

WHITE PAPER

# The new edition of the international laser product safety standard IEC 60825-1

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## SUMMARY

In May 2014, the third edition of the international laser product safety standard IEC 60825-1 was published. The main changes, compared to the earlier edition, relate to the retinal thermal MPEs and AEL for Class 1, 2 and 3R. For pulsed emission, the rules to perform an AEL or MPE analysis have changed significantly, as well as, for extended sources, a time dependent  $\alpha_{\max}$  was introduced. The MPE/AEL values are in rare cases lower than compared to Edition 2, but for most practical cases the new limits result in a significant increase of the permitted emission level for the “safe” classes or of the MPE for the eye (and therefore also a decrease of the NOHD for Class 3B and Class 4). Other changes relate to alternative style of labels, a new Class 1C, a more appropriate classification scheme for laser illuminated lamps, and changes in the measurement requirements.

## INTRODUCTION

The international laser safety standard IEC 60825-1 was published in May 2014 as Edition 3 [1]; at the same time, Edition 2 [2] was automatically withdrawn at the IEC level (but continues to be used on a national level in a transition period). As is the general arrangement, IEC does not develop MPEs as biological exposure limits, but adopts the values that are developed and recommended by ICNIRP. ICNIRP published revised exposure limits in their 2013 guidelines [3]. In a parallel process, the United States’ Standard for the safe use of lasers, ANSI Z136.1 [4] was also revised, as the ANSI MPE values are based on the same set of injury threshold data and there is also a significant overlap of expert members between the ANSI bioeffects subcommittee and the ICNIRP Standing Committee IV on Optics. It is noted that ANSI Z136.1 is a user safety guideline document for the USA and although it also contains a classification scheme, it is not directly applicable for the manufacturer of products; the classification scheme is intended to be applied by the user when the mode of installation of a laser changes the accessible laser radiation and the necessary user safety measures can be adopted to reflect that change. Although almost all changes of the exposure limits are harmonized between the ANSI, ICNIRP and IEC document, in some cases the ANSI limits are different compared to ICNIRP (and therefore IEC limits); this White Paper is centred on the changes of IEC 60825-1.

Since the exposure limits (MPEs) for the eye are the direct basis for the AEL (accessible emission limits) for the laser product safety classes Class 1, 1M, 2, 2M and 3R [5], any changes in the MPEs will also result in equivalent changes of the AEL values and thus in the permitted output powers for these classes. It is stressed here that with the exception of the wavelength range of 1250 - 1400 nm, **all the changes of the retinal thermal limits are relevant only for pulsed emission/exposure**. This means that the limit for cw lasers (such as 1 mW for Class 2, or 5 mW for Class 3R in the visible wavelength range) will not change (i.e. cw limits only change in the wavelength range of 1250 nm to 1400 nm). Since Class 3B AELs (i.e. the border between Class 3B and Class 4) are not directly derived from MPEs, they are not affected, but the NOHD of pulsed Class 3B and Class 4 systems will in most cases be affected. Regarding Class 3B it is noted that due to the change of the AELs of Class 3R (which in almost all practical cases is an increase) some products that were in the lower range of Class 3B under Edition 2.0 will become Class 3R or potentially even Class 2 (when in visible) or Class 1 under Edition 3.0. Similarly, products that are pulsed and were Class 3R under Edition 2.0 could well become Class 2 or Class 1 under Edition 3.0. Only in very rare cases will the permitted output level become more restrictive (i.e. smaller) under Edition 3 as compared to Edition 2: this can be the case for pulse durations less than 18  $\mu$ s and wavelengths between 400 nm and 1050 nm (for wavelengths between 1050 nm and 1400 nm for pulse durations less than 50  $\mu$ s) for systems which emit at a very low repetition rate of less than 39 pulses within 10 s.

It is pointed out that classification of products and labelling based on IEC 60825-1 Edition 2 [2] is also accepted by the CDRH for products sold in the USA; as specified in “Laser Notice 50” of the CDRH. IEC 60825-1 Edition 2.0 therefore also has high significance for placing laser products on the US market. At the time of writing of this White Paper, the CDRH has not yet issued a new Laser Notice that would express that Edition 3 of IEC 60825-1 is accepted in the same as Edition 2 is accepted based on Laser Notice 50.

As is customary, the 3rd edition of IEC 60825-1 was a parallel project between IEC and the European standardisation organisation CENELEC. As a consequence, the text that was published as IEC 60825-1:2014 Ed. 3.0, was in Europe issued as identical text in the standard EN 60825-1:2014 Ed. 3.0. Since CENELEC does not actually publish and sell standards, the document is published on a national level, and the British

Standards Institute was the first to publish the third edition as BS EN 60825-1 in August 2014. The German version of EN 60825-1 Ed. 3.0 was published in July 2015, and is available as DIN EN 60825-1:2015. On April 17th 2015, EN 60825-1 Edition 3.0 was listed in the Official Journal of the European Union as harmonised standard under the Low Voltage Directive 2006/95/EC; the transition period where Edition 2 still lends the presumption of conformity was for this version of the LVD set as 19.6.2017. Also in the CENELEC database, Edition 3.0 had a date (referred to DOW) of 19.6.2017 when conflicting standards (i.e. Edition 2.0) had to be withdrawn on a national basis. When the new LVD 2014/35/EU came into force, the list of harmonised standards that is published in the Official Journal did not contain a date of cessation of presumption of conformity of superseded standard, i.e. of Edition 2. This might have been an oversight; however, it was confirmed by CENELEC and the European Commission that this list of harmonised standards is the valid one for the new LVD. Since there are some advantages for manufacturers to keep using Edition 2.0 (for instance to avoid uncertainties how the product is to be dealt with at the workplace under the AORD), in May 2017 it was decided by CENELEC to change the DOW for Edition 3 to 2019-06-19 and to also use this date in future lists of harmonised standards for the LVD for the cessation of presumption of conformity of superseded standard.

Regarding the exposure limit values (ELV) that are defined in the European Directive on artificial optical radiation (AORD) [6] and the respective national transpositions which are by-laws to the work place safety legislation in the member states of the European Union, it is pointed out that the ELV were directly adopted from the earlier ICNIRP guidelines, and it is not clear when the ELV that are valid at the workplace on the European level (the AORD) will be updated to reflect the ICNIRP guidelines published in 2013. On a legal level, the product safety standard EN 60825-1 (specifying emission limits) is not related to the AORD which specifies exposure limits for workers in the European Union, where national exposure limit values shall not be less restrictive (but can be more restrictive, i.e. lower, by legal principle). In practical terms, the classification system of laser products is of great value to simplify safety evaluations at the work place, particularly for the “safe” laser classes (see for instance the non-binding guide for the AORD [7]). It is hoped that in practice, products classified as Class 1 or Class 2 under the third edition of EN 60825-1 will also be permitted by national work place safety inspectors to be treated in the same way as products that are classified as Class 1 and Class 2 under Edition 2, namely with the assumption that they are safe and no user safety measures are necessary. The alternative, that Class 1 and Class 2 products when classified under EN 60825-1 Edition 3.0 have to be analysed at the workplace in terms of the exposure of a worker potentially exceeding the ELV of the AORD, would for many products, such as distance sensors, laser pico-projectors, 3D cameras or gesture control devices, which will soon have a very high distribution density, incur an extreme and therefore unrealistic effort, which could also be seen as undue, considering these are safe products, used without any safety measures as consumer products. Until the AORD is updated, which will take several years, it can only be hoped that also “new” Class 1 and Class 2 products are treated at the workplace as stated in the non-binding guide for the AORD, i.e. considered as “safe”. The issue is under discussion in the responsible European Commission Directorate General DG EMPL.

This White Paper will concentrate on the changes of IEC 60825-1 Edition 3 with respect to the MPE and AEL values. Amendments other than of the MPE or AEL values will be listed but not discussed in detail.

## **CHANGES OTHER THAN MPEs AND AEL**

There are some significant changes in IEC 60825-1 Edition 3.0 that are not directly related to MPEs and AEL values, and the main ones are summarised in the following.

### **Measurement Conditions**

Condition 2 (the “eye loupe” condition) has been removed from the measurement condition requirements (in Edition 2, for the simplified analysis, Condition 2 for the retinal hazard region was basically to place a 7 mm aperture at 70 mm distance from the reference point). This leaves Condition 1 (“telescope” condition) and Condition 3 (“naked-eye” condition), which were, however, not renamed or renumbered. If considered necessary for specific product categories, a special measurement and testing condition that considers usage of high-magnification lenses for highly diverging beams emitted from small sources can be included in product-

specific standards, such as in IEC 60825-2 for optical fibre communication systems. The removal of Condition 2 is based on the conclusions that were already reflected in Interpretation Sheet 1 for IEC 60825-1 Edition 2 (ISH-1) [8] which in turn is mainly based on work of the group at Seibersdorf Laboratories presented at ILSC 2009 [9]. While the definition of Class 1M and Class 2M in principle is not changed, these laser classes are now characterising products where exposure with telescopes can be hazardous, and no longer apply to highly divergent beams; in a sense, Condition 3 (7 mm aperture at a minimum distance of 100 mm distance in the wavelength range of 400 nm to 1400 nm) covers both the emission that is accessible for the naked eye with a very restrictive assumption regarding pupil diameter and distance, as well as the emission that is accessible under normal circumstances for eye loupes with intermediate magnifications.

The application rules for Condition 1 were also amended in that it is now permitted that *“Condition 1 is not applied for classification of laser products intended for use exclusively indoors and where intrabeam viewing with telescopic optics such as binocular telescopes is not reasonably foreseeable.”* Following general product safety design rules, for the case of large-diameter collimated beams and emission in the wavelength range of 1350 nm to 1400 nm where up to 500 mW is permitted to pass through a 7 mm aperture for Condition 3, it might be prudent for some products to also apply Condition 1 for the case of indoor products, considering the risk for fire or skin burn when the beam would be focused by concave reflective surfaces (i.e. to limit the power through a 50 mm aperture at 2 m distance to 500 mW).

## Class 1C

A new class has been introduced, Class 1C, where C stands for “contact” but in some interpretations also stands for “conditional” (see also ILSC 2009 paper by D. Sliney and J. Dennis [10]). Currently the application of this new class is limited to products intended for treatment of the skin or internal tissue in contact or close to the skin where the product is designed to be safe for the eye. In future amendments of the standard, the concept might be extended to materials processing laser products which are used in contact with surfaces and feature sufficient engineering safety measures so that no eye protection is needed and the product is also safe when placed on transmitting surfaces.

It should be noted that a product is permitted to be classified as Class 1C only if and when a vertical standard exists that further defines the requirements for the engineering means (for instance contact switch) that make the product safe for the eye as well as, for the case of home-use devices, that limits exposure levels for the skin to safe levels (there is no need to limit the emitted power levels that are incident on the tissue for surgical devices); see also [11]. Recently, such a product specific standard was developed and is to be published in May 2016: IEC 60335-2-113 *Household and similar electrical appliances - Safety - Part 2-113: Particular requirements for cosmetic and beauty care appliances incorporating lasers and intense light sources*.

## Light Output Classified as Lamp

For laser products designed to function as conventional lamps, i.e. where laser radiation is used to replace lamp sources, it is possible under Edition 3.0 to assess the optical radiation output under the IEC 62471 series [12] and not under IEC 60825-1. This amendment, reflected mainly by a new subclause 4.4, was mainly prompted by blue laser sources being used to produce white light by directing the laser onto a wavelength conversion phosphor (the same principle as used to produce white LEDs based on blue LED emitters) as well as laser radiation being used for cinema projectors. The emitted optical radiation of such systems is either broadband (phosphor) or at least multi-wavelength, as well as diffuse (phosphor) and extended sources (projectors). However, because for such products the radiation is “originally” produced by a laser, the product as such still falls under IEC 60825-1 (in the same way as a product, where *no* laser beam is emitted, such as a DVD player or burner, falls in the scope of IEC 60825-1 and needs to be classified according to IEC 60825-1). The problem was dealt with by IEC TC76 by permitting under Edition 3.0 that the emitted light is treated and classified under an IEC 62471 standard when the product is designed to function as conventional light source and when the radiance of the product (including reasonably foreseeable single faults) is below  $(1 \text{ MW} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}) / \alpha$ , where  $\alpha$  is the angular subtense of the apparent source specified in radian ( $\alpha$  is limited to values between 0,005 rad and 0,1 rad) determined at 20 cm distance from the product. For the determination of the radiance value to be compared against the criterion, an averaging angle of acceptance of 5 mrad is permitted. What was not specified in the standard is the averaging aperture stop for the determination of the

radiance value; for a normal light emission that is designed to function as conventional lamp or luminaire (such as a car headlamp), the beam is larger than for instance a 7 mm aperture and the averaging over that dimension is not relevant. However, for the case that the criterion is applied to beams that are smaller than the usual 7 mm aperture to reflect a dilated pupil, the averaged radiance would be smaller than the real radiance and relatively high-power beams would theoretically be permitted and would remain below the radiance criterion if the radiance were averaged over a 7 mm aperture stop.

Regarding the radiance criterion in subclause 4.4 it should be also noted that this is NOT a safety limit, i.e. to remain below that limit does not mean that the emission of the product is “safe”. It could still well be a Risk Group 3 product under the IEC 62471 series.

The second criterion is that the angular subtense of the apparent source has to be larger than 5 mrad determined at 20 cm distance, which ensures that the product does not constitute a point source and cannot emit a collimated laser beam, i.e. there has to be some level of spatial incoherence as otherwise the apparent source would not be larger than 5 mrad. In the upcoming Interpretation Sheet it is planned to specify that the criterion for the determination of  $\alpha$  is the 50% level (i.e. 50% of the peak radiance within the apparent source defines the “edge” to determine  $\alpha$ ) and that for multiple sources the outer edges are used to determine  $\alpha$ .

That the emitted radiation (i.e. the radiation that is “neglected” for laser classification) has some level of incoherence or is broadband is *not* a criterion for the application of subclause 4.4, i.e. it could for instance well be that the emission of a laser illuminated projector has three distinct wavelengths. That the emission cannot have a high degree of spatial coherence is indirectly given by the criterion for a minimum value of the angular subtense of the apparent source, but is no specific criterion that would be given in terms of degree of coherence.

If there is no “normal” laser radiation accessible, these products will be classified as Class 1 under IEC 60825-1:2014, where the optical radiation that is emitted and functions as light source is “neglected” for the classification based on IEC 60825-1; this emitted optical radiation has to be then assessed under the IEC 62471 series of standards. Thus a laser illuminated phosphor emitter could for instance be Class 1 according to IEC 60825-1 Edition 3.0 and Risk Group 3 under IEC 62471. It is noted that a product specific part for projectors was in the meantime developed and published as IEC 62471-5 in June 2015 [13].

## Risk Analysis

The role of risk analysis was emphasized in the 3<sup>rd</sup> edition of IEC 60825-1, as discussed in more detail in Paper #601 of the ILSC 2013 proceedings [14]. While this is not really a change in the requirements, the amended text helps to strengthen the role of risk analysis not only in terms of probability of exposure but also in terms of actual risk for injury, based on injury thresholds.

## Alternative Labels

After a long development process and earlier attempts, symbol-labels are given as an alternative to worded labels to reduce the burden for manufacturers regarding multiple language labels for products (however, for the higher hazard classes, the labels still include some worded warnings). Some examples are given in Figure 1.

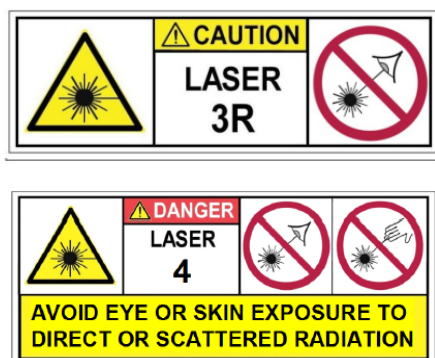


Figure 1. Examples of alternative labels according to IEC 60825-1 Edition 3.0

## Engineering Specifications

There were some adjustments in the engineering specifications, such as that for hand-held battery powered Class 3B devices there is no need for a remote interlock connector. For Class 3R outside the wavelength range of 400 nm – 700 nm, instead of an emission indicator, a momentary switch that must be continually depressed to allow emission is permitted. The wording for some requirements was elaborated and clarified with notes.

## Presentation of MPEs also as “Power through Aperture”

Following the example of ICNIRP (but see also [15]), the MPEs for the eye in the wavelength range of 400 nm to 1400 nm were, besides the usual presentation as irradiance/radiant exposure (with the exposure level averaged over a circular 7 mm limiting aperture) presented also as “permitted power/energy through a 7 mm aperture stop” which is often easier to communicate and understand (for instance the MPE is 1 mW for 0,25 s exposure duration in the visible wavelength range, i.e. 1 mW permitted through a 7 mm aperture, and this is easier to communicate as to express it as  $25 \text{ W m}^{-2}$  where the irradiance is averaged over the aperture).

## Analysis of Complex Extended Sources

Clause 4.3 d) specifies how complex extended sources (i.e. non-uniform or multiple) need to be analysed to determine the parameter  $\alpha$  as well as the accessible emission. This clause was contained in Edition 2.0 already in an almost identical way. To clarify that the angle of acceptance (or field of view) that is to be applied for the analysis of the image of the apparent source needs to be varied both in terms of position and shape not only in one dimension but in both dimensions (x and y), the text was amended as follows:

“For the evaluation of assemblies of points or for partial areas, the angle of acceptance  $\gamma$  is to be varied *in each dimension* between  $\alpha_{\min}$  and  $\alpha_{\max}$ , i.e.  $\alpha_{\min} < \gamma < \alpha_{\max}$ , to determine the partial accessible emission associated with the respective scenario.”

With this it was clarified that in the general case (if the source is not circularly symmetric) the analysis field of view (angle of acceptance) to “cut out” a certain part of the image of the apparent source cannot only be circular but also oblong; further clarification on this issue is to be published in an interpretation sheet which is in the process of preparation; see also ILSC 2015 Paper [16] with detailed discussion and examples.

## Re-order of Clauses

Last but not least, the main clauses were reordered to reflect the practical process: first, for a given product, the class needs to be determined (now Clauses 4 and 5; in Edition 2 these were Clauses 8 and 9), and then, depending on the class, product safety features (such as key switches) – now Clause 6 – and warning labels - now Clause 7 - are required. In earlier editions of IEC 60825-1, the clauses dealing with engineering specifications and labels came first and then the test requirements for determination of the class were specified.

## CHANGES OF MPES AND AELS

In the subsequent sections of this White Paper, the changes of the limits and the impact for products are discussed. Whenever the term “limits” is used, it means MPEs for retinal thermal injury as well as the AEL for Class 1, Class 2 and Class 3R as applicable (i.e. Class 3R being 5 times the AEL of Class 1 or Class 2 depending on wavelength range).

It is not in the scope of this White Paper to discuss the underlying bio-effects and the injury threshold data base; these are discussed in other publications, and there are two reviews that cover most of the changes ([17] and [18]).

## 1250 nm to 1400 nm

The factor  $C_7$  is significantly increased in the wavelength range of 1250 nm to 1400 nm. In the 2nd edition,  $C_7$  remained at a value of 8 for wavelengths between 1200 nm and 1400 nm as shown in Figure 2 by the dashed line.

The new factor  $C_7$  features an exponential factor that is added to the level of 8 and that leads to significantly higher values starting at wavelengths of about 1250 nm.

$$8 + 10^{0,04(\lambda-1250)} \quad \text{for} \quad 1200 \text{ nm} \leq \lambda \leq 1400 \text{ nm}$$

For the example of the wavelength of 1310 nm, often used in the telecommunication industry, the new factor  $C_7$  equals 259, which is a factor of 32 higher than the previous factor  $C_7$ .

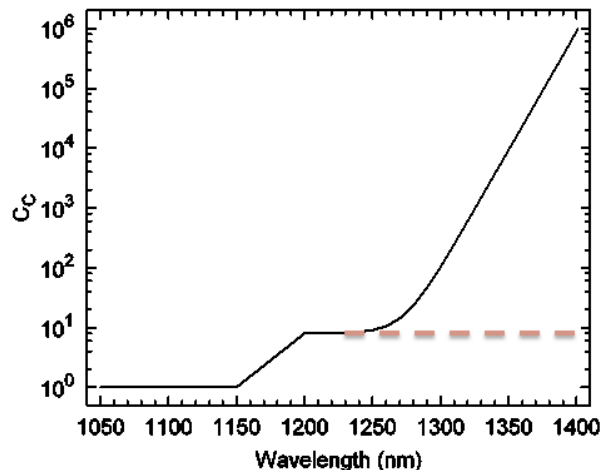


Figure 2. Previous (dashed) and new factor  $C_7$ . Note that there is also a new dual limit to protect the anterior parts of the eye, not shown here.

For a wavelength of 1400 nm, the factor  $C_7$  equals  $10^6$ , which is a factor of 125 000 higher than the current value. While such high levels are permitted in terms of retinal hazard, these are power levels that can injure the skin or the anterior parts of the eye (cornea, lens, iris). Thus an additional limit was specified, referred to as “dual limit”. This dual limit is realised differently for MPEs given in the appendix of the standard and the limits for the emission of products in terms of classification. Regarding the MPEs, the exposure of the eye is not permitted to reach those high levels, as a dual exposure limit was introduced to protect the anterior parts of the eye by requiring that the exposure of the eye is limited by the MPE for the skin to protect the anterior parts of the eye (cornea, lens, iris). This is to reflect that the retinal thermal MPE with  $C_7$  applies to exposure of the retina and since the radiation is greatly reduced by absorption of the pre-retinal media, as reflected by  $C_7$ , the retina is not at risk, but at the corresponding levels, the anterior parts of the eye could be at risk. The simplest solution to protect the anterior parts of the eye was to require that the skin MPE is not exceeded, which apply anyway, since the eye would not be exposed alone. It should be noted that this additional skin limit is only given in the (non-normative) MPE section of IEC 60825-1, and is not reflected in the classification requirements in this form. For classification as Class 1, 1M, and 3R, the upper range of the accessible emission (measured with Condition 1 or Condition 3, as applicable) is limited to the AEL value of Class 3B for the wavelength range between 1250 nm and 1400 nm, i.e. for cw sources to 0,5 Watt. For small sources ( $C_6 = 1$ ), the wavelength where the new “retinal thermal” AEL for Class 1 reaches 0,5 Watt is at 1310 nm, i.e. for wavelengths longer than 1310 nm and small sources, the Class 3B AEL is the limiting factor; for extended sources with higher retinal thermal AELs, this limitation will occur at shorter wavelengths. The accessible emission (AE) that is compared against the AEL of Class 3B is determined with the same aperture at the same distance as the accessible emission that is compared against the AEL of the class that is intended for the product – the two AE values can still be different as for comparison against Class 3B limits, an open field of view is to be used, while for the retinal thermal AEL, the AE can be smaller when the apparent source is larger than  $\alpha_{\max}$ . For Condition 3, due to the distance of the aperture to the product, for diverging beams, levels of radiation that significantly exceed 500 mW (Class 3B AELs) are permitted to be emitted for Class 1 products

(when the beam diameter at the aperture is larger than 7 mm). This was critically commented upon in the development phase by some experts, including the author of this White Paper, as not prudent particularly for consumer products (a similar issue exists for divergent beams and extended sources also for the wavelength range less than 1300 nm). However, it was felt by the majority of the experts who participated in the discussion that the hazard that exists at contact or very close distances is properly addressed by the warning label that is necessary if the radiation determined with a 3,5 mm aperture at the closest point of human access exceeds the AEL of Class 3B (this requirement was already contained in Edition 2.0) as required in Clause 7.13 titled “Warning for potential hazard to the skin or anterior parts of the eye”. See also discussion below in Section “Time dependent  $\alpha_{\max}$ ”.

The ICNIRP approach with respect to the dual limit was to limit the exposure of the eye (for cases where only the eye is exposed) in the wavelength range of 780 nm to 1400 nm to twice the exposure limit of the skin. For the visible wavelength range, where for pulsed sources with large apparent sources also high retinal exposure limits are permitted, the iris needs to be protected and here the dual limit is given by ICNIRP as the skin exposure limit. However, for practical purposes, permitting a level of twice the skin MPE is only relevant when the skin (around the eye, or the eye lid) is not exposed.

In ANSI Z136.1 published in 2014, the dual limit was specified in a more sophisticated way, by extrapolating the corneal limits as defined for wavelengths longer than 1400 nm into the regime of wavelengths below 1400 nm. At the same time the corneal MPEs for wavelengths up to 1500 nm were raised for exposure durations less than 10 seconds; for a pulse duration of less than 1 ms, the difference to previous limits is a factor of 3.

## Reduction for Nano-second Pulses

For single pulses (for multiple pulses see subsequent sections) that have pulse durations less than the previous (Edition 2)  $T_i$  of 18  $\mu\text{s}$  for wavelength up 1050 nm and  $T_i = 50 \mu\text{s}$  for wavelengths between 1050 nm and 1400 nm, the new limit is lower, since the new  $T_i$  equals 5  $\mu\text{s}$  and 13  $\mu\text{s}$ , respectively. This is in effect a lowering of the limits for small sources and single pulses by a factor of 2,5 (see Figure 3).

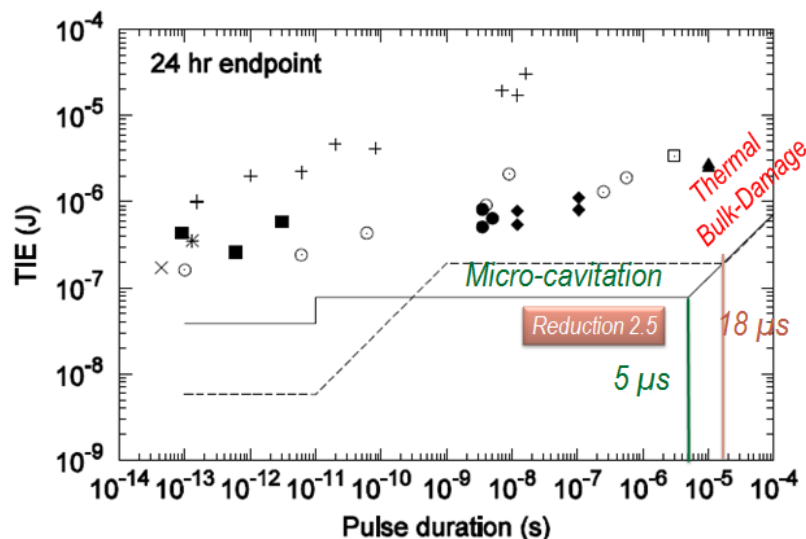


Figure 3. Threshold data plot courtesy of D Lund and BE Stuck, with previous (dashed) and new (line) exposure limits.

The same reduction applies to the complete wavelength range of 400 nm to 1400 nm, but for wavelengths above about 1250 nm this reduction (that is related to the emission duration dependency) is “compensated” by the increase of  $C_7$ . It also has to be emphasized that this reduction of the single pulse limit is in many cases compensated by making the rules for multiple pulses less restrictive, and for extended sources by the introduction of a time dependent  $\alpha_{\max}$ .

## Increase for Ultrashort Pulses

As is shown in Figure 3, the limits in the ultrashort pulse duration range were raised by extending the nanosecond limit (constant energy/radiant exposure) down to 10 ps. The cross-over point, when the new single pulse limits become higher than the previous one is at 312 ps. At 10 ps there is a step-function of 2 and then for shorter pulses again a constant energy/radiant exposure limit value down to  $10^{-13}$  seconds (100 fs) applies. This new limit for pulse durations less than 10 ps is, for visible wavelengths, a factor of 6,5 above the previous limit. Note that the factor  $C_4$  ( $C_A$  in ICNIRP and ANSI - derived from the wavelength dependence of retinal absorption for wavelengths above 700 nm and that reaches a value of 5 for 1050 nm to 1400 nm) is only applied to the limits longer than 10 ps; for shorter pulses,  $C_4$  is not part of the limit (because for ultrashort pulses, non-linear effects lead to absorption independent of the retinal absorption coefficient) and therefore, the step function of 2 only applies in the visible wavelength range. For 1400 nm, for instance, due to the lack of  $C_4$  for shorter pulses, the step function is a factor of 10. Since the previous limits contained the factor  $C_4$  also for pulse durations less than 10 ps, the new limits for the case of 1400 nm are only a factor of  $6,5/5 = 1,3$  above the previous limits.

## Time Dependent $\alpha_{\max}$

For pulsed extended sources, the effective permitted emission level can increase by up to a factor of 20, depending on the angular subtense of the apparent source and pulse duration. While the limit as such has not changed, the value of  $\alpha_{\max}$  is limited to a pulse duration dependent (or more precisely "emission duration" dependent) value which can be as small as 5 mrad:

$$\alpha_{\max} = \begin{array}{ll} 5 \text{ mrad} & \text{for } t < 625 \mu\text{s} \\ 200 t^{0,5} \text{ mrad} & \text{for } 625 \mu\text{s} \leq t \leq 0,25 \text{ s} \\ 100 \text{ mrad} & \text{for } t > 0,25 \text{ s} \end{array}$$

For exposure durations/emission durations above 0,25 s, i.e. for cw emission or for averaging pulsed emission over that emission duration, there is no change compared to earlier editions, since  $\alpha_{\max}$  remains at 100 mrad.

For sources that are larger than  $\alpha_{\max}$ ,  $C_6 = \alpha_{\max} / \alpha_{\min}$  (i.e. a smaller value as before) but also the angle of acceptance  $\gamma$  is limited to the value of  $\alpha_{\max}$ , and therefore only the **partial** emission which is within  $\alpha_{\max}$  constitutes the accessible emission that is to be compared against the emission limit, so the level that originates from the total apparent source can be correspondingly larger. For a homogeneous circular source profile with  $\alpha > \alpha_{\max}$ , this effect of reduced accessible emission is equivalent to comparing the total energy that passes through the aperture stop with the limit (and not only the part within  $\alpha_{\max}$ ), but at the same to increase the limit with a factor of  $C_6 = \alpha^2 / (\alpha_{\min} \alpha_{\max})$ . This is shown in Figure 4 as a relative increase as function of angular subtense of the apparent source. The lower line is the previous dependence, and the lines that branch off to higher values come from the new pulse duration dependent  $\alpha_{\max}$  when the limit is expressed as total accessible emission and not just what is within  $\alpha_{\max}$ . The maximum difference between old and new limit sets is a factor of 20 which applies to pulse durations less than 625  $\mu\text{s}$  where  $\alpha_{\max} = 5 \text{ mrad}$  and for angular subtense values of 100 mrad or larger. It is noted that the treatment of the time dependent  $\alpha_{\max}$  by increasing  $C_6$  with the square of  $\alpha$  for values of  $\alpha$  beyond  $\alpha_{\max}$  is only applicable to *homogenous* circular sources; for irregular sources, or non-circular sources, the analysis has to be done with a field of view restricted to  $\alpha_{\max}$  and then  $C_6$  is limited to  $\alpha_{\max} / \alpha_{\min}$  (but also the accessible emission is smaller than before, and the overall effect again is to permit a maximum increase of the emission by a factor of up to 20).

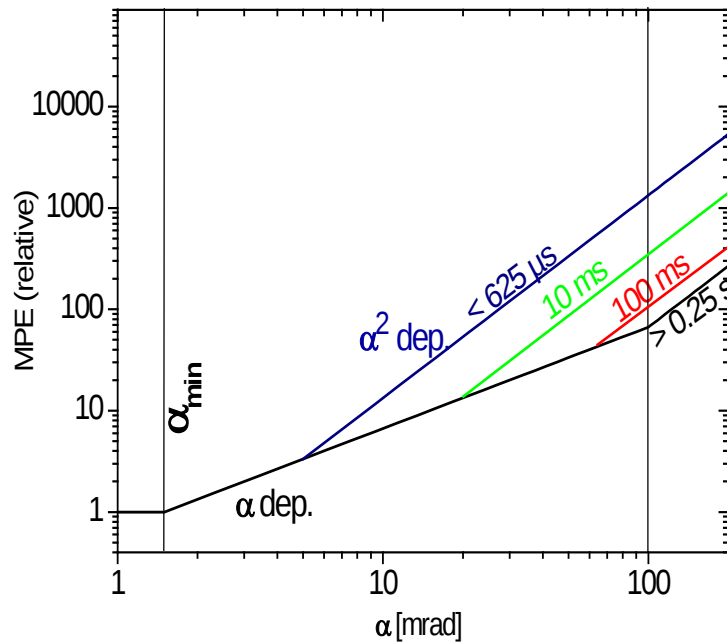


Figure 4. For homogeneous apparent sources it is possible to reflect the impact of the time dependent  $\alpha_{\max}$  by expressing an effective  $C_6$  that increases as  $\alpha^2$  beyond  $\alpha_{\max}$  and the accessible emission as compared against the AEL is not limited by a field of view that is equal to  $\alpha_{\max}$ .

Obviously this change only affects pulsed sources and sources that are extended and larger than 5 mrad. Examples for extended sources are diffuse sources (for instance used for hair removal), diffractive optical elements (DOE) and VCSEL arrays with individual emitters spaced close enough (so that the analysis method for irregular extended sources does not apply to one emitter), but also possibly scanners.

For pulsed extended sources, the retinal limits are increased to such high levels that exposure at or below the exposure limits for the retina, the iris can potentially be injured. Since such beams have to have a larger divergence (the angular subtense cannot be larger than the divergence, see for instance [5, 19]), this situation and hazard is only relevant if the emitter is close to the eye. ICNIRP has defined a dual limit for the eye as not to exceed the skin limit for visible wavelengths and twice the skin MPE for wavelengths in the infrared range. In Edition 3 of IEC 60825-1, there is no dual exposure limit explicitly specified for that case (only for the wavelength range of 1200 nm to 1400 nm), but because the eye-lid is covered by skin, the skin MPEs are in practice an “automatically” implied dual limit (otherwise the person would not be allowed to blink). Also there is a cautionary note in the MPE table and that exposure below the MPE for the skin would also protect the anterior parts of the eye. For classification, that issue (which for the classification is also about potential injury of the skin at contact) is accounted for in Edition 3 of IEC 60825-1 in a dedicated clause 7.13 (a similar warning was already required under Edition 2 but not in a dedicated clause) by requiring a warning label on the product when the AEL for Class 3B is exceeded where the accessible emission is determined with a 3,5 mm aperture in contact with the product. For diffuse sources, the permitted power for Class 1 or Class 2 is particularly high, mainly because of the classification distance of 100 mm and  $C_6$  (also for cw sources). For the example of a Class 2 cw product, and a diffuse source (lambertian emitter) of 1 mm diameter, the permitted emitted total power equals 5,4 Watt and for 5 mm diameter source 27 Watt [20]. In the view of the author of this White Paper, it is questionable whether this approach (a warning label) is sufficient to produce an acceptable product, i.e. where the exposure at contact can induce quite severe skin burns but the product is Class 1 and there is only a warning label on it. For consumer products, this might be problematic in terms of requirements for general product safety.

## Multiple Pulses - Small Sources

For small sources and extended sources up to 5 mrad angular subtense, for pulse durations longer than  $T_i$  (which is 5  $\mu\text{s}$  for wavelengths up to 1050 nm and 13  $\mu\text{s}$  for > 1050 nm up to 1400 nm), the pulse additivity factor  $C_5$  ( $C_P$  in ANSI and ICNIRP) is set equal to 1. Setting  $C_5 = 1$  leaves the single pulse limit (requirement 1 in clause 4.3 f) and the average power limit (requirement 2 in clause 4.3 f) as applicable for multiple pulse emissions. For sources up to 5 mrad it only depends on the pulse repetition frequency if the average power or the single pulse limit is the limiting factor. This critical repetition frequency can be calculated and for the example of the wavelength of 400 nm to 1050 nm equals 13 kHz for an exposure duration/time base of 0,25 s, and 5 kHz for an emission duration of 10 s, respectively. For pulse repetition rates less then these values, the single pulse limit is the limiting one, for pulse repetition rates above these values, the average power limits the emission.

The resulting increase in permitted output levels, compared to the previous multiple pulse rules is significant: for the case of 0,25 s time base (or for an MPE analysis, exposure duration), the permitted energy per pulse is up to a factor of 7,5 higher and for an emission duration of 10 s, up to a factor of 15 (as the extreme values that apply at the respective critical frequencies).

Different rules apply for the case of pulse durations less than  $T_i$  (5  $\mu\text{s}$  up to 1050 nm wavelength, 13  $\mu\text{s}$  for > 1050 nm up to 1400 nm), and it is noted that these apply independently of the angular subtense of the apparent source, i.e. both for values of  $\alpha$  larger as well as for values of  $\alpha$  smaller than 5 mrad:

For the case that the time base is longer than 0,25 s (i.e. for classification as Class 1) and the number of pulses  $N$  exceeds 600 within that time base, the following factor has to be applied (for  $N$  up to 600 pulses,  $C_5=1$ ):

$$C_5 = (N/600)^{-0,25} \text{ where the smallest value of } C_5 \text{ is limited to } 0,4.$$

For a time base up to and including 0,25 s (i.e. for classification as Class 2 or Class 3R in the visible), for pulse durations less then  $T_i$ , the correction factor  $C_5 = 1$ , i.e. no reduction (independent of the angular subtense of the apparent source).

As shown in Figure 5, the factor 1/600 in  $C_5$  means that for  $N=600$ ,  $C_5 = 1$  and then decreases with  $N^{-0,25}$ , as is known as a basic dependency from Edition 2. The equivalent presentation is to specify  $C_5 = 5 \cdot N^{-0,25}$  for  $N > 600$ , since  $600^{0,25} = 5$ . The plateau where  $C_5$  is equal to 0,4 applies to pulse numbers  $N$  greater 24414.

Since the single pulse limit is reduced by a factor of 2,5 (due to the reduction of  $T_i$  from 18  $\mu\text{s}$  to 5  $\mu\text{s}$ , see above) and the new limits remain at that lower level up to 600 pulses while the previous limit starts to decrease with  $N^{-0,25}$  right away, the new limits are more restrictive than the current ones only for pulse numbers up to  $N=39$ . For  $N \geq 600$  the new limits are a factor of 2 less restrictive than the previous ones.

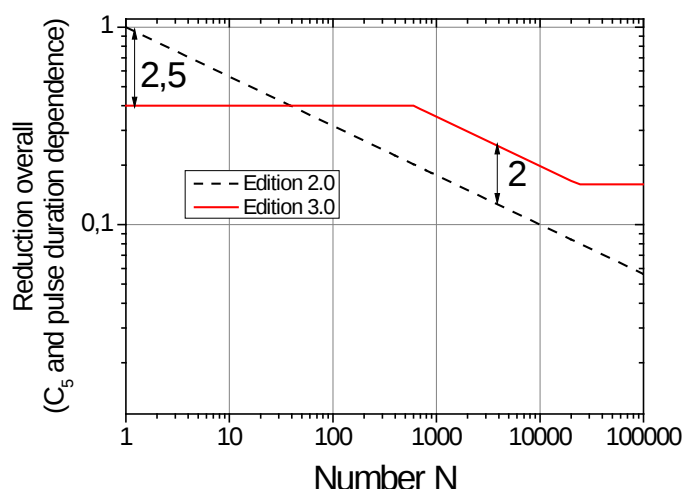


Figure 5. Relative change of the exposure limit and AEL for Class 1 for multiple pulses with pulse durations less than  $T_i$  (5  $\mu\text{s}$  for 400 nm to 1050 nm; 13  $\mu\text{s}$  for 1050 nm to 1400 nm)

## Multiple Pulses - Extended Sources

As noted above, for sources which feature a value of  $\alpha \leq 5$  mrad, and for pulse durations longer than  $T_i$ , the correction factor  $C_5$  is generally equal to unity, which greatly simplifies the analysis as well as makes it usually less restrictive as compared to earlier editions. For extended sources, when  $\alpha > 5$  mrad, the situation is different, as there, a reduction is needed to account for the additivity of pulses: the factor  $C_5$  is defined for pulse durations longer than  $T_i$  as follows:

$\alpha > 5$  mrad:  $C_5 = N^{-0.25}$  with following limited reduction factor (equivalent to maximum values of  $N$  used):

$\alpha \leq \alpha_{\max}$ :  $C_5$  not less than 0,4 (maximum  $N$ : 40)

$\alpha > \alpha_{\max}$ :  $C_5$  not less than 0,2 (maximum  $N$ : 625)

$\alpha > 100$  mrad:  $C_5 = 1$

This means that while the  $N^{-0.25}$  reduction factor, that is known from earlier editions, applies for sources between 5 mrad and 100 mrad angular subtense, the reduction factor is limited to a minimum value of 0,4 for sources smaller than  $\alpha_{\max}$  and to not less than 0,2 for the case of sources larger than  $\alpha_{\max}$  up to 100 mrad. For sources larger than 100 mrad, there is no reduction factor needed as the analysis is sufficiently covered by the single pulse and the average power requirement. Obviously in the above criteria,  $\alpha$  is not limited to  $\alpha_{\max}$  (as it is limited for the determination of  $C_6$ ), but it is the actual angular subtense of the apparent source.

It is not straight forward to specify for which conditions which requirement (average power, or single pulse reduced by  $C_5$ ) is the limiting one. The analysis was performed and is published in Reference [21], but it is rather complex and more of a theoretical value, for instance regarding the question of how to optimize a product design for a given class, and in practice, for existing products, it might be easier to just apply both criteria and see which one is the most restrictive one.

Some interpretation is also needed when it comes to oblong sources, since  $\alpha$  is generally specified as to be the arithmetic mean of the longest and shortest dimension. An interpretation sheet is currently developed which clarifies those issues and in the draft it is specified that it is permitted to apply the arithmetic mean value to determine  $\alpha$  - with the exception of the criterion  $\alpha > 100$  mrad where both dimensions need to be larger than 100 mrad. See also the ILSC 2015 paper [22] for a more detailed discussion.

## Pulse Groups

It has always been recognised that, as a general basic rule, the accessible emission as determined for any emission duration has to be below the respective AEL that applies for that emission duration. From this it follows that for irregular pulse trains, the average power criterion is to be applied not only by using the time base as averaging duration, but also with shorter averaging durations, such as one pulse group, as this could be more restrictive. For the average power criterion to analyse pulses, this principle still applies.

When it comes to apply  $C_5$  for irregular pulse trains, under earlier editions, since  $C_5$  was generally equal to  $N^{-0.25}$  and was not limited in terms of applicable number of pulses  $N$ , there was never a question of having to apply  $C_5$  to pulse groups, since counting individual pulses for the determination of  $N$  was always the most restrictive case. Under Edition 3.0, where  $C_5$  is limited to a maximum number of  $N$  of 40 or 625, it could be the case that it is necessary to treat groups of pulses as “effective” pulses, i.e. treating a group of pulses as one thermally effective pulse, and the pulse train then consists of a number of these pulse groups as “effective” pulses. In this case,  $N$  is then the number of pulse groups, the AEL is determined for the pulse group duration and the accessible emission is the energy of the pulse group. In this way, a pulse group is considered as an effective pulse and  $C_5$  is applied to reduce the AEL applicable to the pulse group. This treatment, for pulse group durations longer than  $T_i$ , is not specifically expressed in the current wording of Edition 3, but based on simple thermal considerations it is clearly necessary at least when the pulses in the pulse group are close enough together, as thermally, if there is negligible cooling between the pulses of the pulse group, the pulse group features an equivalent temperature-time behaviour as if the pulse group were a “solid” pulse. If requirement 3 ( $C_5$ ) is not applied to pulse groups, it would be possible to split up a solid pulse of for instance 1 ms duration (where for extended sources  $C_5$  applies to the series of 1 ms pulses) into a series of pulses with durations less than 5  $\mu$ s where for Class 2,  $C_5=1$  and this would then “wrongly” permit, in the extreme, a factor of 50 higher energy per 1 ms pulse (group). ANSI Z 136.1 (2014) expressed this in the way that  $C_P$  (equivalent to  $C_5$ ) is to be applied to “pulses and pulse groups”; in IEC 60825-1 Edition 3.0 it is not expressed in this

specific way. This is going to be clarified in an upcoming Interpretation Sheet for Edition 3 of IEC 60825-1, and probably also a corrigendum or amendment. See also Reference [22] for further discussion, also on other issues pertaining to pulsed emission.

## Non-retinal Multiple Pulse Issues

While the limits that pertain to wavelengths above 1400 nm as such were not changed, based on the 2013 revision of ICNIRP, the correction factor  $C_5$  is no longer applicable for the exposure limits for the eye in that wavelength range. Consequently, this amendment is also reflected in the multiple pulse rules of Edition 3.0. This leaves the single pulse requirement and the average power requirement as the applicable analysis criteria of pulsed emission in the wavelength range above 1400 nm and for an MPE analysis of pulsed exposure in that wavelength range.

Similarly, in earlier editions of the standard, it was not clear if the multiple pulse reduction factor  $C_5$  is to be applied to the AEL of Class 3B. It was clarified in Edition 3.0 Clause 4.3 f) that this is not necessary.

## Scanned Emission

Edition 3.0 of IEC 60825-1 also specifies that scanned emission can be evaluated by considering the scanned retinal emission (if the image *does* scan across the retina) by an equivalent pulse [23] that is determined by using the general procedure of how to analyse extended sources, i.e. by using a field of view (angle of acceptance) to represent a certain area on the retina. This concept was used in practical safety analysis of retinal scanning by many experts also under earlier editions and is now specifically described in this way in subclause 5.4.3 NOTE 3 of Edition 3.0. It needs to be emphasised, however, that the general principles of how to analyse extended sources still apply, i.e. the accommodation of the eye needs to be varied to obtain the most restrictive image of the apparent source, and the distance to the product needs to be varied and classification applies to the most restrictive position. For scanned emission, for the analysis as extended source, it is often the case that the most restrictive position is further than 100 mm from the scanning mirror and that the worst case accommodation often is to accommodate to a point in space where the scanning beam has the pivot point (i.e. the mirror) and the retinal image is therefore not moving.

As in other cases, it is of course simpler (but more restrictive) to analyse a product assuming that it is a small source, and then the “Default (simplified) evaluation” method given in subclause 5.4.2 of Edition 3.0 applies.

## MEET THE AUTHOR

Karl Schulmeister, PhD, is a consultant on laser and broadband radiation safety at the Seibersdorf Laboratories, where also a specialised accredited test house is operated. Karl is a member of the ICNIRP Scientific Expert Group and served as the project leader for the development of IEC 60825-1 Edition 3.0. The research in his group over the last ten years concentrated on thermally induced injury that also provided scientific input for amending the spot size dependence and multiple pulse rules of the retinal thermal limits.

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