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Safety of laser products –

Part 13:
Measurements for classification of laser products

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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SAFETY OF LASER PRODUCTS –

Part 13: Measurements for classification of laser products

FOREWORD

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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 60825-13, which is a technical report, has been prepared by IEC technical committee 76: Optical radiation safety and laser equipment.

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

Enquiry draft	Report on voting
76/332/DTR	76/345/RVC

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

This technical report is to be used in conjunction with IEC 60825-1:1993 and its Amendment 1 (1997) and Amendment 2 (2001), referred to in this report as "the standard".

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

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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- withdrawn;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

A bilingual version of this publication may be issued at a later date.

SAFETY OF LASER PRODUCTS –

Part 13: Measurements for classification of laser products

1 Scope

This part of IEC 60825 provides manufacturers, test houses, safety personnel, and others with practical guidance on methods to perform radiometric measurements or analyses to establish the emission level of laser energy in accordance with IEC 60825-1 (herein referred to as "the standard"). The measurement procedures described in this technical report are intended as guidance for classification of laser products in accordance with that standard. Other procedures are acceptable if they are better or more appropriate.

Information is provided for calculating accessible emission limits (AELs) and maximum permissible exposures (MPEs), since some parameters used in calculating the limits are dependent upon other measured quantities.

This document is intended to apply to lasers, including extended sources and laser arrays. Users of this document should be aware that the procedures described herein for extended source viewing conditions may yield more conservative results than when using more rigorous methods.

NOTE Work continues on more complex source evaluations and will be provided as international agreement on the methods is reached.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60825-1:1993, *Safety of laser products – Part 1: Equipment classification, requirements and user's guide* [1)]
Amendment 1 (1997)
Amendment 2 (2001)

IEC 61040, *Power and energy measuring detectors, instruments and equipment for laser radiation*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions contained in IEC 60825-1 as well as the following apply.

3.1
angular velocity
speed of a scanning beam in radians per second

1) There exists a consolidated edition (1.2) of IEC 60825-1 (1993), including its Amendment 1 (1997) and Amendment 2 (2001).

3.2
beam profile
the irradiance distribution of a beam cross-section

3.3
beam waist
the minimum diameter of an axis-symmetric beam. For non-symmetric beams, there may be a beam waist along each major axis, each located at a different distance from the source

3.4
charge-coupled device
CCD
self-scanning semiconductor imaging device that utilizes metal-oxide semiconductor (MOS) technology, surface storage, and information transfer

3.5
critical frequency
the pulse repetition frequency above which a pulsed laser can be modelled as CW for the purposes of laser hazard evaluation

3.6
Gaussian beam profile
a profile of a laser beam which is operated in the lowest transverse mode, TEM_{00}

NOTE A Gaussian beam profile may also be produced by passing non-TEM_{00} laser beams through beam shaping optical elements.

3.7
measurement aperture
the aperture used for classification of a laser to determine the power or energy that is compared to the AEL for each class

3.8
pulse repetition frequency
PRF
the number of pulses occurring per second, expressed in hertz (Hz)

3.9
Q-switch
a device for producing very short, high peak power laser pulses by enhancing the storage and dumping of energy in and out of the lasing medium, respectively

3.10
Q-switched laser
a laser that emits short, high-power pulses by means of a Q-switch

3.11
Rayleigh distance
Z_r
the distance from the beam waist where the beam diameter has increased by a factor of $2^{0,5}$ for Gaussian or near-Gaussian beam profiles

NOTE Rayleigh distance is often referred to as the confocal parameter.

3.12
responsivity
R
the output of a detector expressed as $R = O/I$, where O is the detector's electrical output and I is the optical power or energy input

4 Applicability

4.1 General

This report is intended to be used as a reference guide by (but not limited to) manufacturers, testing laboratories, safety officers, and officials of industrial or governmental authorities. This report also contains interpretations of IEC 60825-1 pertaining to measurement matters and provides supplemental explanatory material.

4.2 Initial considerations

Before attempting to make radiometric measurements for the purpose of product classification or compliance with the other applicable requirements of IEC 60825-1, there are several parameters of the laser that must first be determined.

a) Emission wavelength(s)

Lasers may emit radiation at one or more distinct wavelengths.

The emission wavelength, wavelengths, or spectral wavelength distribution can typically be obtained from the manufacturer of the laser. Depending on the type of laser, the manufacturer may specify a wavelength range rather than a single value. Otherwise, the emission wavelength, wavelengths or spectral distribution can be determined by measurement, which is beyond the scope of this technical report. See 7.1 for assessing the AEL for multiple wavelengths.

b) Time mode of operation

The time mode of operation refers to the rate at which the energy is emitted. Some lasers emit continuous wave (CW) radiation; other lasers emit energy as pulses of radiation. Pulsed lasers may be single pulsed, Q-switched, repetitively pulsed, or mode locked. Measurements of scanned or modulated CW radiation at a fixed location also result in a train of pulses.

In addition, the pulse train may be encoded, but have an average duty factor (emission time as a fraction of elapsed time, expressed as a decimal fraction or percentage).

c) Reasonably foreseeable single fault conditions

The IEC 60825-1 specifies that tests shall be performed under each and every reasonably foreseeable single fault condition. It is the responsibility of the manufacturer to ensure that the accessible radiation does not exceed the AEL of the assigned class under all such conditions.

d) Measurement uncertainties

It is important to consider potential sources of error in measurement of laser radiation. Clause 5 of this technical report addresses measurement uncertainties.

e) Collateral radiation

Collateral radiation entering the measurement aperture may affect measured values of power or energy and pulse duration. Test personnel should ensure that the measurement setup blocks or accounts for collateral radiation that would otherwise reach the detector.

f) Product configuration

If measurements are being made for the purpose of classification, then the configuration(s) of the product that are intended during all operating conditions, including maintenance, service, and single fault conditions must be known. If measurements are being made to determine the requirements for safety interlocks, labels and information for the user, then the product must be evaluated under the configurations applicable for each of the defined categories of use (operation, maintenance, and service) in accordance with the standard.

IEC technical committee 76 (TC 76) recognises the existence of equivalent measurement procedures, which could yield results that are as valid as the procedures described in this technical report. This report describes measurement procedures that are adequate to meet the measurement requirements of IEC 60825-1 when measurements are needed. In many cases actual radiometric measurements may not be necessary, and compliance with the requirements of IEC 60825-1 can be determined from an analysis of a well-characterised source and the design of the actual product.

Under some circumstances it may be necessary to partially disassemble a product to undertake measurements at the required measurement location, particularly when considering reasonably foreseeable single fault conditions. Where a final laser product contains other laser products or systems, it is the final product that is subject to the provisions of the standard.

5 Instrumentation requirements

Measurement instruments to be used shall comply with the latest edition of IEC 61040 (Power and energy measuring detectors, instruments and equipment for laser radiation). Which instrument class (between class 1 and class 20 giving the approximate value of the possible measurement uncertainty) is to be used depends on the measurement precision needed.

Where instruments not fully compliant with IEC 61040 are used, the individual contributions of different parameters to the total measurement uncertainty have to be evaluated separately. The main points to be considered are those given in IEC 61040:

- change of responsivity with time;
- non-uniformity of responsivity over the detector surface;
- change of responsivity during irradiation;
- temperature dependence of responsivity;
- dependence of responsivity on the angle of incidence;
- non-linearity;
- wavelength dependence of responsivity;
- polarisation dependence of responsivity;
- errors in averaging of repetitively pulsed radiation over time;
- zero drift;
- calibration uncertainty.

Calibrations should be traceable to national standards.

Tests for the determination of measurement uncertainties of the instrument shall be done according to IEC 61040.

For measurement uncertainties of CCD arrays and cameras see ISO 11554.

6 Classification flow

Known or measured parameters of the product enable calculation of AELs and measurement conditions. In addition, fault conditions that increase the hazard must be analysed. Then, a product emission measurement (or several different measurements) will determine if the emission is within the AEL of the class under consideration.

Tables 1 to 4 of IEC 60825-1 provide the accessible emission limits. These tables have rows for the wavelength ranges and columns for the emission durations. Within each row and column entry, there exist one or more formulas containing parameters that are defined in "Notes to Tables 1 to 4" of 9.3 of IEC 60825-1.

The classification flow is illustrated in Figures 1 and 2.

First determine whether the laser is pulsed or continuous wave. If the pulse duration is greater than 0,25 s, the laser is considered continuous wave. For a continuous wave laser, refer to the flowchart in Figure 1, and for a pulsed laser refer to the flowchart in Figure 2.

Next, the wavelength must be determined.

If the laser is pulsed or scanned, the pulse width (PW) and pulse repetition frequency (PRF) must also be determined.

Which class or classes are of interest must be determined. For instance, for a low power application not in the 400 nm – 700 nm region, Class 1, Class 1M and Class 3R might be considered. For a visible wavelength source, Class 1, Class 1M, Class 2, and Class 2M might be considered.

Next, the classification time base must be determined. This can be determined in terms of default values (8.4e) in the standard), or determined from the definition of the T_2 parameter (Notes to Tables 1 to 4 in the standard), or from considering the particular temporal output properties of the product in question.

This information is needed to locate the row and column entries of Tables 1 to 4 in the standard containing the formula or formulas of interest. The parameters used in the formulas will determine what other parameters need to be determined. They include, primarily, apparent source size (or the angular subtense equivalent, α), and the measurement acceptance angle γ_p for the visible photochemical hazard. Generally, only simple extended sources are addressed in this document. Considering the source to be a small source and setting C_6 = 1 is a conservative estimate if the apparent source size is not known.

Next, the measurement conditions must be determined (9.3 and Table 10 in the standard) and AEL (Tables 1 to 4 in the standard). For a pulsed laser, several conditions given in 8.4f) of the standard must be evaluated to ensure all fall within the AEL.

Once the AEL has been determined, the output data should be evaluated. The output data may be provided by the manufacturer or measured directly. If output data are provided by the manufacturer, it must be verified that the measurements were performed in accordance with clause 9 of the standard. If the accessible emission is less than the AEL, the laser may be assigned to that Class. For a pulsed laser, the AEL of the Class applies for all emission durations within the time base.

If the accessible emission is not less than the AEL, a higher class AEL should be chosen and assessed. This is repeated until the AEL is not exceeded or the laser product is assigned to Class 4.

The system must be evaluated in accordance with the standard to insure that a reasonably forseeable single fault cannot cause the laser to emit radiation higher than the AEL for the assigned class. If this criterion is met, the laser classification is known.

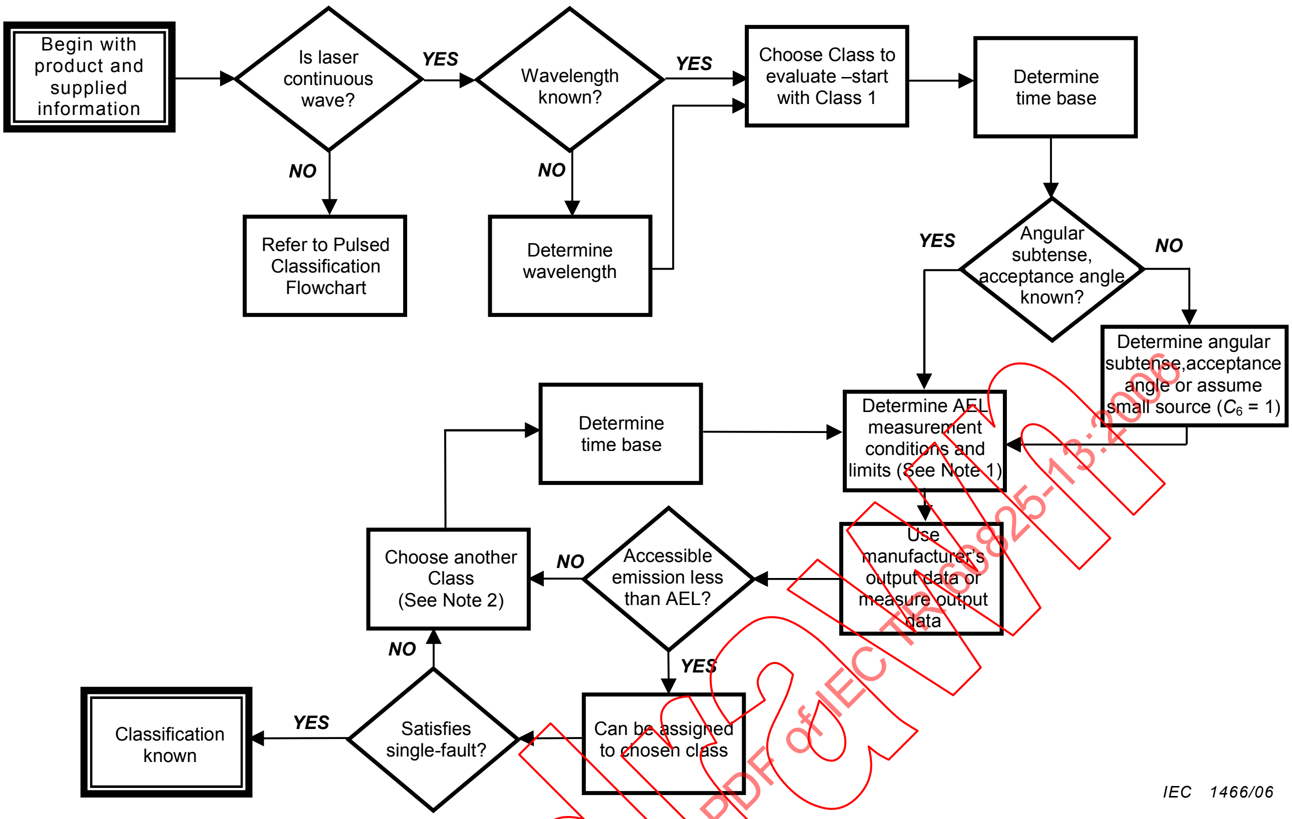


Figure 1 – Continuous wave laser classification flow

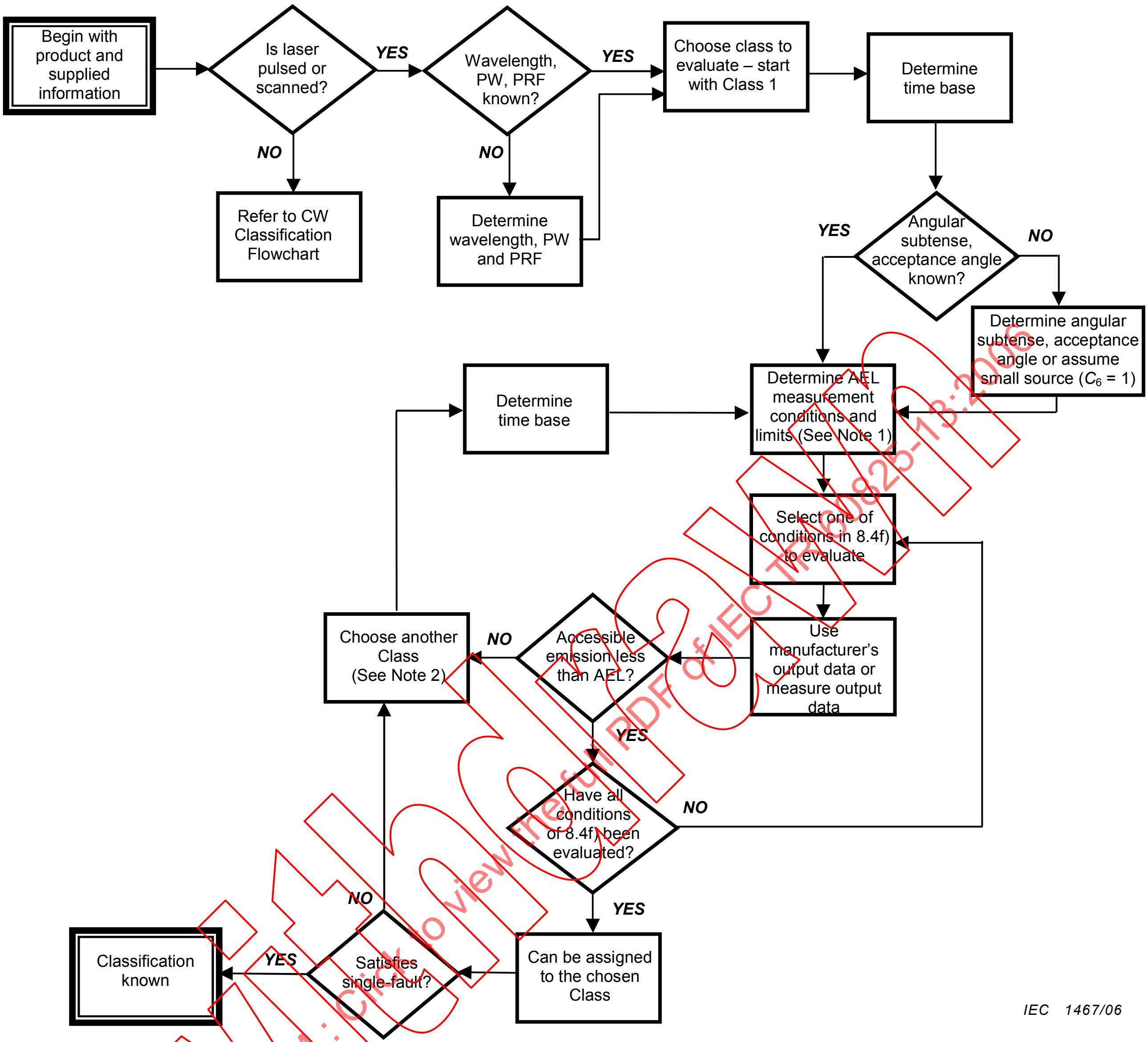


Figure 2 – Pulsed laser classification flow

NOTE 1 There may be more than one condition to be met if a product is to be assigned a certain class. For instance, in the wavelength region 400 – 600 nm, neither the thermal nor photochemical limit (each with its own measurement conditions) should be exceeded for a Class to apply. Also, if a product has a pulsed output, none of the three limits (single pulse, pulse train and average power) may be exceeded.

NOTE 2 If Class 1 or Class 2 requirements are not satisfied, it is appropriate to evaluate product emission using the Class 1M or Class 2M requirements. If a product emission satisfies the Class 1M or Class 2M requirements, it is not necessary to satisfy the Class 3R requirements.

7 Parameters for calculation of accessible emission limits

7.1 Wavelength (λ)

7.1.1 Wavelength determination

It is usually not necessary to determine this parameter to great accuracy. In general, optical hazards are not strong functions of wavelength. There are several exceptions (refer to Figure 3):

a) 302,4 nm – 315 nm region: over this range, the T_1 and C_2 parameters change significantly;

b) 450 nm – 600 nm region: over this range, the photochemical hazard decreases by a factor of 1 000;

c) 1 150 nm – 1 200 nm region: over this range, the thermal hazard decreases by a factor of eight;

d) 400 nm: at wavelengths greater than 400 nm, the hazard is mainly retinal; at shorter wavelengths, it is mainly non-retinal;

e) 1 400 nm; at wavelengths greater than 1 400 nm, the hazard is mainly non-retinal; at shorter wavelengths, it is mainly retinal.

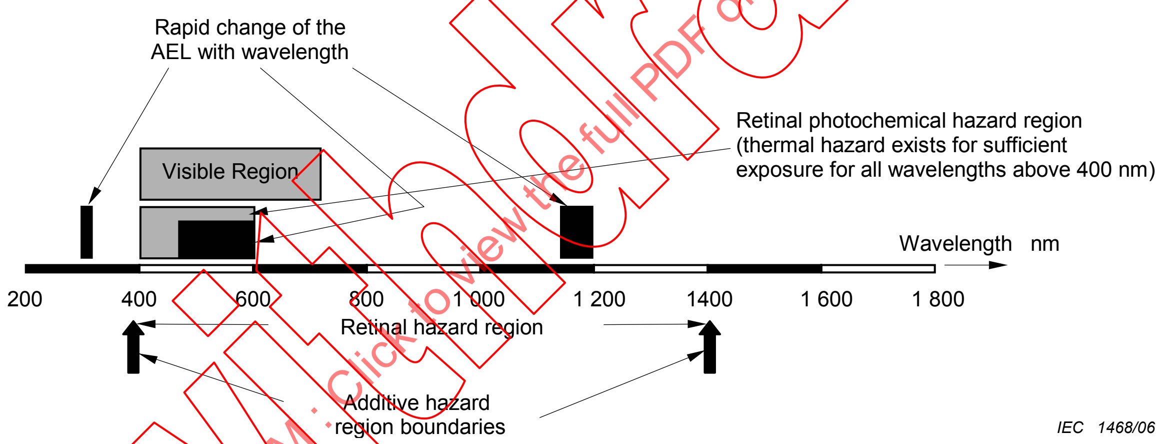


Figure 3 – Important wavelengths and wavelength ranges

For a narrow laser line, a wavelength provided by the manufacturer will likely be all that is necessary, and the remainder of 7.1 as well as 7.2 and 7.3 below need not be considered.

If the range of possible wavelengths (product-to-product variation) is a sizeable fraction of 1), 2) or 3) above, either the most hazardous (shortest) wavelength may be used, or the wavelength may be measured for a given product.

In regions 1), 2) or 3), a piece-wise summation may be required, determining the limit at several wavelengths and weighting by the output associated with that wavelength. This is discussed in detail below in sections 7.2.1 and 7.3.

Additive refers to hazards that must be considered together. For instance, multiple emissions less than 400 nm, or between 400 nm and 1 400 nm, or greater than 1 400 nm are additive. For spectrally broad or multiple emissions in each area, the hazards are additive, and a piecewise summation must be performed, as described in item b) of 8.4 of IEC 60825-1. If a product emits wavelengths in two of these ranges (e.g., 700 nm and 1 500 nm), then the two wavelengths should be considered separately using the relevant AELs for each wavelength. For classification purposes, the higher class will apply.

For lasers whose possible range of output wavelength or output spectrum includes wavelengths greater than 1 400 nm and/or less than 400 nm, special considerations should be made with regard to the AEL. The hazards on either side of the boundary wavelengths are different, and the effects are different. To be assigned a given class, the power or energy in each spectral region must be less than each corresponding AEL.

7.1.2 Ocular hazard regions

The thermal hazard exists for sufficient exposure at all wavelengths above 400 nm.

The retinal photochemical hazard is only a consideration from 400 nm to 600 nm, and for exposure times greater than 1 s.

The hazard regions are broken down as follows:

- 180 nm to 400 nm. The hazard is mainly photochemical and non-retinal for CW exposure and thermal for pulsed exposure. (The standard does not address wavelengths shorter than 180 nm.)
- 400 nm to 600 nm. In this range, both thermal and photochemical hazards must be considered. For the photochemical hazard, emission times of less than 10 s (or 1 s for the wavelength region 400 to 484 nm with apparent sources between 1,5 and 82 mrad) need not be considered.
- 400 nm to 1 400 nm. In this range, the retinal hazard region, the hazard to the retina predominates.
- 1 400 nm to 1 mm. At wavelengths greater than 1 400 nm the penetration depth of the radiation is much smaller than for wavelengths between 400 nm and 1 400 nm. The hazard is thermal but mainly non-retinal.

7.2 Multiple wavelength sources

The term multiple wavelength sources refers to sources that emit radiation in two or more discrete wavelengths. Multiple line lasers clearly fall into this category.

Lasers that emit pulses shorter than 100 fs can contain a relatively large wavelength bandwidth. The wavelength bandwidth for these lasers should be evaluated with the procedure in 7.3 if the AEL or MPE limit varies more than 10 % for the wavelength band of the laser pulse.

7.2.1 Single hazard region

For several sources at different wavelengths whose radiation produces the same type of hazard, a weighted sum must be used to determine whether the product meets or exceeds the AEL for a given class. For a single wavelength the criterion may be stated as:

If $P_{\text{meas}} < AEL$,

then the product does not exceed the class limit

where P_{meas} is the measured power (or energy or other quantity specified), and AEL is the class power (or energy or other quantity specified) limit. This can be restated as:

If $P_{\text{meas}} / AEL < 1$,

then the product does not exceed the class limit

In this form, this can be extended to two wavelengths:

If $P_{\text{meas}}(\lambda_1) / AEL(\lambda_1) + P_{\text{meas}}(\lambda_2) / AEL(\lambda_2) < 1$,

then the product does not exceed the class limit

For more than two wavelengths, this can be extended to a general summation:

$$\text{If} \sum_{i=1,2,3...} [P_{\text{meas}}(\lambda_i) / AEL(\lambda_i)] < 1,$$

then the product does not exceed the class limit

This only applies to one type of hazard at a time (i.e., photochemical and thermal hazards are treated separately).

NOTE While the thermal hazard limit values are different for the visible range (400 nm to 700 nm) and the near infrared range (700 nm to 1 400 nm), the time bases (either the emission duration t or the calculated parameter T_2) are the same. Thus, the summation formula above still applies.

7.2.2 Two or more hazard regions

If a product emits two different wavelengths, and they are not in the same hazard region (e.g., λ_1 = 300 nm and λ_2 = 430 nm), each wavelength is to be treated separately:

If $P_{\text{meas}}(\lambda_1) < AEL(\lambda_1)$ and $P_{\text{meas}}(\lambda_2) < AEL(\lambda_2)$,

then the product does not exceed the class limit

If either condition is not satisfied, comparison with the AEL of higher classes should be considered.

7.3 Spectrally broad sources

Some lasers (e.g., ultrashort-pulse lasers) have an appreciable spectral width. The implications of this are that classification may require assessment in more than one spectral region.

7.3.1 Spectral regions with small variation of the AEL with wavelength

If the spectral output of the emitter does not include any of spectral regions 1), 2) or 3) or the boundary wavelengths of 4) or 5) (see 7.1 above), the distribution can be approximated by a single wavelength.

1) If the AEL does not vary with wavelength, any choice of wavelength within the emitter spectrum is equivalent.
2) If the AEL varies slowly with wavelength, and the wavelength emitter spectrum is contained within one spectral range in the limit table, the limit for the peak or centre of the distribution can be calculated, including shorter wavelengths corresponding to 10 % of peak irradiance of the distribution. If the AEL difference is less than about 1 %, the peak or centre wavelength may be used. A conservative approach is to use the most restrictive wavelength concerned.

7.3.2 Spectral regions with large variation of the AEL with wavelength (302,5 nm – 315 nm, 450 nm – 600 nm and 1 150 nm – 1 200 nm)

If the emitter has some or all of its spectral output in the three regions in which the limits vary greatly with wavelength, two approaches may be used.

1) Calculate the AEL using the lower wavelength boundary for the appropriate region. Since AELs for shorter wavelengths are almost always more restrictive than AELs for longer wavelengths, this simple and conservative approach may be used. However, this may result in a limit that is overly restrictive. If the AEL calculated is acceptable (e.g., the product is Class 1 with this assumption), no further calculations are needed.

b) Calculate the sum of the measured power divided by the AEL as a function of wavelength. Use the general summation in 7.2.1 above.

   Assume, for instance, a source with a triangular spectral distribution, which has a lower wavelength limit of 400 nm, a peak at 460 nm, and an upper wavelength limit of 520 nm. The AEL from 400 nm to 450 nm is constant. Above 450 nm, the AEL increases exponentially with the C_3 factor. If:

$$P_{meas}(400\text{ nm} < \lambda < 450\text{ nm}) \,/\, AEL\,(400\text{ nm} < \lambda < 450\text{ nm}) + \sum_{450<\lambda_i<520\text{ nm}} [P_{meas}(\lambda_i)/AEL(\lambda_i)] < 1$$

   then the applicable AEL is not exceeded.

7.3.3 Spectral regions containing hazard-type boundaries (near 400 nm and 1 400 nm)

If the output spectral distribution includes a hazard region boundary (400 nm and 1 400 nm), the output in each region is independent. Follow the procedure of 7.2.2 and 7.3.2 for each spectral region, if necessary.

7.3.4 Very broad sources

A determination of power or energy per unit wavelength is required. If this information is not available from the manufacturer, spectral measurements should be performed. It is beyond the scope of this document to detail this here. Some information on broadband source measurements is provided in CIE S009 – Photobiological Safety of Lamps and Lamp Products.

If a laser product does not emit radiation below 315 nm, calculations can be simplified. The following information is needed:

a) total power or energy between 315 nm and 400 nm measured as required by the standard (P_a or Q_a);
b) total power or energy between 400 nm and 700 nm measured as required by the standard for thermal limits (P_b or Q_b);
c) total power or energy between 400 nm and 450 nm measured as required by the standard for photochemical limits (P_c or Q_c);
d) power spectral distribution or energy spectral distribution from 450 nm to 600 nm measured as required by the standard for photochemical limits ($P_d(\lambda)$ or $Q_d(\lambda)$);
e) Power or energy spectral distribution from 700 nm to the long wavelength limit of the distribution measured as required by the standard for thermal limits ($P_e(\lambda)$or $Q_e(\lambda)$).

While the procedure applies to both power and energy, only power (P) will be used here.

– Choose an AEL. (Refer to Clause 9 of IEC 60825-1 for formulas and instructions on calculating limits.)
– Calculate the ultraviolet limit AEL_a, and the ratio $R_a = (P_a \,/\, AEL_a)$.
– Calculate the visible thermal limit AEL_b, and the ratio $R_b = (P_b \,/\, AEL_b)$.
– Calculate the visible photochemical limit AEL_c for (400 nm < λ < 450 nm) and $AEL_d(\lambda)$ for the range (450 nm < λ < 600 nm). Sum ratios:

$$R_{cd} = P_c \,/\, AEL_c + \sum_{450\text{ nm}<\lambda_i<600\text{ nm}} [P_d(\lambda_i) \,/\, AEL_d(\lambda_i)]$$

– Calculate the infrared thermal limit $AEL_e(\lambda)$ for 700 nm to the long wavelength end of the range. Sum ratios:

$$R_e = \sum_{700\ \text{nm} < \lambda_i < \lambda_{max}} [P_e(\lambda_i) / AEL_e(\lambda_i)]$$

The product is assigned to the lowest laser Class for which ALL of the following are true:

$R_a < 1{,}0$;

$R_b + R_e < 1{,}0$; and

$R_{cd} < 1{,}0$

7.4 Source temporal characteristics

If the product emits radiation continuously and with constant power, the analysis is straightforward. The emission time must be determined, either specified in the standard as a fixed duration, or specified by a calculated duration (i.e., T_2 is a function of apparent source size or source angular subtense). This allows the applicable AEL to be calculated. For such products, the remainder of 7.4 need not be considered.

7.4.1 Sources with limited "ON" time

If a product can emit radiation only for a limited period of time that is less than the time basis for that class specified in the standard, the shorter time can be used to calculate the applicable AEL. Shorter emission times result in higher peak power limits. Note that it is necessary to consider the AEL for all time durations up to the time base for classification.

7.4.2 Periodic or constant duty factor sources

Some products contain sources that produce a regular series of pulses, or an encoded (irregular) series. The irregular series may be considered as a regular series if the maximum duty factor is known. Duty factor here refers to the fraction or percentage of time the source is emitting.

For 3 microsecond long pulses at 120 pulses per second, the duty factor is 120 x 3 x 10^{-6}/1 or 0,036 %.

For an encoded series of pulses, using pulse train of 120 possible pulse positions of 3 microsecond long pulses every second with a 50 % encoding rate (50 % of the pulse positions contain a pulse, and 50 % do not), the duty factor is 0,5 x 120 x 3 x 10^{-6}/1 or 0,018 %.

Also, refer to Table 9 in IEC 60825-1 (time durations T_i below which pulse groups are summed) for further information on how to calculate limits. The pulse rate, duty factor, encoding duty factor and Table 9, along with the tables for the AELs, are needed to calculate the effective pulse power and duration, as well as the effective pulse rate.

Three limits must be considered:

i) the limit for a single pulse, based on the pulse width;

ii) the limit for the average power for the specified or calculated classification time base;

iii) the limit for the average pulse energy from pulses within a pulse train, taking account of C_5.

Item f) of 8.4.of the standard specifies that the most restrictive of requirements i), ii), and iii) be applied when determining the AEL for repetitively pulsed or modulated lasers for thermal limits for wavelengths of 400 nm and above. Requirement iii) applies a correction factor to the single pulse AEL based on the number of pulses emitted during the applicable time base or T_2, whichever is shorter.

7.4.2.1 Pulse duration

The standard defines the pulse duration as the time increment measured between the half peak power points at the leading and trailing edges of the pulse. Therefore, the duration of interest is the time interval between the point, on the leading edge, at which the amplitude reaches 50 % of the peak value and the point, on the trailing edge, that the amplitude returns to the same value (see Figure 4).

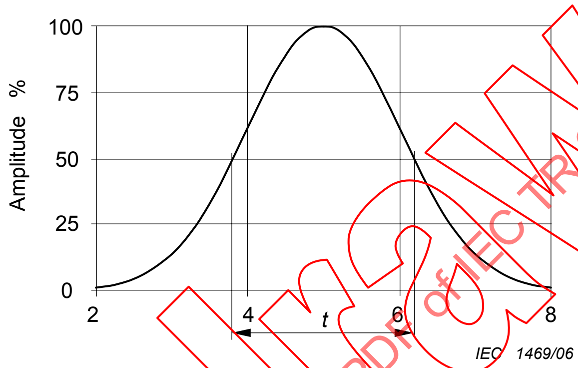


Figure 4 – Pulse duration definition

The pulse duration, *t*, can be accurately determined using a measurement instrument consisting of a photosensitive detector and an oscilloscope or similar device. The measurement instrument is subject to the following requirements.

a) The time response or frequency response of the entire measurement set-up must be sufficient to measure the duration accurately.

b) The radiation to be measured must be sufficiently spread over the active area of the detector such that there will be neither local saturation points nor local variations in sensitivity of the detector.

c) The radiant exposure or irradiance of the radiation must not exceed the maximum specified for the measurement instrument.

Single pulsed, Q-switched, mode-locked, and repetitively pulsed or scanning lasers all require some knowledge of pulse duration in order to classify the product. In the case of scanned radiation, pulse duration should be determined at all accessible positions in the scan pattern. This is necessary because, depending on the type of deflector, the beam speed may not be constant over the entire length of the scan line. For scanning products that incorporate a laser operating in continuous wave (CW) mode, the pulse duration depends on beam diameter and beam speed. For scanning products that incorporate a pulsed or modulated laser, the modulation frequency, the beam diameter, and the scan velocity should be considered in product classification and in emission duration calculations.

7.4.3 Sources with amplitude variation

If pulses are not "flat-top" (constant amplitude during the pulse ON time, see Figure 5 below), detailed analysis of the pulse structure may be required.

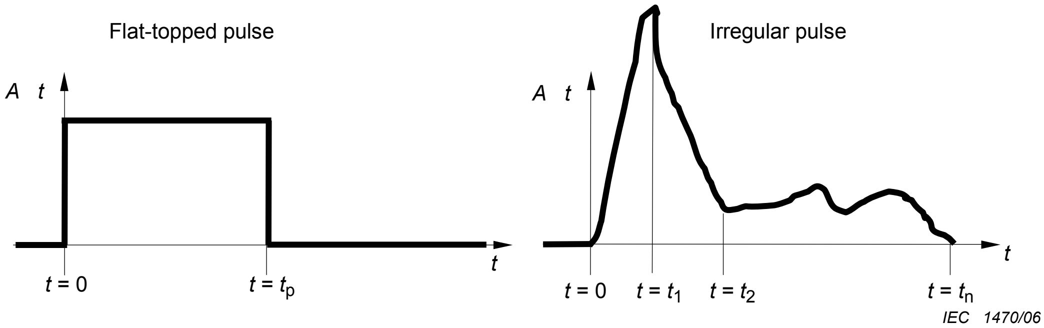


Figure 5 – Flat-topped and irregular pulses

For the flat-top pulse, a simplified analysis is possible; only pulse amplitude $A(t)$ and pulse duration t_p should be considered.

For the second pulse, a piece-wise analysis may be necessary. Consider total energy from $t = 0$ to $t = t_1$, $t = 0$ to $t = t_2$ and $t = 0$ to $t = t_p$ as a minimum. Apply the evaluations in 7.4 to all of the incremental durations identified.

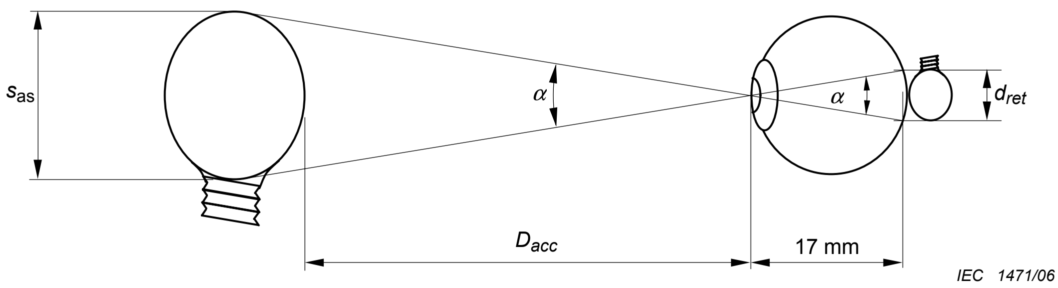
7.4.4 Sources with varying pulse durations or irregular pulses

For trains of pulses with varying durations and/or varying amplitudes, the total-on-time-pulse (TOTP) method may be used as described in item f)iii) of 8.4 of the standard.

7.5 Angular subtense (α)

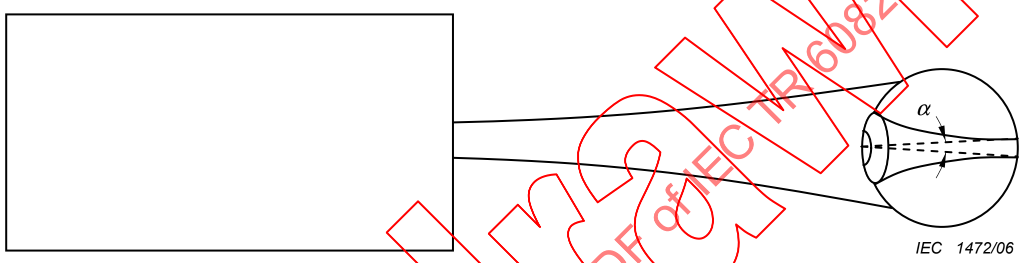
Within the thermal retinal hazard region (wavelength region 400 nm - 1 400 nm) the AELs depend on the angular subtense, α, of the apparent source, through the correction factor C_6 (see Tables 1-4 of the standard). The formula to be used to calculate the AEL depends on the value of T_2, and T_2 depends on α.

The apparent source is the real or virtual object that forms the smallest retinal image for a given evaluation location of the retinal hazard. The angular subtense of the apparent source is determined by the smallest retinal image size that the eye can produce by accommodation (i.e., by varying the focal length of the eye lens). The angular subtense of the apparent source is used as a measure of the retinal image size. This angular subtense is the planar angle subtended by the diameter of the apparent source at the lens of the eye, see Figure 6a and 6b. The angular subtense of the apparent source may vary with position along the axis of the beam. With the exception of surface emitters (such as totally diffused transmitted or reflected beams or LEDs without lens caps or reflectors) the location of the apparent source is also a function of the position of the eye in the beam.



The example shows a beam transmission through, or reflection from, a diffuser such as a frosted light bulb where the light bulb is both the real source and the apparent source.

Figure 6a – Angular subtense (α) and apparent source size (s_{as}) of an incoherent or a diffuse source



This situation is more complex than for a simple source such as in Figure 6a, and both the angular subtense and the location of the apparent source typically change with the position in the beam.

Figure 6b – Angular subtense of a general laser beam at one position in the beam

Figure 6 – Examples of angular subtense

The same power or energy spread over a larger retinal spot, in most cases, reduces the retinal hazard, as expressed by C_6. Therefore, this can be an important parameter for intermediate (1,5 < α < 100 mrad) and large (α > 100 mrad) individual sources and for arrays of sources. However, it is often unnecessary to determine the angular subtense and C_6 can be assumed to be equal to one (1). This provides the most conservative assessment. A laser hazard or classification assessment should always start with the assumption that $C_6 = 1$. If this is sufficient, i.e., the AEL values of the assumed laser Class are not exceeded, there is no need to perform any further analysis.

Most single lasers without beam modifying optics are small sources, $C_6 = 1$, and the location of the apparent source is not significant for laser safety. For these products, the remainder of 7.5 need not be considered.

For a general laser beam, the determination of α, and thus the use of $C_6 > 1$, is beyond the scope of this edition. It will be treated in the next amendment.

For surface emitters, such as diffusely transmitted or reflected laser beams or bare LEDs (without modifying optics), a simplified analysis can be used, as described in 7.5.2.2.

The special case of source arrays with the assumption that each individual source is small ($\alpha_s \leq$ 1,5 mrad), is analysed in 7.5.3. Simple sources with non-circular emission patterns are illustrated in 7.5.3.4. Some considerations that apply specifically to the evaluation of scanning lasers are described in 7.8.

7.5.1 Location of the beam waist

For small sources, or for all sources when assuming C_6 = 1, the accessible emission level can be measured at a predetermined distance from a reference point. The reference points are listed in Table 1 below. For the case of diffuse sources and semiconductor or large area emitters without modifying optics, the reference points for determination of the accessible emission level in Table 1 are valid also for measurements of intermediate and large sources using C_6 > 1.

Table 1 – Reference points

Type of product	Reference point
Semiconductor emitters (laser diodes, superluminescent diodes)	Physical location of the emitting chip
Scanned emission (including scanned line lasers)	Scanning vertex (pivot point of the scanning beam)
Line laser	Focal point of the line (vertex of the fan angle)
Output of fibre	Fibre tip
Diffuse sources	Surface of diffuser
Others	Beam waist

NOTE 1 If the reference point is located inside the protective housing (i.e., is not accessible) at a distance from the closest point of human access further than the measurement distance specified in the standard, the measurement shall be carried out at the closest point of human access.

The technique for estimating the location of the beam waist given below may be used for small sources and Gaussian beams. A necessary condition for this estimation to be valid is that the analysis is performed at a position outside the Rayleigh range where ray optics applies, so that the far field divergence can (and should) be used.

NOTE 2 Information on apparent source location can be found in Enrico Galbiati: Evaluation of the apparent source in laser safety. (See Bibliography).

Choose a convenient reference plane (and make sure that the divergence is constant, i.e. the reference plane is in the far field). Determine the far field divergence angle, θ. The beam waist is located at a distance r from the reference plane (see Figure 7):

$$r = (d)/(2\tan(\theta/2)),$$

where r is the distance from the reference plane to the virtual point of focus of a small source.

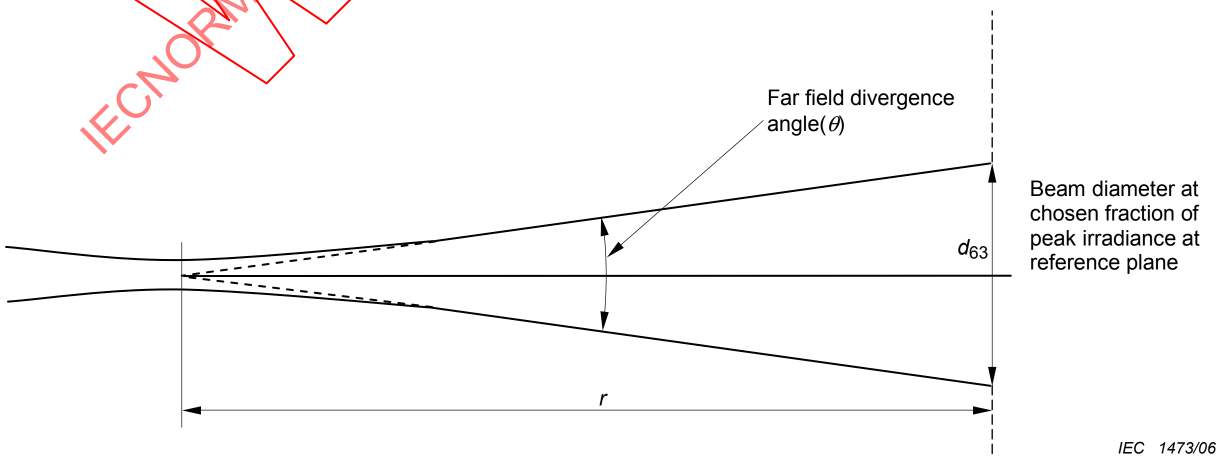


Figure 7 – Location of beam waist for a Gaussian beam

In some cases (e.g., for line lasers with cylindrical lenses, or general astigmatic beams) multiple beam waists may exist. For line lasers, see Table 1. General astigmatic beams are beyond the scope of this document.

Scanning beams are analysed further in 7.8.

7.5.2 Methods for determining angular subtense (α)

There are several suggested methods for determining the angular subtense of the apparent source. The different methods provide various degrees of accuracy and obviously various amounts of effort and cost. The method used is determined by the amount of accuracy needed, i.e., the proximity to the MPEs or AELs, and for some cases, the complexity of the case. The following methods discussed in this report are listed in order of increasing complexity:

a) conservative default method (7.5.2.1);
b) method used for simple sources such as surface emitters or totally diffused beams (7.5.2.2);
c) beam propagation method (7.5.2.3);
d) artificial eye method (7.5.2.4).

7.5.2.1 Conservative default method

If α is not known, and there is no method available to make an experimental evaluation, either a reasonable estimate may be made that can be quantitatively justified or a conservative default value may be chosen.

The default value for α is 1,5 mrad; below this value there is no change in the AEL. This results in C_6 = 1,0 and T_2 = 10 s. While limits calculated in this manner may be artificially low, it is a safe method to employ. As pointed out above, it is a good routine to always attempt this method as a first approximation. Often, no further analysis is needed.

7.5.2.2 Method used for surface emitters or diffused beams

For surface emitters, such as diffusely transmitted or reflected laser beams or bare laser diodes (without modifying optics), a simplified analysis can be used. For these sources the real source is the same as the apparent source and therefore the size of the real source can be used to determine the angular subtense. Therefore, s_{as} in Figure 6a becomes equal to the diameter of the real source, and D_{acc}, the accommodation distance of the eye to the source, becomes equal to the real distance between the eye and the source. The equation below can be used to determine α:

$$\alpha = 2\arctan(s_{as}/2D_{acc}) = 2\arctan(d_s/2r),$$

where arctan is the inverse of the tangential trigonometric function. If α is sufficiently small, the trigonometric function can be simplified:

$$\alpha \sim (d_s/r),$$

where d_s is the diameter of the surface emitter and r is the distance between the surface emitter and the eye (or measurement aperture).

With the use of optics (e.g., integral lens, projection lens or reflector), the apparent source size and location are changed. This requires more detailed analysis, which is beyond the scope of this document and will be addressed in the next amendment.

7.5.2.3 Beam propagation method

This method is based on wave optics rather than ray optics. One important finding of this approach is that the most hazardous viewing distance can be greater than 100 mm. A detailed analysis of this method is beyond the scope of this document.

7.5.2.4 Artificial eye method

The most direct and accurate method is to determine the retinal irradiance conditions (using the hazard measure of power or energy per retinal spot diameter). Using an artificial eye to represent the human eye, the hazard for a range of viewing conditions can be measured.

Theoretically, the eye is usually modelled as a thin lens at the position of the cornea with an equivalent focal length (in air) ranging from 14,5 mm to 17 mm, depending on the accommodation of the eye. The retina is 17 mm from the (2nd principal plane of the) lens and the space is assumed to be filled with air. The focal length of 17 mm is equivalent to a relaxed eye (focusing at infinity) and the 14,5 mm focal length corresponds to the 10 cm near accommodation point of the eye, i.e., the closest distance at which the eye can produce a sharp image of an object. Hyperopic and myopic eyes are not considered in the standard. An aperture with a diameter of 7 mm at the lens models the pupil of the eye.

A detailed analysis of this method is beyond the scope of this document.

7.5.3 Multiple sources and simple non-circular beams

Not all laser products have a single emitter or circular emission pattern. Multi-source examples are multi-channel fibre optic transmitters, multi-element signs and signals (e.g., traffic lights and directional arrows), and multi-segment signs and characters. Simple sources (e.g. diffused beams and LEDs without beam modifying optics) can have arbitrary shapes but still be easily treated if they are homogeneous (see 7.5.3.4).

In theory, with multiple emitters, all combinations should be considered to determine the most hazardous set. One small bright source may or may not be the worst case. Similarly, all the sources taken together may or may not be the most hazardous.

In reality, not all combinations need be considered. If all sources are intended to be equally bright, the analysis can frequently be simplified.

Linear arrays are easier to analyse than two-dimensional arrays. Nonetheless, it is possible to do the two dimensional analysis to determine the most hazardous case.

7.5.3.1 Procedure

Start with a single source. Within the scope of this document, it is assumed that the single source is always a small source (C_6 = 1). Determine the sequence of sources to be analysed. For each case, determine the angular subtense of the combination of sources (see below). This will allow calculation of the AEL for each case. For the analysis of a combination of small sources, the location of the apparent source can be approximated as the location of the actual source array (at all positions in the beams) and the actual spacing between the individual sources is used to calculate the angular subtense, see Figure 9. Only array sizes up to the field of view corresponding to α_{max} = 100 mrad in either direction need to be considered.

Then, a measurement of the accessible emission (power through the 7 mm measurement diameter) is done for each combination of sources, and compared to the calculated AEL. The field of view (or acceptance cone) is limited in the measurement set-up (using a variable field aperture) so that only the sources considered for each case contribute to the measured power, see Figures 8a and 8b.

An example of a four channel one-dimensional array of fibre optic sources with the same average power and equal spacing is shown in Table 2. S_0 is the single source dimension (since the single source is assumed to be small in this document, α_1 is always 1,5 mrad), r is the measurement distance (i.e., the distance between the real source array and the detector, see Figure 8a, or the real source array and the imaging lens, see Figure 8b, and Δ is the centre-to-centre spacing between the single sources, see Figure 9. Note that, according to the standard, α_v and α_h must always be limited to be between 1,5 mrad and 100 mrad, before the arithmetic mean is calculated.

Table 2 – Four source array

Number of Sources	**Apparent source size** mm	**Angular subtense** mrad	**AEL of evaluated Class** mW	**Accessible emission** mW
1	$s_{v1} = s_{h1} = s_0$	$\alpha_{v1} = \alpha_{h1} = \alpha_1 = s_0/r$;	AEL_1	P_1
2	$s_{v2} = s_0$; $s_{h2} = s_0 + \Delta$	$\alpha_{v2} = s_{v2}/r$; $\alpha_{h2} = s_{h2}/r$; $\alpha_2 = (\alpha_{v2}+\alpha_{h2})/2$	AEL_2	P_2
3	$s_{v3} = s_0$; $s_{h3} = s_0+2\Delta$	$\alpha_{v3} = s_{v3}/r$; $\alpha_{h3} = s_{h3}/r$; $\alpha_3 = (\alpha_{v3}+\alpha_{h3})/2$	AEL_3	P_3
4	$s_{v4} = s_0$; $s_{h4} = s_0+3\Delta$	$\alpha_{v4} = s_{v4}/r$; $\alpha_{h4} = s_{h4}/r$; $\alpha_4 = (\alpha_{v4}+\alpha_{h4})/2$	AEL_4	P_4

If the power or energy varies between individual sources or the sources are not equally spaced, the number of cases to analyze is increased. For example, there will be six possible combinations of two sources within a four source array. Geometry and similarity between sources will determine the possible degree of simplification.

The division of the paired values of accessible emission and AEL of the evaluated Class must be less than one for all evaluated cases. Then, the product can be assigned to the evaluated Class.

7.5.3.2 Complexities of multiple channel links

For the case of n channels, all cases from 1 channel to n channels must be considered to determine the most restrictive limit. Usually the simplifying assumption is made that all channels emit the same average power as the peak channel. That will be assumed here. If that is not the case, the analysis may be more complicated, but possibly worth doing so that the calculated most restrictive condition is not overly restrictive. If the array is two-dimensional (not constrained to lie on a straight or curved line), there may be several arrangements for a certain intermediate number (between 1 and n) to be considered.

Cases to be evaluated are determined by considering a variable circular aperture at the emission plane. The minimum source emission aperture diameter contains one channel. The maximum emission source aperture diameter corresponds to an acceptance full angle at the 7 mm measurement aperture of 100 mrad. Determine α from the source array dimensions of the case to be evaluated, and measure the accessible emission through the 7 mm aperture. The AEL corresponding to the α of this case is compared to the measured accessible emission. The accessible emission must not exceed the AEL of the assigned class for any possible combination of sources.

See Figure 8a and 8b below for the measurement geometry. Calculations depend on the angular subtense, α (of the combination of sources to be evaluated). Thus, determination of the appropriate α values is critical for the multi-channel case. Considering each single source as a small source, α corresponds to the acceptance cone of Figure 8a or Figure 8b. (For the single channel case, assuming the minimum default value of α = 1,5 is sufficient.)

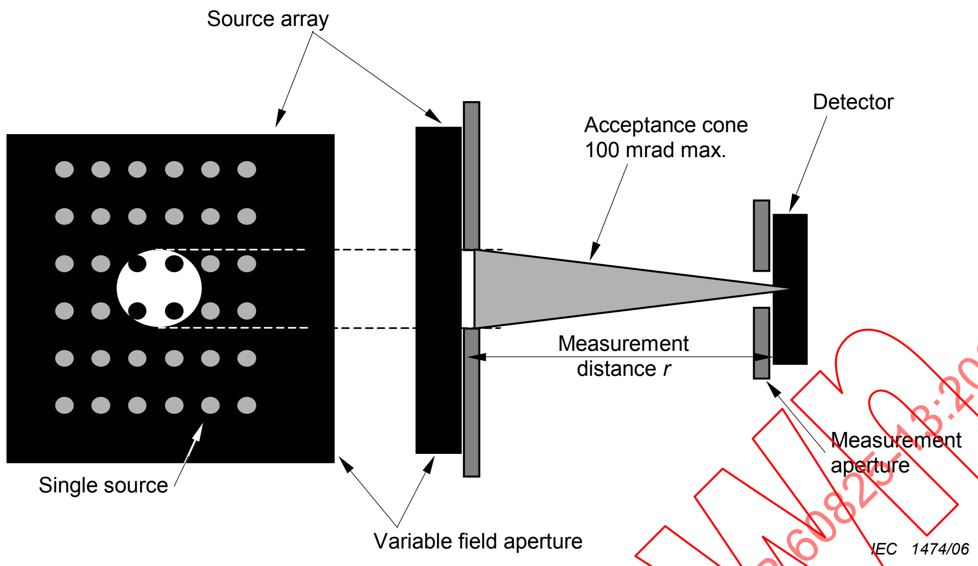


Figure 8a – Measurement geometry for an accessible source

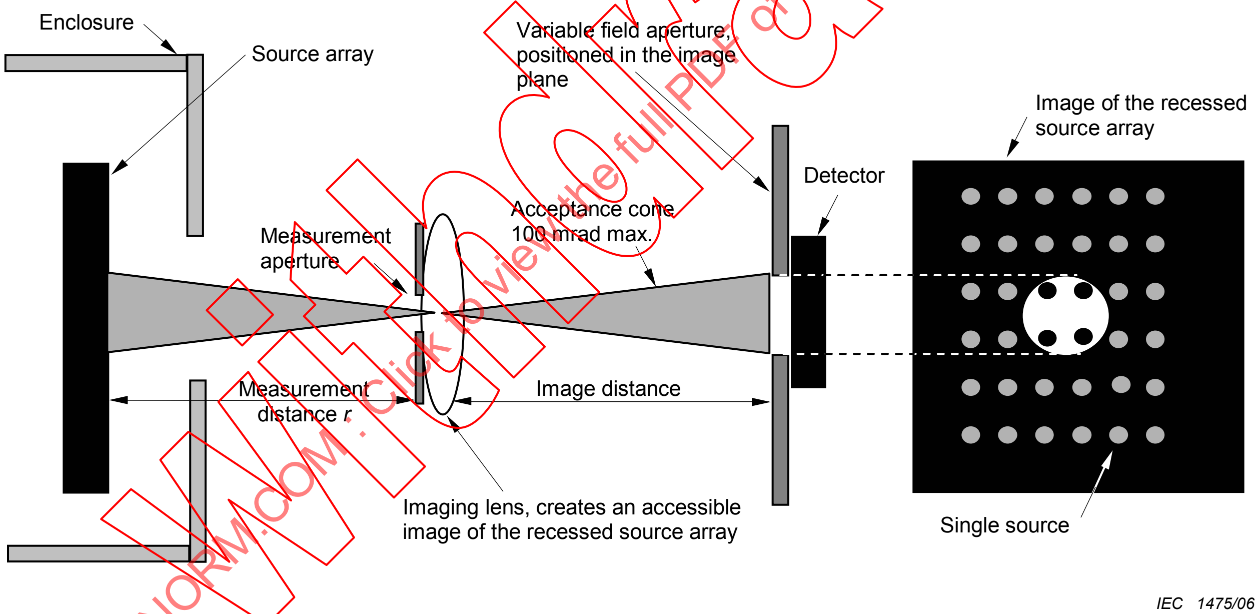


Figure 8b – Measurement geometry for a recessed source

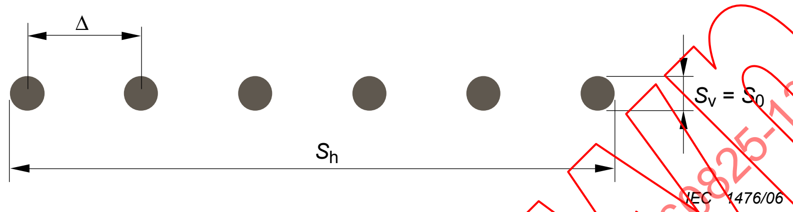
Figure 8 – Source measurement geometries

7.5.3.3 Angular subtense of a linear array

For simplicity, assume (1) a linear array of identical sources with (2) identical spacing. If either of these assumptions is not applicable, the analysis is more complicated. If the spacing is different in the two directions, the parameter Δ becomes Δ_x and Δ_y (see Figure 9). This analysis applies to the retinal hazard spectral region only (400 nm to 1 400 nm).

Figure 9 illustrates how to determine the angular subtense of a linear array of sources.

Assuming the individual sources to be small, the angular subtense is calculated from the source array dimensions. Division by the measurement distance *r* (see Figures 8a and 8b) gives the angular subtense for each orthogonal dimension. The equivalent α value is calculated by averaging the two orthogonal α's, α_v and α_h. With almost all fibre cores and optical sources for optical fibres being smaller than 0,15 mm (corresponding to a minimum α value of 1,5 mrad at 100 mm distance) the default minimum value is often used in the calculation. Thus, the source size s_0 of a single fibre or single source is almost always taken to be 0,15 mm, although it is usually smaller. According to the standard, the angular subtense in each orthogonal direction (α_v or α_h) is always limited to be $\geq\alpha_{min}$ (and $\leq\alpha_{max}$) before calculating the arithmetic mean, α, of the array.



Key

Δ = center-to-center spacing

S_v = vertical size = S_0 (one source size)

S_h = horizontal size = $S_0 + (n\text{-}1)\Delta$

α_v = S_v/r

α_h = S_h/r

α = $(\alpha_v + \alpha_h)/2$

Figure 9 – Linear array apparent source size

Values of T_2 and C_6 can be determined from α for each combination of sources. Using these values and the C_4 and C_7 parameters derived from the emission wavelength, the AEL per channel can be calculated. If the evaluation position is in the far field and the beam from each single source can be assumed to be a Gaussian beam, the beam diameter of a single source at each distance can be determined from the beam divergence, and the fraction of the emitted power collected in a 7 mm aperture can be calculated using the coupling parameter (see 7.8.7). This can be used to determine the allowable power per channel for each combination, and the minimum value would be the most restrictive case.

7.5.3.4 Simple non-circular sources

For a simple source such as a diffused beam or an LED without beam modifying optics, the emitting source is the same as the apparent source, regarding both location and size. So far only circular symmetric sources have been considered. If the source is non-circular, the effective angular subtense is given by:

$$\alpha_{x+y} = (\alpha_x + \alpha_y)/2$$

where α_x and α_y are the angular subtenses along the two orthogonal directions, as shown below in Figure 10.

The angular subtense that is greater than α_{max} or less than α_{min} is to be limited to α_{max} or α_{min}, respectively, prior to calculating the mean.

For a rectangular source, α_x and α_y are the long and short dimensions of the real sources.

For an elliptical source, α_x and α_y are twice the semi-major and semi-minor axes of the ellipse.

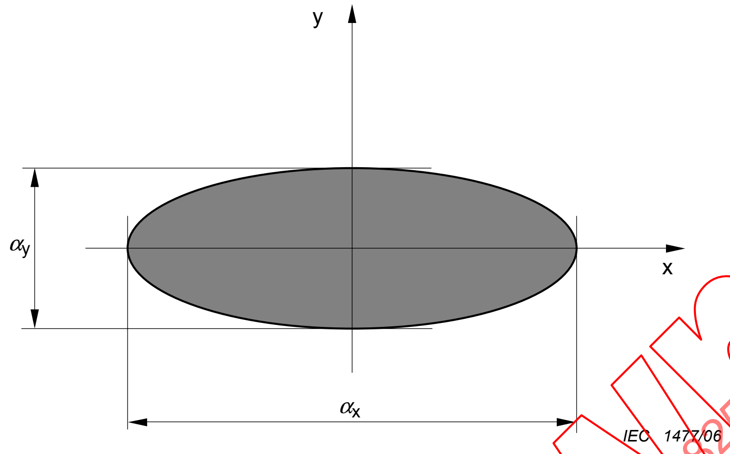


Figure 10 – Effective angular subtense of a simple non-circular source

7.6 Emission duration

In item e) of 8.4 in IEC 60825-1, three classification time bases are specified:

a) 0,25 s for visible wavelengths for Classes 2, 2M and 3R;

b) 100 s for all except cases for which a) and c) apply;

c) 30 000 s for intentional long term viewing.

An exception exists for the retinal hazard region of 400 nm to 1 400 nm for the thermal hazard only. If the parameter T_2 is specified in the appropriate box of the table giving the formulas for limits, calculate T_2, and use it if appropriate. T_2 ranges from 10 s for small sources to the default value of 100 s for large sources (see item *f*) of 8.4 of the standard).

7.7 Measurement conditions

Refer to Table 10 in IEC 60825-1.

Measurement conditions include:

a) diameter of the measurement aperture;

b) distance between measurement aperture and source or apparent source;

c) acceptance angle of radiation measurement device;

d) emission angle limit (divergence or angular subtense of the apparent source) of radiation to be measured.

Care should be taken to limit measured radiation to radiation in the main beam. Any off-axis radiation that reaches the detector via reflection or scattering from non-measurement system surfaces should be excluded.

Since the maximum acceptance angle for radiation measurements is 100 mrad, for large sources (α > 100 mrad) the energy from any portion of the source outside of that angle need not be collected.

The angular subtense of the apparent source is to be determined from a distance greater than or equal to 100 mm from the apparent source for evaluations to satisfy Condition 2 of Table 10 of the standard. If the apparent source is recessed by more than the specified measurement distance according to the standard, the evaluation for Condition 2 is to be at the closest point of human access.

For evaluations to satisfy Condition 1 of Table 10 of the standard, the specified distance is 2 m from the closest point of human access. If angular subtense is to be used to calculate a value of $C_6 > 1$, all distances must be considered until the condition of maximum hazard is found. Under some Condition 1 evaluations, it is appropriate to multiply the angular subtense by a factor of 7 to account for a magnified image. For these cases for Condition 1, the maximum angle over which laser energy need be collected would be (100 mrad)/7 = 14,3 mrad. However, the multiplication factor may be less than 7 (see section 9 of the standard for more information on the multiplication factor).

7.8 Scanning beams

In many applications, a simple calculation assuming $C_6 = 1$ and a pulse duration corresponding to the beam scanning across the full measurement aperture at a distance of 100 mm from the vertex of the scanning beam results in classification that meets the product requirements. If a less restrictive limit is desired, this section outlines a method to determine a more accurate AEL that may allow a lower classification or more output power in the same classification.

NOTE As specified in 9.3 of the standard, Condition 1 and Condition 2 do not apply to scanning beams.

7.8.1 Stationary angular subtense (α_s)

If we assume the scanning system is disabled and the eye is focused at a particular distance, Z, the stationary angular subtense is the subtended angle of the beam diameter (d) at distance Z. Figure 11 shows an optical layout for a disabled scanning system where the location of the point being imaged by the eye is beyond the vertex of the scanning beam.

$$\alpha_s = d/Z$$

where

d = beam diameter at location of point of eye focus

Z = Distance from measurement aperture to location of point of eye focus

NOTE The retinal image irradiance profile is only directly proportional to the beam irradiance profile at the point of accommodation when all of the rays that form the beam actually enter the aperture stop AP. In other cases, an “artificial eye” model or experimental setup must be used to determine the angular subtense.

NOTE The beam diameter is determined in accordance with the standard, e.g., the diameter encircling 63 % of the energy, d_{63}, can be used. For a Gaussian beam this is equal to the 1/e (36,8 %) diameter.

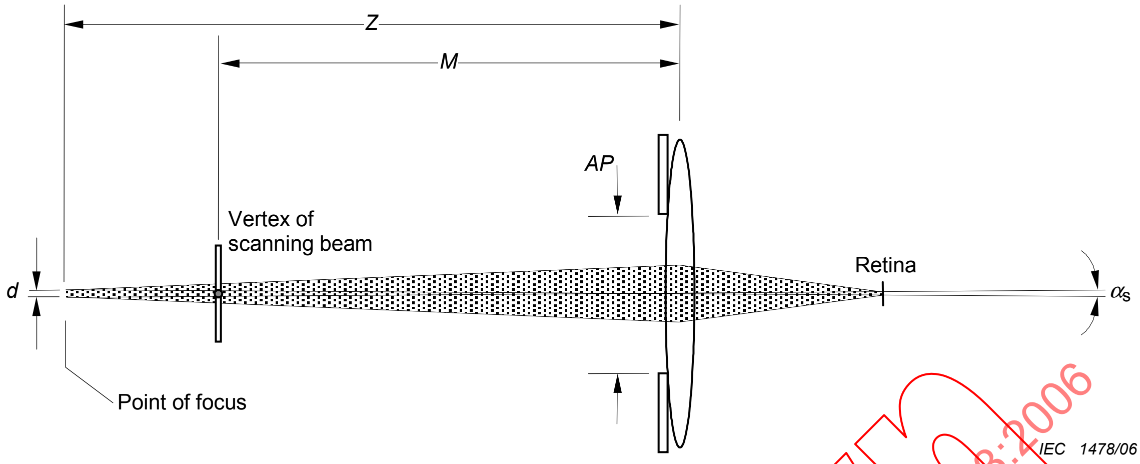


Figure 11 – Imaging a stationary apparent source located beyond the scanning beam vertex

7.8.2 Scanned pulse duration (T_p)

Figure 12 shows this optical system while scanning at two different times (t_0 and t_1) corresponding to when the centre of the beam has reached the edges of the measurement aperture (AP).

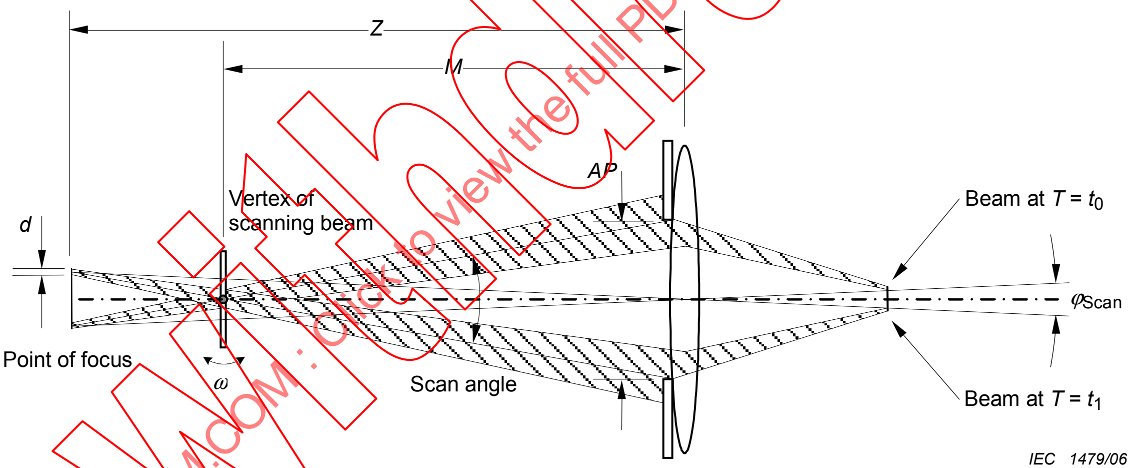


Figure 12 – Imaging a scanning apparent source located beyond the scanning beam vertex

NOTE The scan element is shown as a transparent rather than reflective element in order to simplify the optical layout.

For constant angular velocity, the pulse duration used for classification is

$$T_p = t_1 - t_0 = [\tan^{-1}(AP / M)] / \omega \approx AP / M \cdot \omega$$

where

ω = angular velocity of the scanning beam in rad/s;

AP = measurement aperture diameter as defined in Table 10 of the standard (e.g., 7 mm for λ < 1 400 nm);

M = distance from measurement aperture to scanning vertex.

NOTE Since M is much larger than AP, a small angle approximation is used to simplify the equations.

As the distance from the scan element increases, the angle, φ_{scan}, subtended by the measurement aperture decreases, resulting in decreased pulse duration. This may not be the case when the beam is larger than the measurement aperture or the scan velocity function is non-linear. See 7.4.2.1 regarding measurement of pulse duration and pulse repetition frequency.

7.8.3 Scanning angular subtense (α_{scan})

The scanning angular subtense, α_{scan}, is used to calculate C_6 for scanning beams. If the eye is not focussed on the scanning beam vertex, the beam forms a scan line on the retina, which subtends an angle of φ_{scan}. This is dependant on the measurement aperture and the distance between the scanning beam vertex and the location of the image:

$$\varphi_{scan} = 2 \cdot \tan^{-1}\{(AP / 2) \cdot [(1/M) - (1/Z)]\} \approx AP \cdot [(1/M) - (1/Z)]$$

NOTE 1 The scanning beam vertex is not necessarily at the surface of the scanning element.

NOTE 2 This formula is valid regardless of which side of the scanning beam vertex the point of eye focus is located.

φ_{scan} cannot be used to define the angular subtense along the scanning direction for calculation of C_6 because for a brief time all of the energy is directed to a single point on the retina. However, for durations less than T_i as specified in Table 9 of the standard (e.g. 18×10^{-6} s for 400 nm < λ < 1 050 nm), the hazard is not dependent on the beam shape and integration is allowed. In this case, the scanning angular subtense can be increased to φ_T corresponding to the movement of the beam on the retina in time T_i and given by the formula:

$$\varphi_T = (T_i / T_p) \cdot \varphi_{scan} \quad \text{If } T_p \geq T_i$$

$$\varphi_T = \varphi_{scan} \quad \text{If } T_p < T_i$$

Substituting equations for T_p and φ_{scan}, yields:

$$\varphi_T = T_i \cdot M \cdot \omega \cdot [(1/M) - (1/Z)]$$

The scanning angular subtense α_{scan} is given by the formula:

$$\alpha_{scan} = \max[(\alpha_s + \varphi_T), \alpha_{min}]$$

where α_s = Stationary angular subtense along the scanning axis.

NOTE If α_s is less than α_{min}, α_s is not replaced with α_{min}.

For any point of eye focus, C_6 can be calculated with the formula:

$$C_6 = (\alpha_{nscan} + \alpha_{scan})/(2 \cdot \alpha_{min})$$

here α_{nscan} = angular subtense along the non-scanning axis or α_{min}, whichever is larger.

7.8.4 Bi-directional scanning

If the scanning system is bi-directional, there is a location at the end of the scan line where the beam stops and reverses direction. If this point is accessible, it must be considered in determining the AEL. Since the angular velocity is non-linear, the pulse duration, T_p, is not given by the formula in 7.8.2 and must be measured or derived for the velocity as a function of angular position. In order to calculate C_6, φ_T should be measured or derived as the angle that the beam moves away from the endpoint in time (T_i/2). The duration is half because the beam reverses direction at the end of the scan line, while remaining in the same region on the retina.

7.8.5 Number of scan lines in aperture (*n*)

In the case of multiple scan lines originating from a single point on a scanning element, scan line separation typically increases with increasing distance from the scanning element. The number of scan lines in the aperture affects the number of pulses in the pulse train during the applicable time base. The equation below expresses the number of pulses in the pulse train, *N*, as a function of pulse repetition frequency, the number of scan lines in the aperture, and the applicable time base.

$$N = (PRF) \cdot n \cdot T$$

where

N = the number of pulses in the pulse train during the applicable time base, or T_2, whichever is smaller;

PRF = pulse repetition frequency of a single scan line;

n = number of scan lines in aperture;

T = applicable time base or T_2, whichever is smaller.

See 7.4.2.1 concerning measurement of pulse duration and pulse repetition frequency.

In scanning systems where multiple scan lines enter the pupil from different field sources, the corresponding images on the retina are at different locations. If these sources are separated by more than 100 mrad, they are considered to be independent and are treated as isolated sources. For angular separation less than 100 mrad, the AEL is calculated for each source individually, as well as all combinations of multiple sources to determine the most restrictive case. If multiple sources are considered as one irregular source, the number of pulses is the number of times the irregular pattern is formed. For example, if source A and source B have a combined C_6 value of $C_{6(A+B)}$ and both are simultaneously scanned across the measurement aperture *N* times during the measurement period, the AEL will refer to the sum of power from A and B reduced by the repetitive pulse criteria for *N* pulses, rather than 2**N*. See 8.4 of the standard concerning measurement of multiple and irregular sources.

7.8.6 Maximum hazard location

The maximum hazard location is where the combination of angular subtense, pulse duration, number of pulses, and collected energy (or power) results in the most restrictive classification. If the stationary beam is larger than the measurement aperture at a distance greater than 100 mm, the maximum hazard location may be closer to the apparent source (than calculated for a smaller beam) because the higher C_6 value is offset by the reduced coupling parameter. In the case of multiple scan lines, the distance just prior to the transition to fewer scan lines inside the measurement aperture may be the location of maximum hazard. When evaluating a distance to determine the most hazardous location, all of the variables are to be measured at that distance.

For simple scanning beam systems, the following two cases should be examined for the maximum hazard condition. Also see the example in Clause A.4.

7.8.6.1 Infinite focus (relaxed eye)

If α_{scan} is considered to calculate $C_6 > 1$, the condition where the eye is focussed at infinity is important to consider. In this case, $Z = \infty$ and $\alpha_s \to 0$ if the laser beam is of reasonable quality. This yields the result that α_{scan} is not dependent on the distance from the scanning vertex, *M*, but is only dependent on T_i and the angular scan velocity.

$$\alpha_{scan} = \max\left[(T_i \cdot \omega),\ \alpha_{min}\right]$$