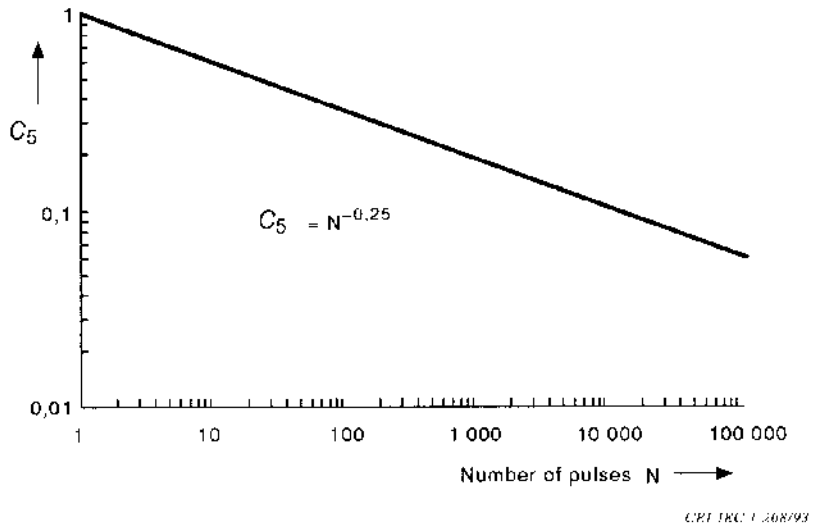

Figure 7 – Correction factor C_5 shown for N (number of pulses) between 1 and 100 000

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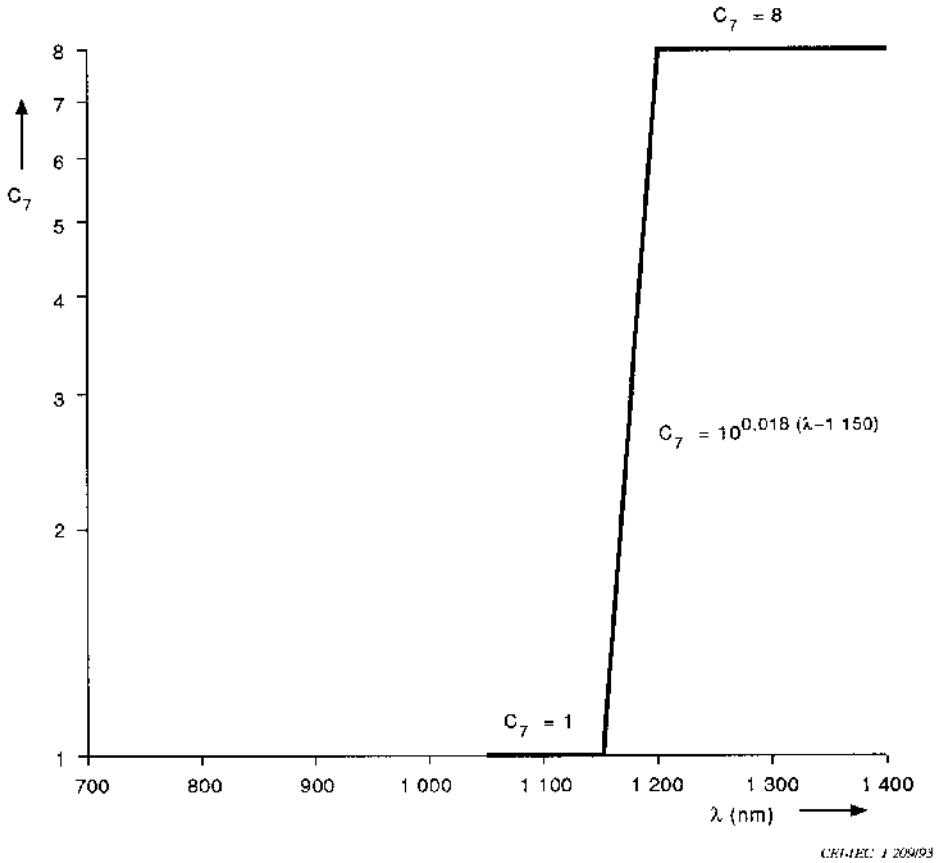

Figure 8 – Correction factor C_7 for λ = 1 050 nm to 1 400 nm

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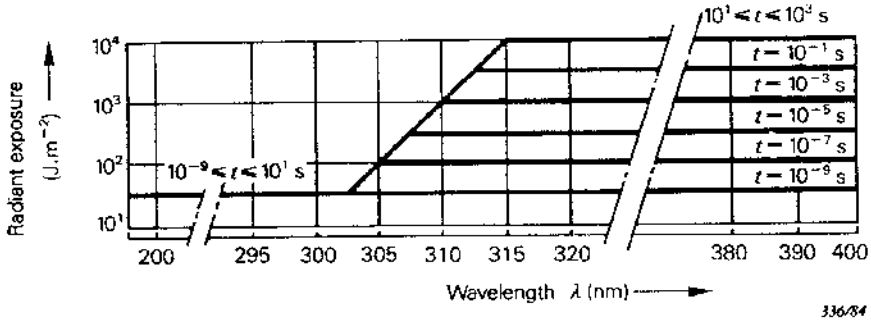

Figure 9a – MPE for direct ocular exposure to ultra-violet radiation at selected emission durations from 10^{-9} s to 10^3 s

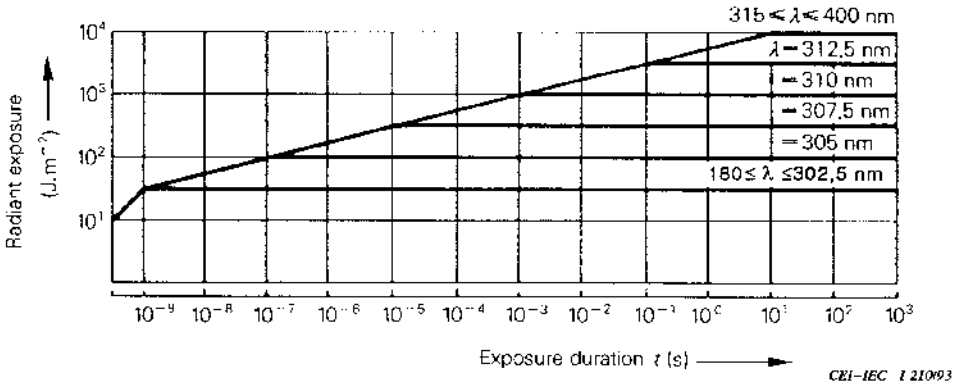

Figure 9b – MPE for direct ocular exposure to ultra-violet radiation for exposure durations from 10^{-9} s to 10^3 s at selected wavelengths

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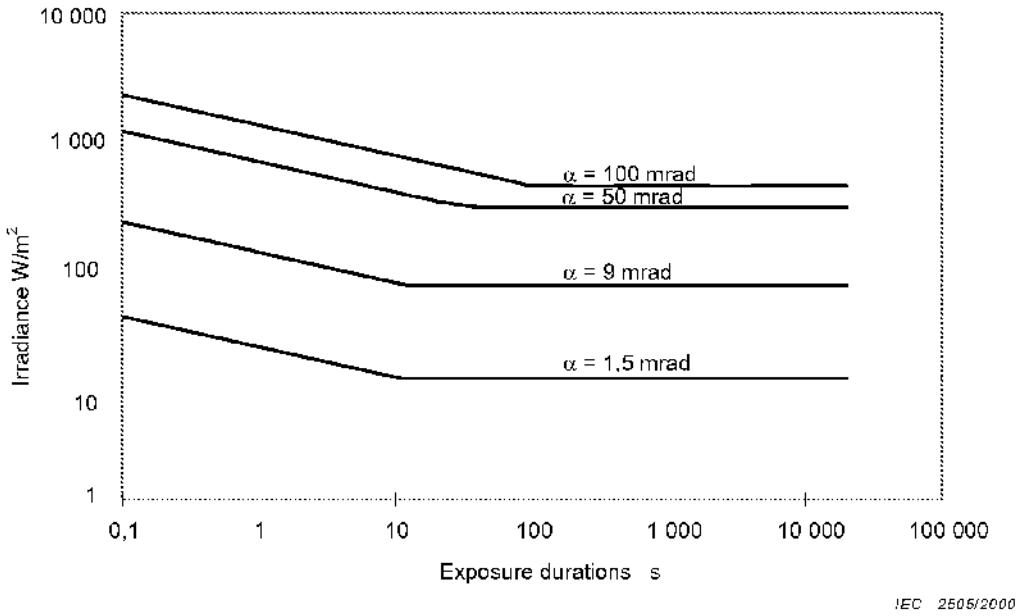

Figure 10a – MPE for direct ocular exposure to protect against thermal injury (λ = 400 nm to 700 nm) for exposure durations greater than 0,1 s for selected source sizes between 1,5 mrad and 100 mrad

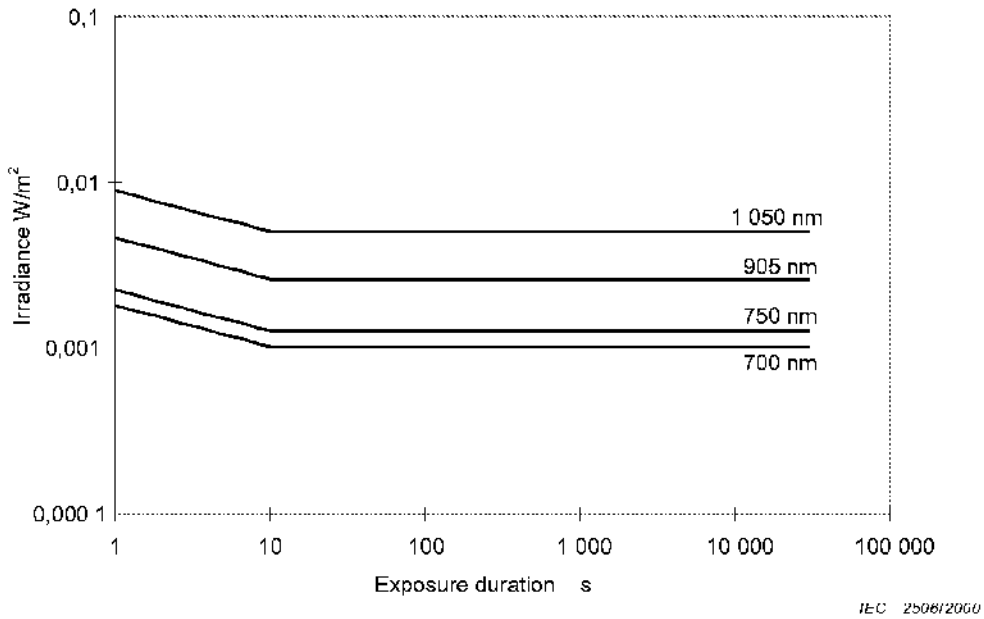

Figure 10b – MPE for direct ocular exposure (C_6 = 1) for exposure durations greater than 1 s for selected wavelengths between 700 nm and 1 050 nm

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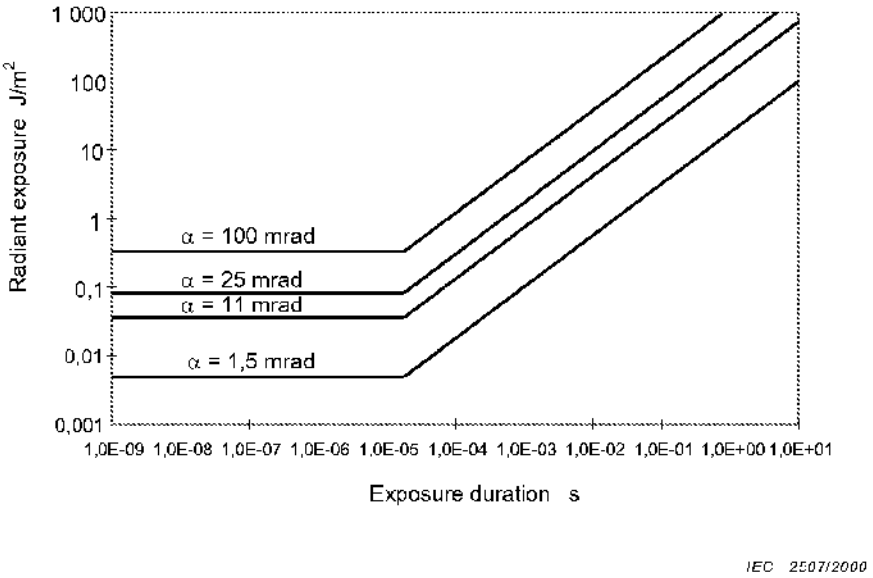

Figure 11a – MPE for ocular exposure (λ = 400 nm to 700 nm) to a single exposure at selected angular subtenses for the source

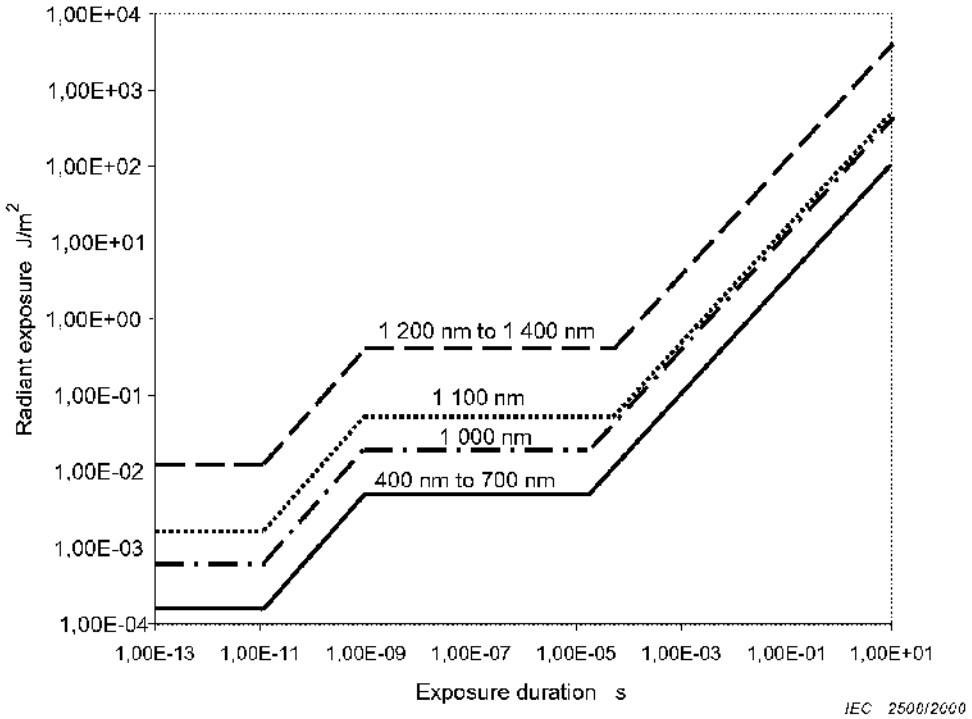

Figure 11b – MPE for ocular exposure at selected wavelengths from 400 nm to 1 400 nm and C_6 = 1

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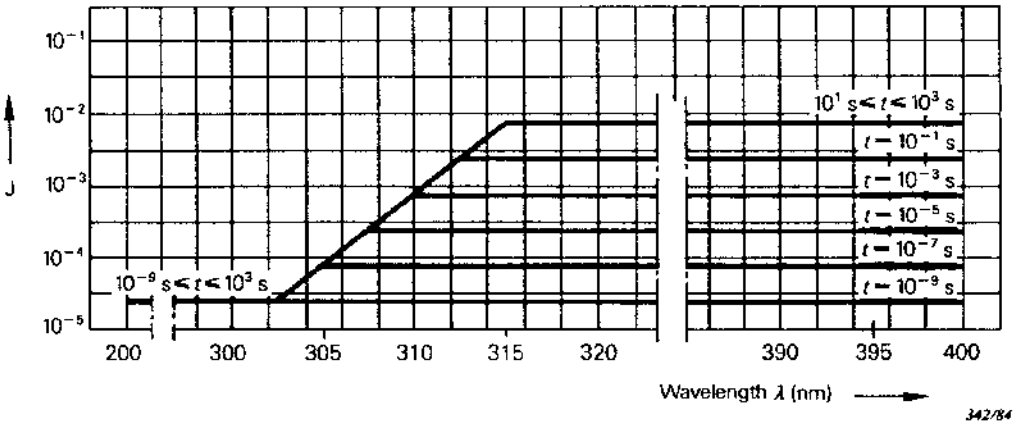

Figure 12a – AEL for Class 1 ultra-violet laser products for selected emission durations from 10^{-9} s to 10^{3} s

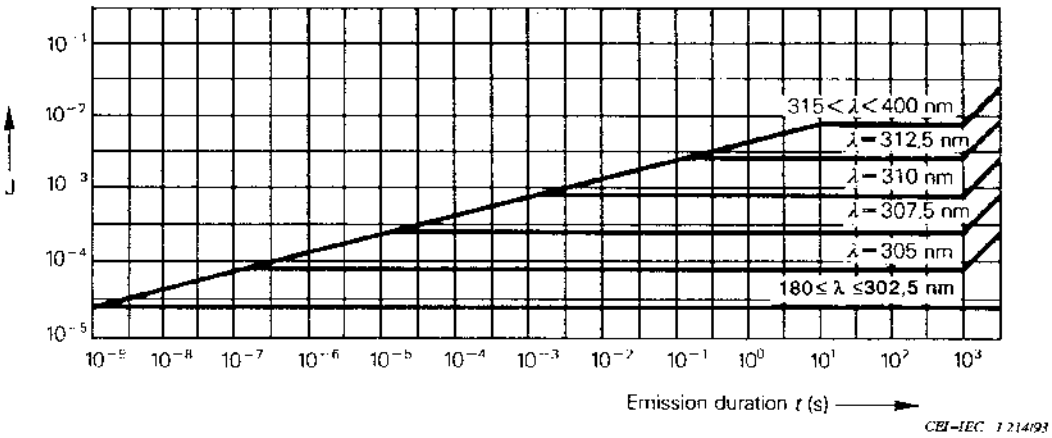

Figure 12b – AEL for Class 1 ultra-violet laser products for emission durations from 10^{-9} s to 10^{3} s at selected wavelengths

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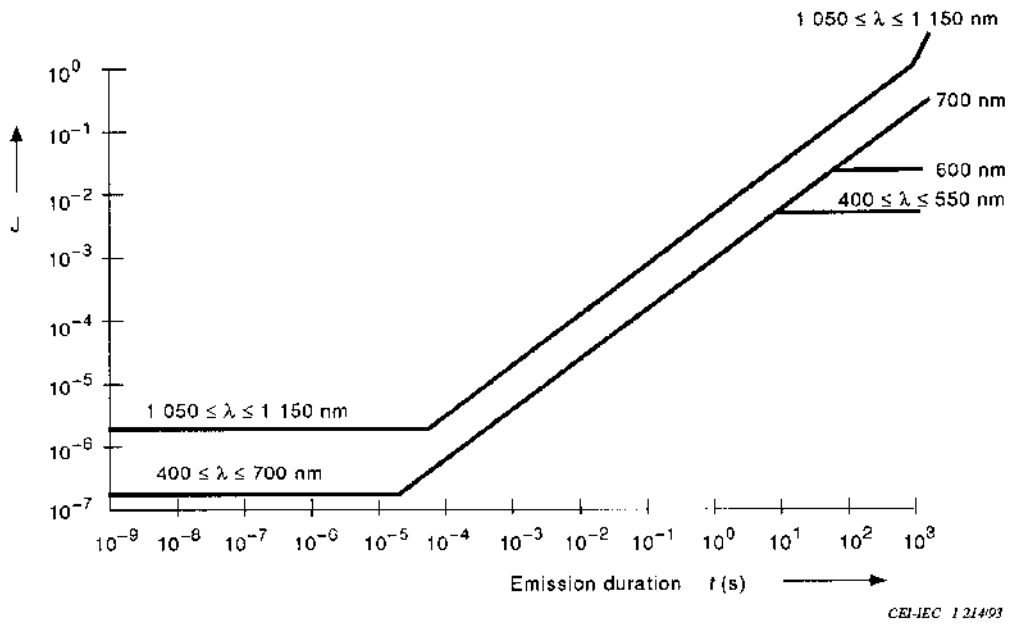

Figure 13 – AEL for Class 1 visible and selected infra-red laser products (case $C_6 = 1$)

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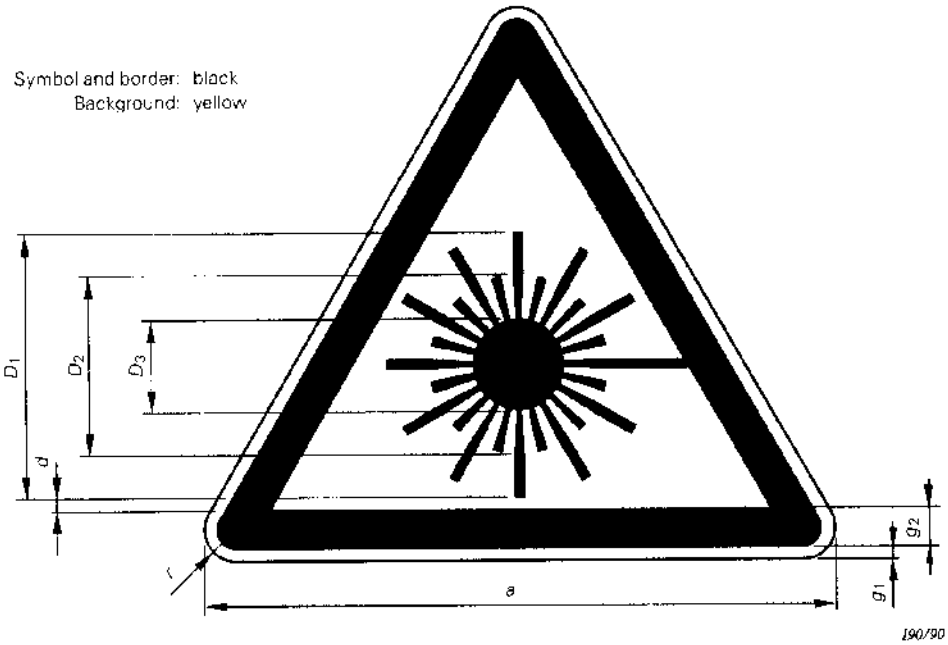

Dimensions in millimetres

a	g_1	g_2	r	D_1	D_2	D_3	d
25	0,5	1,5	1,25	10,5	7	3,5	0,5
50	1	3	2,5	21	14	7	1
100	2	6	5	42	28	14	2
150	3	9	7,5	63	42	21	3
200	4	12	10	84	56	28	4
400	8	24	20	168	112	56	8
600	12	36	30	252	168	84	12
The dimensions D_1, D_2, D_3, g_1 and d are recommended values.							

NOTE 1 The relationship between the greatest distance L from which the label can be understood and the minimum area A of the label is given by: $A = L^2/2\ 000$, where A and L are expressed in square metres and metres respectively. This formula applies for distance L less than about 50 m.

NOTE 2 These dimensions are recommended values. As long as they are proportional to the values, the symbol and border may be of any legible size as required to suit the size of the laser product.

Figure 14 – Warning label – Hazard symbol

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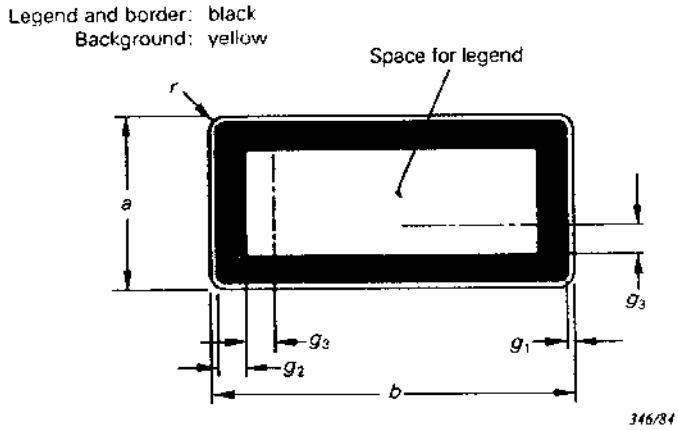

Dimensions in millimetres

$a \times b$	g_1	g_2	g_3	r	Minimum height of lettering
26 × 52	1	4	4	2	Lettering shall be of a size which renders it legible
52 × 105	1,6	5	5	3,2	
84 × 148	2	6	7,5	4	
100 × 250	2,5	8	12,5	5	
140 × 200	2,5	10	10	5	
140 × 250	2,5	10	12,5	5	
140 × 400	3	10	20	6	
200 × 250	3	12	12,5	6	
200 × 400	3	12	20	6	
250 × 400	4	15	25	8	
The dimension g_1 is recommended.					

NOTE 1 The relationship between the greatest distance L from which the label can be understood and the minimum area A of the label is given by: $A = L^2/2\,000$, where A and L are expressed in square metres and metres respectively. This formula applies for distance L less than about 50 m.

NOTE 2 These dimensions are recommended values. The label may be of any size necessary to contain the required lettering and border. The minimum width of each border dimension g_2 and g_3 shall be 0,06 times the length of the shorter side of the label.

Figure 15 – Explanatory label

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Annex A
(informative)

Examples of calculations

Symbols used in the examples of this annex:

Symbol	Unit	Definition
a	m	Diameter of the emergent laser beam.
AEL	W, J, $W \cdot m^{-2}$ or $J \cdot m^{-2}$	Accessible emission limit.
α	rad	The angle subtended by an apparent source (or a diffuse reflection) as viewed at a point in space.
α_f	rad	Angle at the eye subtending the apparent source of radiation at a distance of r_f = 100 mm.
α_{min}	rad	Minimum angle subtended by a source for which the extended source criterion applies.
α_{max}	rad	The value of angular subtense of the apparent source above which the MPEs and AELs are independent of the source size. (α_{max} = 0,1 rad)
$C_1, C_2, ..., C_7$	1	Correction factors (see notes to tables 1 to 4)
d_u	m	Diameter of the smallest circle at a specified distance, r, from the apparent source that contains u % of the total laser power (or energy). In the case of a Gaussian beam, d_{63} corresponds to the points where the irradiance (or radiant exposure) falls to 1/e of its central peak value.
D_e	m	Diameter of the exit pupil of an optical system.
D_o	m	Diameter of the objective of an optical system.
η	1	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	1	Square root of the ratio of retinal irradiance or radiant exposure received by an optically aided eye to that received by an unaided eye.
H	$J \cdot m^{-2}$	Radiant exposure or
E	$W \cdot m^{-2}$	irradiance at a specified distance, r, from the apparent source.
H_o	$J \cdot m^{-2}$	Emergent beam radiant exposure or
E_o	$W \cdot m^{-2}$	irradiance at zero distance from the apparent source.
L_p	$J \cdot m^{-2} \cdot sr^{-1}$	Integrated radiance of an extended source.
λ	nm	Wavelength of laser radiation.
M	1	Magnification of an optical instrument.

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Symbol	Unit	Definition
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	1	Number of pulses contained within an exposure duration
NA	1	Numerical aperture of a laser source.
NA_m	1	Numerical aperture of a microscope objective
NOHD	m	Nominal ocular hazard distance.
OD	1	Optical (transmittance) density defined as the logarithm to base 10 of the reciprocal of the transmittance (see also IEV 845-04-66; symbol *D* is not used here to avoid confusion with diameters).
P_o	W	Total radiant power (radiant flux) of a CW laser, or average radiant power of a repetitively pulsed laser.
P_p	W	Radiant power within a pulse of a pulsed laser.
ϕ	rad	Divergence angle of an emergent laser beam.
π	1	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 notes to tables 1 to 4).
w_o	µm	Mode field diameter for a single-mode optical fibre measured at the $1/e^2$ points of the optical power distribution (see also IEV 731-03-65)*.

* IEC 60050(731):1991, *International Electrotechnical Vocabulary (IEV) – Chapter 731: Optical fibre communication.*

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A.1 Maximum permissible exposure (MPE) – Introduction

The maximum permissible exposure is defined in 3.51 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:

- the wavelength of the radiation;
- the exposure time or pulse duration;
- the spectrum of wavelengths, when the tissue is exposed to more than one wavelength;
- the nature of the tissue exposed;
- the angular subtense of the source (which determines the size of the retinal image) in the wavelength range from 400 nm to 1 400 nm.

The examples presented in this annex illustrate the calculation procedures for intrabeam viewing, for diffuse reflections and extended sources, and for pulsed or modulated exposures. The 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 the calculation of the MPE is necessary.

A.2 Maximum permissible exposure (MPE) – Single and multiple small sources

Small-source viewing occurs when the angular subtense of the source is $\leq \alpha_{min}$. The following three examples illustrate the calculation procedures for single and multiple small-source viewing conditions.

Example A.2-1

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

Solution:

The MPE values can be found in table 6. At the intersection of the wavelength range from 315 nm to 400 nm and exposure duration column 1×10^{-3} s to 10 s, the MPE is found to be equal to C_1 J·m ^{2}. C_1 can be calculated from the formula given in the notes to tables 1 to 4.

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

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

In terms of irradiance obtained after dividing by t,

$$E_{MPE} = 3{,}15 \times 10^4\ \text{W·m}^{-2}.$$

Example A.2-2

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

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Solution:

In table 6, the MPE is found at the intersection of the wavelength range from 400 nm to 700 nm and exposure duration $t = 5 \times 10^{-5}$ s to 10^{-3} s. The MPE value then is

$$H_{MPE} = 18 \times t^{0,75} \times C_6 \text{ J·m}^{-2}.$$

For intrabeam viewing of a small source, $\alpha \leq \alpha_{min}$, and $C_6 = 1$ (see notes to tables 1 to 4).

Thus,

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

Example A.2-3

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

Solution:

In table 6, the MPE is found at the intersection of the wavelength range from 700 nm to 1 050 nm and exposure duration $t = 10^{-7}$ s to $1,8 \times 10^{-5}$ s. The MPE expressed as a radiant exposure is given by

$$H_{MPE} = 5 \times 10^{-3} \times C_4 \times C_6 \text{ J·m}^{-2}.$$

The coefficient C_4 can be calculated from the formula given in the notes to tables 1 to 4:

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

Since $C_6 = 1$ (small source viewing conditions),

$$H_{MPE} = 5 \times (10^{-3}) \times 2,57 \times 1 \text{ J·m}^{-2} = 12,9 \times 10^{-3} \text{ J·m}^{-2}$$

Example A.2-4: Complex laser diode array source

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

An intrabeam photograph (using infrared film) taken at a distance of 1 m from the exit aperture reveals that each diode subtends a projected line image 2,2 mrad long and less than 0,5 mrad across. Each diode is separated by an angle of 3,0 mrad centre-to-centre, and the two rows are separated by an angle of 2,3 mrad (see figure A.1). Using an infrared image converter with an OD 4 filter to reduce glare, it is revealed that these angular separations are constant from all viewing distances between 10 cm and 2 m (this behaviour is explained in chapter 15 of Sliney and Wolbarsht, *Safety with Lasers and other Optical Sources*, New York: Plenum Publishing Co., 1980).

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Solution

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

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

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

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

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

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

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

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

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

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

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

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Single-diode group

The individual diodes subtend angles of 0,5 mrad (vertical) and 2,2 mrad (horizontal). The MPE for rectangular sources is determined by the arithmetic mean of the two angular subtenses. As stated in 13.4.2, before determining the mean, any angular subtense less than 1,5 mrad or greater than 100 mrad should be replaced by 1,5 mrad or 100 mrad, respectively. Therefore the mean is as follows:

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

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

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

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

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

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

Horizontal two-diode group

A plausible group of the array to consider is two horizontally adjacent diodes subtending angles of 0,5 mrad (vertical) by 5,2 mrad (horizontal). Replacing 0,5 mrad by 1,5 mrad as stated in 13.4.2, the arithmetic mean of the two angular dimensions is (1,5 + 5,2)/2 mrad = 3,35 mrad. The correction factor is C_6 = 3,35/1,5 = 2,23 and the applicable MPE is as follows:

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

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

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

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

Vertical two-diode group

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

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

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

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

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

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Four-diode group

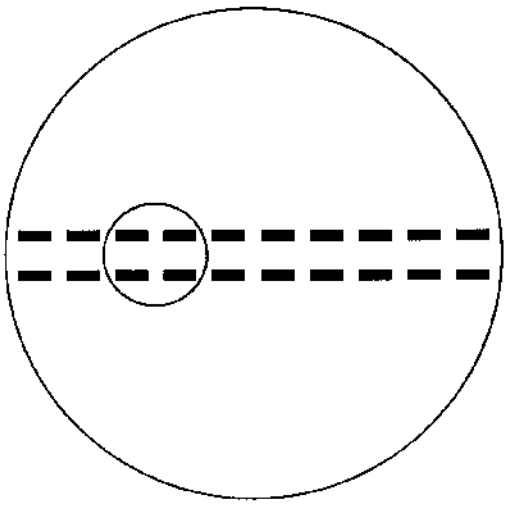
Another plausible sub-unit of the array to consider is four adjacent diodes (2 by 2) subtending angles of 2,8 mrad (vertical) by 5,2 mrad (horizontal). The arithmetic mean of the two angular dimensions is 4 mrad. Hence the correction factor is C_6 = 4/1,5 = 2,67. The applicable MPE is as follows:

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

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

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

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



CEI 1216/93

Figure A.1 – Laser diode array with two groupings

One row of 10 diodes

Another interesting grouping to evaluate is one entire row of 10 diodes subtending angles of 0,5 mrad (vertical) and 29,2 mrad (horizontal). Replacing 0,5 mrad by 1,5 mrad, as stated in 13.4.2, the arithmetic mean of the two angular dimensions is (1,5 + 29,2)/2 mrad = 15,3 mrad. Hence the correction factor is C_6 = 15,3/1,5 = 10,2.

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

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

$$E_{\mathrm{ten}} = E_{\mathrm{diode}} \times 10 = 180 \times 10\ \mathrm{W{\cdot}m^{-2}} = 1\,800\ \mathrm{W{\cdot}m^{-2}}$$

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

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20-diode group

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

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

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

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

Additional remarks

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

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

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

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

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

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

This value should be compared with the following:

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

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

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

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Thu Sep 18 11:44:41 2003

Required optical density

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

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

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

Use of an optical device

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

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

Since the measurement method requires a maximum acceptance angle of α_{max} = 100 mrad to collect the radiation (see 8.4 d)), when one of the two angular dimensions of the grouping, e.g. the horizontal one (indicated by α_{hor}), is greater than α_{max}, the power of the grouping should be reduced to a factor of $\alpha_{max}/\alpha_{hor}$, to exclude the part of the source which is outside the acceptance angle. Furthermore, any angular subtense should be limited to α_{max} before determining the arithmetic mean to be used for the calculation of C_6, as stated in 13.4.2. However in this specific example, all the angular subtenses are less than α_{max}.

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

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

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

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

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Thu Sep 18 11:44:42 2003

A.3 Maximum permissible exposures (MPE) – diffuse reflections and extended sources

Examples of extended source viewing are:

1) Laser radiation within the wavelength range 400 nm to 1 400 nm is reflected from a diffusing surface (apparent source).
2) The image formed on the retina of the eye by the diffuse reflection is larger than a certain minimum value of the retinal image, determined by the limiting angular subtense α_{min}, where α_{min} is equal to 1,5 mrad.

The limiting angular subtense α_{min} is measured at a distance of no less than 100 mm from the apparent source (see 8.4 c)).

Example A.3-1

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

a) What is the range over which extended source viewing conditions exist?
b) What is the MPE at a distance of 2,5 m from the diffuser?

Solution:

The angular subtense is defined by the equation:

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

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

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

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

For this example

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

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

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

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

where

C_7 = 1 for λ = 1 064 nm (see notes to tables 1 to 4). For the small source viewing situation, $\alpha \leq \alpha_{min}$, C_6 = 1, and the MPE is

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

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Thu Sep 18 11:44:42 2003

b) At distances less than $r_{1,max}$ = 13 m, extended source viewing conditions exist, and $C_6 = \alpha/\alpha_{min}$ for $\alpha_{min} < \alpha \leq \alpha_{max}$ = 0,1 rad. At the distance of r_1 = 2,5 m,

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

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

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

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

Example A.3-2

Find the maximum radiant energy from the laser in example A.3-1 permitting non-hazardous viewing of the output reflected from a perfect diffuser located less than 0,2 m from the observer's eye.

Solution:

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

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

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

and the diffuse reflection MPE expressed as an integrated radiance is

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

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

The integrated radiance MPE for this problem is obtained by substituting the small source MPE obtained in example A.3-2:

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

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

$$H = \pi \times L_p$$

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

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

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Thu Sep 18 11:44:42 2003

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

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

Example A.3-3

Calculate the minimum safe viewing distance normal to a perfect diffusing screen if the output from the laser in example A.3-2 is focused on the screen.

Solution:

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

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

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

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

$$r_{NOHD} = \left(\frac{Q \cos}{\pi H_{MPE,\text{small src.}}} \right)^{1/2}$$

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

$$r_{NOHD} = \sqrt{\frac{0{,}42 \text{ J} \times \cos(0)}{\pi \times 0{,}05 \text{ J} \cdot \text{m}^{-2}}} = 1{,}6 \text{ m}$$

A.4 Maximum permissible exposure (MPE) – Repetitively pulsed systems

The rules applying to exposures from repetitively pulsed systems (or exposures from scanning laser systems) are set out in 13.3.

Example A.4-1

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

Solution:

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

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Thu Sep 18 11:44:42 2003

Subclause 13.3 includes three criteria which must be considered, and the most restrictive one applies to this evaluation. The value of C_6 is 1 in these calculations since the beam is emitted from a small source.

From 13.3a), the exposure from any single-pulse shall not exceed the single-pulse MPE. Thus, the radiant exposure for the time period of 10^{-8} s from table 6 is

$$H_{single} = 5 \times 10^{-3} \times C_6\ J \cdot m^{-2} = 5 \times 10^{-3} \times 1\ J \cdot m^{-2} = 5 \times 10^{-3}\ J \cdot m^{-2}$$

From 13.3b), the average exposure for a pulse train of exposure duration T shall not exceed the MPE for a single pulse of exposure duration T. For the total 0,25 s exposure duration, table 6 limits the radiant exposure to

$$H_T = 18\ t^{0,75}\ C_6\ J \cdot m^{-2} = 18 \times (0,25)^{0,75} \times 1\ J \cdot m^{-2} = 6,36\ J \cdot m^{-2}$$

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

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

From 13.3c), the average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5 (where $C_5 = N^{-1/4}$). The maximum exposure duration for which requirement c) should be applied is T_2 in the wavelength range 400 nm to 1 400 nm, where $T_2 = 10$ s for $\alpha \leq \alpha_{min}$.

Since the laser is operating at a high repetition rate, note 2 to 13.3c) is applicable. This requires that, if multiple pulses appear within the period of T_i (see table 9 for $T_i = 18 \times 10^{-6}$ s) they are counted as a single pulse to determine N and the radiant exposure of the individual pulses is added to be compared to the MPE of T_i. Hence, the effective pulse repetition frequency is:

$$F_E = 1/T_i = 1/(18 \times 10^{-6}) = 55,56\ kHz$$

The MPE for a pulse of duration T_i is given in table 6 as $5 \times 10^{-3}\ C_6\ J \cdot m^{-2} = 5 \times 10^{-3}\ J \cdot m^{-2}$.

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

$$N_E = T \times F_E = 0,25 \times 55,56 \times 10^3 = 1,39 \times 10^4$$

For $N_E = 1,39 \times 10^4$ pulses each of duration T_i in the 0,25 s period the radiant exposure under this criteria would be:

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

Conditions 13.3a) and 13.3b) are applicable to a pulse of energy, Q, while condition 13.3c) is applicable to a pulse of energy $= Q \times T_i \times F = 18 \times Q$. Hence, dividing H_{train} by 18 (to give $2,55 \times 10^{-5}\ J \cdot m^{-2}$) enables the three MPEs calculated from 13.3 to be compared. In this example criteria 13.3b) and 13.3c), which are equal, are the most restrictive; the single-pulse MPE for this system would be $2,55 \times 10^{-5}\ J \cdot m^{-2}$.

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Thu Sep 18 11:44:43 2003

Example A.4-2

Determine the intrabeam MPE for direct ocular exposure to the radiation from a Nd:YAG laser (λ = 1 060 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 blink reflex. A reasonable estimate of a hazardous chance exposure time can be taken as 10 s. For this time period, the total number of pulses is:

$$N = T \times F = 10\ \text{s} \times 20\ \text{Hz} = 200$$

Subclause 13.3 includes three criteria which must be considered, and the most restrictive one applies to this evaluation. The value of C_6 is 1 in these calculations since the beam is emitted from a small source. The value of C_7 from notes to tables 1 to 4 is also 1 for the 1 060 nm wavelength.

From 13.3a), the exposure from any single pulse shall not exceed the single pulse MPE. Thus the radiant exposure from table 6 for the time period of 1 ms is:

$$H_{\text{single}} = 90\ t^{0,75}\ C_6\ C_7\ \ \text{J}\cdot\text{m}^{-2} \quad = 90 \times 0{,}001^{0,75} \times 1 \times 1\ \text{J}\cdot\text{m}^{-2} = 0{,}506\ \text{J}\cdot\text{m}^{-2}.$$

From 13.3b), the average exposure for a pulse train of exposure duration T shall not exceed the MPE for a single pulse of exposure duration T. For the 10 s duration (the total exposure time), table 6 limits the radiant exposure to:

$$H_{\text{T}} = 90\ t^{0,75}\ C_6\ C_7\ \text{J}\cdot\text{m}^{-2} = 90 \times 10^{0,75} \times 1 \times 1\ \text{J}\cdot\text{m}^{-2} = 506\ \text{J}\cdot\text{m}^{-2}$$

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

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

From 13.3c), the average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5 (where $C_5 = N^{1/4}$). For the N = 200 pulses in the 10 s period, the radiant exposure under this criteria would be:

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

Since the limit from the repetitive pulse criteria of 13.3 c) is the most restrictive, the single pulse MPE for this system would be 0,135 J·m^{-2}. The MPE could also be expressed in terms of irradiance as:

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

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A.5 Nominal ocular hazard distance (NOHD)

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

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

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

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

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

where I = radiant intensity ($W \cdot sr^{-1}$) (see 9.2 on measurements).

If I is not known and cannot be measured, the value for P_o in equation (1) above can be increased by 2,5 for laser systems known to have a multi-mode beam structure.

The term $e^{-\mu r}$ accounts for losses due to atmospheric attenuation and may be neglected for most purposes, simplifying equation (1) to:

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

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

$$\text{NOHD} = \frac{\sqrt{4P_o/\pi\,E_{MPE}} - a}{\phi} \qquad (3)$$

If the effects of atmospheric attenuation are to be included, a simple solution to equation (1) in terms of r, cannot be found. However, the following approach will lead to an oversafe result:

$$r_\mu = 0{,}5\,r_c\,(1 + e^{-\mu r_c}) \qquad (4)$$

where

r_μ is the distance including atmospheric attenuation, and

r_c is the distance calculated from equation (3).

A reliable estimate for μ, the atmospheric attenuation coefficient, can be obtained from the following formula:

$$\mu = 10^{-3} \times \frac{3{,}91}{V} \times \left(\frac{0{,}55}{\lambda}\right)^A \ m^{-1} \qquad (5)$$

where

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

V = visual range in km

λ = wavelength in μm ($0{,}4 < \lambda < 2$).

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Thu Sep 18 11:44:43 2003

Use of optical viewing aids

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

If the diameter of the exit pupil of the optical viewing aid is not greater than 7 mm, the increase in the amount of radiation entering the eye is dependent on the factor:

$$G = \frac{\text{diameter of objective lens or aperture of viewing aid}}{\text{theoretical pupillary diameter}} = \frac{D_o}{7 \times 10^{-3}}$$

The extended NOHD now becomes

$$\text{NOHD} = \text{basic NOHD} \times G + \frac{a(G-1)}{\phi}$$

in the worst case where the beam diameter is greater than the objective lens diameter, and when the exit pupil diameter is less than the eye pupil diameter.

Unless provided with special laser attenuating filters, no allowance should be made for transmission losses in viewing optics, as many devices have a high transmittance (0,8) extending well into the infra-red region of the spectrum above 2 000 nm.

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

Example A.5-1

A laser with a Gaussian beam profile 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 (3) gives:

$$\text{NOHD} = \frac{\sqrt{(4 \times 4)/10\pi} - 0{,}001}{0{,}7 \times 10^{-3}}\,\text{m} = \frac{0{,}7136 - 0{,}001}{0{,}7 \times 10^{-3}}\,\text{m} = 1{,}018\,\text{km}$$

Example A.5-2

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

Solution:

The new NOHD is:

$$\text{NOHD} = \frac{\sqrt{(4 \times 4)/10\pi} - 7 \times 10^{-3}}{0{,}1 \times 10^{-3}}\,\text{m} = 7{,}07\,\text{km}$$

Note the importance of beam divergence in determining the NOHD. Also note that in this case, the beam exit diameter a can be neglected.

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Example A.5-3

The laser in example A.5-2 operates at 550 nm. Calculate the modified NOHD, assuming a visual range of 20 km.

Solution:

The atmospheric attenuation coefficient, μ, is obtained using equation (5):

$$\mu = 10^{-3} \times \frac{3{,}91}{20} \times \left(\frac{0{,}55}{0{,}55}\right)^{A} = 1{,}95 \times 10^{-4}\ \mathrm{m}^{-1}$$

The modified NOHD can now be obtained from equation (4):

$$r_{\mu} = 0{,}5 \times 7{,}07\ (1 + e^{-(1{,}95 \times 10^{-4} \times 7{,}07 \times 10^{3})})\ \mathrm{m} = 4{,}4\ \mathrm{km}$$

NOTE An exact solution of equation (1) results in an NOHD of 4,3 km.

Example A.5-4

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

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

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

Solution:

a) The output power $P_0 = 3 \times 10^{-3}$ W, and the initial beam diameter a = 0,013 m. The beam divergence is therefore

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

For an exposure duration between 10 s and 3×10^4 s, the appropriate MPE is given in table 6 as one of three possibilities depending on the exposure duration, t, relative to the break point, T_2, and for $t > T_2$ on the value of α:

1st case: For an exposure duration $t \leq T_2$

$$H_{\mathrm{MPE}} = 18\ t^{0{,}75}\ C_6\ \mathrm{J \cdot m^{-2}}$$

which is equivalent to

$$E_{\mathrm{MPE}} = 18\ t^{-0{,}25}\ C_6\ \mathrm{W \cdot m^{-2}}$$

2nd case: For an exposure duration $t > T_2$ and $\alpha \leq 1{,}5$ mrad

$$E_{\mathrm{MPE}} = 10\ \mathrm{W \cdot m^{-2}}$$

Thus, for this problem with an exposure duration of $t > T_2$ the MPE is constant and independent of exposure duration.

3rd case: For an exposure duration $t > T_2$ and $\alpha > 1{,}5$ mrad

$$E_{\mathrm{MPE}} = 18\ T_2^{\ 0{,}25}\ C_6\ \mathrm{W \cdot m^{\ 2}}$$

NOTE All correction factors are listed in the notes to tables 1 to 4. The irradiance expressions are often a more convenient form for the solution of ranging problems.

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Thu Sep 18 11:44:43 2003

This is a small-source type viewing condition; therefore, $\alpha \leq \alpha_{min}$, C_6 = 1 and T_2 = 10 s (it should be emphasized that the source size is never the diameter of the laser output beam unless the beam passes through a diffuser or the beam is emitted from a laser array).

This part of the problem is solved by equating the irradiance MPE expression given above with the irradiance at a range r expression (i.e., equation (1)), and solving for the exposure duration t. Thus, assuming that case 1 is valid (i.e., $t < T_2$), then the maximum exposure duration is obtained by solving the following expression for t:

$$E_{MPE} = 18\ t^{-0,25} = \frac{4\,P_o}{\pi\,(a + r\,\phi)^2}$$

$$18\ t^{-0,25} = \frac{4 \times 3 \times 10^{-3}}{\pi\,(0,013 + 60 \times 10^{-4})^2} = 10,58\ \mathrm{W \cdot m^{\ 2}}$$

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

The exposure duration t = 8,38 s is less than T_2, so there is no reason to evaluate the second and third cases.

For b): The minimum range for safe viewing can be obtained by solving equation (3) for the nominal ocular hazard distance (NOHD). In this case, the exposure duration t = 180 s is used which is greater than T_2 and therefore case 2 applies where E_{MPE} = 10 W·m^{-2}:

$$r_{NOHD} = \frac{1}{\phi} \times \left[\sqrt{\frac{4\,P_o}{\pi\,E_{MPE}}} - a\right]$$

$$r_{NOHD} = \frac{1}{10^{-4}} \times \left[\sqrt{\frac{4 \times 3 \times 10^{-3}}{\pi \times 10}} - 0,013\right] = 65,4\ \mathrm{m}$$

Example A.5-5

A hand-held infra-red laser surveying instrument has the following characteristics:

wavelength λ is 903 nm;

pulse repetition frequency F is 300 Hz;

peak power per pulse P_p is 30 W;

energy per pulse Q_p is 6 × 10^{-7} J;

beam divergence ϕ is 10 mrad;

effective exit aperture diameter (equivalent circular section beam) is 55 mm.

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

a) for viewing by the unaided eye, and

b) when using 8 × 50 binoculars.

Solution:

a) Unaided eye condition

There are three stages to this assessment for a pulsed laser source; the first two are on the basis of the pulses entering the eye, and the third is determined by the accumulative and averaged effects of a multi-pulse exposure.

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Thu Sep 18 11:44:44 2003

In this example, it is assumed that the subtense α is less than α_{min} and for a small source $C_6 = 1$. If there is no intentional viewing, the exposure time to be used is 100 s; during this time the number of pulses is:

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

Single-pulse assessment

From the laser specification 700 nm < λ < 1 050 nm, the pulse width t_p is given by $30\ \text{W} \times t_p = 6 \times 10^{-7}$ J, thus $t_p = 20$ ns.

Table 6 gives the single-pulse MPE for this radiation with the exposure time of 20 ns, as:

$$H_{MPE} = 5 \times 10^{-3}\ C_4\ C_6\ \text{J·m}^{-2}$$

where $C_4 = 10^{(903-700)/500} = 2{,}55$ and $C_6 = 1$.

Multiple pulse assessment

From 13.3c), the average exposure from pulses within a pulse train shall not exceed the MPE for a single pulse multiplied by the correction factor C_5 (where $C_5 = N^{-1/4}$). The maximum exposure duration for which requirement c) should be applied is T_2 in the wavelength range 400 nm to 1 400 nm, where $T_2 = 10$ s for $\alpha \leq \alpha_{min}$. Hence:

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

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

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

From the value of $H_{MPE,\ train}$ the corresponding value in irradiance can be derived:

$$E_{MPE,\ train} = \frac{H_{MPE,\ train}}{t_p} = \frac{1{,}72 \times 10^{-3}}{20 \times 10^{-9}} = 8{,}61 \times 10^4\ \text{W·m}^{-2}$$

To find the range at which this threshold for a reduced single pulse is exceeded, the range equation of the previous example is used:

$$r_{NOHD} = \frac{1}{\phi} \times \left[\sqrt{\frac{4\,P_p}{\pi \times E_{MPE,\ train}}} - a \right]$$

$$r_{NOHD} = \frac{1}{0{,}01} \times \left[\sqrt{\frac{4 \times 30}{\pi \times 8{,}61 \times 10^4}} - 0{,}055 \right] = -3{,}39\ \text{m}$$

This value of r_{NOHD} is negative. Thus, according to the multiple-pulse assessment, it is safe to suffer exposure to this laser beam at any range, on the basis of the reduced single-pulse value.

Average exposure assessment

The MPE for an exposure duration of 100 s is obtained from table 6. Since $\alpha \leq 1{,}5$ mrad $T_2 = 10$ s, therefore the condition $t > T_2$ applies:

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

where $C_4 = 2{,}55$ and $C_7 = 1$.

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Thu Sep 18 11:44:44 2003

The limit for the average irradiance of the pulse train (see 13.3) is the following:

$$E_{MPE,\ avg} = 10 \times 2{,}55 \times 1 = 25{,}5\ \mathrm{W{\cdot}m^{-2}}$$

The average power of the pulse train is:

$$P_{avg} = P_p \times t_p \times F = 30\ \mathrm{W} \times 20 \times 10^{-9}\ \mathrm{s} \times 300\ \mathrm{Hz} = 1{,}8 \times 10^{-4}\ \mathrm{W}$$

Therefore the limit for the distance is

$$r_{NOHD} = \frac{1}{\phi} \times \left(\sqrt{\frac{4\,P_{avg}}{\pi\,E_{MPE,avg}}} - a \right)$$

$$r_{NOHD} = \frac{1}{0{,}01} \times \left[\sqrt{\frac{4 \times 1{,}8 \times 10^{-4}}{\pi \times 25{,}5}} - 0{,}055 \right] = -5{,}2\,\mathrm{m}$$

This result is negative. Thus, on the basis of the averaged exposure, the instrument is safe for viewing by the unaided eye at any distance. Therefore, for this instrument when only viewing by the unaided eye is involved, the appropriate NOHD is zero.

b) Binocular viewing condition

The pupil exit diameter of this instrument is 50/8 mm = 6,25 mm. Since this is less than 7 mm, it is assumed that all of this radiation enters the eye.

The increase in irradiance at the eye over that which exists at the instruments objective lens is given by:

$$G^2 - \left(\frac{D_o}{7 \times 10^{-3}} \right)^2 - \left(\frac{5{,}0 \times 10^{-2}\ \mathrm{m}}{7 \times 10^{-3}\ \mathrm{m}} \right)^2 - 51$$

where it is assumed that there is no attenuation through the optics.

Since the single-pulse assessment gives the most restricted condition for r in this case, the reduced single-pulse MPE ($E_{MPE,train}$) must be used to determine the NOHD. The maximum permitted irradiance at the objective lens is reduced by the factor G^{-2}:

$$E_{MPE(binocular)} = G^{-2} \times E_{MPE(unaided)} = 1{,}96 \times 10^{-2} \times 8{,}61 \times 10^4 = 1{,}69 \times 10^3\ \mathrm{W{\cdot}m^{-2}}$$

The range from the laser at which the single-pulse irradiance falls to $1{,}69 \times 10^3\ \mathrm{W{\cdot}m^{-2}}$ is given by

$$r_{NOHD} = \frac{1}{0{,}01} \times \left[\sqrt{\frac{4 \times 30}{\pi \times 1{,}69 \times 10^3}} - 0{,}055 \right] = 9{,}5\,\mathrm{m}$$

It is consequently hazardous for this laser instrument to be viewed with binoculars at distances of less than 9,5 m.

This example serves to illustrate the wide hazards involved in using invisible radiation lasers in open areas. Because of the requirement for 50 mm diameter collecting optics in classification, the above mentioned laser product would be classified as Class 3B.

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Example A.5-6

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

wavelength = 1 060 nm;

peak power per pulse P_p = 1,5 MW;

energy per pulse Q_p = 45 mJ;

pulse repetition rate = 12 per minute;

exit aperture beam diameter = 10 mm;

beam divergence angle = 1 mrad.

What is the effective NOHD on the basis of the single-pulse threshold (a) for exposure of the unaided eye, and (b) when intrabeam viewing through 50 mm diameter optics is involved? (Effects of beam attenuation or refractive focusing due to atmospheric transmission are neglected in these calculations.)

Solution:

a) Unaided eye condition

The pulse width t_p can be calculated from the condition $P_p \times t_p = Q_p$ by $1{,}5 \times 10^6 \times t_p = 45 \times 10^{-3}$

giving t_p = 30 ns (i.e. $10^{-9} < t_p < 5 \times 10^{-5}$ s). The pulse repetition frequency F is 12/60 = 0,2 Hz.

In this example, it is assumed that $\alpha \leq \alpha_{min}$ and for a small source C_6 = 1. If there is no intentional viewing, the exposure duration to be used is 100 s; during this time, the number of pulses is

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

The intrabeam MPE is taken as the most restrictive calculated from the application of 13.3.

Single-pulse assessment (condition 13.3a))

From table 6, the MPE for a single-pulse exposure from this laser is

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

where C_6 = 1 and C_7 = 1, therefore

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

Average irradiance assessment (condition 13.3b))

From table 6, the MPE for the exposure duration of 100 s is

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

where C_6 = 1 and C_7 = 1. There are 20 pulses in 100 s, therefore the average MPE per pulse is

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

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Multiple-pulse assessment (condition 13.3c))

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

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

The conclusion is that condition 13.3c) produces the most restrictive MPE per pulse and therefore, $H_{MPE} = 4{,}2 \times 10^{-2}\ \mathrm{J{\cdot}m^{-2}}$ for intrabeam viewing. The range equation of the previous example can be used to calculate r_{NOHD}; however, because the mode structure of this solid-state laser is not specified, the pulse energy should be increased by a factor 2,5. Therefore,

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

$$r_{NOHD} = \frac{1}{10^{-3}} \times \left[\sqrt{\frac{4 \times 2{,}5 \times 45 \times 10^{-3}}{\pi \times 4{,}2 \times 10^{-2}}} - 0{,}01 \right] = 1{,}84\ \mathrm{km}$$

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

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

$$r_{NOHD} = \frac{1}{10^{-3}} \times \left[\sqrt{\frac{4 \times 2{,}5 \times 0{,}1 \times 45 \times 10^{-3}}{\pi \times 4{,}2 \times 10^{-2}}} - 0{,}01 \right] = 574\ \mathrm{m}$$

b) Binocular viewing condition

When 50 mm diameter collecting optics are involved in the intrabeam viewing of this laser, the NOHD is increased because the maximum permitted irradiance is reduced by the gain factor:

$$G^{-2} - \left(\frac{7\ \mathrm{mm}}{50\ \mathrm{mm}} \right)^2 - 1{,}96 \times 10^{-2}$$

The equation for the multiple-pulse assessment, modified by the insertion of the gain factor $1{,}96 \times 10^{-2}$, gives the following result for the NOHD:

$$r_{NOHD} = \frac{1}{10^{-3}} \times \left[\sqrt{\frac{4 \times 2{,}5 \times 45 \times 10^{-3}}{\pi \times 1{,}96 \times 10^{-2} \times 4{,}2 \times 10^{-2}}} - 0{,}01 \right] = 13{,}18\ \mathrm{km}$$

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

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A.6 Accessible emission limits for diverging beam, small sources

Introduction:

Intrabeam viewing conditions exist whenever the conditions of extended source viewing are not met, i.e., whenever the apparent source (e.g. approximately the beam waist for beams with high divergence) forming the retinal image appears at an angle α not larger than the limiting angular subtense α_{min} when determined at the measurement distance (not less than 100 mm). Examples of such sources are laser beams (collimated or focused), beams through a small aperture, optical fibre ends, or the emitting surface of a semiconductor laser.

All of the examples in clause A.6 assume that the beam emerging from the small source is diverging (i.e., not collimated) and that the far-field beam profile is Gaussian. The Gaussian approximation simplifies calculations and works well as a conservative estimate for many divergent beam sources (e.g., optical fibre). In addition, all of the examples assume that intentional viewing is not inherent in the design or function of the sources described; therefore, the time base is 100 s (see 8.4 e)).

Diameter of a divergent beam

The diameter of a divergent beam, d_{63}, at a distance r from the apparent source is required to perform AEL and MPE calculations involving an aperture. Most manufactures of divergent beam sources will specify the divergence in terms of a numerical aperture or NA. The NA of a point source is defined as the sine of one-half the divergence, ϕ, of the output beam, as measured at the 5 %-of-peak-irradiance points. That is

$$\mathrm{NA} = \sin\frac{\phi}{2}$$

and

$$\frac{\phi}{2} = \arcsin(\mathrm{NA})$$

For a Gaussian beam, the beam diameter that corresponds to the 5 %-of-peak-irradiance points contains 95 % of the total power or energy. The beam diameter, d_{95}, at a distance r from the apparent source is given by:

$$d_{95} = a + 2\,r\tan\frac{\phi}{2} = a + 2\,r\tan\left(\arcsin(\mathrm{NA})\right)$$

Since a is of the order of a few tens of µm, it can be ignored in most situations. In addition, for safety calculations the beam diameter at the 63 % total power (or energy) points is used rather than the 95 % points. The conversion factor for a Gaussian beam is 1,7 (i.e., d_{95}/d_{63} = 1,7); hence, the beam diameter is approximated by:

$$d_{63} = \frac{d_{95}}{1{,}7} = \frac{2\,r}{1{,}7}\tan\left(\arcsin(\mathrm{NA})\right) = \frac{2\,r\,\mathrm{NA}}{1{,}7} \qquad (1)$$

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_o, and the wavelength, λ, of the source. The beam diameter of a single-mode optical fibre, at a distance r, is approximated by:

$$d_{63} = \frac{2\sqrt{2}\,r\,\lambda}{\pi\,w_o} \qquad (2)$$

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

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Power passing through an aperture

Many of the classification procedures require the measurement of the power (or energy) passing through a specified aperture located at a specified distance from the apparent source. For a Gaussian beam, the fraction of the total power (or energy) passing through a circular aperture of diameter, d_a, at a distance r, can be expressed in terms of a coupling parameter

$$\eta = 1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2} \qquad (3)$$

where d_{63} is the beam diameter, determined at the 63 % points (i.e., 1/e points for a Gaussian beam) at the aperture distance. The total power (or energy) passing through the aperture is

$$P_a = \eta\, P_o \quad \text{or} \quad Q_a = \eta\, Q_o \qquad (4)$$

where P_o is the total power (and Q_o is the total energy) emitted from the apparent source.

Example A.6-1

An optical-fibre transmitter emits at a wavelength of 850 nm from a 100 µm core diameter multi-mode fibre with a numerical aperture of 0,3. If the transmitter is operated in CW mode, what is the maximum total power allowed for classification as

a) Class 1, and

b) Class 1M.

Solution:

a) Class 1

The time base used for a Class 1 system is 100 s. Table 1 indicates that the AEL for emission in the wavelength range 700 nm to 1 050 nm with an exposure duration in the range from 10 s to 3×10^4 s depends on the value of T_2 given in the notes to tables 1 to 4 by the expression:

$$T_2 = 10 \times 10^{(\alpha - 1{,}5\ \text{mrad})/98{,}5}\ \text{s}$$

Since we have a small source $\alpha \le \alpha_{min}$ then $T_2 = 10$ s and $t > T_2$. From table 1

$$P_{AEL} = 3{,}9 \times 10^{-4}\ C_4\ C_7\ \text{W}$$

where

$C_4 = 2$, $C_7 = 1$ and hence $P_{AEL} = 7{,}8 \times 10^{-4}$ W

The measurement specifications given in 9.3 indicate that the P_{AEL} for a source that failed condition 2 of table 10 must be compared to the power collected though a 7 mm aperture at a distance of 14 mm from the source. In this example, the beam diameter at the measurement distance is

$$d_{63} = \frac{2\,r\,NA}{1{,}7} = \frac{2 \times 14 \times 0{,}3}{1{,}7} = 4{,}94\ \text{mm}$$

and all of the emitted power will pass through the 7 mm measurement aperture. Therefore, the maximum Class 1 output power is the P_{AEL} value of 0,78 mW.

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This maximum total output power value is for CW operation. In the case of a digital transmission with a duty cycle of 50 %, the pulse power of a single pulse in the train may be up to twice the CW power derived above (depending on the characteristics of the pulse train (see 8.4f)) repetitively pulsed or modulated lasers).

b) Class 1M

If the level of radiation as determined according to table 10 is larger than the AEL of Class 1 for condition 1 or condition 2 and less than the AEL of Class 3B, but the level of radiation measured with an aperture stop of 7 mm diameter at a distance of 100 mm from the apparent source is less than or equal to the AEL of Class 1, the laser product is assigned to Class 1M.

In this example, the beam diameter at the measurement distance of 100 mm is

$$d_{63} = \frac{2\,r\,NA}{1{,}7} = \frac{2 \times 100 \times 10^{-3} \times 0{,}3}{1{,}7} = 35{,}3\,\text{mm}$$

and the fraction of the total emitted power that passes through the measurement aperture is

$$P_a = \eta\,P_o = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] P_o = \left[1 - e^{-\left(\frac{7}{35{,}3}\right)^2}\right] P_o = 0{,}039\,P_o$$

The maximum Class 1M output power is obtained by equating P_a with P_{AEL}:

$$P_{o,max} = \frac{P_{AEL}}{\eta} = \frac{0{,}78}{0{,}039} = 20\,\text{mW}$$

Since this is less than the P_{AEL} (500 mW) of Class 3B. Therefore, in this example, the maximum Class 1M output power is 20 mW.

Example A.6-2

An optical fibre transmitter emitting at 780 nm is used for digital data transmission at a rate of 125 Mbits/s. The transmission code used is a balanced code (i.e., equal numbers of one-bits and zero-bits in any group of two or three bytes long) and, therefore, the average power emitted is not data dependent. The numerical aperture of the product transmitter port has been determined to be within the range 0,16 to 0,18. Determine (a) Class 1, (b) Class 1M and (c) Class 3R power limits and determine which are applicable.

Solution:

Since the emission is modulated, the requirements in 8.4 for repetitively pulsed or modulated lasers must be considered. The high data rate (i.e., short pulse times) results in the most restrictive of the three requirements identified in 8.4 being requirement "b". In this situation, the emission is treated like a CW source with a power level equal to the average power emitted from the transmitter.

a) Class 1

The time base used for a Class 1 system is 100 s. Table 1 indicates that the AEL for emission in the wavelength range 700 nm to 1 050 nm with an exposure duration in the range from 10 s to 3×10^4 s depends on the value of T_2 given in the notes to tables 1 to 4 by the expression:

$$T_2 = 10 \times 10^{(\alpha - 1{,}5\,\text{mrad})/98{,}5}\ \text{s}$$

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Since we have a small-source $\alpha \leq \alpha_{min}$ then T_2 = 10 s and $t > T_2$. From table 1

$$P_{AEL} = 3{,}9 \times 10^{-4}\ C_4\ C_7\ \text{W}$$

where $C_4 = 10^{0{,}002(\lambda - 700)} = 1{,}445$ and $C_7 = 1$ therefore

$$P_{AEL} = 3{,}9 \times 10^{-4} \times 1{,}445 \times 1 = 0{,}56\ \text{mW}$$

The measurement specifications given in 9.3 indicate that the P_{AEL} for a source that failed condition 2 of table 10 must be compared to the power collected though a 7 mm aperture at a distance of 14 mm from the source. In this example, the beam diameter at the measurement distance is

$$d_{63} = \frac{2\,r\,NA}{1{,}7} = \frac{2 \times 14 \times 0{,}16}{1{,}7} = 2{,}63\ \text{mm}$$

The fraction of the total emitted power (P_a) that passes through a 7 mm measurement aperture 14 mm from the source is

$$P_a = \eta\, P_o = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] P_o = \left[1 - e^{-\left(\frac{7}{2{,}63}\right)^2}\right] P_o \approx P_o$$

Therefore, the maximum emitted power for Class 1 is 0,56 mW.

b) Class 1M

If the level of radiation as determined according to table 10 is larger than the AEL of Class 1 for condition 1 or condition 2 and less than the AEL of Class 3B, but the level of radiation measured with an aperture stop of 7 mm diameter at a distance of 100 mm from the apparent source is less than, or equal to, the AEL of Class 1, the laser product is assigned to Class 1M.

In this example, the beam diameter at the measurement distance of 100 mm is

$$d_{63} = \frac{2\,r\,NA}{1{,}7} = \frac{2 \times 100 \times 0{,}16}{1{,}7} = 18{,}82\ \text{mm}$$

and the fraction of the total emitted power that passes through the measurement aperture is

$$P_a = \left[1 - e^{-\left(\frac{7}{18{,}82}\right)^2}\right] P_o = 0{,}13\, P_o$$

Thus, the maximum emitted power corresponding to Class 1M ($P_{o,max}$) is

$$P_{o,max} = \frac{P_{AEL}}{\eta} = \frac{0{,}56}{0{,}13} = 4{,}33\ \text{mW}$$

Since this is less than 500 mW (the Class 3B AEL), the maximum Class 1M emitted power is 4,33 mW.

c) Class 3R

The Class 3R limits are 5 times Class 1. For this example, that would be

$$P_{Class\ 3R} = 5 \times (P_{Class\ 1}) = 2{,}80\ \text{mW}$$

Since Class 1M > Class 3R, there is no Class 3R. Any power over 4,33 mW but less than 500 mW for this example, would be defined as Class 3B.

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Example A.6-3

An optical fibre transmitter emitting at 1 300 nm is used for digital data transmission at a rate of 630 Mbits/s. The transmission code used is a balanced code and, therefore, the average power emitted is not data dependent. The transmitter assembly is pigtailed to a single mode fibre having a mode field diameter of 10 µm.

a) Determine the maximum average output power for Class 1M and Class 3R AELs.

b) Determine the maximum average output power for Class 1M and Class 3R AELs if the emitting wavelength is 1 550 nm.

Solution:

As in example A.6-2 the output can be treated like a CW emission at a power level equal to the average emitted power due to the high data transmission rate and the balanced code.

a) 1 300 nm

At a wavelength of 1 300 nm and a time base of 100 s, the maximum average emitted power for Class 1M and Class 3R is found as follows:

Class 1M

The time base used for a Class 1 system is 100 s. Table 1 indicates that the AEL for emission in the wavelength range 1 050 nm to 1 400 nm with an exposure duration in the range from 10 s to 3×10^4 s depends on the value of T_2 given in the notes to tables 1 to 4 by the expression:

$$T_2 = 10 \times 10^{(\alpha - 1{,}5\ \text{mrad})/98{,}5}\ \text{s}$$

Since we have a small-source $\alpha \leq \alpha_{min}$ then $T_2 = 10$ s and $t > T_2$. From table 1:

$$P_{AEL} = 3{,}9 \times 10^{-4}\ C_4\ C_7\ \text{W}$$

where $C_4 = 5$ and $C_7 = 8$ therefore

$$P_{AEL} = 15{,}6\ \text{mW}$$

This aperture power is then corrected for the aperture coupling loss with the coupling parameter η (defined in equation (3)) to obtain the maximum emitted power level for the AEL condition. The coupling parameter depends upon the diameter of the beam at the distance the aperture is located from the source (100 mm). For the single-mode fibre in this example the beam diameter is given by equation (2):

$$d_{63} = \frac{2\sqrt{2}\, r\, \lambda}{\pi\, \omega_o} = \frac{2 \times \sqrt{2} \times 100 \times 1\ 300}{\pi \times 10} = 11{,}7\ \text{mm}$$

The fraction of the total emitted power (P_a) that passes through a 7 mm measurement aperture 100 mm from the source is

$$P_a = \eta\, P_o = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] P_o = \left[1 - e^{-\left(\frac{7}{11{,}7}\right)^2}\right] P_o = 0{,}30\, P_o$$

The maximum emitted power corresponding to Class 1M ($P_{o,max}$) is

$$P_{o,max} = \frac{P_{AEL}}{\eta} = \frac{15{,}6}{0{,}3} = 51{,}8\ \text{mW}$$

Because 51,8 mW is less than 500 mW, Class 1M = 51,8 mW

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Class 3R

At a wavelength of 1 300 nm and a time base of 100 s table 3 gives the small source ($\alpha \leq \alpha_{min}$) AEL expression for total emitted power as

$$P_{AEL} = 2 \times 10^{-3}\ C_4\ C_7\ \text{W}$$

where $C_4 = 5$ and $C_7 = 8$, therefore

$P_{AEL} = 2 \times 10^{-3} \times 5 \times 8 = 80$ mW

Due to the small beam divergence of a single-mode fibre, essentially 100 % of the emitted power is coupled into a 7 mm aperture at 14 mm from the source. Hence, the aperture coupling parameter $\eta = 1$ and the maximum average power level with respect to the total power condition can be equated with the AEL value (i.e., $P_{max} = P_{AEL}$).

Because 80 mW > 51,8 mW, Class 3R exists for this example. Therefore, for this example, the product can be any of the following classes based on the output power: Class 1, Class 1M, Class 3R, Class 3B or Class 4.

b) 1550 nm

Class 1M

If the same system is operated at 1 550 nm, then the procedure for performing the calculations is the same except that the AEL expression and apertures associated with the 1550 nm wavelength are used.

Since we have a small-source $\alpha \leq \alpha_{min}$ and $t = 100$ s, then from table 1

$$P_{AEL} = 10\ \text{mW}$$

The beam diameter at 100 mm is

$$d_{63} = \frac{2\sqrt{2}\, r\, \lambda}{\pi\, \omega_o} = \frac{2 \times \sqrt{2} \times 100 \times 1550}{\pi \times 10} = 13{,}95\ \text{mm}$$

The fraction of the total emitted power (P_a) that passes through a 3,5 mm measurement aperture 100 mm from the source is

$$P_a = \eta\, P_o = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] P_o = \left[1 - e^{-\left(\frac{3{,}5}{13{,}95}\right)^2}\right] P_o = 0{,}061\ P_o$$

The maximum emitted power corresponding to Class 1M ($P_{o,max}$) is

$$P_{o,max} = \frac{P_{AEL}}{\eta} = \frac{10}{0{,}061} = 164\ \text{mW}$$

Since $P_{o,max}$ is more than five times the Class 1 AEL, there is no Class 3R for this product.

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Annex B
(informative)

Biophysical considerations

B.1 Anatomy of the eye

See figure B.1.

Figure B.1(A)

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

Figure B.1(B)

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

Figure B.1(C)

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

Figure B.1(D)

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

Figure B.1(E)

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

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B.2 The effects of laser radiation on biological tissue

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

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

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

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

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

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

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

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

CIE Spectral region [a]	Eye	Skin	
Ultra-violet C (180 nm to 280 nm)	Photokeratitis	Erythema (sunburn) Accelerated skin ageing process Increased pigmentation	
Ultra-violet B (280 nm to 315 nm)			
Ultra-violet A (315 nm to 400 nm)	Photochemical cataract	Pigment darkening Photosensitive reactions	Skin burn
Visible (400 nm to 780 nm)	Photochemical and thermal retinal injury		
Infra-red A (780 nm to 1 400 nm)	Cataract, retinal burn		
Infra-red B (1,4 µm to 3,0 µm)	Aqueous flare, cataract, corneal burn		
Infra-red C (3,0 µm to 1 mm)	Corneal burn only		

[a] The spectral regions defined by the CIE are short-hand notations useful in describing biological effects and may not agree perfectly with spectral breakpoints in the MPE tables.

B.2.1 Hazards to the eye

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

Visible and near infra-red lasers are a special hazard to the eye because the very properties necessary for the eye to be an effective transducer of light result in high radiant exposure being presented to highly pigmented tissues. The increase in irradiance from the cornea to the retina is approximately the ratio of the pupil area to that of the retinal image. This increase arises because the light which has entered the pupil is focused to a "point" on the retina. The pupil is a variable aperture but the diameter may be as large as 7 mm when maximally dilated in the young eye. The retinal image corresponding to such a pupil may be between 10 µm and 20 µm in diameter. With intra-ocular scattering and corneal aberrations considered, the increase in irradiance between the cornea and the retina is of the order of 2×10^5.

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If an increase of 2×10^5 is assumed, a 50 $W \cdot m^{-2}$ beam on the cornea becomes 1×10^7 $W \cdot m^{-2}$ on the retina. In this standard, a 7 mm pupil is considered as a limiting aperture as this is a worst-case condition and is derived from figures obtained from the young eye where pupillary diameters of this order have been measured. An exception to the assumption of a 7 mm pupil was applied in the derivation of exposure limits to protect against photoretinitis whilst viewing bright visible (400 nm to 700 nm) laser sources for periods in excess of 10 s. In this latter situation, a 3 mm pupil was assumed as a worst-case condition; however, a 7 mm irradiance averaging aperture for measurement was still considered appropriate due to physiological movements of the pupil in space. Hence, AELs for durations greater than 10 s are still derived for a 7 mm aperture.

If an intense beam of laser light is brought to a focus on the retina only a small fraction of the light (up to 5 %) will be absorbed by the visual pigments in the rods and cones. Most of the light will be absorbed by the pigment called melanin contained in the pigment epithelium. (In the macular region some energy in the 400 nm to 500 nm range will be absorbed by the yellow macular pigment.) The absorbed energy will cause local heating and will burn both the pigment epithelium and the adjacent light sensitive rods and cones. This burn or lesion may result in a loss of vision. Photochemical injuries, although non-thermal, are also localized in the pigment epithelium.

Depending on the magnitude of the exposure, such a loss of vision may or may not be permanent. A visual decrement will usually be noted subjectively by an exposed individual only when the central or foveal region of the macula is involved. The fovea, the pit in the centre of the macula, is the most important part of the retina as it is responsible for sharpest vision. It is the portion of the retina that is used "to look right at something". This visual angle subtended by the fovea is approximately equal to that subtended by the moon. If this region is damaged, the decrement may appear initially as a blurred white spot obscuring the central area of vision; however, within two or more weeks, it may change to a black spot. Ultimately, the victim may cease to be aware of this blind spot (scotoma) during normal vision. However, it can be revealed immediately on looking at an empty visual scene such as a blank sheet of white paper. Peripheral lesions will only be registered subjectively when gross retinal damage has occurred. Small peripheral lesions will pass unnoticed and may not even be detected during a systematic eye examination.

In the wavelength range from 400 nm to 1 400 nm, the greatest hazard is retinal damage. The cornea, aqueous humour, lens and vitreous humor are transparent for radiation of these wavelengths. In the case of a well-collimated beam, the hazard is virtually independent of the distance between the source of radiation and the eye, because the retinal image is assumed to be a diffraction-limited spot of around 10 μm to 20 μm diameter. In this case, assuming thermal equilibrium, the retinal zone of hazard is determined by the limiting angular subtense α_{min}, which generally corresponds to retinal spot of approximately 25 μm in diameter.

In the case of an extended source, the hazard varies with the viewing distance between the source and the eye, because whilst the instantaneous retinal irradiance only depends on the source's radiance and on the lens characteristics of the eye, thermal diffusion of energy from larger retinal images is less efficient, leading to a retinal spot-size dependence for thermal injury which does not exist for photochemical injury (dominating only in the 400 nm to 600 nm spectral region). In addition, eye movements further spread the absorbed energy for CW laser exposures, leading to different dependencies of risk for differing retinal image sizes.

In the derivation of limits for ocular exposure in the retinal hazard region, correction factors for eye movements were only applied for viewing durations exceeding 10 s. Although physiological eye movements known as saccades do spread the absorbed energy in minimal retinal images (of the order of 25 μm or less) within the 0,1 s to 10 s time regime, the limits provide a desired added safety factor for this viewing condition. At 0,25 s, the mean retinal spot illuminated is approximately 50 μm. By 10 s, the illuminated retinal zone becomes approximately 75 μm and the added safety factor for the minimal image condition becomes 1,7 over a stabilized eye, with the spot-size dependence taken into account. By 100 s, it is rare to achieve an illuminated zone (measured at 50 % points) as small as 135 μm leading to an additional safety factor of 2-3 or more for the minimal image condition.

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The data from eye-movement studies and retinal thermal injury studies were combined to derive a break-point in viewing time T_2 at which eye movements compensated for the increased theoretical risk of thermal injury for increased retinal exposure durations if the eye were immobilized. Because the thermal injury threshold expressed as radiant power entering the eye decreases as the exposure duration t raised to the –0,25 power (i.e. a reduction of only 44 % per tenfold increase in duration), only moderate increases in the exposed retinal area will compensate for the increased risk for longer viewing times. The ever-increasing retinal area of irradiation resulting from greater eye movements with increased viewing time takes longer to compensate for the reduced impact of thermal diffusion in larger extended sources. Thus, for increasing angular subtense α, the break-point T_2 increases from 10 s for small sources to 100 s for larger sources. Beyond 100 s there is no further increase in risk of thermal injury for small and intermediate size images. The specification of limits and measuring conditions attempt to follow these variables with some simplification leading to a conservative determination of risk. It is conservatively assumed that retinal thermal injury thresholds vary inversely with retinal image size (stabilized) between approximately 25 µm to 1 mm (corresponding to angular sizes of 1 µm to 59 mrad), whilst beyond 1,7 mm (corresponding to angular sizes greater than 100 mrad), there is no spot-sized dependence.

For photochemically induced retinal injury there is no spot size dependence for a stabilized image. Unlike thermal injury mechanism, the thresholds for photochemical injury are highly wavelength dependent and are exposure dose dependent, i.e. the thresholds decrease inversely with the lengthening of exposure time. Studies of photochemical retinal injury from welding arcs subtending angles of the order of 1 mrad to 1,5 mrad showed typical lesion sizes of the order of 185 µm to 200 µm (corresponding to visual angles of 11 mrad to 12 mrad), clearly showing the influence of eye movements during fixation; these and other studies of eye movements during fixation led to the derivation of MPEs to protect against photochemical retinal injury. These studies also led to MPE irradiance to be specified as being averaged over 11 mrad for exposure durations between 10 s and 100 s. Hence, sources with an angular subtense α less than 11 mrad were treated equally with "point-type" sources, and the concept of α_{min} was extended to CW laser viewing. This approach was not strictly correct, as an irradiance measurement of an 11-mrad source is not equivalent to irradiance averaging over a field of view (γ) of 11 mrad unless the source had a rectangular ("top-hat") radiance distribution. Hence, in this edition of the standard, distinction is made between angular subtense of a source and irradiance averaging for photochemical MPE values. For viewing times in excess of approximately 30 s to 60 s, the saccadic eye motion during fixation is generally overtaken by behavioural movements determined by visual task, and it is quite unreasonable to assume that a light source would be imaged solely in the fovea for durations longer than 100 s. For this reason, the angle of acceptance γ_p is increased linearly with the square-root of t. The minimal angular subtense α_{min} correctly remains at the reference angle of 1,5 mrad for all exposure durations used in thermal retinal hazard evaluation. However, for photochemical retinal hazard assessment, the concept is actually different, as the angle γ_p is a linear angle of acceptance for the measurement of irradiance, and this is important to apply only for extended sources greater than approximately 11 mrad.

Viewing distance. In the case of a "point-type", diverging-beam source, the hazard increases with decreasing distance between the beam waist and the eye. The reason is that, with decreasing distance, the collected power increases, while the size of the retinal image can be assumed to remain nearly diffraction-limited for true laser sources down to a distance as close as 100 mm (due to the accommodation capabilities of the eye). The greatest hazard occurs at the shortest accommodation distance. With further reduced distance, the hazard to the unaided eye is also reduced, as there is a rapid growth of the retinal image and a corresponding reduction of the irradiance, even though more power may be collected. To simulate the risk of optically aided viewing of a collimated beam with binoculars or a telescope, the closest distance of approach of 2 m with a 50-mm aperture was assumed based upon the closest distance for clear viewing.

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For the purpose of this standard, the shortest accommodation distance of the human eye is set to 100 mm at all wavelengths from 400 nm to 1 400 nm. This was chosen as a compromise, because all but a few young people and very few myopics cannot accommodate their eyes to distances of less than 100 mm. This distance may be used for the measurement of irradiance in the case of intrabeam viewing (see 8.2).

For wavelengths of less than 400 nm or more than 1 400 nm, the greatest hazard is damage to the lens or the cornea. Depending on the wavelength, optical radiation is absorbed preferentially or exclusively by the cornea or the lens (see table B.1). For diverging-beam sources (extended or point-type) of these wavelengths, short distances between the source and the eye should be avoided.

In the wavelength range from 1 500 nm to 2 600 nm, radiation penetrates into the aqueous humour. The heating effect is therefore dissipated over a greater volume of the eye, and the MPEs are increased for exposures less than 10 s. The greatest increase in the MPEs occurs for very short pulse durations and within the wavelength range of 1 500 nm to 1 800 nm where the absorbing volume is greatest. At times greater than 10 s, heat conduction redistributes the thermal energy so that the impact of the penetration depth is no longer significant.

B.2.2 Skin hazards

In general terms, the skin can tolerate a great deal more exposure to laser beam energy than can the eye. The biological effect of irradiation of skin by lasers operating in the visible (400 nm to 700 nm) and infra-red (greater than 700 nm) spectral regions may vary from a mild erythema to severe blisters. An ashen charring is prevalent in tissues of high surface absorption following exposure to very short-pulsed, high-peak power lasers. This may not be followed by erythema.

The pigmentation, ulceration, and scarring of the skin and damage of underlying organs may occur from extremely high irradiance. Latent or cumulative effects of laser radiation have not been found prevalent. However, some limited research has suggested that under special conditions, small regions of human tissue may be sensitized by repeating local exposures with the result that the exposure level for minimal reaction is changed and the reactions in the tissues are more severe for such low-level exposure.

In the wavelength range 1 500 nm to 2 600 nm, biological threshold studies indicate that the risk of skin injury follows a similar pattern to that of the eye. For exposures up to 10 s, the MPE is increased within this spectral range.

B.3 MPEs and irradiance averaging

In this standard, the maximum permissible exposure (MPE) values recommended by the ICNIRP have been adopted. The irradiance-averaging apertures (measurement apertures) recommended by the ICNIRP were adopted, or an additional safety factor applied by IEC TC76. The determination and derivation of the AELs, although generally based upon the MPEs, necessitated a risk analysis and determination of reasonably foreseeable exposure conditions. The choice of measurement aperture played a role in the derivation of AELs and reflects both biophysical and physiological factors. In some cases, considerations of risk assessment and simplification of expression played a role. Table B.2 provides a summary of the factors assumed in the choice of measurement apertures. In general, the recommendations of the ICNIRP were followed, or added safety factors applied.

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B.4 Reference documents

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Table B.2 – Explanation of measurement apertures applied to the MPEs

Spectral band λ	Exposure time t	Aperture diameter	Comments and rationale for aperture diameter
180 nm to 400 nm	$t < 3 \cdot 10^4$ s	1 mm	Scatter in corneal epithelium and in stratum corneum leads to 1 mm; assumption of no movement of exposed tissue for continuous exposure conditions is applied by IEC. However, ICNIRP recommends 3,5 mm for lengthy exposures due to eye movements
400 nm to 600 nm photochemical	$t > 10$ s	3 mm in derivation of MPE, but 7 mm used for measurements	Lateral motion of 3-mm diameter pupil in space to produce 7-mm aperture averaging for CW exposures applicable for photochemical injury mechanism
400 nm to 1 400 nm thermal	All times t	7 mm	Diameter of dilated pupil and lateral motion in CW exposures
> 1 400 nm	$t < 0{,}35$ s	1 mm	Thermal diffusion in stratum corneum and epithelial tissues
> 1 400 nm	$0{,}35 \text{ s} < t < 10$ s $t > 10$ s	$1{,}5 \cdot t^{3/8}$ mm 3,5 mm	Greater thermal diffusion and movement of target tissue relative to beam after 0,35 s
$10^5 <$ $< 10^6$ nm	All t	11 mm	Aperture to be greater than diffraction limit (i.e., approximately 10×) for accurate measurements

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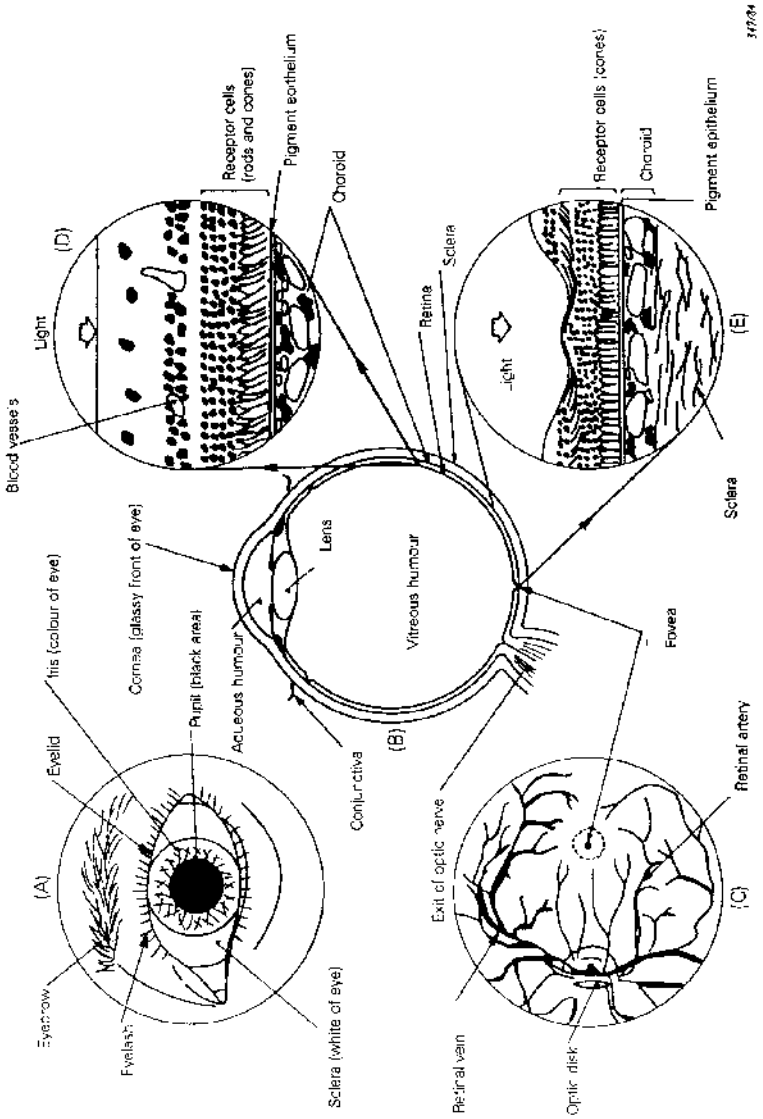

Figure B.1 – Anatomy of the eye

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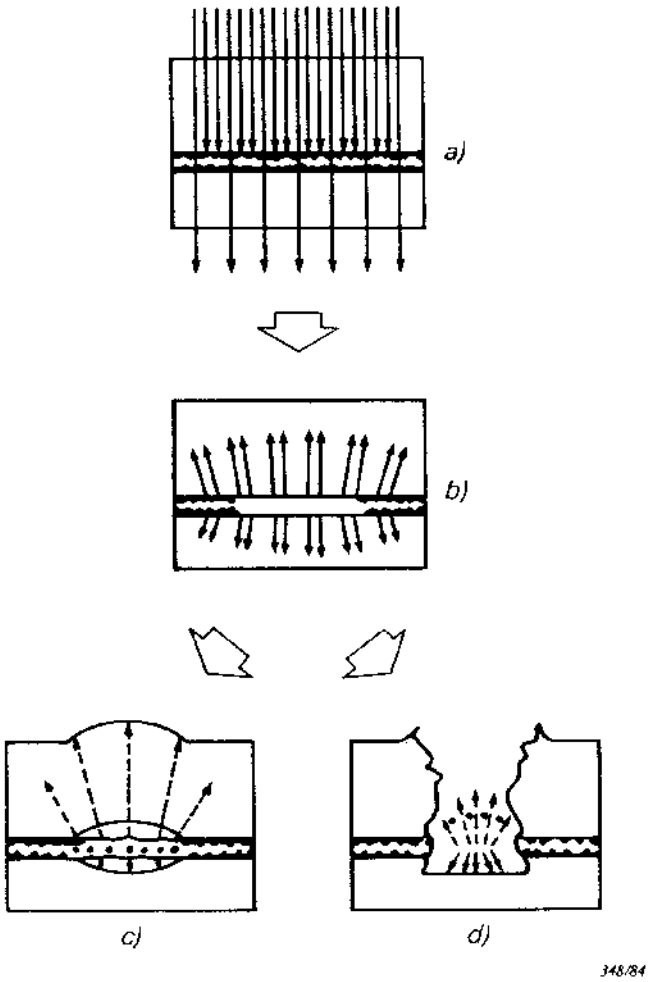

a) Laser energy is absorbed by the system.

b) The absorbed energy produces heat which is conducted to surrounding tissues.

c) In long-pulse or CW lasers the persistence of the thermal front gives rise to a progressively enlarging lesion.

d) In short-pulse lasers the high power density gives rise to explosive rupture of cells and damage by physical displacement.

Figure B.2 – Diagram of laser-induced damage in biological systems

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Annex C
(informative)

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Annex D
(informative)

Summary tables

Table D.1 – Summary of the physical quantities used in this part 1

This table summarizes the physical quantities referred to in this part 1, and gives the unit (and the symbol for the unit) used for each of them. The definitions of the SI base units are taken from ISO 1000. The units and symbols are taken from IEC 60027-1.

Quantity	Name of unit	Unit symbol	Definition
Length	metre	m	The metre is the length of the path travelled by light in vacuum during a time interval of 1/229 792 458 of a second
	millimetre	mm	10^{-3} m
	micrometre	µm	10^{-6} m
	nanometre	nm	10^{-9} m
Area	square metre	m^2	1 m^2
Mass	kilogram	kg	The mass equal to the mass of the international prototype of the kilogram
Time	second	s	The duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state caesium-133 atom
Frequency	hertz	Hz	The frequency of a periodic phenomenon equal to one cycle per second
Plane angle	radian	rad	The plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius
	milliradian	mrad	10^{-3} rad
Solid angle	steradian	sr	The solid angle which, having its vertex in the centre of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere
Force	newton	N	1 $m \cdot kg \cdot s^{-2}$
Energy	joule	J	1 N·m
Radiant exposure	joule per square metre	$J \cdot m^{-2}$	1 $J \cdot m^{-2}$
Integrated radiance	joule per square metre per steradian	$J \cdot m^{-2} \cdot sr^{-1}$	1 $J \cdot m^{-2} \cdot sr^{-1}$
Power	watt	W	1 $J \cdot s^{-1}$
	milliwatt	mW	10^{-3} W
Irradiance	watt per square metre	$W \cdot m^{-2}$	1 $W \cdot m^{-2}$
Radiance	watt per square metre per steradian	$W \cdot m^{-2} \cdot sr^{-1}$	1 $W \cdot m^{-2} \cdot sr^{-1}$
NOTE For convenience, multiples and submultiples of units have been included where appropriate.			

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Table D.2 – Summary of manufacturer's requirements

Requirements subclause	Classification						
	Class 1	Class 1M	Class 2	Class 2M	Class 3R	Class 3B	Class 4
Description of hazard class 8.2	Safe under reasonably foreseeable conditions	As for Class 1 except may be hazardous if user employs optics	Low power; eye protection normally afforded by aversion responses	As for Class 2 except may be more hazardous if user employs optics	Direct intrabeam viewing may be hazardous	Direct intrabeam viewing normally hazardous	High power; diffuse reflections may be hazardous
Protective housing 4.2		Required for each laser product; limits access necessary for performance of functions of the products					
Safety interlock in protective housing 4.3	Designed to prevent removal of the panel until accessible emission values are below that for Class 3R				Designed to prevent removal of the panel until accessible emission values are below that for Class 3B		
Remote control 4.4	Not required					Permits easy addition of external interlock in laser installation	
Key control 4.5	Not required					Laser inoperative when key is removed	
Emission warning device 4.6	Not required				Gives audible or visible warning when laser is switched on or if capacitor bank of pulsed laser is being charged. For Class 3R only, applies if invisible radiation is emitted		
Attenuator 4.7	Not required					Gives means besides the On/Off switch to temporarily block beam	
Location controls 4.8	Not required				Controls so located that there is no danger of exposure to AEL above Classes 1 or 2 when adjustments are made		
Viewing optics 4.9	Not required	Emission from all viewing systems must be below Class 1M AEL					
Scanning 4.10	Scan failure shall not cause product to exceed its classification						
Class label 5.1 to 5.6	Required wording		Figures 14 and 15 and required wording				
Aperture label 5.7	Not required				Specified wording required		
Service entry label 5.9.1	Required as appropriate to the class of accessible radiation						
Override interlock label 5.9.2	Required under certain conditions as appropriate to the class of laser used						
Wavelength range label 5.10 & 5.11	Required for certain wavelength ranges						
LED label 5.12	Make required word substitutions for LED products						
User information 6.1	Operation manuals must contain instructions for safe use. Additional requirements apply for Class 1M and Class 2M						
Purchasing and service information 6.2	Promotion brochures must specify product classification; service manuals must contain safety information						
Medical products 7.1	For the safety of medical laser products, IEC 60601-2-22 applies						
NOTE This table is intended to provide a convenient summary of requirements. See text of this standard for complete requirements.							

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Table D.3 – Summary of user precautions

Requirements subclause	Classification						
	Class 1	Class 1M	Class 2	Class 2M	Class 3R	Class 3B	Class 4
Laser safety officer 10.1	Not required but recommended for applications that involve direct viewing of the laser beam				Not required for visible emission Required for non-visible emission	Required	
Remote interlock 10.2	Not required					Connect to room or door circuits	
Key control 10.3	Not required					Remove key when not in use	
Beam attenuator 10.4	Not required					When in use prevents inadvertent exposure	
Emission indicator device	Not required				Indicates laser is energized for non-visible wavelengths	Indicates laser is energized	
Warning signs 10.5	Not required					Follow precautions on warning signs	
Beam path 10.6	Not required	Class 1M[a] as for Class 3B	Not required	Class 2M[b] as for Class 3B	Terminate beam at end of useful length		
Specular reflection 10.7	No requirements	Class 1M[a] as for Class 3B	No requirements	Class 2M[b] as for Class 3B	Prevent unintentional reflections		
Eye protection 10.8	No requirements					Required if engineering and administrative procedures not practicable and MPE exceeded	
Protective clothing 10.9	No requirements					Sometimes required	Specific requirements
Training 10.10	No requirements	Class 1M[a] as for Class 3R	No requirements	Class 2M[b] as for Class 3R	Required for all operator and maintenance personnel		

[a] Class 1M laser products that failed condition 1 of table 10. Not required for Class 1M laser products that failed condition 2 of table 10.

[b] Class 2M laser products that failed condition 1 of table 10. Not required for Class 2M laser products that failed condition 2 of table 10.

NOTE This table is intended to provide a convenient summary of precautions. See text of this standard for complete precautions.

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Annex E
(informative)

High power laser considerations particularly appropriate to materials-processing laser products

E.1 General considerations

High power laser radiation has the potential ability to change by heating the shape, reflectivity, transmission or refractive index of optical components it passes through or is reflected from. This in turn can distort, reflect and/or deflect the laser radiation, and may permanently damage the optical component. Furthermore, sufficiently high power radiation has the ability to penetrate the wall of a protective housing by melting or vapourizing the material of its construction. The threshold for these effects depends on laser wavelength, peak power, exposure time and the thermomechanical and optical properties of the material irradiated. Environmental factors, especially airborne dust, can enhance the absorption of laser radiation. In principle, any Class 4 laser is capable of producing such effects.

Some of the effects encountered in the safety context are:

i) High power laser radiation melting, vapourizing, ablating, or in some other way penetrating a protective housing and/or producing toxic fumes.

ii) Significant energy absorption from a high power laser beam by a reflective or transmissive beam forming component, giving rise to changes in the properties of the reflected or transmitted beam (and consequently the generation of an errant beam) by virtue of:

   a) deformation of the component;

   b) induced changes in the bulk refractive index and absorption coefficient of the component.

   Thermal lensing is an effect caused by a) and/or b);

   c) induced changes in the surface absorption and/or reflectivity of the component. Multi-layer dielectric coatings are particularly prone to laser damage;

   d) catastrophic failure, i.e. penetration (burn through) of an opaque component (e.g. a mirror) or cracking of a transmissive component (e.g. a lens).

iii) Non-linear effects such as frequency doubling and stimulated Brillouin scattering.

E.2 Errant laser radiation

E.2.1 Errant radiation produced in normal operation of the laser product includes secondary reflections from beam line components. However, within the constraints of normal operation, service, and maintenance operations, certain fault conditions may arise in which relatively strong errant beams could be produced. These include:

- damage to beam path components by laser radiation, the environment or by mechanical impact;
- misalignment or displacement of a beam path component (for example, due to vibration, or failure of an automatic positioning device or a control software failure);
- penetration of a workpiece by laser radiation during processing or anomalous (strong or refocused) workpiece reflection;
- (following servicing) misalignment of a beam path component or the failure to replace a beam path component or a radiation barrier.

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E.2.2 It is not always practical or desirable to build a protective housing capable of preventing human access to errant laser radiation under all the above conditions, but there is much that can be done by way of engineering design to limit or prevent some of the conditions outlined in E.2.1 from arising.

Measures include:

- controlling the environment in which beam path components are located (in particular, preventing particulate matter and/or condensation from collecting on laser irradiated surfaces of beam path components);
- securely mounting beam path components with minimum mechanical distortion of optical surfaces and adequate isolation from thermally and mechanically induced stresses;
- limiting unnecessary freedom of movement of component holders;
- installing mechanical stops or limit switches as a back up to prevent collisions between components in relative motion within the protective housing;
- fixing beam path components, their holders, and any screening within the protective housing so that tools are required for their removal;
- installing interlocking to ensure the presence of beam path components before operation (especially components which are mechanically controlled, for example, for beam switching);
- monitoring the overall transmission of laser power or deviations from the defined laser beam path;
- monitoring some aspect of the laser processing, for example optical emission;
- mechanically restricting access to the region of laser processing (for example, excluding foreign objects by means of a shroud).

E.2.3 In addition to the above engineering features, instructions may be needed to limit the intended use of the product, for example, to prevent the processing of a workpiece of such a material or surface curvature as would greatly increase the intensity of specular reflections or produce focusing of such radiation. For example, use may be limited to materials with unpolished, plain surfaces. Any limitations would need to be clearly defined in the information for the user and the product marked up accordingly.

E.3 Design of protective housings

E.3.1 Protective housings may be made up of passive guards and/or active guards to contain errant laser radiation. Passive guards rely on the intrinsic ability of their material of construction to resist penetration by laser radiation. Active guards make use of sensors or other devices to limit the time for which hazardous levels of errant radiation can persist within the protective housing. Active protection does not include real time human monitoring or manual shut-down of the laser.

E.3.2 Passive guards

In welding, cutting and drilling laser products, relatively thin walled, uncooled housing walls can provide adequate passive protection from errant radiation in normal operation, and under fault conditions arising beyond the laser focusing optics by virtue of the fact that such radiation is highly divergent.

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The passive protection afforded by a protective housing can be enhanced by a local enclosure (e.g. a tube surrounding the laser beam, or a shroud surrounding the region of the workpiece undergoing processing), and by the strategic positioning of beam stops (e.g. below the workpiece, and behind beam turning mirrors). Where local enclosure is used, its presence during operation should be ensured either by interlocking or by securing it in position such that tools are required for its removal. Any part of a solid workpiece surface not on the defined beam path may be considered as contributing to beam enclosure within the protective housing if its presence can be ensured during operation (e.g. by use of a proximity sensor).

E.3.3 Active guards

An active guard must be capable of containing errant laser radiation incident on its surface for a time which safely exceeds the maximum time take for electronic (or other) means of detection of such errant laser radiation and laser source shut-down. This may involve, for example:

- a detector which forms an intrinsic part of the guard and relies on partial penetration of the housing for its operation (e.g. a monitor of the excess pressure of a fluid trapped within a double skinned wall);
- a detector which senses errant laser radiation on the guard directly, or by some secondary effect, such as a temperature rise.

E.4 Beam stop

Beam stops should be designed so that they operate in a fail-safe manner and, by engineering design, prevent full penetration at maximum laser power. The latter may be achieved by the use of low volatility/high thermal conductivity materials of construction, a large absorbing surface area, and/or by the incorporation of thermal sensors interlocked with the safety system.

E.5 Other conditions

E.5.1 Due regard should be given to the effect of the laser radiation generated by a laser product on the integrity of its protective housing and on the continuity of all signals or utilities relating to the safety of the laser product (e.g. electric or pneumatic supply cables operating automated workhandling equipment inside a protective housing), and to the associated hazards, including fire and fumes, caused by the laser exposure of these components.

E.5.2 Due regard should be given to the associated hazards from gases (for example, oxygen) used to assist laser-target interactions and from any fumes that are produced. These hazards include explosions, fires, toxic effects and oxygen depletion.

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Annex F
(informative)

Related IEC Standards

This annex lists the other IEC documents related to mechanical and electrical safety that may incorporate lasers or LEDs and be associated with this part 1.

Note: When the international publication has been modified by CENELEC common modifications, the relevant EN/HD applies.

EN 41003:1993, *Particular safety requirements for equipment to be connected to telecommunication networks*

IEC 60065:1998, *Audio, video and similar apparatus – Safety requirements*

Note: Harmonized as EN 60065:1993 (modified)

IEC 60204-1:1992, *Electrical equipment of industrial machines – Part 1: General requirements*
Amendment 1, 1999

Note: Harmonized as EN 60204-1:1992 (modified). Although the title of IEC 60204 indicates that its use is restricted to "industrial machines", the scope of EN 60204 has been broadened to include those machines covered by the EEC Directives relating to safety of machinery. This change is reflected in the title of EN 60204.

IEC 60601-2-22:1995, *Medical electrical equipment – Part 2: Particular requirements for the safety of diagnostic and therapeutic laser equipment*

Note: Harmonized as EN 60601-2-22:1992 (not modified)

IEC 60950:1999, *Safety of information technology equipment*

Note: Harmonized as EN 60950:1992 + A1:1993 + A2:1993 (modified)

IEC 61010-1:2001, *Safety requirements for electrical equipment for measurement, control and laboratory use – Part 1: General requirements*

Note: Harmonized as EN 61101-1:1993 (modified)

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Annex G
(informative)

Information to be provided by manufacturers of LEDs

This annex provides a listing of the radiometric specifications of Light Emitting Diodes (LEDs). The provision of these specifications by manufacturers of LEDs will be of use to manufacturers of equipment using those LEDs in complying with the requirements of IEC 60825-1. In this annex LED includes infrared emitting diodes.

The manufacturer of LEDs should provide the following data using the upper one-sided 95 % confidence limit values where appropriate (see note 1). Electrical and optical characteristics for LEDs should be specified according to IEC 60747-5-2, IEC 60747-12-1 and IEC 60747-12-3.

G.1 Minimum data required for components intended for inherent Class 1 operation

- Statements of the operating conditions under which Class 1 operation is ensured. This allows the equipment manufacturer to determine compliance with IEC 60825-1 by analysis of the circuit used to drive the LED without test of the product that incorporates the LED.

G.2 Essential data if component is not inherently Class 1 (parametric)

- Peak wavelength, in nanometres
- Divergence, half-intensity angle in degrees
- Apparent source size, in millimetres (or angular subtense, in milliradian) using power measurement method in 8.2 of IEC 60825-1
- Location of apparent source, in millimetres (from a stated reference surface)
- Radiance, $W \cdot m^{-2}\, sr^{-1}$
- Radiant intensity, min. and max. $W \cdot sr^{-1}$
- Reference temperature of data (normally 25 °C) (see note 2)
- Physical identification (for example, package profile, lead-outs, dimensions, etc.)

G.3 Essential data if component is not inherently Class 1 (graphical or tabular)

- Radiant intensity, $W \cdot sr^{-1}$ versus input current, in milliamperes
- Spectral distribution, relative emission versus wavelength
- Temperature dependence of peak wavelength
- Temperature dependence of radiant intensity (at a stated current)
- Information of intensity distribution as a function of emission angle
- Burn-out time versus current (see note 8)

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G.4 Additional data to assist safety assessment

- Statement of the intended use of the LED, for example, intended as an indicating surface-emitting LED or for other use (see note 3).

NOTE 1 Confidence limits provide the statistical rationale that the values stated are those which result in the maximum hazard, taking into account variations among actual devices and measurement uncertainties.

NOTE 2 25 °C is normal room temperature and is intended to provide a common reference that can be used to compare devices from all manufacturers. The temperature dependence data will allow assessment to be made for different conditions of use.

NOTE 3 A surface-emitting LED in this context is a component without gain where the emission from the component surface can be viewed directly. It may have a built-in lens or reflector.

NOTE 4 Where the LED wavelength is selected by polarity, for example, a two-colour red/green LED, the device shall be evaluated according to IEC 60825-1 for each wavelength.

NOTE 5 Where the LED is capable of emitting at different wavelengths simultaneously, the device shall be evaluated according to IEC 60825-1 as a multiple wavelength emitter.

NOTE 6 For an array of multiple LEDs, the array group shall be evaluated according to IEC 60825-1, annex A.2, example A.2.4.

NOTE 7 The LED Class should normally be based on continuous operation unless it is known that the LED device will fail within a particular time, or unless the device emission duration is limited in the end application.

NOTE 8 It is possible that an LED will have a much larger current flowing through it under fault conditions within the end equipment. When over-driven, an LED will emit a higher radiated output but the excess current may cause the device to burn out within a certain time. By providing information on the time taken for a device to burn out at specified currents, the end equipment manufacturer may determine the LED Class of their equipment under fault conditions.

G.5 Reference documents

IEC 60747-5-2:1997, *Discrete semiconductor devices and integrated circuits – Part 5-2: Optoelectronic devices – Essential ratings and characteristics*

IEC 60747-12-1:1995, *Semiconductor devices – Part 12: Optoelectronic devices – Section 1: Blank detail specification for light emitting/infrared emitting diodes with/without pigtail for fibre optic systems and sub-systems*

IEC 60747-12-3:1998, *Semiconductor devices – Part 12-3: Optoelectronic devices – Blank detail specification for light-emitting diodes – Display application*

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Annex H
(informative)

Overview of associated parts of IEC 60825

The associated parts of IEC 60825 are intended for use in conjunction with the basic standard IEC 60825-1. Each part covers a defined scope and provides additional normative and informative guidance to enable the manufacturer and user to correctly classify and use the product in a safe manner by taking account of the particular conditions of use and competence/training of the operator/user. The information covered may include rationale, examples, clarification, methods, labelling, and any additional limits and requirements.

Table H.1 – Overview of additional data in associated parts of IEC 60825

Part No.	Type	Description	Product designer	Product supplier	Product user	Safety critical component supplier	Test methods	Hazard assessment	Related standards
1	Standard	Equipment classification, requirements and user's guide	Yes	Yes	Yes	Yes	Yes	Yes	
2	Standard	Safety of optical fibre communication systems (provides application notes and examples)	Yes	Yes	Yes	Yes	Yes	Yes	
3	Technical report	Guidance for laser displays and shows	No	No	Yes	No	No	Yes	
4	Standard	Laser guards (also addresses ability of high-power lasers to remove guard material)	Yes	Yes	Yes	Yes	Yes	Yes	
5	Technical report	Manufacturer's checklist for IEC 60825-1 (suitable for use in a safety report)	Yes	Yes	No	Yes	No	No	
6	Technical specification	Safety of products with optical sources, exclusively used for visible information transmission to the human eye (includes indicating LEDs)	Yes	Yes	No	Yes	Yes	Yes	
7	Technical specification	Safety of products emitting 'infrared' optical radiation, exclusively used for wireless 'free air' data transmission and surveillance (NOHD <2,5 m)	Yes	Yes	No	Yes	Yes	Yes	
8	Technical report	Guidelines for the safe use of medical laser equipment	No	No	Yes	No	No	No	IEC 60601-2-22
9	Technical report	Compilation of maximum permissible exposure to incoherent optical radiation (broadband sources)	No	No	Yes	No	Yes	Yes	
10	Technical report	Laser safety application guidelines and explanatory notes	Yes	Yes	No	No	Yes	No	ISO 13694

NOTE This table is intended to provide an indication of content – see text of the particular standard for complete requirements. Some parts listed above may be under discussion by working groups and may not be formally published.

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Annex ZA (normative)
Other international publications quoted in this standard with the references of the relevant European publications

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

NOTE When the international publication has been modified by CENELEC common modifications, indicated by (mod), the relevant EN/HD applies.

IEC publication	Date	Title	EN/HD	Date
60027-1	1992[a]	*Letter symbols to be used in electrical technology — Part 1: General*	—	—
60050(845)	1987	*International Electrotechnical Vocabulary (IEV) — Chapter 845: Lighting*	—	—
60601-2-22	1992	*Medical electrical equipment — Part 2: Particular requirements for the safety of diagnostic and therapeutic laser equipment*	EN 60601-2-22	1992
60825-2	1993	*Safety of laser products — Part 2: Safety of optical fibre communication systems*	EN 60825-2	1994
61010-1 A1 (mod)	1990 1992	*Safety requirements for electrical equipment for measurements, control and laboratory use — Part 1: General requirements*	EN 61010-1	1993
61040	1990	*Power and energy measuring detectors, instruments and equipment for laser radiation*	EN 61040	1992
Other publications				
ISO 1000	1992	*SI units and recommendations for the use of their multiples and of certain other units*	—	—

[a] IEC 60027-1:1971 A1:1974 A2:1977 was harmonized as HD 245.1 S3:1979.

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National annex NA (informative)
Committees responsible

The United Kingdom participation in the preparation of this European Standard was entrusted by the Electrotechnical Sector Board to Technical Committee EEL/28, upon which the following bodies were represented:

Association of University Radiation Protection Officers

BLWA Ltd. (The Association of the Laboratory Supply Industry)

British Medical Laser Association

British Railways Board

British Telecommunications plc

Department of Health

Department of Trade and Industry (Consumer Safety Unit, CA Division)

Engineering Equipment and Materials Users' Association

Federation of the Electronics Industry

Health and Safety Executive

Institute of Physics

Institute of Electrical Engineers

Machine Tool Technologies Association

Ministry of Defence

National Radiological Protection Board

Royal College of Ophthalmologists

Royal Institute of Chartered Surveyors

SIRA Ltd.

Trades Union Congress

UK Optical Sensors Collaborative Association

UK Laser and Electro-optic Association

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