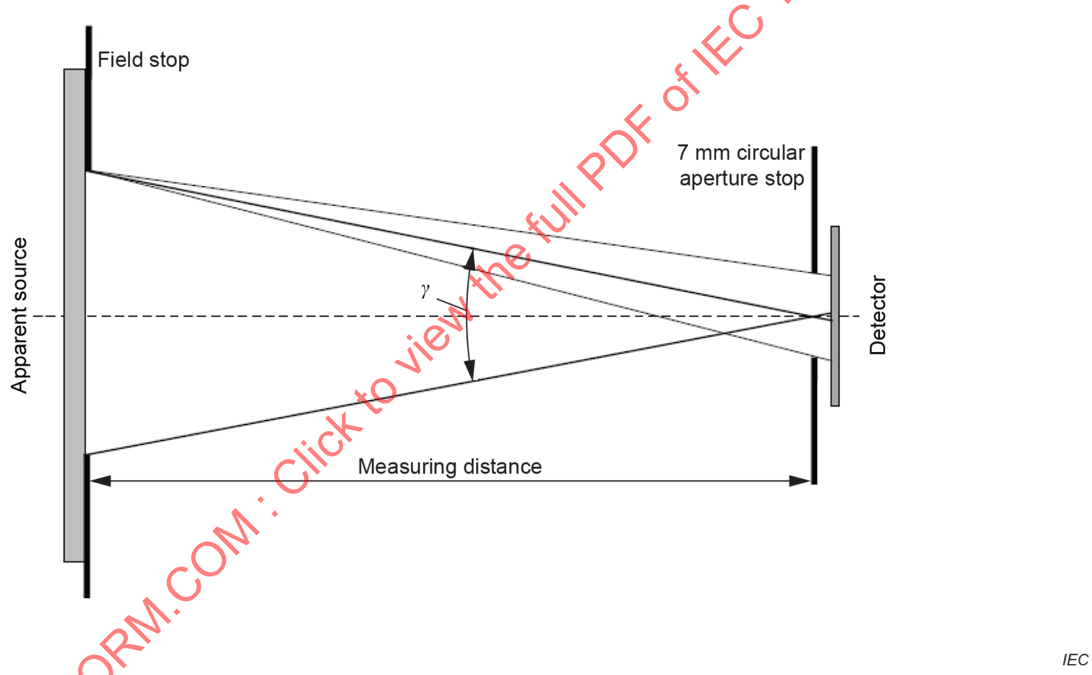


Figure 1b – Direct measurement set-up where the field stop is placed at the source

Figure 1 – Measurement set-ups to achieve a well-defined angle of acceptance

b) For the determination of the level of exposure to be evaluated against all MPEs given in Table 5 other than the retinal photochemical hazard limit, the angle of acceptance should fully encompass the source under consideration (i.e. the angle of acceptance should be at least as large as the angular subtense of the source). 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 or is for other reasons analysed as extended apparent source, the angle of acceptance should 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 in 5.3.3 a).

5.3.4 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 $M \times D$, where D is expressed in millimetres, e.g. 7 × 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 in Table 3.

Table 3 – Typical transmission percentages for binoculars

Wavelength	Transmission
160 nm to 302,5 nm	< 2 %
302,5 nm to 400 nm	70 %
400 nm to 700 nm	90 %
700 nm to 2 800 nm	70 %
2 800 nm to 10^6 nm	< 2 %

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

6 Determining the maximum permissible exposure (MPE)

6.1 General remarks

Levels of maximum permissible exposure, which are based on values developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), are given in Table 4 to Table 8 as functions of the emission wavelength and exposure duration, as measured through the limiting aperture. These tables should be used in conjunction with the correction factors given in Table 9. The MPE applies to the effective exposure obtained by averaging over the area of the relevant limiting aperture as explained in 5.3.1 and 5.3.2.

Table 4 defines the MPE in terms of the irradiance or radiant exposure at the front surface of 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 5.3.3). 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 5. Table 6 and Table 7 contain the MPEs from Table 4 and Table 5 expressed in energy or power. Dual MPEs are applicable for ocular exposure to wavelengths between 1 200 nm and 1 400 nm: reference may need to be made to Table 8 for the skin MPE to ensure that the anterior elements of the eye are not at risk.

Table 8 specifies values of the MPE for the skin. Table 9 specifies correction factors and breakpoints to be used with the MPE tables.

The exposure duration used in determining the MPE from Table 4 to Table 8 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 (30 000 s) exposure time 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 to 700 nm) where purposeful staring is not intended or anticipated, the aversion response time of 0,25 s may be used.

Exposures from several wavelengths should be assumed to have an additive effect provided that the spectral regions are shown as additive by the symbols (O) for ocular and (S) for skin exposure in the matrix of Table 11 (see 6.3). Where the wavelengths radiated are not shown as additive, the hazards should be assessed separately.

Further consideration of the exposure duration is included in the discussion of risk assessment given in 8.3.4.4.

Table 4 – Maximum permissible exposure (MPE) at the cornea for small sources expressed as irradiance or radiant exposure [a,b]

Wavelength λ nm	Exposure time, t s								
	10^{-13} to 10^{-11}	10^{-11} to 10^{-9}	10^{-9} to 10^{-7}	10^{-7} to 5×10^{-6}	5×10^{-6} to 13×10^{-6}	13×10^{-6} to 1×10^{-3}	1×10^{-3} to 10	10 to 10^2	10^2 to 3×10^4
180 to 302,5	3×10^{10} W·m^{-2}		30 J·m^{-2}						
302,5 to 315			For $t \le T_1$, MPE = C_1 J·m^{-2} (Thermal hazard [d]) For $t > T_1$, MPE = C_2 J·m^{-2} (Photochemical hazard [d])					C_2 J·m^{-2}	
315 to 400			C_1 J·m^{-2}					10^4 J m^{-2}	
400 to 450	1×10^{-3} J·m^{-2}	2×10^{-3} J·m^{-2}			$18\ t^{0,75}$ J·m^{-2}			100 J·m^{-2}	C_3 W·m^{-2}
450 to 500								100 C_3 J·m^{-2} and [c] 10 W·m^{-2}	
500 to 700								10 W·m^{-2}	
700 to 1 050	1×10^{-3} J·m^{-2}	$2 \times 10^{-3}\ C_4$ J·m^{-2}			$18\ t^{0,75}\ C_4$ J·m^{-2}			$10\ C_4\ C_7$ W·m^{-2}	
1 050 to 1 400[e]	$1 \times 10^{-3}\ C_7$ J·m^{-2}	$2 \times 10^{-2}\ C_7$ J·m^{-2}				$90\ t^{0,75}\ C_7$ J·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}	
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}					

[a] For correction factors and units, see Table 9; the exposure level that is compared with the MPE values is to be averaged over the appropriate aperture (Table 2).

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

[c] In the wavelength range between 450 nm and 500 nm, dual limits apply and the exposure should not exceed either limit applicable.

[d] For repetitively pulsed UV lasers, neither limit should be exceeded.

[e] In the wavelength range between 1 200 nm and 1 400 nm, the limits to protect the retina given in this table may not adequately protect the anterior parts of the eye (cornea, iris), and caution needs to be exercised. There is no concern for the anterior parts of the eye if the exposure does not exceed the skin MPE values.

Table 5 – Maximum permissible exposure (MPE) at the cornea for extended sources in the wavelength range from 400 nm to 1 400 nm (retinal hazard region) expressed as irradiance or radiant exposure

<table>
<tr><th rowspan="2">Wavelength
λ
nm</th><th colspan="7">Exposure time, t
s</th></tr>
<tr><th>10^{-13} to
10^{-11}</th><th>10^{-11} to
$5,0 \times 10^{-6}$</th><th>$5,0 \times 10^{-6}$ to
$1,3 \times 10^{-5}$</th><th>$1,3 \times 10^{-5}$ to
10</th><th>10 to
10^2</th><th>10^2 to
10^4</th><th>10^4 to
3×10^4</th></tr>
<tr><td rowspan="4">400 to 700</td><td rowspan="4">$1 \times 10^{-3}\ C_6$ J·m^{-2}</td><td rowspan="4">$2 \times 10^{-3}\ C_6$ J·m^{-2}</td><td colspan="2" rowspan="4">$18\ t^{0,75}\ C_6$ J·m^{-2}</td><td colspan="3">400 nm to 600 nm – Retinal photochemical hazard [a]</td></tr>
<tr><td>$100\ C_3$ J·m^{-2}
using
γ_{ph} = 11 mrad</td><td>$1\ C_3$ W·m^{-2}
using
$\gamma_{ph} = 1,1\ t^{0,5}$ mrad</td><td>$1\ C_3$ W·m^{-2}
using
γ_{ph} = 110 mrad</td></tr>
<tr><td colspan="3">AND [b]</td></tr>
<tr><td colspan="3">400 nm to 700 nm – Retinal thermal hazard
For $t \leq T_2$, MPE = $18\ t^{0,75}\ C_6$ J·m^{-2}
For $t > T_2$, MPE = $18\ C_6\ T_2^{-0,25}$ W·m^{-}</td></tr>
<tr><td>700 to 1 050</td><td>$1 \times 10^{-3}\ C_6$ J·m^{-2}</td><td>$2 \times 10^{-3}\ C_4\ C_6$ J·m^{-2}</td><td colspan="2">$18\ t^{0,75}\ C_4\ C_6$ J·m^{-2}</td><td colspan="3">For $t \leq T_2$, MPE = $18\ t^{0,75}\ C_4\ C_6$ J·m^{-2}
For $t > T_2$, MPE = $18\ C_4\ C_6\ T_2^{-0,25}$ W·m^{-2}</td></tr>
<tr><td>1 050 to 1 400[c]</td><td>$1 \times 10^{-3}\ C_6\ C_7$ J·m^{-2}</td><td colspan="2">$2 \times 10^{-2}\ C_6\ C_7$ J·m^{-2}</td><td>$90\ t^{0,75}\ C_6\ C_7$ J·m^{-2}</td><td colspan="3">For $t \leq T_2$, MPE = $90\ t^{0,75}\ C_6\ C_7$ J·m^{-2}
For $t > T_2$, MPE = $90\ C_6\ C_7\ T_2^{-0,25}$ W·m^{-2}</td></tr>
</table>

NOTE Exposure limits for some ocular tissues may be different for ophthalmic instruments – see ISO 15004-2.

[a] The angle γ_{ph} is the limiting measurement angle of acceptance.

[b] In the wavelength range between 400 nm and 600 nm, dual limits apply and the exposure needs to 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 1,5 mrad and 82 mrad, the dual photochemical hazard limit of 100 C_3 J·m^{-2} should be applied for exposures greater than or equal to 1 s.

[c] In the wavelength range between 1 200 nm and 1 400 nm, the limits to protect the retina given in this table may not adequately protect the anterior parts of the eye (cornea, iris), and caution needs to be exercised. There is no concern for the anterior parts of the eye if the exposure does not exceed the skin MPE values.

Table 6 – Maximum permissible exposure (MPE) of Table 4 (C_6 = 1) for the wavelength range from 400 nm to 1 400 nm expressed as power or energy [a,b]

<table>
<tr><th rowspan="2">Wavelength
λ
nm</th><th colspan="6">Emission duration, t
s</th></tr>
<tr><th>10^{-13} to 10^{-11}</th><th>10^{-11} to 5×10^{-6}</th><th>5×10^{-6} to 13×10^{-6}</th><th>13×10^{-6} to 10</th><th>10 to 10^2</th><th>10^2 to 3×10^4</th></tr>
<tr><td>400 to 450</td><td rowspan="3">$3,8 \times 10^{-8}$ J</td><td rowspan="3">$7,7 \times 10^{-8}$ J</td><td rowspan="3" colspan="2">$7 \times 10^{-4}\ t^{0,75}$ J</td><td>$3,9 \times 10^{-3}$ J</td><td rowspan="2">$3,9 \times 10^{-5}\ C_3$ W</td></tr>
<tr><td>450 to 500</td><td>$3,9 \times 10^{-3}\ C_3$ J
and [c]
$3,9 \times 10^{-4}$ W</td></tr>
<tr><td>500 to 700</td><td colspan="2">$3,9 \times 10^{-4}$ W</td></tr>
<tr><td>700 to 1 050</td><td>$3,8 \times 10^{-8}$ J</td><td>$7,7 \times 10^{-8}\ C_4$ J</td><td colspan="2">$7 \times 10^{-4}\ t^{0,75}\ C_4$ J</td><td rowspan="2" colspan="2">$3,9 \times 10^{-4}\ C_4\ C_7$ W</td></tr>
<tr><td>1 050 to 1 400[d]</td><td>$3,8 \times 10^{-8}\ C_7$ J</td><td colspan="2">$7,7 \times 10^{-7}\ C_7$ J</td><td>$3,5 \times 10^{-3}\ t^{0,75}\ C_7$ J</td></tr>
</table>

NOTE The exposure level to be compared with the MPE expressed as power or energy is to be determined as power or energy that passes through an aperture with a diameter of 7 mm (the MPE values expressed in this table are obtained from the values of Table 4 by multiplication with the area of an aperture with 7 mm diameter).

[a] For correction factors and units, see Table 9.

[b] The MPEs for exposure durations below 10^{-13} s are set to be equal to the equivalent power values of the MPEs at 10^{-13} s.

[c] In the wavelength range between 450 nm and 500 nm, dual limits apply and the exposure needs to not exceed either limit applicable.

[d] In the wavelength range between 1 200 nm and 1 400 nm, the limits to protect the retina given in this table may not adequately protect the anterior parts of the eye (cornea, iris), and caution needs to be exercised. There is no concern for the anterior parts of the eye if the exposure does not exceed the skin MPE values.

Table 7 – Maximum permissible exposure (MPE) of Table 5 (extended sources) for the wavelength range from 400 nm to 1 400 nm expressed as power or energy [a,b]

Wavelength λ nm	Emission duration, t s						
	10^{-13} to 10^{-11}	10^{-11} to 5×10^{-6}	5×10^{-6} to 13×10^{-6}	13×10^{-6} to 10	10 to 10^2	10^2 to 10^4	10^4 to 3×10^4
400 to 700	$3{,}8 \times 10^{-8}\ C_6$ J	$7{,}7 \times 10^{-8}\ C_6$ J	$7 \times 10^{-4}\ t^{0{,}75}\ C_6$ J		400 nm to 600 nm – Retinal photochemical hazard [d, e]		
					$3{,}9 \times 10^{-3}\ C_3$ J using γ_{ph} = 11 mrad	$3{,}9 \times 10^{-5}\ C_3$ W using $\gamma_{ph} = 1{,}1\ t^{0{,}5}$ mrad	$3{,}9 \times 10^{-5}\ C_3$ W using γ_{ph} = 110 mrad
					AND [c]		
					400 nm to 700 nm – Retinal thermal hazard		
					For $t \le T_2$, MPE = $7 \times 10^{-4}\ t^{0{,}75}\ C_6$ J		
					For $t > T_2$, MPE = $7 \times 10^{-4}\ C_6\ T_2^{-0{,}25}$ W		
700 to 1 050	$3{,}8 \times 10^{-8}\ C_6$ J	$7{,}7 \times 10^{-8}\ C_4\ C_6$ J	$7 \times 10^{-4}\ t^{0{,}75}\ C_4\ C_6$ J		For $t \le T_2$, MPE = $7 \times 10^{-4}\ t^{0{,}75}\ C_4\ C_6$ J For $t > T_2$, MPE = $7 \times 10^{-4}\ C_4\ C_6\ T_2^{-0{,}25}$ W		
1 050 to 1 400[f]	$3{,}8 \times 10^{-8}\ C_6\ C_7$ J	$7{,}7 \times 10^{-7}\ C_6\ C_7$ J		$3{,}5 \times 10^{-3}\ t^{0{,}75}\ C_6\ C_7$ J	For $t \le T_2$, MPE = $3{,}5 \times 10^{-3}\ t^{0{,}75}\ C_6\ C_7$ J For $t > T_2$, MPE = $3{,}5 \times 10^{-3}\ C_6\ C_7\ T_2^{-0{,}25}$ W		

NOTE 1 Exposure limits for some ocular tissues may be different for ophthalmic instruments – see ISO 15004-2.

NOTE 2 The exposure level to be compared with the MPE expressed as power or energy is determined as power or energy that passes through an aperture with a diameter of 7 mm (the MPE values expressed in this table are obtained from the values of Table 5 by multiplication with the area of an aperture with 7 mm diameter).

[a] For correction factors and units, see Table 9.

[b] The MPEs for exposure durations below 10^{-13} s are set to be equal to the equivalent power values of the MPEs at 10^{-13} s.

[c] In the wavelength range between 450 nm and 600 nm, dual limits apply and the exposure should not exceed either limit applicable.

[d] The angle γ_{ph} is the limiting measurement angle of acceptance.

[e] If exposure times between 1 s and 10 s are used, for wavelengths between 400 nm and 484 nm and for apparent source sizes between 1,5 mrad and 82 mrad, the dual photochemical hazard limit of $3{,}9 \times 10^{-3}\ C_3$ J is extended to 1 s.

[f] In the wavelength range between 1 200 nm and 1 400 nm, the limits to protect the retina given in this table may not adequately protect the anterior parts of the eye (cornea, iris) and caution needs to be exercised. There is no concern for the anterior parts of the eye if the exposure does not exceed the skin MPE values.

Table 8 – Maximum permissible exposure (MPE) of the skin to laser radiation [a,b]

Wavelength λ nm	Exposure time, t 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		For $t \leq T_1$, MPE = C_1 J·m^{-2} For $t > T_1$, MPE = C_2 J·m^{-2}			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}	$1,1 \times 10^4\ t^{0,25}$ J·m^{-2}		2 000 W·m^{-2}	
700 to 1 400	$2 \times 10^{11}\ C_4$ W·m^{-2}	200 C_4 J·m^{-2}	$1,1 \times 10^4\ C_4\ t^{0,25}$ 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} [c]	
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}			

[a] For correction factors and units, see Table 9.

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

[c] 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 is inversely proportional to the irradiated skin area.

Table 9 – Correction factors and breakpoints for use in MPE evaluations

Parameter	Spectral region nm
$C_1 = 5,6 \times 10^3\ t^{0,25}$	180 to 400
$T_1 = 10^{0,8(\lambda - 295)} \times 10^{-15}$ s	302,5 to 315
$C_2 = 30$	180 to 302,5
$C_2 = 10^{0,2(\lambda - 295)}$	302,5 to 315
$T_2 = 10 \times 10^{[(\alpha - \alpha_{min})/98,5]}$ s for $\alpha_{min} < \alpha \leq 100$ mrad	400 to 1 400
$T_2 = 10$ s for $\alpha \leq 1,5$ mrad	400 to 1 400
$T_2 = 100$ s for $\alpha > 100$ mrad	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 – see 6.2 c) [a]	400 to 1 400
$C_6 = 1$	180 to 400 and 1 400 to 10^6
$C_6 = 1$ for $\alpha \leq \alpha_{min}$ [b]	400 to 1 400
$C_6 = \alpha/\alpha_{min}$ for $\alpha_{min} < \alpha \leq \alpha_{max}$ [b]	400 to 1 400
$C_6 = \alpha_{max}/\alpha_{min}$ for $\alpha > \alpha_{max}$ [b,c]	400 to 1 400

Parameter	Spectral region nm
$C_7 = 1$	700 to 1 150
$C_7 = 10^{0,018(\lambda - 1\,150)}$	1 150 to 1 200
$C_7 = 8 + 10^{0,04(\lambda - 1\,250)}$	1 200 to 1 400

α_{min} = 1,5 mrad

α_{max} = 5 mrad for $t < 625$ µs

200 $t^{0,5}$ mrad for 625 µs ≤ t ≤ 0,25 s

100 mrad for $t > 0,25$ s

N is the number of pulses contained within the applicable duration (6.2 c)).

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. The MPEs for these exposure durations and wavelengths have been derived by calculating the equivalent radiant power or irradiance from the radiant power or radiant exposure applying at 10^{-9} s for wavelengths less than 400 nm and greater than 1 400 nm.

NOTE 2 See Table 2 for limiting apertures.

NOTE 3 In the formulae in Table 4 to Table 8 and in these notes, the wavelength is expressed in nanometres, the emission duration t is expressed in seconds and α is expressed in milliradians.

NOTE 4 For emission durations which fall at the cell border values (for instance 10 s) in Table 4 to Table 8, the lower limit applies. Where at cell borders (i.e. not applying to explicit equations) the symbol "<" is used, this means less than or equal to. When wavelength ranges are specified, wavelength range λ_1 to λ_2 means $\lambda_1 \leq \lambda < \lambda_2$.

[a] C_5 is only applicable to pulse durations shorter than 0,25 s. See rules to determine C_5 in 6.2 c).

[b] C_6 is only applicable for thermal retinal limits.

[c] The maximum limiting angle of acceptance γ_{th} should be equal to α_{max} (but see 5.3.3 b)).

6.2 Repetitively pulsed or modulated lasers

The following methods should be used to determine the MPE to be applied to exposures to repetitively pulsed radiation.

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.

The MPE for ocular exposure for wavelengths less than 400 nm and longer than 1 400 nm, as well as the MPE for skin exposure, is limited by the most restrictive of requirements a) and b).

The MPE for ocular exposure for wavelengths from 400 nm to 1 400 nm is determined by using the most restrictive of requirements a), b) and c). Requirement c) applies only to the retinal thermal limits and not to the retinal photochemical limits.

The three potential limits are as follows.

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

b) The average irradiance, or power, for a pulse train of exposure duration T does not exceed the MPE given in Table 4 to Table 8 for a single pulse of exposure duration T. For irregular pulse patterns (including varying pulse energies), T needs to be varied between T_i and the maximum assumed exposure duration (see Table 9). For regular pulse patterns it is sufficient to average over the assumed maximum exposure duration only.

NOTE To add the radiant exposure within T and compare this value against the MPE expressed as radiant exposure is mathematically equivalent to the average irradiance over T and comparing this value against the MPE expressed as irradiance (which is determined by dividing the radiant-exposure MPE by T).

c) The exposure per pulse does not exceed the MPE for a single pulse multiplied by the correction factor C_5. C_5 is only applicable to individual pulse durations shorter than 0,25 s.

$$\text{MPE}_{\text{s.p.train}} = \text{MPE}_{\text{single}} \times C_5$$

where

MPE$_{\text{single}}$ is the MPE for a single pulse;

MPE$_{\text{s.p.train}}$ is the MPE for any single pulse in the pulse train.

If pulse duration $t \leq T_i$, then the following applies.

- For maximum anticipated exposure duration less than or equal to 0,25 s:
  C_5 = 1,0.
- For maximum anticipated exposure duration larger than 0,25 s:
  if $N \leq 600$, C_5 = 1,0;
  if $N > 600$, $C_5 = 5 \cdot N^{-0,25}$ with a minimum value of C_5 = 0,4.

If pulse duration $t > T_i$, then the following applies.

- For $\alpha \leq 5$ mrad:
  C_5 = 1,0.
- For 5 mrad $< \alpha \leq \alpha_{max}$:
  $C_5 = N^{-0,25}$ for $N \leq 40$;
  C_5 = 0,4 for $N > 40$.
- For $\alpha > \alpha_{max}$:
  $C_5 = N^{-0,25}$ for $N \leq 625$;
  C_5 = 0,2 for $N > 625$;
  unless $\alpha > 100$ mrad, where C_5 = 1,0 in all cases.

N is the effective number of pulses in the pulse train within the assessed exposure duration (when pulses occur within T_i (see Table 10), N is less than the actual number of pulses, see below). The maximum exposure duration that needs to be considered for the assessment is T_2 (see Table 9) or the anticipated exposure duration, whichever is shorter.

If multiple pulses appear within the period of T_i (see Table 10) 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.

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.

Table 10 – Duration T_i below which pulse groups are summed up

Wavelength	T_i
400 nm ≤ λ < 1 050 nm	5×10^{-6} s
1 050 nm ≤ λ < 1 400 nm	13×10^{-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

6.3 Multiple wavelengths

When a laser emits radiation at several widely different wavelengths, 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 Table 4 to Table 8 provided that the spectral regions are shown as additive by the symbols (O) for ocular and (S) for skin exposure in the matrix of Table 11. Where the wavelengths radiated are not shown as additive, the hazards should be assessed separately.

Table 11 – 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 C.1.

[b] Where ocular MPEs are being evaluated for 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) should be assessed independently and the most restrictive value used.

6.4 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 5.3.3), the MPEs given in Table 5 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 decrease, i.e. become more restrictive. (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 decrease with distance until $\alpha = \alpha_{min}$. (α_{min} = 1,5 mrad.)

The thermal ocular hazard MPEs given in Table 5 are a function of the factor C_6. For a source subtending an angle larger than α_{max}, C_6 is equal to $\alpha_{max}/\alpha_{min}$, where, since α_{max} changes from 5 mrad to 100 mrad depending on exposure duration t, C_6 also changes from 3,33 to 66,7.

For sources subtending an angle smaller than α_{min}, C_6 is equal to 1 and the MPEs given in Table 4 and Table 6 apply.

NOTE For a simplified worst-case analysis, C_6 = 1 can be assumed even if the source is extended. This will potentially result in a smaller MPE and larger NOHD as compared to a full analysis which also considers that the angle of acceptance is limited to α_{max}, but it greatly simplifies the analysis.

The correction factor C_6 is given by:

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

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

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

6.5 Hazard distance and hazard area

6.5.1 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; however, it should be noted that transitory effects such as dazzle and flash blindness can occur for visible laser beams beyond this distance.

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 5.3.4.)

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 outdoor use of collimated-beam Class 1M and Class 2M laser products. 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 nominal skin-hazard distance (NSHD) in an analogous manner to NOHD but using the skin MPE.

6.5.2 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 three-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 recognize 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 NOHA is truncated at this opaque feature.

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

7 Associated hazards

7.1 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.

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.

7.2 Hazards arising from the laser

7.2.1 Electricity

Many lasers utilize 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 electricity supply and can recharge to some extent when left disconnected after discharge for extended periods of time). 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.

7.2.2 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 summarized 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.

7.2.3 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.

7.2.4 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.

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

7.2.6 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.

7.2.7 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.

7.2.8 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 utilized 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 need 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.

7.2.9 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.

7.3 Hazards arising from the environment

7.3.1 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.

7.3.2 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.

7.3.3 Atmospheric effects

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.

7.3.4 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

7.3.5 Power supply interruption or fluctuation

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

7.3.6 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.

7.3.7 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 need to be performed, and the influence on human performance of the equipment that needs to be used; and
– organizational aspects, which relate to the "safety culture" of the organization concerned, and include the framework within which an individual needs 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.

7.4 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 8. Relevant national or regional requirements may apply.

NOTE Some countries have legislation governing the control of specific hazards.

8 Evaluating risk

8.1 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 that 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 7.

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 5.1.2) 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 summarized 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 installation of new laser equipment into an existing laser facility, the modification or relocation of existing laser equipment, or changes to the way in which the laser equipment is to be used all require a re-assessment of the risk.

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 in 8.2, 8.3 and 8.4.

8.2 Risk assessment: Stage 1 – Identifying potentially injurious situations

8.2.1 General

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 that the user should focus on when listing potentially injurious situations are described in 8.2.2, 8.2.3 and 8.2.4.

8.2.2 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 7 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.

8.2.3 The laser environment

The laser environment covers the following aspects.

– 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. localized restricted area within premises having no public access; unrestricted area within premises having no public access; public access areas.

8.2.4 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.

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

8.3.1 General

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 need 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. By placing the emphasis on an evaluation of the circumstances, conditions and events under which hazardous levels of exposure could occur, control measures (see Clause 9) 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 8.3.2, 8.3.3 and 8.3.4.

8.3.2 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 the following.

– Likely: will occur frequently.
– Possible: can occur sometimes/occasionally.
– Improbable: very unlikely to occur.

8.3.3 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 the following.

– 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.

8.3.4 Resultant risk

8.3.4.1 General

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

Important considerations are described in 8.3.4.2, 8.3.4.3 and 8.3.4.4.

8.3.4.2 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.

8.3.4.3 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 localized retinal injuries can lead to serious loss of vision.

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.

f) Invisible laser radiation may not trigger an aversion response, so longer exposure durations may occur.

g) Surfaces that appear non-reflective (or opaque) at visible wavelengths may produce specular reflections (or be transparent), for example at infrared wavelengths.

8.3.4.4 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.

8.4 Risk assessment: Stage 3 – Selecting control measures

Where the level of risk is found to be unacceptable, then control measures need to be introduced to reduce the risk to an acceptable level. These control measures are covered in Clause 9. 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.

9 Control measures

9.1 General

Where a risk assessment (Clause 8) 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 laser products in Classes 1, 2 and 3R, although consideration should always be given to the possibility that an unusual or particular circumstance may require that special control measures be adopted.

The most effective way of controlling any hazard is to eliminate the source of the hazard. One should therefore consider whether, given the hazard, the task needs to be done at all or whether there is any non-hazardous alternative, or failing that a less-hazardous alternative. Whenever the use of a specific laser is under consideration, the feasibility of using a laser of a lower class should always be considered.

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.
– 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 organization), 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.

9.2 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.

9.3 Enclosing the hazard

9.3.1 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 be regarded as forming a protective enclosure if the need for personnel to be physically present in the laser environment can be eliminated.

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, vaporization 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 need to 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 unauthorized removal of all or part of the enclosure, thereby gaining access to the laser radiation, is an important consideration (see 9.3.3).

9.3.2 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 9.4.5.2), 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).

9.3.3 Interlock protection

9.3.3.1 Purpose of interlock protection

Access to a user-installed protective enclosure should be controlled by measures that are commensurate with the level of risk. 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 9.4.1, 9.4.2 and Annex A.)

The guidelines for the user-installed interlocks given in 9.3.3.2, 9.3.3.3 and 9.3.3.4 are intended as recommendations of good practice but are not manufacturing requirements. (Manufacturing requirements for laser products are specified in IEC 60825-1.)

9.3.3.2 Design of interlock systems

For an interlock that performs a safety critical function, the following recommendations apply.

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.

   NOTE 1 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.

   NOTE 2 This is normally satisfied by the manufacturer in the design of the product.

9.3.3.3 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.

9.3.3.4 Interlock override

For interlock systems that have provision for an override facility, so permitting access for servicing or other adjustment work, the following recommendations apply.

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

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

c) 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 unauthorized persons.

9.4 Hazard mitigation

9.4.1 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.

9.4.2 Laser controlled areas

9.4.2.1 General

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. Appropriate warnings should be displayed at the entrance of the laser controlled area and on the protective housing of Class 3B and Class 4 laser products.

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).

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 adequately be managed by other engineering means, e.g. locks, and particularly where the use of personal protective equipment is required inside the laser area. If interlocks are fitted to an entryway, they should 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 electricity 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 12.

Table 12 – Laser controlled areas

Laser class	Nature of hazard	Example of controlled area	Outline of protective control measures
Class 1 Class 2	Minimal 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.
Class 1C	Skin hazard if misused	Unrestricted	Follow manufacturer's instructions for safe use.
Divergent-beam Class 1M[a] Divergent-beam Class 2M[a]	Localized eye hazard if optical viewing instruments such as eye loupes are used.	Localized 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 needs to 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.

Laser class	Nature of hazard	Example of controlled area	Outline of protective control measures
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 might show 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 to adequately reduce the risk.

[a] In the first and second editions of IEC 60825-1, divergent-beam lasers that could have become hazardous under magnified viewing were classified as Class 1M or Class 2M (as appropriate).

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 9.3.3.4.) 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 an interlock has an override facility it should have a clear means of annunciating that it is overridden, e.g. audible or visual, or both.

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. In the cases where entry into or exit from a laser controlled area without interrupting the emission is required, consideration should be given to the risk of uncontrolled laser radiation exiting the area into unprotected areas. For example, there may need to be a maze to ensure there is no direct beam path to the area outside of the laser controlled area.

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.

Safety signs should be displayed at the entrance to the laser controlled area. These should comply with the requirements of ISO 3864-1 in terms of colours, layout and dimensions and ISO 7010 in terms of symbols.

Where practicable, the signs should only be displayed when they are relevant. For example, temporary laser controlled area laser warning signage should only be displayed when a laser hazard exists. Warning signs that are displayed when there is mostly no hazard quickly lose their value as personnel begin to ignore them. This can be achieved by, for example, using illuminated signs, reversible signs, or using a sliding cover. Where intermittent signage is used (that is, at locations that are not exclusively used as laser controlled areas) preference should be given to automated signs that are linked to laser operation.

Each of the three signs – warning, mandatory and prohibition – should be separate and in specific colours (see Figure 2).

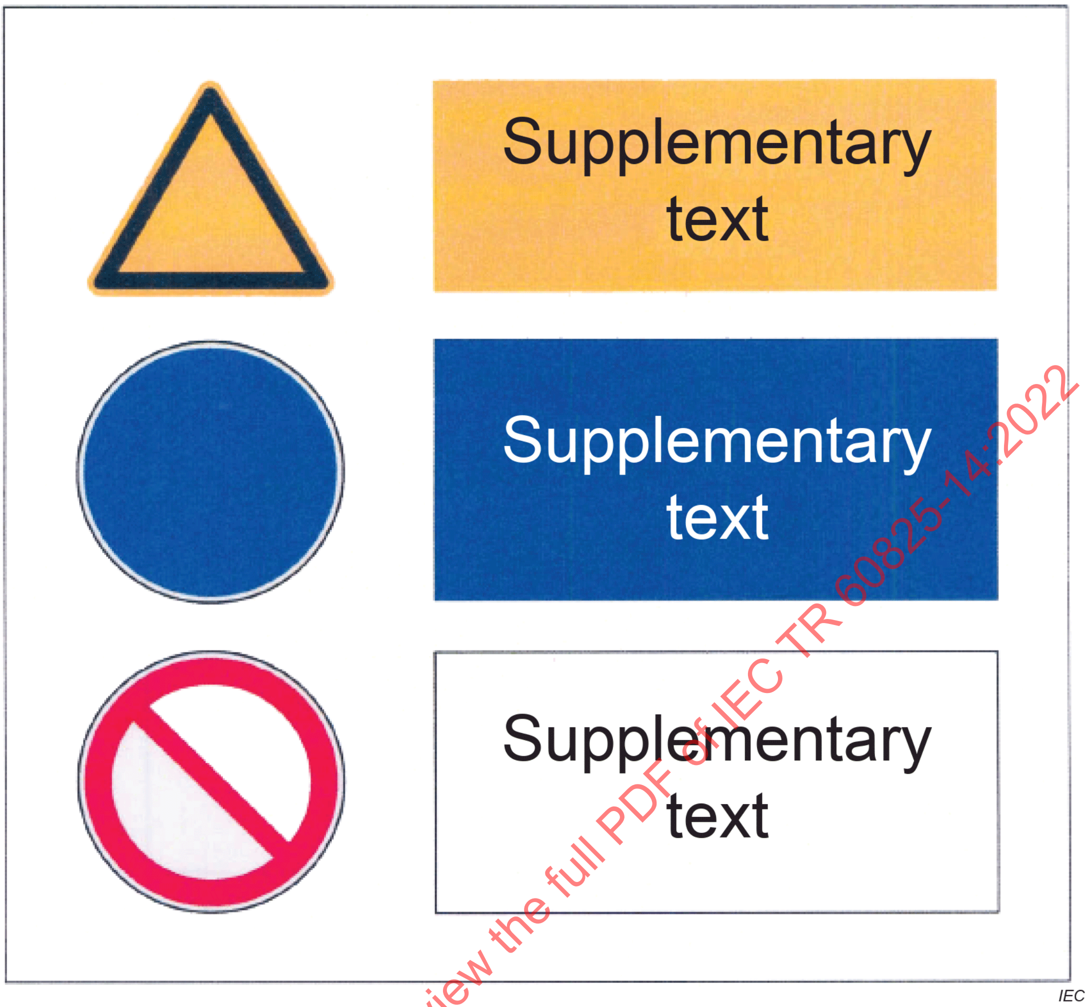


Figure 2 – Combination of safety signs

9.4.2.2 Warning sign

A laser hazard warning sign should be displayed (see Figure 3).

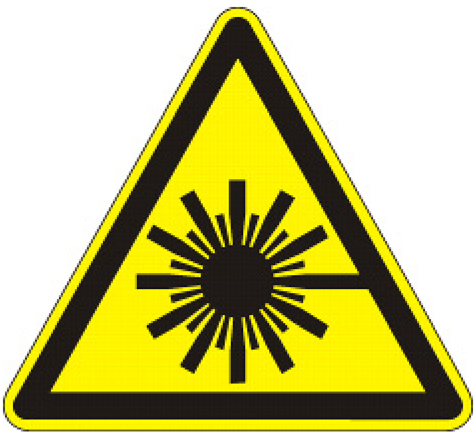


Figure 3 – Warning; Laser beam symbol (ISO 7010-W004:2011-05),

The symbol should be accompanied by supplementary information, such as:

Laser Controlled Area

or

Laser Radiation

This may be qualified by additional information. For example, if an external red light is connected to the laser power supply, the text "when red light is on" could be added if the sign is permanently displayed, but the area is not always a laser controlled area.

Other warning signs should be displayed, if appropriate, for non-laser hazards.

9.4.2.3 Mandatory sign

If appropriate, signs should be displayed requiring those entering the area to wear protective eyewear, gloves or clothing. These should be accompanied by supplementary information giving the specific requirements. This is particularly important for environments where personal protective equipment is generally required for other purposes, such as chemistry laboratories. Figure 4 shows an example mandatory sign for protective eyewear.

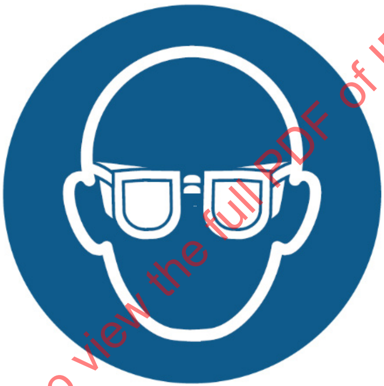


Figure 4 – Wear eye protection symbol (ISO 7010-M004:2011-05)

The symbol should be accompanied by supplementary information, such as:

Wear appropriate laser eye protection

Where appropriate, information on the wavelength(s) and required protection should also be given.

9.4.2.4 Prohibition sign

A prohibition sign (such as Figure 5) should be displayed with supplementary information providing details of the prohibition. However, consideration needs to be given to the literal interpretation of some prohibition signs. For example, supplementary information stating "knock and wait" is problematic because it has no means of progressing further.

Figure 5 – No thoroughfare symbol (ISO 7010-P004:2011-05)

The symbol should be accompanied by supplementary information, such as:

Authorized persons only
(accompanied by a list of authorized persons)

9.4.2.5 Illuminated signs

Illuminated signs can be used to complement non-illuminated signs or can be used to replace them provided they meet the same requirements for colours and separation. Display screens may also be used to replicate safety signs.

9.4.2.6 Location of signs

Signs should be located such that they are likely to be seen by people who need to see them. This will generally mean that they should be located at eye height for the representative population. Signs placed above entrance ways are less likely to be seen.

ISO 3864-1 provides requirements for sign colours and also dimensions based on viewing distance.

It can be useful to include the name of the person responsible for the area from whom further information can be obtained.

9.4.3 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 organization, 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 authorized 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;
f) action to be taken in the event of emergencies;
g) the incident reporting procedure and the action to be taken in the event of a suspected accident;
h) details of requirements, if any, for authorization for hazardous operations, e.g. procedures for approval of servicing (permit to work).

The above information, which is necessary during laser operation, should be displayed at the laser working area. Local rules should be reviewed regularly to ensure their continued relevance to requirements.

9.4.4 Localized risk reduction

9.4.4.1 General precautions

Within all laser controlled areas, steps should be taken to reduce the risk of injury to persons authorized 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-organized 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 (using covers over optical tables, beam tubes, optical fibres, etc.);
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);
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;
n) for Class 4 lasers, remote operation as much as possible so that operators do not need to be in the laser controlled area.

9.4.4.2 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.

9.4.5 Personal protection

9.4.5.1 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, especially where access to laser radiation from Class 3B and Class 4 lasers is possible. 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 PPE is able to provide sufficient protection. Injuries have occurred when PPE was worn and so it should not be treated as totally effective and only issued as a last resort when residual risks remain or to offer redundancy to weaker controls.

Where PPE 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.

9.4.5.2 Specifying eye and face 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. Combined eye and face protection may take the form of a mask or respirator, along with optical filters, to protect the skin and eyes from exposure to laser radiation. Both eye protection and combined eye and face protection 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 and face protection.

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

a) There exists a risk that an accidental exposure of the eyes or skin could occur that exceeds the MPE.

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

c) The eye and face protection 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 eye and face protection to withstand 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 eye and face protection without discomfort and without any significant visual impairment.

d) The eye and face protection is only used within a controlled area that effectively encloses the laser hazard and from which persons not wearing such protection are excluded.

When using eye and face protectors, compatibility with the other protectors such as respirators, earmuffs, helmets, etc. should be considered. Additionally, the filter should be compatible with test equipment and displays so operators are not tempted to remove eye and face protection to read meters or operate other equipment.

Where the use of laser eye and face protection is being considered, the specification and selection of the protection should be carried out with care, taking into account the specification of the laser or laser system for which the protection is required, the circumstances under which accidental exposure could occur, and the applicable safe exposure limit (the MPE). Normally, the MPE for the eye should be used; but where the MPE for the skin is more restrictive than that for the eye, the MPE applicable to the skin should be used instead. Face protection should always be used in preference to eye protection whenever the anticipated worst-case exposure to laser radiation is greater than the MPE for the skin. MPE values are given in Table 4 to Table 9.

The protection should be capable of reducing the laser exposure below the applicable MPE. This capability is dependent on the protector's transmission (optical density, OD) at the laser wavelength(s). In addition, the protector should be able to withstand the incident laser exposure without being damaged in a way that could affect its protective properties; this applies to protective filters and frames. Damage mechanism could include burns, cracks, photo-bleaching including reversible photo-bleaching, delamination of coatings and saturable absorption. This capability is dependent on the protector's resistance to laser radiation, sometimes called resistance category (RC). In some current standards for eyewear, these two parameters are linked, meaning that choice of the correct OD automatically results in an appropriate level of resistance or RC. However, it is possible that the two parameters, OD and resistance or RC, may be specified independently based on risk assessment of foreseeable accidental exposure; in which case the product standard covering the eyewear should be consulted to ensure that the meaning of a stated resistance or RC is understood.

It is not normally advisable to use eye protection (as opposed to face protection) as a protective measure against laser radiation where there is a risk of injury to the skin; that is, where the potential exposure exceeds the skin MPE. Under such circumstances, the use of alternative methods to reduce the risk of accidental exposure, including enclosure of the laser beam or face (and hand) protection, should be investigated. In certain applications, however, including some medical procedures and for servicing high-power laser systems, this may not be feasible, and adequate supporting control measures should be adopted in addition to the use of eye protection, in order to reduce the risk of harm occurring.

When choosing appropriate eye and face protection the following should be considered:

a) the reasonably foreseeable worst-case exposure (E_{max}) determined in accordance with 5.3 and the beam diameter at locations where accidental ocular or facial exposure could occur (these parameters enable the ability of the eye and face protection to withstand the incident laser radiation to be established);
b) the maximum length of time over which accidental exposure could occur before laser emission is terminated or the individual wearing the protection takes avoiding action to prevent continuing exposure;
c) the actual exposure expressed in terms of either the incident irradiance ($W \cdot m^{-2}$) or the incident radiant exposure ($J \cdot m^{-2}$);
d) the applicable value of the ocular and skin MPE (determined in accordance with Clause 5), and specified in the same units as the effective exposure;
e) the wavelength of operation. Laser eyewear – and, potentially, a face protector – utilizes filter materials to provide protection over certain defined wavelength ranges. Use of the incorrect eyewear will usually mean that insufficient protection is provided;
f) the optical density $D(\lambda)$ of the eye and face protection 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 $D(\lambda)$ required to give the minimum necessary level of eye protection can be calculated from the formula:

$$D(\lambda) = \log10[(E_{max})/(\text{MPE})]$$

NOTE 1 The irradiance or radiant exposure is used for comparison with the MPE. The effective exposure used in the above equation is that value obtained by averaging over the area of the relevant limiting aperture in accordance with 4.3.

NOTE 2 Some national standards (applicable in Europe and elsewhere) adopt a different system for the specification of laser eye protection that is not directly equivalent to the optical density requirement defined in the formula above.

g) the type of laser operation, CW or pulsed, and pulse duration;

h) ability of eye and face protector material, filters and frame, to withstand exposure to laser radiation under worst-case exposure scenario without compromising required level of protection for the duration of accidental exposure.

Other important factors include:

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

j) 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);

k) degradation or modification of the absorbing material of the filter, including radiation-induced transparency (photo-bleaching or saturable absorption);

l) mechanical strength of materials and resistance to shock; environmental stability to exposure to elevated temperature, high humidity and UV during storage and transportation;

m) the angular dependence of the protection, i.e. the variation of optical density with angle of incidence. This can be a relevant factor where protection is provided by multilayer dielectric coatings rather than by absorption within the filter material;

n) reflection from filters and frames, especially for eye protectors with dielectric coatings;

o) any relevant national requirements or regulations.

Eye and face protection should be permanently marked to indicate:

1) the operating wavelength;

2) the optical density at the operating wavelength, or a scale number that represents this information in a coded form;

3) where applicable, the maximum irradiance or radiant exposure that the eye or face protection can withstand without its protective properties being compromised.

Other eyewear considerations include the following.

– Where different kinds of eye and face protection are in use, it can be helpful to use colour-coding or other means to link each pair with its particular laser.

– 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 MPE for a time base of 0,25 s where protection is afforded by the natural aversion response.

– Eye and face protection 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. Eye and face protection should be checked periodically for signs of wear or damage. The date of checking should be recorded and the eye and face protection replaced when necessary. Eye and face protection should also be examined for suitability on each occasion prior to use.

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, eye and face protection that has been subjected to a single incident of accidental exposure at a high level of exposure should be replaced.

NOTE 3 More restrictive national requirements for the eyewear or additional requirements for shelf and use life might exist.

9.4.6 Protective clothing

In some cases, it may be necessary to provide other protective clothing for work in laser controlled areas where it is not reasonably practicable to ensure adequate protection entirely by the use of engineering or administrative controls. 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 there exists (in addition to any risk to the eyes) a serious risk of harm to the skin sufficient to cause a significant burn or lead to permanent scarring (see Clause 8); however, in such circumstances complete enclosure of the hazard should always be the preferred solution.

Class 4 laser radiation presents a risk of fire, so protective clothing should be made of fire- and heat-resistant materials. For such protective clothing, special attention is needed to ensure resistance to laser radiation for reasonably foreseeable exposure scenarios. For example, the protective clothing may be in the laser beam for several seconds before the user becomes aware.

9.5 Equipment servicing

9.5.1 Increased risks during laser equipment servicing

Laser products are classified on the basis of the level of laser radiation accessible during operation. Installation, maintenance and servicing, on the other hand, may require removal of protective covers, disabling of the product's protective features 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. Installation, servicing and maintenance operations may require a higher level of safety training than is necessary for normal operation.

Before installation or servicing 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.

Where external service or installation personnel are utilized, the LSO or safety personnel should request a safety plan and confirm appropriate qualifications. Additionally, external personnel should be given local induction training and internal personnel should be advised of any temporary changes to local procedures or controls.

9.5.2 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, and where persons could be present who are unauthorized, unaware of the presence of the laser hazard or are not appropriately trained or supervised in the necessary safety procedures.

The guidance for temporary controlled areas is the same as for laser controlled areas in general (see 9.4.2). 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.

9.5.3 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 minimum practicable;

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

c) first checking beam alignment close to the laser and then progressively further away, to minimize 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 visualizing 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 minimize stray reflections.

9.5.4 Visiting installation and 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. Visiting service personnel should, as far as practicable, comply with the safety policies and procedures of the organization being visited. 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.

10 Maintenance of safe operation

Regular inspection of laser equipment and monitoring of laser working areas such as laser path, interlock function and PPE before operation 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 12) 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.

11 Contingency plans

11.1 General

Where Class 3B or Class 4 lasers are used, or where the potential for accidental exposure to laser radiation in excess of the MPE exists, contingency plans should be prepared. The contingency plans should consider three scenarios:

a) a traumatic or serious eye injury (for Class 3B and Class 4 lasers only);

b) an actual skin injury (for Class 1C and Class 4 lasers only); and

c) a non-traumatic (minor) eye injury or an exposure in excess of the MPE that had the potential to cause an eye injury.

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.

11.2 Dealing with an actual eye injury

A plan should be in place to manage a person who has an eye injury following exposure to laser radiation. Factors to be considered include the following.

a) Immediate first aid action should be taken, which should include calling for medical assistance. Unless advised otherwise, the injured person should be seated.

b) It is generally appropriate to treat the incident as a medical emergency and immediate action should be taken to get the injured person to an appropriate medical facility – usually an accident or emergency hospital due to the risk of shock.

c) Unless advised otherwise by a person appropriately trained, it may be appropriate to place a sterile gauze over the eye to prevent physical contact with the eye.

d) The route to the hospital should be identified in the plan, along with alternative routes to allow for congestion or road works.

e) Basic information about the laser beam should accompany the injured person to the hospital. Such information should include the part of the eye most likely to be at risk from the wavelengths of the laser beams in use at the time.

f) The plan should be recorded, be easily available and rehearsed at appropriate periods. It may be appropriate to develop a pack of information that can be easily grabbed and taken with the injured person.

11.3 Dealing with an actual skin injury

Apart from chronic exposure to ultraviolet radiation, which may result in lesions developing over time, the most likely skin injury from a laser beam will be a thermal burn. This should be treated in the same manner as a burn caused by a flame or exposure to a hot surface or substance. Medical advice should be sought on whether attendance at a hospital is required, based on the depth and area of the burn.

11.4 Dealing with a suspected eye injury

If there is no obvious eye trauma or the risk assessment suggested that eye exposures to laser radiation in excess of the MPE were unlikely, then any suspected incident is unlikely to be an emergency. If the laser beam had the potential to be a retinal hazard (400 nm to 1 400 nm) then it may be appropriate to undertake a quick test of visual function by using either an Amsler grid or asking the individual to read some small text.

It may be appropriate to place a sterile gauze over the affected eye to minimize the risk of the individual rubbing their eye and causing corneal abrasions.

If a minor injury is suspected, or if reassurance is required, this should not be treated as a medical emergency and it may be appropriate to discuss a plan of action with an eye hospital with specific experience of laser eye injuries. If the healthcare professional considers that an examination should be carried out, they should provide advice on when to attend the healthcare institution. This is usually between 24 hours and 48 hours after the suspected incident due to the time a minor lesion takes to develop. Therefore, there should be adequate time to travel to an appropriate healthcare institution. Basic information about the laser beam should accompany the injured person to the hospital. Such information should include the part of the eye most likely to be at risk from the wavelengths of the laser beams in use at the time.

12 Incident reporting and accident investigation

Any incident should be reported to the management of the facility where the incident occurred.

NOTE In some countries, legislation requires the reporting of occupational incidents and accidents to the appropriate regulatory authority.

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 incident, 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.

13 Medical surveillance

Pre-employment (as a laser worker), routine and end-of-employment (as a laser worker) ophthalmic examinations of employees working with laser equipment have no value as part of a health surveillance programme and are not recommended. 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. Regular eye examinations, as routinely carried out by an optometrist, are encouraged to ensure good eye health and the detection of evolving pathology. However, such examinations are not justified on the basis of working with lasers alone.

Medical surveillance following an eye exposure incident can have value for reassurance and medico-legal reasons.

NOTE In some countries, legislation requires medical surveillance following exposures to laser radiation in excess of the MPE.

Employers of users of lasers that emit ultraviolet radiation where inadequate protection of the skin is provided, or has not been provided in the past, should consider routine skin examinations. However, it is usually difficult to distinguish any lesions developing as a result of exposure to artificial ultraviolet radiation and from exposures to solar radiation.

Annex A
(informative)

Examples of interlock systems for laser controlled areas

A.1 General

Annex A 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.

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 Figure A.1 and Figure A.2. 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 reset 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 authorized persons, should only be installed if its use is justifiable and safety is not compromised (see 9.4.2). 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.

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 needs to 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 Emergency stop switch

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

A.2.7 Electric locks (door strikes)

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

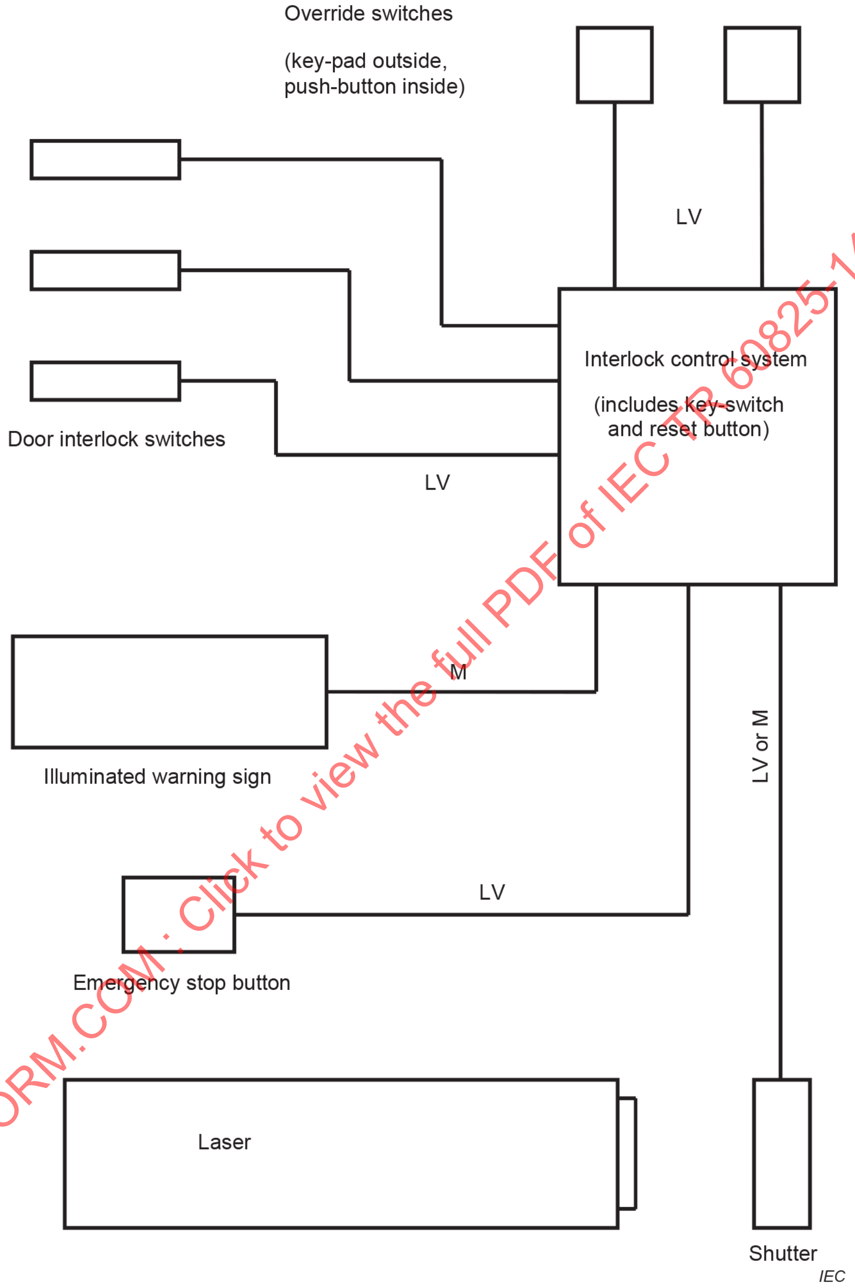
Emergency stop switches should be fitted outside each door wherever a locking system is used to allow entry in the event of an emergency. On the inside of each door a push-button override switch will always allow exit and may be considered adequate, although at least one easily accessible emergency stop switch 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-energizing the door strikes, thus allowing exit.

A.2.8 Non-locking interlock systems (see Figure A.1)

These are the most common type 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 authorized 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 unauthorized 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.2.9 Locking interlock systems (see Figure A.2)

These systems physically prevent unauthorized 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 needs to 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.2.7), 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.

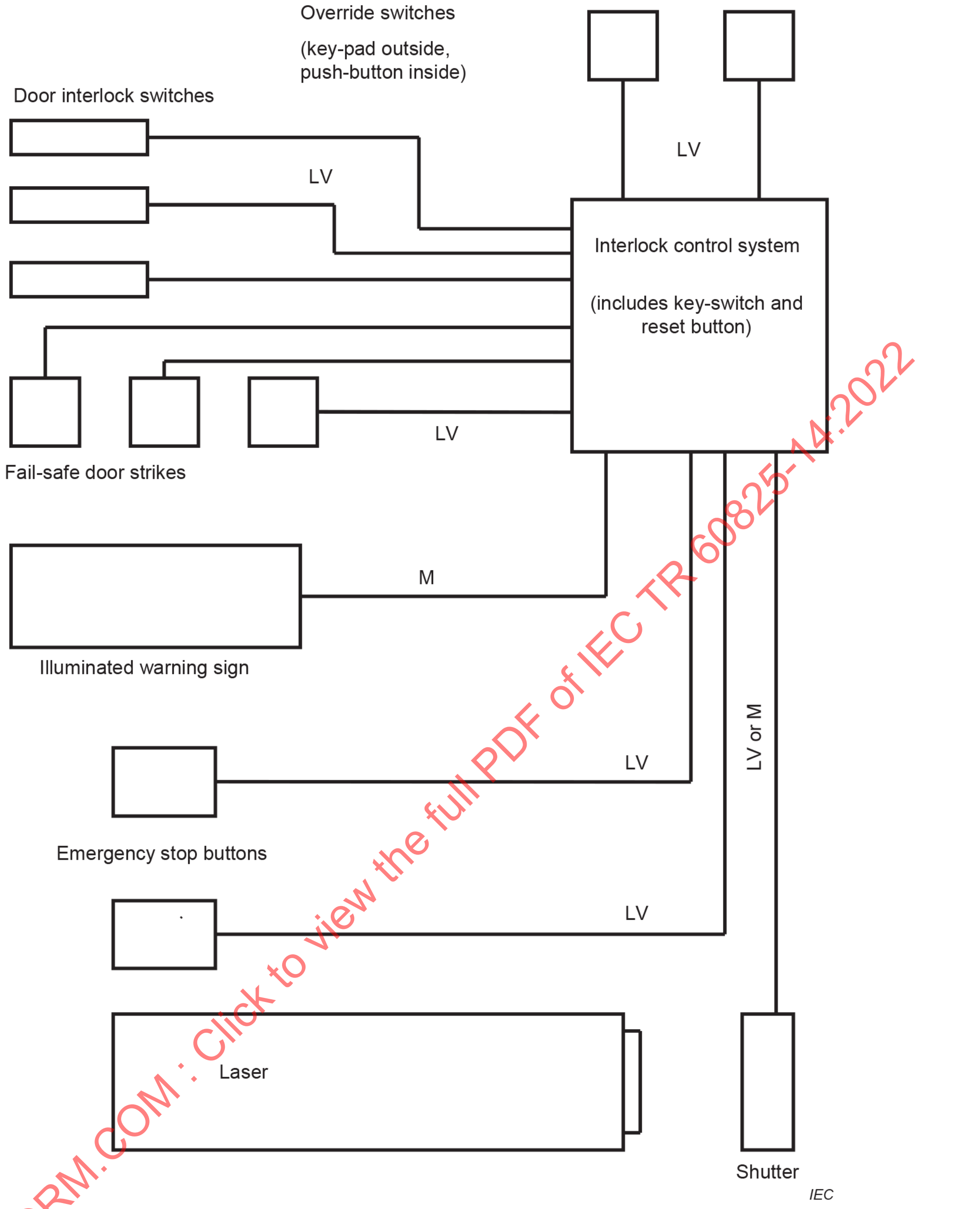


Key

LV low voltage

M mains

Figure A.1 – Non-locking interlock system



Key

LV low voltage

M mains

Figure A.2 – Locking interlock system

Annex B
(informative)

Examples of calculations

B.1 General

Annex B provides a selection of worked examples. The determination of maximum permissible exposure (MPE) is introduced in Clause B.3 with examples for small source viewing of CW or single-pulse laser output in Clause B.4, and repetitively pulsed systems in Clause B.5. The determination of nominal ocular hazard distance (NOHD) for small sources is covered in Clause B.6 and for extended sources in Clause B.7. Calculation of the optical density of laser eye protectors is presented in Clause B.8, and a multiple small source calculation is provided in Clause B.9.

B.2 Symbols used in the examples of Annex B

The symbols used in Annex B are defined in 3.2.

B.3 Maximum permissible exposure (MPE) – Overview

The maximum permissible exposure is defined in IEC 60825-1 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 Annex B 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 continuous wave (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 Table 4 to Table 7 provide MPE values for ocular exposures, whereas Table 8 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

B.4.1 General

Small source viewing occurs when the angular subtense of the source (α) is $\leq \alpha_{min}$. The following four examples illustrate the calculation procedures for single, small source viewing conditions, to CW or single-pulse laser output.

B.4.2 Example for a helium-cadmium laser

Calculate the MPE for a helium-cadmium laser, λ = 325 nm, with an emission duration of T = 10 s.

Solution:

The applicable MPE value can be found in Table 4, at the intersection of the wavelength range from 315 nm to 400 nm ($\lambda = \lambda_1$ to λ_2 means $\lambda_1 \leq \lambda < \lambda_2$, see Table 9, NOTE 4) and exposure duration column 10 s to 100 s ($t = t_1$ to t_2 means $t_1 \leq t < t_2$, see Table 9, NOTE 4). The MPE is found to be

$$H_{MPE} = 1 \times 10^4 \text{ J·m}^{-2}$$

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

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

B.4.3 Example for a pulsed ruby laser

Determine the maximum permissible single-pulse exposure for a pulsed ruby laser, λ = 694 nm, with a pulse duration of $t = 1 \times 10^{-3}$ s.

Solution:

In Table 4, the MPE is found at the intersection of the wavelength range from 500 nm to 700 nm and exposure duration $t = 1 \times 10^{-3}$ s to 10 s. The MPE value is

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

Thus,

$$H_{MPE} = 18 \times (1 \times 10^{-3})^{0,75} = 0,10 \text{ J·m}^{-2}$$

To obtain the MPE in terms of peak irradiance, divide by the pulse duration t:

$$E_{MPE} = H_{MPE}/t = 0,1/(1 \times 10^{-3}) = 101 \text{ W·m}^{-2}$$

B.4.4 Example for a single pulse of a gallium-arsenide laser

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 4, the MPE is found at the intersection of the wavelength range from 700 nm to 1 050 nm and exposure duration $t = 1 \times 10^{-9}$ s to 1×10^{-7} s. The MPE expressed as a radiant exposure is given by:

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

The correction factor C_4 can be calculated from the formula given in Table 9:

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

Thus,

$$H_{MPE} = 2 \times 10^{-3} \times 2,57 = 5,14 \times 10^{-3} \text{ J·m}^{-2}$$

B.4.5 Example for a continuous wave helium-neon laser

Calculate the MPE for an accidental exposure to a continuous wave helium-neon (He-Ne) laser, $\lambda = 633$ nm.

Solution:

As the laser is operating in the visible part of the spectrum and intentional viewing is not foreseen, an exposure duration limited by the aversion response to $T = 0,25$ s will be used (see 6.1). The MPE values can be found in Table 4 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

B.5.1 General

The rules applying to exposures from repetitively pulsed laser products (or exposures from scanning laser systems) are set out in 6.2.

B.5.2 Example for a pulsed argon laser

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

Solution:

As the laser is operating in the visible part of the spectrum and intentional viewing is not foreseen, an exposure duration limited by the aversion response to $T = 0,25$ s will be used. If intentional viewing of small-source radiation in the wavelength range 450 nm to 500 nm is foreseen for exposure durations of 10 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 6.2 includes three criteria that needs to be considered, and the most restrictive one applies to this evaluation.

From 6.2 a), the exposure from any single pulse should not exceed the single-pulse MPE. Thus, for limit a) the MPE for the single-pulse duration, $t = 1 \times 10^{-8}$ s from Table 4 as considering a small source ($\alpha \leq \alpha_{min}$) is

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

From 6.2 b), the exposure for a pulse train of exposure duration T should not exceed the MPE for a single pulse of exposure duration T. For requirement b) the MPE for the total exposure duration, $T = 0{,}25$ s, is found using the Table 4 limits to be

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

It is often convenient for comparison to put the MPEs for requirements a), b) and c) on to a common baseline, usually the MPEs are converted to be relative to a single pulse. Thus, as there are $N = 1 \times 10^6 \times 0{,}25 = 2{,}5 \times 10^5$ pulses in the $T = 0{,}25$ s period, the average irradiance criteria can be converted into a single-pulse MPE of

$$H_{MPE_b} = H_{MPE_T} / N = 6{,}36/(2{,}5 \times 10^5) = 2{,}55 \times 10^{-5}\ \text{J·m}^{-2}$$

From 6.2 c), the exposure from pulses within a pulse train should not exceed the MPE for a single pulse multiplied by the correction factor C_5. To assess requirement c), we need to consider the pulse duration(s), the number of pulses in the applicable time duration, the duration T_i, the maximum anticipated exposure duration and the angular subtense. However, in this case we need only consider the pulse duration ($t = 1 \times 10^{-8}$), the duration T_i (see Table 10 for $T_i = 5 \times 10^{-6}$ s for this wavelength) and the maximum anticipated exposure duration ($T = 0{,}25$ s).

Subclause 6.2 c) states that, if multiple pulses appear within the period of T_i (see Table 10 for $T_i = 5 \times 10^{-6}$ s) they are counted as a single pulse to determine N and the radiant exposure of the individual pulses are added and compared to the MPE of T_i. Hence, it is necessary to confirm if multiple pulses appear within the duration T_i. If the period between the pulses of the laser is less than the duration T_i ($1/F < T_i$) or alternatively the actual pulse repetition frequency is greater than the effective pulse repetition frequency ($F > F_E$), 6.2 c) needs to be taken into account. In this example:

$$F = 1\ \text{MHz} > F_E = 1/T_i = 1/(5 \times 10^{-6}) = 200\ \text{kHz; (or } 1/F = 1 \times 10^{-6}\ \text{s} < T_i = 5 \times 10^{-6}\ \text{s)}$$

and therefore multiple pulses can occur within the duration T_i, so we need to consider pulse grouping.

Thus, we find the MPE of T_i, which from Table 4 is

$$H_{\mathrm{MPE}_{\mathrm{Ti}}} = 2 \times 10^{-3}\ \mathrm{J \cdot m^{-2}}$$

Subclause 6.2 c) also requires the grouped pulses to be "added to be compared to the MPE of T_i". In the case when all pulses contain the same energy, adding all the grouped pulses and comparing them to the MPE of T_i is equivalent to dividing the MPE by the number of grouped pulses and comparing it with a single pulse. This also puts requirement c) on a baseline relative to a single pulse for ease of comparison with requirements a) and b). So, we find an effective single-pulse MPE:

$$H_{\mathrm{MPE}_{\mathrm{aE}}} = H_{\mathrm{MPE}_{\mathrm{Ti}}} / (F \times T_i) = 4 \times 10^{-4}\ \mathrm{J \cdot m^{-2}}$$

To find C_5 it is necessary to return to the rules for requirement c) and work through them as appropriate. In this case our pulse duration is less than T_i so we only need to consider the rules under the first "if" statement (i.e. $t \leq T_i$), which says that if the pulse duration is less than T_i and the maximum anticipated exposure duration is less than or equal to 0,25 s, then C_5 = 1,0.

NOTE When the number of pulses is to be calculated for pulse grouping, it is an effective number of pulses (N_E), which is less than the actual number of pulses (N) that needs to be found.

Therefore, now we have an effective single-pulse MPE ($H_{\mathrm{MPE}_{\mathrm{aE}}}$) and a value for C_5 that accounted for the pulse grouping requirements (C_{5E}), so we apply requirement c)

$$H_{\mathrm{MPE}_{\mathrm{c}}} = H_{\mathrm{MPE}_{\mathrm{aE}}} \times C_{5E} = 4 \times 10^{-4}\ \mathrm{J \cdot m^{-2}}$$

As all MPEs are on a single-pulse baseline they can be compared directly and the MPE is the most restrictive of requirements a), b) and c). Thus, the single-pulse MPE for this system would be

$$H_{\mathrm{MPE}} = 2{,}55 \times 10^{-5}\ \mathrm{J \cdot m^{-2}}.$$

B.5.3 Example for a pulsed Nd:YAG laser

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. Based on knowledge of the operation of the device, a Laser Safety Officer doing the hazard assessment would establish the foreseeable exposure duration. In this example, it is assumed to be 10 s.

NOTE In the case where the LSO cannot establish a foreseeable exposure duration based on operational knowledge, guidance for accidental exposure durations can also be found in 6.1.

Subclause 6.2 includes three criteria that need to be considered, and the most restrictive one applies to this evaluation.

From 6.2 a), the exposure from any single pulse should not exceed the single-pulse MPE. Since the beam is emitted from a small source the MPE is determined from Table 4 and is 90 $t^{0,75}$ C_7 J·m^{-2}. The value of C_7 is found in Table 9. At a wavelength of 1 064 nm C_7 = 1 and hence the MPE from Table 4 for the time period of 1 ms is:

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

From 6.2 b), the exposure for a pulse train of exposure duration T should not exceed the MPE for a single pulse of exposure duration T. For the 10 s duration (the total exposure time), from Table 4 using the 10 to 10^2 column (see Table 9, NOTE 4), the MPE is:

$$E_{\text{MPE}_\text{T}} = 10\ C_4\ C_7\ \text{W·m}^{-2} = 10 \times 5 \times 1 = 50\ \text{W·m}^{-2}$$

where C_4 = 5 for a wavelength of 1 050 nm to 1 400 nm from Table 9.

We choose to convert the MPE for the exposure duration T on to a single-pulse baseline for ease of comparison with requirement a). In this case, as the MPE is an irradiance we divide it by the number of pulses per second (F) to do the conversion. Thus, the average irradiance criterion results in a single-pulse radiant exposure of:

$$H_{\text{MPE}_\text{b}} = \frac{E_{\text{MPE}_\text{T}}}{F} = \frac{50}{20} = 2,5\ \text{J}\cdot\text{m}^{-2}$$

From 6.2 c), the exposure from pulses within a pulse train should not exceed the MPE for a single pulse multiplied by the correction factor C_5. In this case it can be seen that multiple pulses do not appear within the duration T_i = 13 × 10^{-6} s (see Table 10) and so no grouping of pulses is required. As the pulse duration (t = 1 ms) is greater than the duration T_i (T_i = 0,013 ms) and the angular subtense ($\alpha \le \alpha_{\text{min}}$ as small source) is less than or equal to 5 mrad, C_5 = 1. The radiant exposure under these criteria would be:

$$H_{\text{MPE}_\text{c}} = H_{\text{MPE}_\text{a}} \times C_5 = 0,506 \times 1 = 0,506\ \text{J·m}^{-2}$$

Since the limit from the reduced pulse criteria of 6.2 c) does not change the single-pulse MPE for 6.2 a) and both are more restrictive than the exposure from 6.2 b), so the MPE for this system would be 0,506 J·m^{-2} relative to a single pulse. The MPE could also be expressed in terms of peak irradiance, if comparison with the laser's peak pulse power was required, for the duration of each pulse as:

$$E_{\text{MPE}} = \frac{H_{\text{train}}}{t} = \frac{0,506}{1 \times 10^{-3}} = 506\ \ \text{W}\cdot\text{m}^{-2}$$

B.6 Nominal ocular hazard distance (NOHD)

B.6.1 General

As explained in 6.5, the NOHD represents that range at which, under ideal conditions, the irradiance and the radiant exposure fall below the appropriate MPE.

The following examples use far-field formalisms and make the simplifying assumption that the beam is in the far-field in order to demonstrate applications using MPE. It should be noted that far-field assumption may not always be conservative and in those cases more detailed consideration using more accurate models should be given. For example, in cases where the beam converges to an external waist, when distance being considered is small enough such that this distance does not extend to the far-field, a more accurate model may be required.

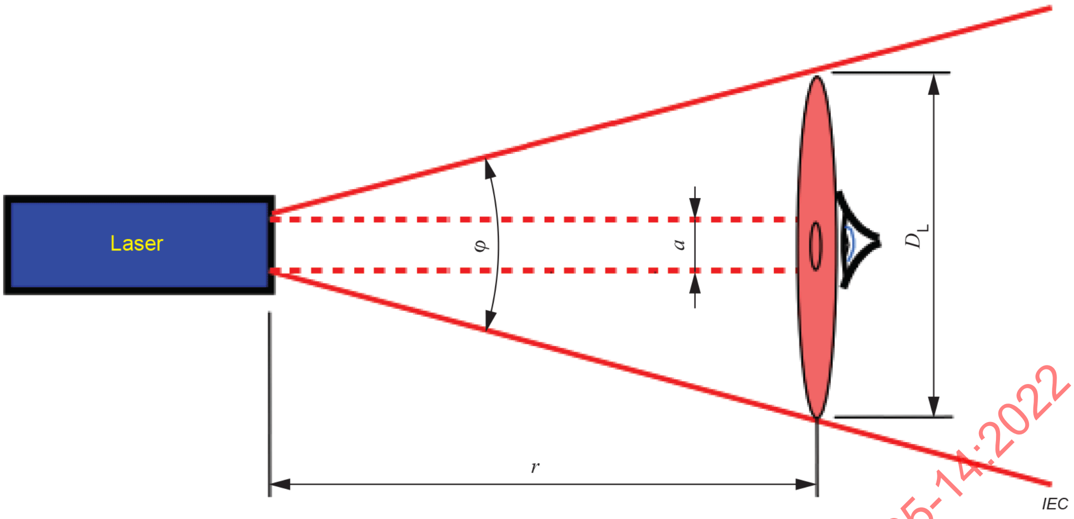


Figure B.1 – Nominal ocular hazard distance

$$D_L = r\varphi + a$$

$$A = \frac{\pi D_L^2}{4}$$

$$E = \frac{P}{A}$$

The irradiance at a distance r from a laser source is given by:

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

where

a is the d_{63} diameter of the laser exit aperture (or the beam diameter at a location from which we measure the distance r);

r is the distance from the laser exit aperture;

φ is the beam divergence angle (full cone angle) in the far field (far field is defined as where the beam diameter increases linearly, for a Gaussian beam this is the Rayleigh distance);

P_o is the output power of the laser at the exit aperture;

μ is the attenuation coefficient in the atmosphere, and depends strongly on the wavelength of the laser beam.

The parameters are described also in Figure B.1.

NOTE 1 In the near-field for Gaussian profiles the approximation of the beam diameter ($r\varphi + a$) can be replaced by $\sqrt{d_o^2 + (r\varphi)^2}$, where d_o is the beam waist diameter. All Hermite-Gaussian modes have the same beam divergence (or far field angle) but if the divergence angle ($\varphi = 2\lambda/(\pi a)$) is calculated and not measured, the TEM_{00} mode beam diameter a_o needs to be used, not the total measured beam diameter. The position of the beam waist also needs to be known, and it is generally not the same as the exit aperture, but depends on the laser resonator design. Hence, the beam waist diameter is generally not the same as the beam diameter at the exit aperture.

NOTE 2 If far-field approximations are used in the near field, an underestimation of the hazard can occur.

NOTE 3 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 most gas lasers produce beams having Gaussian profiles and many modern solid-state lasers also produce a Gaussian profile. However, a significant number of solid state and diode lasers often produce distinctly non-regular multi-mode beam structures, and in this latter case the following formula is used:

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

where I is the radiant intensity (W·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 a factor of k = 2,5 for laser systems known to have a multi-mode beam structure. The symbol k can also be used to account for beams of unknown mode structure and has values ranging from k = 1 for a Gaussian TEM_{00} mode to k = 2,5 for Gaussian beam profiles of unknown mode structure. Alternatively, accurate spatial profiling of the beam can be used to find the maximum irradiance, E_{max} (or radiant exposure, H_{max}) and k can be calculated as:

$$k = \frac{E_{max}}{E_{63}} = \frac{H_{max}}{H_{63}}, \text{ where } E_{63} \text{ is } \frac{4P_o}{\pi(d_{63})^2} \text{ and } H_{63} \text{ is } \frac{4Q_o}{\pi(d_{63})^2}.$$

The term $e^{-\mu r}$ accounts for losses due to atmospheric attenuation and may be neglected for simplicity or where short distances are being considered. Simplifying Equation (B.1) and accounting for the k factor gives:

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

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

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

or

$$R_{NOH} = \frac{1}{\varphi}\sqrt{\frac{4 \times k \times Q_o}{\pi \times H_{MPE}}} - \frac{a}{\varphi} \qquad \text{(B.4)}$$

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 Equation (B.5)[1]

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

1 Electro-Optical Imaging System Performance (G.C. Holst 5th edition, 2008)

where

$A = 0{,}585\ V^{0{,}33}$, for $V < 6$ km or

$A = 1{,}3$, for 6 km < V < 50 km

V is the visual range in km (defined at 550 nm), and

λ is the wavelength in nm (400 nm < λ < 2 000 nm).

NOTE 4 The 2 000 nm upper bound is suggested as this model accounts for aerosol scattering not absorption. It can be extended up to 10 000 nm; however, there are strong CO_2 and H_2O absorption regions in this wavelength range that will not be accounted for, resulting in a conservative estimate.

For general safety assessments, a visibility of V = 23,5 km, which corresponds to a standard clear condition or greater, should be used as a worst-case assumption. Especially considering that the visibility conditions might quickly change. This simplifies Equation (B.5):

$$\mu = 0{,}166 \times \left(\frac{550}{\lambda}\right)^{1{,}3} \text{ km}^{-1}$$

NOTE 5 More information on atmospheric attenuation constant can for example be found in the reference Electro-Optical Imaging System Performance (G.C. Holst 5th edition, 2008). A chart over atmospheric attenuation coefficient can be found in the reference Safety with Lasers and Other Optical Sources (David Sliney and Myron Wolbarsht), 1980 Plenum Press, New York, p.419.

For specific activities where atmospheric conditions are known, it is plausible to use more representative visibility values; however, in such cases care should be taken to monitor changes in conditions. Additionally, if the laser is aimed at an incline to the horizontal, the atmospheric attenuation will reduce with altitude. The effects of altitude changes can be accounted for; see, for example, "RCA electro-optics handbook" RCA/Commercial Engineering, 1974.

NOTE 6 For the model used here, Equation (B.5), is used to demonstrate how atmospheric conditions can be accounted for if necessary. This model is quite simple and can be replaced by more advanced models,[2] for more representative results; however, due care needs to be taken.

To calculate a reduced NOHD based on atmospheric attenuation, $P_o e^{-\mu r}$ and $Q_o e^{-\mu r}$ are substituted for P_o and Q_o in Equations (B.3) and (B.4), respectively. The resulting equations can then be solved numerically or iteratively to obtain the reduced NOHD. Note the units of μ are km^{-1}, so r needs to be converted from metres to kilometres (divide by 1 000) when solving for the reduced NOHD.

Alternatively, the chart at Figure B.2 can be used to graphically compensate for the atmospheric effect on basic NOHD (i.e. where the power or energy has not been scaled by $e^{-\mu r}$):

[2] MODTRAN® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

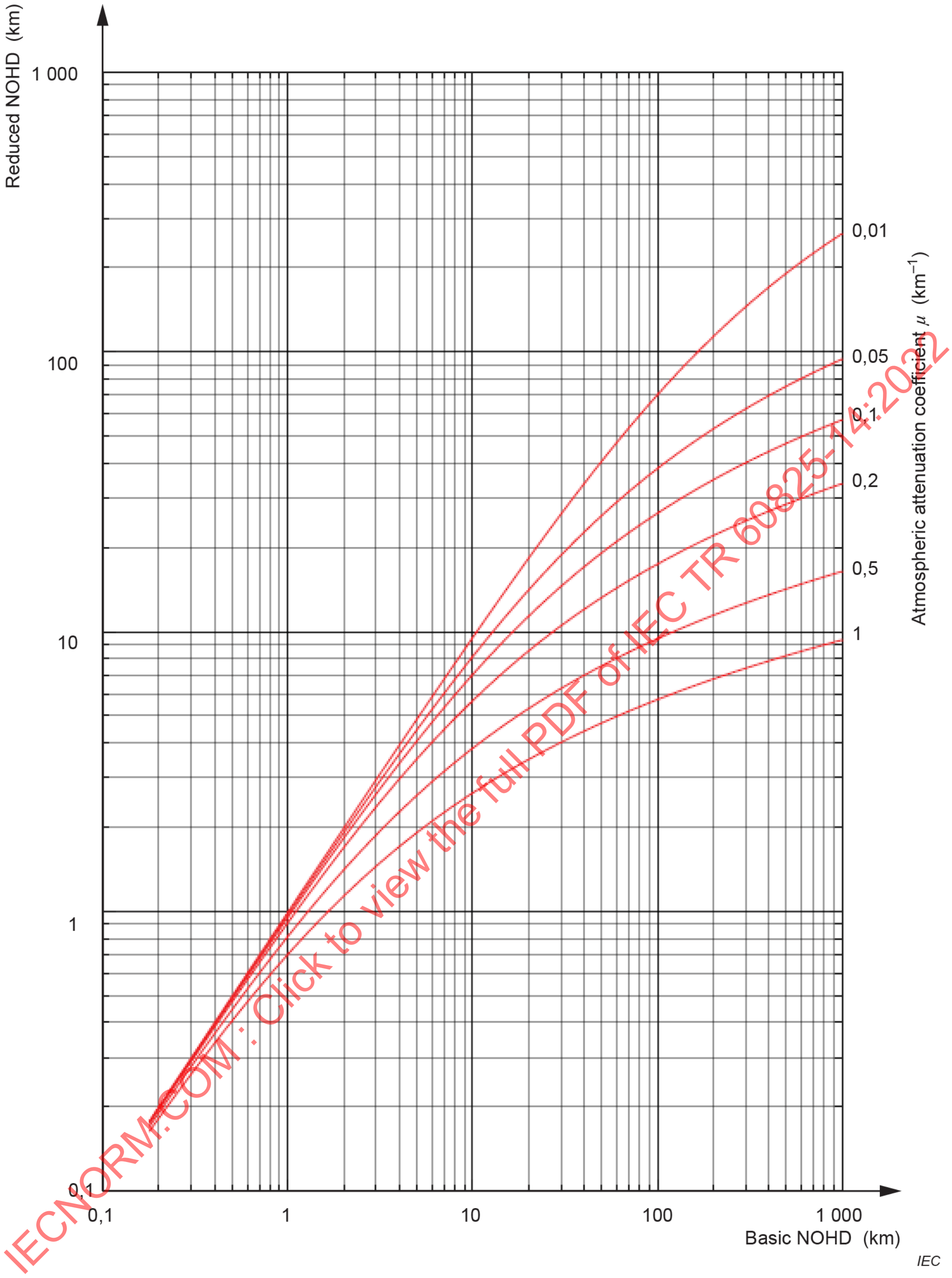


Figure B.2 – Chart for determining the NOHD (with various atmospheric attenuation factors from the NOHD found without considering atmospheric attenuation)

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 the level of laser exposure at the cornea of 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 5.3.4.

For 180 nm ≤ λ < 1 × 10^6 nm where the diameter of the beam exiting the binocular is larger than the limiting aperture,

$$G = \tau \cdot M^2 \tag{B.6}$$

or, where the output beam is smaller than the limiting aperture,

$$G = \frac{\tau D_0^2}{d^2} \quad . \tag{B.7}$$

Use whichever is the smaller, where

- τ is the transmission coefficient of the binoculars or telescope at the appropriate wavelength (= 1 if unknown), or if a filter for the appropriate wavelength is fitted $\tau = 10^{-\text{OD}}$, where OD is the optical density of the filter;
- M is the magnification of the viewing aid;
- d is the diameter of the relevant limiting aperture from Table 2; and
- D_o is the diameter of the objective lens in mm.

NOTE 1 Subclause 5.3.4 provides some typical values of transmission through binoculars that can be used if appropriate.

NOTE 2 It might not be appropriate to use G < 1 as it can lead to confusion with unaided NOHD. For example, when λ < 320 nm or λ > 4 500 nm the radiation is unlikely to be transmitted through the viewing aid.

The extended NOHD now becomes

$$R_{\text{NOH,E}} = \frac{1}{\varphi}\sqrt{\frac{4 \times k \times G \times Q}{\pi \times H_{\text{MPE}}}} - \frac{a}{\varphi} \tag{B.8}$$

Unless provided with special laser attenuating filters or unless the actual transmission of the viewing optics is known at the laser wavelength, it is conservative to make no allowance for transmission losses in viewing optics. For example, many devices have a high transmittance (> 0,9) in the visible spectrum and (0,7) extending well into the infrared region of the spectrum above 2 000 nm.

NOTE 3 The output from Class 1, Class 1M, Class 2, Class 2M and Class 3R laser products could 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.

B.6.2 Example NOHD for a Gaussian beam with negligible atmospheric attenuation

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:

$$R_{\mathrm{NOH}} = \frac{1}{0{,}7 \times 10^{-3}} \sqrt{\frac{4 \times 4}{\pi \times 10}} - \frac{1 \times 10^{-3}}{0{,}7 \times 10^{-3}} = 1018\ \mathrm{m} \approx 1{,}02\ \mathrm{km}$$

B.6.3 Example of NOHD with beam expanding optics

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:

$$R_{\mathrm{NOH}} = \frac{1}{0{,}1 \times 10^{-3}} \sqrt{\frac{4 \times 4}{\pi \times 10}} - \frac{7 \times 10^{-3}}{0{,}1 \times 10^{-3}} = 7\ 066\ \mathrm{m} \approx 7{,}1\ \mathrm{km}$$

Note the importance of beam divergence in determining the NOHD.

B.6.4 Example of NOHD with atmospheric attenuation

The laser in example B.6.3 operates at 550 nm. Calculate the modified NOHD, assuming a visual range of 23,5 km.

Solution:

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

$$\mu = 0{,}166 \times \left(\frac{550}{550}\right)^{1{,}3} = 0{,}166\ \mathrm{km}^{-1}$$

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

$$R_{\mathrm{NOH,reduced}} = \frac{1}{\varphi} \sqrt{\frac{4 \times k \times P_0\, e^{-\mu r}}{\pi \times E_{\mathrm{MPE}}}} - \frac{a}{\varphi}$$

and solving iteratively or numerically such that $r = R_{\mathrm{NOH,reduced}}$ gives

$$R_{\mathrm{NOH,reduced}} = \frac{1}{0{,}1 \times 10^{-3}} \sqrt{\frac{4 \times 4 \times e^{(-0{,}166 \times r/1000)}}{\pi \times 10}} - \frac{7 \times 10^{-3}}{0{,}1 \times 10^{-3}} = 4{,}74\ \mathrm{km}$$

noting that r has been converted from m to km. Alternatively, the chart in Figure B.2 can be used, which for μ = 0,166 km^{-1} gives a corrected NOHD of about 5 km.

NOTE Atmospheric conditions can change on a relatively short time scale and vary as a function of altitude, so care needs to be taken if atmospheric attenuation is to be taken into account. A conservative approach which is taken in this example is to use V = 23,5 km "standard clear".

B.6.5 Example of NOHD for a helium-neon laser with an expanding beam

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.

1) How long is it safe to view the laser directly from a distance of 60 m?
2) What is the minimum distance for safe direct viewing of this laser for a period of three minutes?

Solution:

a) The output power P_o = 3 × 10^{-3} W, and the initial beam diameter a = 0,013 m. The beam divergence from IEC 60825-1:2014 is therefore

$$\varphi = 2\arctan\left(\frac{0{,}018-0{,}013}{2\times 50}\right) \approx \frac{0{,}018-0{,}013}{50} = 1\times 10^{-4}\ \text{rad}$$

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

$$\frac{4kP_o}{\pi(r\varphi + a)^2}$$

thus,

$$E = \frac{4\times 3\times 10^{-3}}{\pi(0{,}013+60\times 1\times 10^{-4})^2} = 10{,}58\ \text{W}\cdot\text{m}^{-2}$$

For an exposure duration between 10 s and 3 × 10^4 s, the appropriate MPE is given in Table 4 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 4 shows that for exposure durations in the range 1 × 10^{-3} s to 10 s the appropriate MPE is

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

which is equivalent to

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

Thus, the maximum exposure duration is obtained by equating 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 s.

b) The minimum range for safe viewing can be obtained by solving Equation (B.3) for the nominal ocular hazard distance (R_{NOH}). In this case, the exposure duration t = 180 s (3 min) and Table 4 gives E_{MPE} = 10 W·m^{-2}:

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

B.6.6 Example for an infrared surveying instrument

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

1) for viewing by the unaided eye, and
2) 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 angular subtense α is less than α_{min}. If there is no intentional viewing, the exposure time to be used is T = 100 s (see 6.1); during this time the number of pulses is

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

The intrabeam MPE is taken as the most restrictive calculated from the application of 6.2.

Single-pulse assessment (condition 6.2 a)):

As $\alpha \leq 1{,}5$ mrad, $C_6 = 1$ and so Table 4 gives the single-pulse MPE for this radiation with the exposure time of 20 ns, as:

$$H_{\mathrm{MPE_a}} = 2 \times 10^{-3} C_4\ \mathrm{J \cdot m^{-2}}$$

where $C_4 = 10^{0{,}002(903 - 700)} = 2{,}55$ (see Table 9), hence:

$$H_{\mathrm{MPE_a}} = 2 \times 10^{-3} \times 2{,}55 = 5{,}1 \times 10^{-3}\ \mathrm{J \cdot m^{-2}}$$

Average irradiance assessment (condition 6.2 b)):

The MPE for exposure duration of 100 s is obtained from Table 4. As all pulses have the same magnitude, duration and spacing, the total exposure duration T = 100 s will result in the most restrictive MPE under requirement 6.2 b). Since $\alpha \leq 1{,}5$ mrad, $C_6 = 1$ and so Table 4 gives an MPE for a duration of T s of:

$$E_{\mathrm{MPE_T}} = 10\, C_4 C_7\ \mathrm{W \cdot m^{-2}}$$

where $C_4 = 2{,}55$ and $C_7 = 1$ (see Table 9). To allow a direct comparison to the MPE for 6.2 a), $E_{\mathrm{MPE_T}}$ is converted to a single-pulse baseline. Since the pulse repetition frequency is 300 Hz, the average MPE per pulse is

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

Multiple-pulse assessment (condition 6.2 c)):

The exposure from pulses within a pulse train should not exceed the MPE for a single pulse multiplied by the correction factor C_5. For this wavelength T_i = 5 × 10^{-6} s (see Table 10), so with F = 300 Hz (T_F = 3,3 ms > T_i) it is not possible to fit multiple pulses within the duration T_i, so pulse grouping is not required. The pulse duration t = 20 ns is less than T_i and the exposure duration is greater than 0,25 s so C_5 depends on N. The maximum exposure duration (T_{reqc}) for which requirement 6.2 c) should be applied to calculate N is T_2 in the wavelength range 400 nm to 1 400 nm, where T_2 = 10 s for $\alpha \leq \alpha_{min}$ (see Table 9). Hence:

$$N = F \times T_{reqc} = F \times T_2 = 300 \times 10 = 3\ 000$$

Here T_{reqc} is the lesser of T (100 s) and T_2 (10 s) in this wavelength region.

As N > 600, C_5 = 5·$N^{-0,25}$ = 0,68 (with a minimum value of C_5 = 0,4 so no need to limit the value), thus:

$$H_{\text{MPE}_\text{c}} = H_{\text{MPE}_\text{a}} \times C_5 = 5{,}1 \times 10^{-3} \times 0{,}68 = 3{,}45 \times 10^{-3}\ \text{J} \cdot \text{m}^{-2}$$

The conclusion is that condition 6.2 c) produces the most restrictive MPE per pulse and therefore H_{MPE} = 3,45 × 10^{-3} J·m^{-2} for intrabeam viewing. Substituting this value of MPE into Equation (B.4) (noting Gaussian so k = 1) gives

$$R_{\text{NOH}} = \frac{1}{0{,}01}\sqrt{\frac{4 \times 600 \times 10^{-9}}{\pi \times 3{,}45 \times 10^{-3}}} - \frac{0{,}055}{0{,}01} = -4{,}0\ \text{m}.$$

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 8 × 50 mm 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 ($R_{NOH,E}$).

Assuming that there is no attenuation through the optics (τ = 1), Equation (B.6) gives $G = M^2 = 8^2$ = 64, and Equation (B.7) gives $G = D_0^2/d^2$ = $50^2/7^2$ = 51, where d = 7 mm is the diameter of the limiting aperture for this wavelength (see Table 2). Thus, substituting G = 51 in Equation (B.8) gives

$$R_{\text{NOH,E}} = \frac{1}{0{,}01}\sqrt{\frac{4 \times 51 \times 600 \times 10^{-9}}{\pi \times 3{,}45 \times 10^{-3}}} - \frac{0{,}055}{0{,}01} = 5{,}13\ \text{m}$$

It is consequently hazardous for this laser product to be viewed with 8 × 50 binoculars at distances of less than 5,13 m.

B.6.7 Example for a Q-switched rangefinder

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:

1) the NOHD for the unaided eye,
2) the NOHD for the unaided eye when a 10 % transmission filter is fitted to the output aperture of the rangefinder, and
3) 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. $1 \times 10^{-11} < t_p < 13 \times 10^{-6}$ s). The pulse repetition frequency F is 12/60 = 0,2 Hz.

In this example, it is assumed that $\alpha \leq \alpha_{min}$. If there is no intentional viewing, the exposure duration to be used is T = 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 6.2.

Single-pulse assessment (condition 6.2 a)):

From Table 4, the MPE for a single-pulse exposure from this laser is

$$H_{MPE_a} = 2 \times 10^{-2} C_7 \text{ J} \cdot \text{m}^{-2}$$

where from Table 9 C_7 = 1; therefore

$$H_{MPE_a} = 2 \times 10^{-2} \text{ J} \cdot \text{m}^{-2}$$

Average irradiance assessment (condition 6.2 b)):

The MPE for exposure duration of 100 s is obtained from Table 4. As all pulses have the same magnitude, duration and spacing, the exposure duration T = 100 s will result in the most restrictive MPE under requirement 6.2 b). Since $\alpha \leq 1,5$ mrad, C_6 = 1 and so Table 4 gives an MPE for a duration of 100 s of:

$$E_{MPE_T} = 10\, C_4 C_7 \text{ W} \cdot \text{m}^{-2}$$

where C_4 = 5 and C_7 = 1 (see Table 9). To allow a direct comparison to the MPE for 6.2 a), E_{MPE_T} is converted to a single-pulse baseline. Since the pulse repetition frequency is 0,2 Hz, the average MPE per pulse is

$$H_{MPE_b} = \frac{E_{MPE_T}}{F} = \frac{10 \times 5 \times 1}{0,2} = 250 \text{ J} \cdot \text{m}^{-2}$$

Multiple-pulse assessment (condition 6.2 c)):

The exposure from pulses within a pulse train should not exceed the MPE for a single pulse multiplied by the correction factor C_5. For this wavelength T_i = 13 × 10^{-6} s (see Table 10), so with F = 0,2 Hz it is not possible to fit multiple pulses within the duration T_i, so pulse grouping is not required. The pulse duration t = 30 ns is less than T_i and the exposure duration is greater than 0,25 s so C_5 depends on N. The maximum exposure duration (T_{reqc}) for which requirement 6.2 c) should be applied to calculate N is T_2 in the wavelength range 400 nm to 1 400 nm, where T_2 = 10 s for $\alpha \leq \alpha_{min}$ (see Table 9). Hence:

$$N = F \times T_2 = 0{,}2 \times 10 = 2$$

As $N \leq 600$, C_5 = 1,0, thus:

$$H_{MPE_c} = H_{MPE_a} \times C_5 = 2 \times 10^{-2} \times 1{,}0 = 2 \times 10^{-2}\ \mathrm{J \cdot m^{-2}}$$

The conclusion is that the multiple pulse assessment does not further reduce the MPE for requirement 6.2 a). Thus 6.2 a) produces the most restrictive MPE per pulse and therefore H_{MPE} = 2 × 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,

$$R_{NOH} = \frac{1}{\varphi}\sqrt{\frac{4 \times 2{,}5 \times Q}{\pi \times H_{MPE}}} - \frac{a}{\varphi}$$

$$R_{NOH} = \frac{1}{1 \times 10^{-3}}\sqrt{\frac{4 \times 2{,}5 \times 45 \times 10^{-3}}{\pi \times 2 \times 10^{-2}}} - \frac{1 \times 10^{-2}}{1 \times 10^{-3}} = 2\,666\ \mathrm{m}$$

The NOHD for the rangefinder is therefore 2,7 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 needs to be reduced by the factor τ = 0,1 to take into account the effect of the 10 % filter. The modified NOHD is therefore given by

$$R_{NOH,reduced} = \frac{1}{1 \times 10^{-3}}\sqrt{\frac{4 \times 2{,}5 \times 0{,}1 \times 45 \times 10^{-3}}{\pi \times 2 \times 10^{-2}}} - \frac{1 \times 10^{-2}}{1 \times 10^{-3}} = 837\ \mathrm{m}$$

c) When 50 mm diameter collecting optics are involved in the intrabeam viewing of this laser beam, 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 τ = 1, $G = 50^2/d^2 = 50^2/49 = 51$ and from Equation (B.8),

$$R_{NOH,E} = \frac{1}{1 \times 10^{-3}}\sqrt{\frac{4 \times 2{,}5 \times 51 \times 45 \times 10^{-3}}{\pi \times 2 \times 10^{-2}}} - \frac{1 \times 10^{-2}}{1 \times 10^{-3}} = 19{,}1\ \mathrm{km}$$

Thus, in view of the very short pulse duration for this laser beam, while a telescopic system is used, even the briefest exposure of the eye to the laser radiation may be hazardous at distances less than 19,1 km from the laser.

B.6.8 Example for a CW optical fibre transmitter

A CW optical fibre transmitter emitting at 1 320 nm is used for diagnostics. The transmitter assembly is pigtailed to a single mode fibre having a mode field diameter of 10 µm.

Determine the maximum output power such that the MPE is not exceeded 100 mm from the output for a 20 s exposure.

Solution:

As the power is required it is convenient to find the MPE in units of irradiance (E_{MPE}). Table 4 conveniently presents the MPE in this form.

MPE for a 20 s exposure:

As this is a small source it is assumed that $\alpha \leq \alpha_{min}$ and so using Table 4 the MPE for wavelength range 1 050 nm to 1 400 nm for a 20 s exposure is:

$$E_{MPE(ret)} = 10\ C_4\ C_7\ \text{W·m}^{-2}$$

From Table 9

$$C_4 = 5$$

$$C_7 = 8 + 10^{0,04(1320 - 1250)} = 639$$

Therefore

$$E_{MPE(ret)} = 31\ 948\ \text{W·m}^{-2}$$

However, footnote e to Table 4 indicates that there is an increased risk to the cornea and the anterior parts of the eye for the wavelength region 1 200 nm to 1 400 nm. Thus, to ensure cornea and anterior parts of the eye are also protected, we are required to ensure that the skin MPE is not exceeded. From Table 8 the skin MPE for a 20 s exposure is:

$$E_{MPE(skin)} = 2\ 000\ C_4\ \text{W·m}^{-2}$$

From Table 9

$$C_4 = 5$$

Therefore

$$E_{MPE(skin)} = 10\ 000\ \text{W·m}^{-2}$$

To ensure the most restrictive limit is applied, it is necessary to consider the smallest of these two MPEs. Both MPEs are in the same units and on the same time baseline but they have different limiting apertures (see Table 2) of 7 mm and 3,5 mm for the eye and the skin, respectively. This means that a simple direct comparison can only be made if the beam diameter exceeds both limiting apertures. Thus, we need to determine the beam diameter at the contact point before the most restrictive limit can be identified.

A single-mode optical fibre is a special case of a point-type optical source. The divergence of a single-mode fibre is specified in terms of the fibre mode-field diameter, w_0, and the wavelength, λ, of the source. The beam diameter of a single-mode optical fibre, at a distance r, is approximated by:

$$d_{63} = \frac{2\sqrt{2} \times r \times \lambda}{\pi \times w_0} \quad \text{(B.9)}$$

where the wavelength, λ, is expressed in the same units as the mode-field diameter, w_0.

Using Equation B.9, the beam diameter at 100 mm is:

$$d_{63} = \frac{2\sqrt{2} \times 0{,}1 \times 1\,320 \times 10^{-9}}{\pi \times 10 \times 10^{-6}} = 11{,}9 \text{ mm}$$

The larger of the beam diameter (11,9 mm) and limiting aperture (7 mm) is used to find the beam irradiance for comparison with both the eye and the skin MPEs. A direct comparison between the eye and skin MPE can be made and therefore the most restrictive of the eye MPE and the skin MPE is

$$E_{\text{MPE}} = 10\,000 \text{ W}\cdot\text{m}^{-2}$$

Given the beam diameter is greater than the limiting aperture, the average power is found by multiplying E_{MPE} by the area of the beam as follows:

$$P_{\text{MPE}} = \frac{E_{\text{MPE}} \times \pi (d_{63})^2}{4} = \frac{1 \times 10^4 \times \pi (11{,}9 \times 10^{-3})^2}{4} = 1{,}1 \text{ W}$$

Therefore, to ensure that the MPE is not exceeded at 100 mm from the output, the power in the fibre cannot exceed 1,1 W.

NOTE If the beam diameter at 100 mm from the output is smaller than both limiting apertures, the average power is found by multiplying E_{MPE} by the area of the respective limiting aperture and selecting the lowest power.

B.7 Diffuse reflections that are extended sources

B.7.1 General

One generic group of extended source viewing occurs when:

a) laser radiation within the wavelength range 400 nm to 1 400 nm is reflected from or transmitted through a diffusing surface, and

b) the image formed on the retina of the eye as a result of viewing the source (the diffuser) is larger than the minimum value of the retinal image as defined by the limiting angular subtense α_{min}, where α_{min} is equal to 1,5 mrad (see Table 9) and is measured at a distance of no less than 100 mm from the apparent source (see 6.4).

For CW or single-pulse lasers, it is possible to identify 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 the source is not extended. This defines one of the three regions for viewing of a diffuse reflection. A second region exists where the subtended angle is ≥ α_{max} with α_{max} corresponding to a range 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. The final zone is within r_{min} where large source viewing conditions prevail, and the hazard is constant.

B.7.2 Example for a reflection from a perfect diffuser

The radiation from a single-pulse Q-switched Nd:YAG laser (λ = 1 064 nm, t = 10 ns) is expanded to form a beam 2 cm in diameter before being reflected from a perfect diffuser (i.e. a Lambertian diffuser, scattering equally into a full hemisphere, without losses (ρ = 1)).

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:

In this case the angular subtense (α) is determined by the equation:

$$\alpha = \frac{d_{63}}{r}$$

where d_{63} is the diameter of the laser beam at the diffusing target and r is the viewing distance.

a) By definition the source is considered extended when $\alpha > \alpha_{min}$ (or $r < r_{max}$); therefore,

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

For this example,

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

At distances less than r_{max} = 13,3 m, extended source viewing conditions exist.

b) For this system extended source viewing conditions occur at distances less than 13,3 m, which is clearly the case at 2,5 m. The MPEs for extended sources in the wavelength range 400 nm to 1 400 nm are found in Table 5. For the specified exposure duration of $t = 1 \times 10^{-8}$ s, the MPE in Table 5 is

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

where, as before, C_7 = 1. C_6 is found in Table 9 and is dependent on α. At the distance of r_1 = 2,5 m,

$$\alpha = \frac{d_{63}}{r} = \frac{0{,}02}{2{,}5} = 8 \times 10^{-3}\ \text{rad}$$

The value of α_{max} is time dependent. From Table 9 for t < 625 µs, α_{max} = 5 mrad. Thus, in this case our angular subtense (8 mrad) exceeds the value of α_{max} for the exposure time (t = 10 ns) that we are considering. To find C_6 we can now return to Table 9 where for $\alpha > \alpha_{max}$, we find that $C_6 = \alpha_{max} / \alpha_{min}$, so

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

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

$$H_{MPE} = 2 \times 10^{-2} \times 3{,}33 \times 1\ J{\cdot}m^{-2} = 6{,}67 \times 10^{-2}\ J{\cdot}m^{-2}$$

B.7.3 Example for close viewing of reflection from a perfect diffuser

Find the maximum radiant energy from the laser in example B.7.2 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 0,2 m the angular subtense α is

$$\alpha = \frac{d_{63}}{r} = \frac{0{,}02}{0{,}2} = 0{,}10\ \text{rad}$$

which is greater than α_{max} = 5 mrad for t < 625 µs. This corresponds to the final zone discussed in B.7.1, where large source conditions prevail, and the hazard is constant. More specifically α_{max} defines the size of the image where the spot size dependence ceases for a given exposure duration. This means that further increases in spot size do not further modify the MPE (C_6 is constant). We thus do not need to include contributions from the source that are outside of the region defined by α_{max} (see 5.3.3). Therefore, the emissions are limited by setting the angle of acceptance (γ) equal to α_{max}.

A hazardous diffuse reflection under this extended source viewing condition is most appropriately described in terms of radiance (L) or integrated radiance (L_t). It follows that the MPE limits should be expressed in the same units as the source under assessment. Therefore, the first step is 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 angle of acceptance. Where the angle of acceptance, $\gamma = \alpha_{max}$ = 5 mrad corresponding to a solid angle, Ω, given by $\Omega_\gamma \approx \pi(\gamma/2)^2 = 1{,}96 \times 10^{-5}$ sr and MPE expressed as an integrated radiance is

$$L_{MPE} = H_{MPE}/\ \Omega_\gamma = (6{,}67 \times 10^{-2}/1{,}96 \times 10^{-5}) = 3\ 395\ J{\cdot}m^{-2}{\cdot}sr^{-1}$$

The integrated radiance of the diffuse reflection is related to the incident beam radiant exposure at the target through the expression (assumes perfect Lambertian diffuser that emits in a projected solid angle of π sr):

$$H = \pi \times L_t$$

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

$$H_{MPE} = \pi\ [sr] \times L_{MPE}\ J{\cdot}m^{-2}\ [sr^{-1}] = 1{,}067 \times 10^4\ J{\cdot}m^{-2}$$

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

$$Q_{MPE} = H_{MPE} \times A = H_{MPE} \times (\pi/4) \times d_{63}^2 = 1{,}067 \times 10^4 \times (\pi/4) \times 0{,}02^2 = 3{,}35\ J$$