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WHITE PAPER

Analysis of the Blue Light Hazard Relative to the Retinal Thermal Hazard for Image Projectors

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CONTENT

Format of decimal figures

Congruent with ISO and IEC standard practice, a decimal comma is used in this report in contrast to the usual usage of a decimal point for English texts (i.e. ½ = 0,5 and not 0.5).

1 INTRODUCTION

In Reference 1 [1], a risk analysis for image projectors that are classified as RG2 according to IEC 62471-5 [2] is presented. This paper centres on the risk for *thermally* induced injury of the retina, as applicable for momentary exposure, noting that bright light induces aversion responses so that prolonged staring into a projector has to be seen as intentional. Due to the limitation of the scope and length of the paper (Reference [1]), the *photochemical* retinal limit (also referred as the *blue-light hazard* limit) was not discussed. In this White Paper, an analysis is presented that compares the effective radiance of a RG2 projector against the blue-light hazard exposure limit for up to 100 s exposure duration. Also, in this 2nd Edition of the White Paper, a risk analysis for photochemically induced retinal injury for intentional staring into a bright projector that emits at the maximum permitted level for RG2 is included.

There are several basic aspects which make photochemical retinal hazards, for momentary exposures, less critical than thermal ones.

The photochemical injury mechanism is based on a dose-relationship, i.e. the injury level as well as the exposure limit is defined as a “dose” value, i.e. as energy per area (referred to as “radiant exposure”, symbol Q, measured in J m^{-2}; for retinal hazards that would be the retinal radiant exposure) or as radiance dose in units of J m^{-2} sr^{-1}. This reflects that the interaction in principle is related only to the dose (i.e. to the number of photons received per tissue area); for higher irradiance levels (power per area, symbol E, measured in W m^{-2}), the critical retinal radiant exposure (the “dose”) is reached sooner (exposure duration, symbol t, measured in seconds). The corresponding equation is $Q = E \cdot t$.

That the dose is basic relevant quantity is also referred to as reciprocity between irradiance and exposure duration and is also known from other photochemical interactions such UV induced sunburn of the skin, photo-keratitis of the cornea and also from exposing photographic film: for a brighter source (higher irradiance E in the image plane on the film), the film exposure duration, t, needs to be reduced in order to achieve a proper “exposure” of the film and avoid over-exposure, which can be also quantified in terms of radiant exposure (Q), i.e. J m^{-2} on the film.

Thus the main quantity regarding a photochemical effect is the retinal radiant exposure Q and not how high the retinal irradiance E is or how long it took (symbol t) to achieve the given radiant exposure. That a certain dose (energy per area, number of photons per area) is necessary to induce an effect means that in order to induce retinal photochemical injury with a short exposure durations such as 0,25 seconds, very high irradiance values (in W m^{-2}) are necessary to achieve the necessary radiant exposure (in J m^{-2}) within 0,25 s. At these high irradiance levels, however, significant heating and a corresponding temperature increase is induced, which would lead to a *thermally* induced injury before the critical dose for photochemical injury can be reached. Therefore, for short exposure durations of less than seconds or a few seconds, *if* the exposure presents a hazard, then the dominating (more critical, or relevant, hazard) is the thermal one. The photochemical hazard on the other hand is (for high enough radiance values and blue dominated spectral light levels) more critical for longer exposure durations and correspondingly lower retinal irradiance levels which do not lead to significant heating of the tissue. For very bright sources, when the staring duration is long enough, at some point the critical dose (radiance exposure on the retina) is reached and photochemically induced retinal injury results, which is known for instance for staring into welding arcs without eye protection.

Because of this “dominance” of thermally induced retinal injury over photochemically induced injury for short exposure durations, many safety standards, such as IEC 60825-1 for laser product safety do not even specify a photochemical retinal limit for 0,25 s exposure duration. However, in IEC 62471-5, for completeness, the retinal photochemical limit is extended down to a time base of 0,25 s for RG2 classification.

2 EXPOSURE LIMITS

Risk group classification of projectors according to IEC 62471-5 is based on comparing *emission* levels (referred to as accessible emission, AE) with Accessible Emission Limit (AEL) values. Product classification needs to be distinguished from *exposure* analysis for a certain distance and exposure duration, both of which can be chosen according to the exposure scenario at hand. See further discussion on risk group classification vs. exposure analysis in Ref. [1].

In the following, we summarise the relevant exposure limits of ICNIRP 2013 guidelines [3], which are at the same time the value of the respective AELs of IEC 62471-5.

2.1 Retinal photochemical limit

The retinal photochemical limit (blue light hazard limit) for exposure durations[1] up to 10 000 s is a constant radiance dose value of

$$EL_B = 10^6 \frac{J}{m^2\,sr}$$

The spectral exposure level $L_\lambda(\lambda)$ is weighted with the blue light hazard action spectrum $B(\lambda)$ which is equal to 1 in the blue part of the spectrum and then reduces logarithmically towards the green part (Fig. 1).

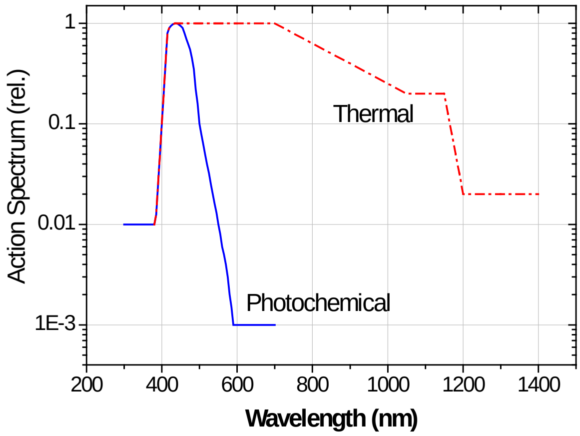

Figure 1. Action spectrum for retinal photochemical (B(λ)) and retinal thermal (R(λ)) limits.

The following formula describes the application of the action spectrum to result in an effective blue-light radiance L_B:

$$L_B = \sum_{300\,nm}^{700\,nm} L_\lambda(\lambda) \cdot B(\lambda)\Delta\lambda$$

This spectral weighting produces an effective blue-light radiance level L_B, which is smaller than the actual radiance, since $B(\lambda)$ strongly reduces the green part of the spectrum and sets the red part of the spectrum - with a value of $B(\lambda) = 0{,}001$; i.e. to practically zero.

As another relevant component in the determination of the exposure level for the retinal photochemical hazard, eye movements are in a simplistic way accounted for by the averaging angle of acceptance (field of view) to average the measured radiance value that is compared against the limit. The specified averaging angle of acceptance has received the symbol of γ_B and equals 11 mrad for exposure durations up to 100 s, and then has an increasing value, up to 110 mrad at an exposure duration of 10 000 s.

The radiance dose exposure limit (10^6 J m^{-2} sr^{-1}) for a given exposure duration can be recalculated into a radiance value when the dose is divided by the exposure duration in seconds. For an exposure duration of 0,25 s, the retinal photochemical limit, expressed as radiance, therefore becomes:

For t = 0,25 s: $EL_B = 4 \cdot 10^6 \frac{W}{m^2\,sr}$

Compared to earlier guidelines, the ICNIRP guideline revision of 2013 did not change the basic retinal photochemical limit, but the averaging angle of acceptance for long term exposure was clarified to be 110 mrad at 10 000 s (in earlier guidelines, the averaging angle for exposure durations exceeding 100 seconds was not well specified).

2.2 Retinal thermal limit

The retinal *thermal* exposure limit EL_{th} for an exposure duration of 0,25 s (ICNIRP 2013 [3]), is numerically equal to the AEL for RG2 (being based on a time base of 0,25 s) of IEC 62471-5 and equals

[11] It is noted that while the exposure limit is defined for such long exposure durations, it does not appear realistic that somebody stares into a source for more than 3 hours with eye movements limited to an angular range of only 110 mrad.

$EL_{th} = \frac{28000}{\alpha} \frac{W}{m^2 \cdot sr}$ where α is the angular subtense of the apparent source given in units of rad, limited to 0,1 rad as a maximum value. The exposure level that is to be compared against the limit is weighted with the action spectrum $R(\lambda)$ which, however, is basically a constant value of unity (1,0) in the visible wavelength range. The exposure level (or for product classification: the accessible emission, AE) as a quantity of radiance can be determined with an averaging field of view (angle of acceptance) that has an angular subtense of γ_{th} = 11 mrad assuming a continuous wave or quasi continuous wave emission. If such an averaging field of view is used for a source that is smaller than 11 mrad, then it is not permitted to use α values in the EL that are smaller than 11 mrad. It is permitted to use smaller values of α (smaller than 11 mrad) when the averaging angle of acceptance is also correspondingly smaller.

3 COMPARISONS

In the following table, the two retinal exposure limits (and for classification of products, the numerically equal AEL) are compared

	Thermal	**Photochemical**
Limit for t = 0,25 s	$\frac{28000}{\alpha} \frac{W}{m^2\,sr}$ where α in rad	$4 \cdot 10^6 \frac{W}{m^2\,sr}$
Limit for t = 0,25 s for α = 0,015 rad (15 mrad)	$1{,}9 \cdot 10^6 \frac{W}{m^2\,sr}$ where α in rad	$4 \cdot 10^6 \frac{W}{m^2\,sr}$ (does not depend on α)
Time dependence for longer exposure durations	Constant radiance value, no further decrease	Decrease with 1/*t* (dose relationship)
Additivity of multiple exposures over longer time	No additivity assumed in limits	Additivity up to 10 000 s
Wavelength weighting	$R(\lambda)$ - Practically no weighting in visible range	$B(\lambda)$ – Only in blue practically no weighting; green reduced and red in practice “taken out” of spectrum
Dependence on α	$1/\alpha$	No spot size dependence in limit
Averaging angle of acceptance for radiance exposure level	11 mrad for continuous sources, but then α not smaller than 11 mrad	11 mrad up to 100 s, then increasing to 110 mrad for 10 000 s

Neglecting averaging of radiance over the angle of acceptance for the moment, i.e. assuming homogeneous radiance profiles that are larger than the averaging angle of acceptance, we can see in the second line of the above table that at 0,25 s exposure duration (or time base), for apparent source angles of 15 mrad observed at 1 m (as is typical for image projectors that can approach the RG2 retinal thermal AEL), the thermal hazard limit is about a factor of 2 smaller (i.e. more restrictive) as compared to the photochemical hazard limit. Neglecting averaging of the exposure limit at the moment, and assuming that all the radiation is within the blue part of the spectrum, the two limits are equal for an α value of 7 mrad (0,007 rad).

However, there is also the issue of spectral weighting, where $R(\lambda)$ results in no - or only marginal - reduction in the visible wavelength range, while due to the strong wavelength dependence of $B(\lambda)$ in the green and red part, for a white projected image (which represents the maximum emission), there is a strong reduction of the effective blue light radiance as compared to the unweighted (or weighted with $R(\lambda)$) radiance, since the non-blue spectral components are weighted with $B(\lambda)$ value that is less than 1. This wavelength weighting affects the exposure level that is (as effective exposure) compared against the respective EL, or for classification, it affects the AE that is compared against the respective AEL. Because the nominal emission (as “maximum” emission) for projectors is defined to be “white”, it is possible to apply the two weighting functions to a number of projectors and derive a ratio, which can then be used for a relative comparison.

The analysis was performed for five different projectors and the ratios of blue light-weighted to the thermal weighted spectra (being less than 1 % different to the unweighted spectra) are:

Projector Type	Factor "Thermal/blue light"
Xenon lamp projector	0,17
"Phosphor" projector (blue laser diode, phosphor and colour wheel)	0,25
1st laser projector with three laser wavelengths (RGB)	0,16
2nd laser projector with three laser wavelengths (RGB)	0,25
Laser projector with six wavelengths	0,17

The smallest ratio was found to be 0,16 for the first RGB projector (but very close to the xenon lamp projector), and the largest ratio was found to be 0,25 for the phosphor as well as the second RGB projector. **These factors reflect that the blue light weighted radiance is at least (as a worst case) a factor of 1/0,25 = 4 smaller (less restrictive) than the thermally weighted radiance.**

3.1 Quantitative comparison

The above information enables a relative characterisation of the blue light hazard when the exposure level for a projector emitting a white image is assumed to be exactly at the retinal thermal limit for 0,25 s exposure duration, i.e. the retinal thermal effective radiance is assumed to be equal to the retinal thermal limit that at the same time is the emission limit for RG2 projectors. With this exposure level, considering the factor from the spectral weighting discussed above, the effective blue light exposure level can be calculated. Finally, this exposure level can be compared against the blue light exposure limit.

For a simplified first analysis, the angular subtense of the apparent source is assumed to be equal to or larger than 11 mrad. This obviates any considerations of averaging of radiance.
The retinal thermal *exposure limit* for a source which subtends an angular subtense of 11 mrad equals
$EL_{thermal} = 2{,}5 \cdot 10^6$ W m^{-2} sr^{-1}
For the present relative analysis, the thermal exposure level is taken equal to this value, i.e. assuming that retinal thermal exposure level is equal to the retinal thermal limit:
$Exposure_{thermal} = 2{,}5 \cdot 10^6$ W m^{-2} sr^{-1}

This *thermal* effective exposure level can be transformed into a *blue-light weighted* exposure level by application of the worst-case factor of 0,25 found above (worst case in the sense of obtaining the maximum blue light level for a given thermally weighted level). This results in a blue light effective radiance level of
$Exposure_{BL} = 0{,}64 \cdot 10^6$ W m^{-2} sr^{-1}

Finally, this exposure level can be compared against the blue-light exposure limit which for 0,25 s exposure duration equals
$EL_{BL} = 4 \cdot 10^6$ W m^{-2} sr^{-1}

and we see for a **11 mrad** source, when the exposure is at the retinal thermal limit, as a worst case wavelength distribution, **the blue light exposure level is a factor of 6,3 below the blue-light exposure limit that applies to 0,25 s.**

In the following table, the above calculations are performed for source sizes of 15 mrad and 20 mrad, additionally to 11 mrad. For larger source sizes, the ratio by which the blue light exposure level is below the limit is larger, i.e. 8,6 for 15 mrad and 11,4 for 20 mrad, respectively. These are typical subtenses of the exit pupil of RG2 projectors that approach the thermal retinal AEL for RG2 at a distance of 1 meter (see Ref. [1]). For projectors that are capable to reach the RG2 thermal limit for the testing distance of 1 meter, or to exceed that limit (i.e. RG3 projectors), the exit pupil for a throw ratio of TR = 2 equals 12 mm for the smaller imager chips. For the case of a smaller throw ratio and small imager chips, the permitted emission for RG2 would be so high (since smaller TR result in smaller exit pupils and correspondingly higher AEL) that these by far exceed thermal limits of projector chips. Thus, at 1 meter distance, α = 11 mrad is a worst case smallest value for projectors which can reach up to the RG2 emission limit to be considered in this main analysis. Smaller exit pupils will be discussed for completeness below the table.

Source size	mrad	11	15	20
	rad	0,011	0,015	0,020
Retinal thermal EL (0,25 s)	$W\ m^{-2}\ sr^{-1}$	$2{,}5 \cdot 10^6$	$1{,}9 \cdot 10^6$	$1{,}4 \cdot 10^6$
Blue light radiance upper range (max. effective exposure level)	$W\ m^{-2}\ sr^{-1}$	$0{,}64 \cdot 10^6$	$0{,}47 \cdot 10^6$	$0{,}35 \cdot 10^6$
Blue light EL for 0,25 s	$W\ m^{-2}\ sr^{-1}$	$4 \cdot 10^6$		
ratio exposure below blue light EL - min		**6,3**	**8,6**	**11,4**
ratio exposure below EL - max		**9,8**	**13,4**	**17,9**
Permitted total "staring duration" with nominal pupil - lower range	seconds	1,6	2,1	2,9
Permitted total "staring duration" with nominal pupil - upper range	seconds	2,5	3,3	4,5

As the final step it will be shown that the ratio found for 11 mrad (6,3) also applies to source sizes smaller than 11 mrad: for the case that the source is smaller than 11 mrad, it is permitted to average the retinal thermal exposure level with 11 mrad field of view, but at the same time the retinal thermal exposure limit is not permitted to be calculated with a smaller α value, i.e. the EL is calculated with 11 mrad and remains at that constant level also for sources that are smaller than 11 mrad. The blue-light EL is a constant radiance value in any case, i.e. does not depend on α and the averaging angle of acceptance for the blue-light radiance is also 11 mrad for exposure durations up to 100 s. Thus the ratio of the two exposure limits remains the same irrespective of the source size and also the radiance values (as exposure levels) are both averaged with 11 mrad angle of acceptance as long as we are considering exposure durations of less than 100 s. **It follows that for sources smaller than 11 mrad, the overall ratios remain the same as for 11 mrad.**

For the case of sources smaller than 11 mrad it is "permitted" that the un-averaged retinal thermal radiance is compared against the retinal thermal limit (producing a larger radiance value as for the case of averaging), and then the retinal thermal EL is permitted to be determined with the smaller α value, and this is more restrictive for the retinal thermal hazard as compared to averaging and using $\alpha = 11$ mrad. Thus in the case of no averaging, the ratio by which the blue-light exposure level is below the blue-light limit is greater, such as a factor of 14 for $\alpha = 5$ mrad.

It follows that the factor of 6,3 of the blue light hazard being less critical than the retinal thermal one for $\alpha = 11$ mrad and an exposure duration of 0,25 s is the "worst-case" value both in terms of source size as well as spectral distribution. For the "best case" spectral distribution found for the five projectors, the ratio is 9,8.

This analysis of the ratio of the limits **applies independently of the distance to the product**, i.e. it applies for instance at the "retinal thermal" hazard distance for RG3 projectors as well as at the 1 meter reference distance for classification of a projector as RG2 (as long as the comparison of the limits is done at the same distance to the product).

The factor of 6,3 as worst case or 9,8 as best case can be interpreted in the following way, considering the dose-relationship of the blue light hazard, i.e. that the basic exposure limit is a dose of 1 MJ $m^{-2}\ sr^{-1}$ applicable up to 10 000 s exposure duration, but noting that the blue light averaging angle of acceptance equals 11 mrad only up to 100 s and then increases to 110 mrad for longer exposure durations.

When the blue light exposure level is a factor of at least 6,3 below the blue light limit for 0,25 s exposure duration, this means that one can look into the source 6,3 times for 0,25 s each and still remain below (or exactly at) the blue-light limit. It would also mean that if one would suppress the aversion response to bright light and at the same time the **pupil** would remain at the "nominal" diameter value of about 3,5 mm (as the background of the derivation of the blue light EL) and **would not constrict** (even though the source is very bright) then the staring duration to reach the blue light limit would **be 1,6 seconds for the worst case spectral distribution, and 2,5 seconds for the "best case" spectral distribution**. All of the above analysis applies for an averaging angle of acceptance for the blue light radiance of 11 mrad, which is meant to consider the impact of eye movements. It would also mean, for the case of multiple exposures, that all of the exposures are at the same retinal site within 11 mrad, and that there are no greater eye movements for the case of intentionally staring into the source.

3.2 Classification at 1 meter distance, exposure at closer distances

Even though not relevant due to technological restrictions (see subsection "3.3 *Permitted emission for RG2 with small exit pupil*"), the case of exit pupils that subtend less than 11 mrad at 1 meter distance and projectors that reach up to the RG2 emission limit (determined at 1 meter distance from the projector's lens) is discussed in the following.

If the angular subtense of the source (assumed here to be homogeneous) at 1 meter for instance subtends an angle of 5,0 mrad, the averaging angle of acceptance of 11 mrad results in an effective (averaged) radiance that is a factor of $(11/5{,}0)^2 = 4{,}8$ lower as the physical radiance associated to accommodation to the exit pupil. When this non-averaged radiance is assumed to be independent of distance (as the basic law of radiometry), then exposure at for instance 50 cm from the lens surface will be associated with a larger exit pupil and the averaged radiance will be larger. For instance if the exit pupil of 5,5 mm diameter is located 10 cm behind the lens surface (inside of the projector), then at 50 cm from the lens, the angular subtense equals 9,2 mrad and the effect of averaging over 11 mrad will be minimal (factor 1,4), i.e. the averaged radiance will be very close to the actual radiance and about a factor of 3,6 higher as the value averaged over 11 mrad at 1 meter from the lens. Thus, when the exposure duration to reach the blue-light hazard exposure limit at 1 meter distance from the lens is 1,6 seconds for the worst case spectral distribution (see above) and 2,5 seconds for the best case spectral distribution, at 50 cm distance to the lens the exposure duration to reach the blue-light hazard limit equals between 0,5 seconds 0,7 seconds depending spectral distribution. This is still longer than the exposure duration associated with normal behaviour and aversion response to bright light of 0,25 seconds. It also needs to be noted that there is a significant safety margin associated to the blue-light hazard exposure limit (compared against injury thresholds) so that exceeding the calculated "permitted" exposure duration to reach the exposure limit does not mean that there is a realistic risk for retinal injury based on photochemical interaction. An assessment based on injury thresholds is provided in the chapter 4.3 below "Comparison of exposure level with injury threshold " of this White Paper.

As mentioned above, exit pupils smaller than 12 mm would be associated with correspondingly larger permitted emission levels that cannot be achieved due to technological limitations. Thus, while projectors with exit pupil diameters less than 12 mm are certainly possible, they would not be able to reach the RG2 limits, as discussed in the next sub-chapter.

3.3 Permitted emission for RG2 with small exit pupil

The permitted emission of a projector can be calculated based on some relevant projector parameters, setting radiance equal to the RG2 radiance limit determined at 1 meter from the lens. The smallest relevant imager chip to consider has a diagonal of 0,67" (see also Reference 1). A conservative assumption for the distance between the exit pupil (within the projector) and the projector's lens surface is 10 cm. With an f-number f/# = 2,5 (a rather large f-number, which is again on the conservative side – a common f-number would be 2,0), the exit pupil diameter D_{EP} can be calculated as function of throw ratio TR:

$$D_{EP} = \frac{TR \cdot Chip - width}{f - number}$$

For a 0,67" imager chip with aspect ratio of 1,6, the chip width equals 14,4 mm and for a TR = 2 the exit pupil diameter equals 11,5 mm. The permitted radiance as determined 1 meter from the lens (1,1 meter from the exit pupil) equals AEL= $2{,}5 \cdot 10^6$ W m^{-2} sr^{-1} (the non-averaged permitted radiance equals $2{,}7 \cdot 10^6$ W m^{-2} sr^{-1}) which can be transformed into 44 Watts of optical emitted power to reach the RG2 limit (see calculation methods of the Annex of IEC 62471-5 how to calculate the AEL for RG2). With a typical ratio of 250 lm per optical watt, this translates to 11 000 lm. Considering the limitations for thermal load for a 0,67" chip, as well as other restrictions, 11 000 lm projectors usually have larger chips, including not a single chip and colour wheel but three chips, one for each colour. But with some future improved cooling system, theoretically this is possible to achieve with a 0,67" imager chip size.

When the throw ratio is reduced (larger beam divergence) to below TR = 2, the exit pupil becomes correspondingly smaller, also permitting higher emission values (since the AEL increases within decreasing exit pupil diameters). For a TR = 1, for instance, the exit pupil diameter equals 5,8 mm and the permitted luminous flux for a RG2 projector equals 45 000 lumen. Even with improved future cooling this level of luminous output power does not have to be considered for small optics as are associated with a 0,67" chip and particularly not for any potential consumer product, due to a maximum brightness on the screen and therefore a minimum size of the screen – a projector with such output levels is a professional cinema projector for a “super-big screen”; for comparison, the brightest Xenon lamp projectors available on the market have 30 000 lm luminous power. This kind of projectors will also be in a dedicated projection booth to both avoid tampering as well as because of the high noise level, and are therefore not relevant when it comes to exposure at distances less than 1 meter for projectors “on a table” as for consumer products.

4 RISK ANALYSIS

When it comes to the actual risk for retinal injury, it is relevant that there is a significant safety margin of about 20 for a pupil diameter of 3,5 mm between the blue light exposure limit and experimentally determined (by ophthalmic observation) injury thresholds. Additionally, for intentionally staring into bright sources, the pupil will constrict to diameters of less than 3,5 mm. In the following, an analysis based on injury thresholds from non-human primates as well as from human volunteers is provided.

4.1 Comparison with exposure limit, accounting for small pupil diameter

As a first step, in order to have input for the expected pupil diameter that can also be used to scale the permitted exposure duration to reach the exposure limit (i.e. not yet basing the analysis on injury thresholds), the luminance in units of cd m^{-2} is calculated for a projector which approaches RG2 limits. Considering the radiance value of $2{,}5 \cdot 10^6$ W m^{-2} sr^{-1} as calculated above, applying the conversion factor of 250 lumen per optical watt results in a luminance of 625 Mcd m^{-2} (i.e. $6{,}3 \cdot 10^8$ cd m^{-2}). Using this value to estimate the pupil diameter from the NASA unified pupil formula [4] the predicted pupil diameter is about 2,0 mm. Variation of the age as input parameter as well as visual target “field diameter” (in degrees) reveals only negligible dependence of the predicted pupil diameter on age and target size. For very high luminance values, the maximum pupil diameter of 2,1 mm is found for the maximum age setting of 80 years (for younger ages, the pupil is closer to 2,0 mm). It is also seen in Figure 2 that for luminance values exceeding roughly 10 Mcd m^{-2} the pupil has a constant predicted diameter of about 2,1 mm. Apparently, the predictions for the pupil diameter for such high radiance values need to be treated with caution, as the experiments to determine pupil diameter as function of luminance will surely not have gone to such high levels. The predicted pupil diameter might therefore not be an “exact” average pupil diameter. From general experience one can certainly expect pupil diameters to become “minimal” and there will also be some personal variability. A pupil diameter of 2,1 mm appears rather as the maximum pupil (and not the average) that can be expected for extreme luminance values (where intentional staring would usually not occur due to aversion responses to bright light).

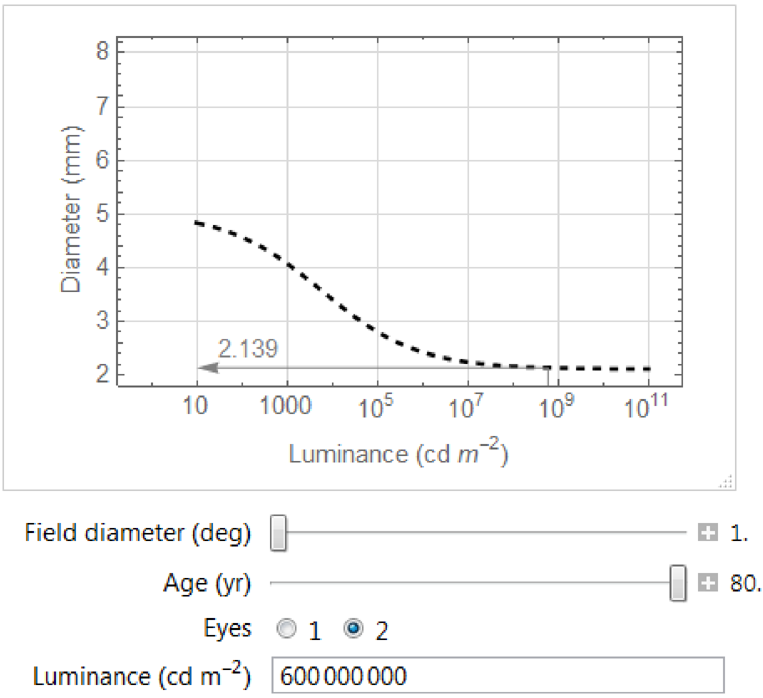

Figure 2. Screenshot of data plotted from NASA unified formula for the pupil diameter

A value of 2,1 mm is also reported by Stamper et al. for the study of pupil constriction as function of time, reported in Reference 5 and reproduced in the ICNIRP 2013 guideline (Figure 4 there). This study also shows that for exposure durations associated to intentional staring into the source, the pupil will have constricted to the smallest value after about 2 seconds exposure duration. When the pupil diameter of 3,5 mm is assumed, as stated by ICNIRP as the basis for the derivation of the BLH limit, then the ratio of area of the pupil (3,5 mm/2,1 mm)^2 = 2,8 can be used to approximately scale the "time to reach the exposure limit". Thus, when the exposure duration to reach the exposure limit with a 3,5 mm pupil equals 1,6 seconds as calculated above for the worst case spectral distribution, then the **exposure duration to reach the exposure limit with a 2,1 mm pupil equals 4,3 seconds**. Considering the level of brightness of a projector approaching the RG2 limit, such a staring duration can be considered as not reasonably foreseeable unless the person intentionally wants to injure him- or herself. It can be criticized for this analysis that the pupil diameter might not be 2,1 mm right away after exposure occurs, and that an accurate analysis would need to integrate the momentary retinal irradiance (which is a function of pupil diameter) over time to determine when the exposure limit is reached, which will occur at somewhat shorter staring durations than 4,3 seconds. Since the pupil as function of exposure duration is not that well defined, the risk analysis is continued by noting that there is a significant safety margin between the exposure limit and the injury threshold, which has a far greater effect in terms of "permitted exposure duration" (in this case to reach the injury threshold).

4.2 Injury threshold studies

Three studies are known where thresholds for photochemically induced injury were characterised. The original study on which the exposure limit for the blue light hazard (BLH) is based upon was performed by Ham et al. [Ref. 6] with non-human primates. Due to suspected dosimetric problems for some of the data, the study was later on repeated by Lund et al. [Ref. 7]. The analysis below refers to the data obtained by Lund et al. Relevant information for the injury thresholds for humans can also be derived from a study with a 532 nm laser beam performed with a human volunteer [8], which supports the data obtained with non-human primates.

In the study by Lund et al. the relevant wavelength for photochemically induced injury is 441,6 nm and an exposure duration of 100 s. The ED50 for examination of the retina with an ophthalmoscope 48 hours after exposure and a retinal spot size of 125 µm was determined to be equal to 7 mJ intra-ocular energy (energy passing through the pupil of the non-human primate; the beam was smaller than the pupil). This threshold can be transformed into a radiance value either by calculating retinal radiant exposure and division by the solid angle subtended by the pupil as seen from the retina, or by calculating corneal radiant exposure, averaged over some pupil area and division by the solid angle subtended by the retinal spot size as seen from the cornea. In both cases the assumption of the pupil diameter also scales the radiance value into which the threshold is transformed. For the threshold given as intraocular energy (or power, which is 70 µW for the 100 s exposure duration) the pupil diameter does not play a role as the laser beam was chosen smaller than the pupil of the non-human primate. The basic injury threshold is *retinal* radiant exposure, which can be calculated by dividing the total intraocular energy by the area of the retinal image and considering transmission losses of 0,45, resulting in a retinal irradiance threshold of 0,26 W cm^{-2} as also stated in the Lund et al. paper. This injury threshold, expressed as retinal irradiance (or retinal radiant exposure) does not depend on pupil diameter. It is rather that for a given irradiance at the position of the cornea, for a light field that is larger than the pupil (as is applicable for a projector), the pupil diameter has an impact on the retinal exposure level.

The comparison of the injury threshold with an exposure level associated to a projector can be done in two ways: either the radiance of the projector as "exposure level" is transformed into retinal irradiance by multiplication with the solid angle subtended by the pupil of the eye (and accounting for transmission losses), or the injury threshold is transformed into radiance which can be directly compared against the radiance of the projector. In the second case, for the transformation of the injury threshold into radiance, the same pupil diameter as would be used to calculate retinal irradiance from the radiance of the projector is used. For the first method (transforming radiance of the projector into retinal irradiance, as "exposure quantity") the pupil diameter has an impact on the exposure level, in the second method (transforming the threshold into radiance) the pupil diameter scales the injury threshold. Assuming a pupil diameter of 3,5 mm, and a focal length of the eye of 17 mm in air, the pupil as seen from the retina subtends a solid angle of 0,033 sr. Since radiance is measured in air, in this case the transmission loss factor of 0,45 is not applied to calculate the retinal radiant exposure. **This results (for an assumed pupil diameter of 3,5 mm) in the injury threshold being expressed as a radiance dose of 17 MJ m^{-2} sr^{-1}.**

A comparison with the exposure limit of 1 MJ m^{-2} sr^{-1} reveals that for a pupil diameter of 3,5 mm the margin between injury threshold and exposure limit is a factor 17. It is emphasised that the margin depends on the assumed pupil diameter. As long as the "required" margin in the derivation of the exposure limit is not defined, it is not fully appropriate to state that the exposure limit is "based" on an approximate pupil diameter of 3,5 mm. For a smaller pupil the margin is larger, for a larger pupil, the margin is smaller. For a 2 mm pupil diameter, the margin between injury threshold as observed by Lund et al. and the exposure limit of 1 MJ m^{-2} sr^{-1} equals 53. For a 7 mm pupil, for instance, the ratio between the injury threshold and the exposure limit equals 4,3.

4.3 Comparison of exposure level with injury threshold

The derived injury threshold for photochemically induced injury is used in the following as the basis for a risk analysis. For a given radiance as “exposure quantity” the exposure duration to reach the injury threshold can be calculated. At this point in the discussion, the maximum permitted radiance for a projector with 11 mrad angular subtense of the exit pupil, consistent with a TR = 2 and the smallest relevant chip size of 0,67” is used, i.e. 2,5 MW m^{-2} sr^{-1} unweighted radiance. Since the injury threshold is applicable for wavelength ranges where the BLH weighting function is $B(\lambda)=1$, the photochemically effective radiance needs to be used in the comparison with the injury threshold. In chapter 3 it was found that the effective radiance is at least a factor of 4 lower than the unweighted one, i.e. a maximum value of 0,63 MW m^{-2} sr^{-1}.

Applying a reduction factor (as “safety margin”) of 2 to reduce the injury threshold given in the previous sub-chapter, the “permitted” exposure duration depends on the assumed pupil size. Even for the extreme situation of a constant 7 mm pupil, the exposure duration to reach the reduced injury threshold equals 3,4 seconds. Considering that the emitted light of an 11 000 lm projector is very bright, this kind of staring duration can be considered as relatively long. Together with the assumption of a non-reactive pupil this can be seen as not relevant for a risk analysis, i.e. it is argued that for the assumption of a non-reactive 7 mm pupil it can be assumed that staring duration longer than the critical one, potentially leading to retinal injury is so unlikely and an extreme scenario that it can be considered as not relevant as criterion for product safety.

The analysis for a normally responsive pupil was performed based on the worst case assumption of a 7 mm pupil at time t = 0, when the projector switches from a totally black image to a fully white image for the maximum permitted emission level for RG2 as calculated above. It is noted that the assumption of a 7 mm pupil when looking into a projector at a distance of 1 meter or closer (since radiance stays constant, the calculation applies to 1 meter distance as well as to shorter distances, provided that the exit pupil of the projector at 1 meter distance is not smaller than 11 mrad) can be seen as not realistic, but is used here in anyway, since the resulting “permitted staring durations” for normally reactive pupils is very long, even for the assumption of a 7 mm pupil at the beginning of the exposure. The retinal momentary irradiance is scaled with the pupil size, which is taken into account to reduce with time, so that it is 3,5 mm after 1 second exposure duration and 2,1 mm after 2 second exposure duration (the prediction of the NASA unified pupil formula), as is consistent with the data by Stamper et al. [Ref. 5]. From 2 seconds onwards, the pupil diameter is set as a constant value of 2,1 mm. The staring time to reach the injury threshold is calculated to be equal to **30 seconds**. This regime of staring duration into a very bright light source can be considered as considerably longer as expected as viewing durations that could be envisioned for conditions of exposure that are “somewhat longer than just momentary”. Even for the case of intentional staring into the source this is very long and it will be difficult to physically do this without eye movements which further would spread the retinal exposure and would lead to an increase in permitted staring duration.

4.4 Discussion for exit pupils smaller than 11 mrad

The emission level of 2,5 MW m^{-2} sr^{-1} unweighted radiance was calculated for a projector with 11 mrad exit pupil, as consistent with a TR = 2 and worst-case f-number. For a smaller throw ratio (larger divergence of the beam) the exit pupil will be smaller and a higher level of emission is permitted for RG2. Although these levels at some point exceed thermal limitations of the projection chip, it is not completely impossible that exit pupils less than 11 mrad with the correspondingly higher permitted radiance for RG2 exist. For a throw ratio of 1,4, about 23 000 lm are permitted for RG2 (based on the reduced value of α in the AEL) which is a projector for large cinema screens. Due to averaging of the retinal thermal accessible emission over 11 mrad and the rule that in that case α shall not be less than 11 mrad, the averaged radiance for the projector with a TR=1,4 is still the same as for a TR=2.

Regarding the photochemical injury analysis, due to eye movements, an averaging angle of 11 mrad is used. Consequently, when the source is smaller than 11 mrad at 1 meter distance, the averaged radiance, representing the irradiance on the retina in the area covered by eye movements, is correspondingly smaller than the radiance of the stationary source. For exposure closer to the projector, due to the averaging becoming less pronounced, the effective radiance would increase up to the point where the exit pupil appears under an angular subtense equal to 11 mrad. For TR = 1, even though not realistic in terms of projector constellation (since the maximum permitted lumen is about 45 000 lm) the net effect is a maximum factor of about 4 of increased radiance. This factor would reduce the staring duration to reach the injury threshold from 30 seconds (for normally reacting pupils with the worst case assumption of a “starting” pupil diameter of 7 mm) to 7,5 seconds, at a distance of about 50 cm from the projector. Again this can be considered longer as an exposure duration relevant for product safety analysis, even for a level of intentional staring into a very bright source at a relatively close distance. For half a meter viewing distance, the **irradiance at the skin of the face and the cornea of the eye is approximately 800 W m^{-2} to 1000 m^{-2} depending on the throw ratio.** Besides the very high level of brightness, this level will be felt as quite hot and is a “signal” that this is a high power source where intentional exposure for a prolonged time is “felt” as potentially hazardous, and to remain within the beam for longer than a few seconds does not appear as a scenario that needs to be considered for product safety analysis.

4.5 Risk for thermal injury from prolonged staring

In the previous subsections it was shown that staring durations that have to be considered as “relevant” for product safety (such as of a few seconds) remain below the potential critical staring durations that could lead to *photochemically* induced injury.

As the final part in this risk analysis, the risk for *thermally* induced injury for exposure durations longer than 0,25 s is discussed. Two factors are most relevant: firstly the retinal thermal injury threshold when expressed as power level is only very weakly reduced with prolonged exposure duration, and secondly even for the case that the pupil is larger as consistent with factors such as the near triad of accommodation of light emitted from the projector even for black image (see discussion in Reference [1]) at the time when the projector emits a fully white image, the subsequent reduction of pupil size will correspondingly reduce the retinal irradiance level.

The dependence on exposure duration is for instance seen in the following plot (Figure 3), where the symbols represent thresholds from non-human primate studies (green symbol: wavelength 532 nm; red symbol: wavelength 635 nm) and the lines are from a computer model for thermally induced injury [Ref. 9] for a retinal spot size of 80 µm. The injury threshold for 0,5 seconds (7 mW) and 5 seconds exposure duration (6 mW) is almost at the same level. The predicted injury threshold for 0,25 seconds as compared to 0,5 seconds is also not significantly higher. This means that for a given retinal irradiance level, the risk for thermally induced injury does not depend significantly on exposure duration.

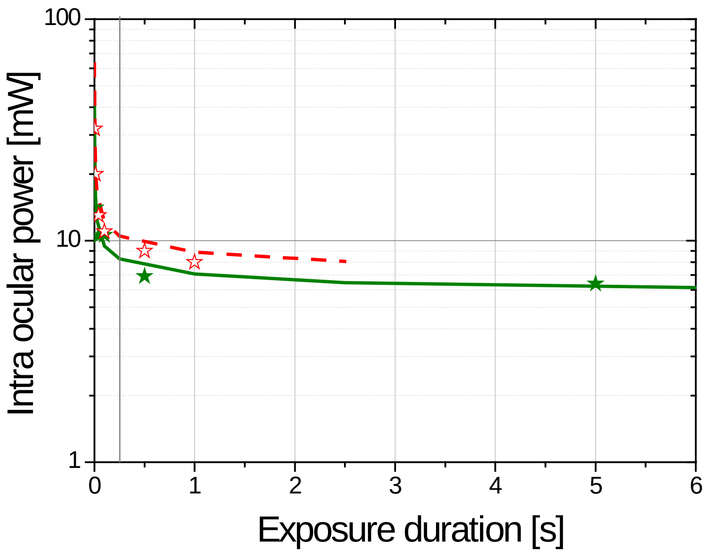

Figure 3. Injury threshold data (star symbols) for non-human primates for green and red wavelengths as function of exposure duration.

For the case of intentional staring into the projector emitting a white image, for normally reacting pupils, the pupil will constrict to about 2 mm diameter within about 2 seconds. Consulting the calculations presented in Reference 1, it is seen that a pupil diameter of 2 mm is well below injury threshold levels for an exposure duration of 0,25 s. Since the dependence on exposure duration is so weak, the conclusion that there is negligible risk for retinal thermal injury for staring durations of many seconds can be extended to thermal injury.

4.6 Exposure of human volunteer

Robertson [8] exposed a human volunteer to radiation from a laser pointer with 532 nm wavelength for exposure durations of 60 seconds, 5 minutes and 15 minutes, respectively. The average power of the laser pointer was somewhat below 5 mW. The head of the human volunteer rested on a chin-rest, i.e. was stabilised and the laser pointer was mounted behind a visual target. Ophthalmoscopic examination of the retina showed a colour change for the site exposed for 60 seconds (which was in the fovea) as well as on the site exposed for 15 minutes (5° off the fovea) but not for the site exposed for 5 minutes (5 degrees off the fovea on the other side). No effect on visual acuity was found as well as no scotomas (black spots in the visual fields which would result from damage of the photoreceptors). Electron microscopy 20 days after exposure at the foveal exposure site (60 seconds exposure duration) and at the 15 min exposure site revealed some pigmentation clumping in the RPE cells but intact photoreceptor cells. This also means that the RPE cells were not “killed” by the exposure, as after 20 days, when the RPE cell layer were non-operative, the attached photoreceptor cells would also have died. That the RPE cells and photoreceptors were functioning is also consistent with the finding that no scotomas were identified and vision was 20/20 before as well as after the exposure.

It is interesting to note that while a 60 second exposure in the fovea resulted in some effect on pigmentation, the 5 minute exposure duration 5° off the fovea did not. The authors comment that this could be due to difficulties in fixating on the off-center targets that might have led to some eye movements and distribution of the laser power over a somewhat larger retinal area. The effect for the 60 second exposure duration is consistent with a thermal mechanism, when we note the thermally induced retinal injury threshold (see Figure 3) for non-human primates at 5 second exposure duration being about 6 mW.

A direct comparison with the exposure limits for the BLH is not possible as the size of the exposed area was not characterized but it is relevant for this work, that no effect of the appearance of the cells was found for 5 minutes of intentional staring into the laser pointer with a stabilized head and that while the appearance of the cells changed for the 15 minutes exposure duration, the RPE cells and photoreceptors apparently maintained their functionality, as there was no effect on visual acuity discernible.

5 CONCLUSIONS AND SUMMARY

In the first part of this White Paper, a general comparison of the blue light hazard exposure level with the blue light hazard (BLH) limit was performed at emission levels permitted for RG2 image projectors based on IEC 62471-5 (2014). It was concluded that for momentary exposure durations the retinal thermal hazard is more restrictive as the BLH, as was expected. It was also possible to calculate, that when the exposure level is at the RG2 thermal exposure limit, then the exposure duration to reach the BLH limit is equal to at least 1,6 seconds (depending on spectral distribution).

For the analysis based on injury thresholds for non-human primates, a reduction factor of 2 was applied to the experimentally found injury thresholds, in order to account for possible effects below ophthalmoscopically visible threshold levels. For normally reacting pupils, the staring duration (assuming minimum eye movements) to reach the reduced injury threshold is computed to be 30 seconds. For the case of non-responsive pupils, the exposure duration to reach the reduced injury threshold was still 3,4 seconds. Basing the analysis on the non-reduced injury thresholds found for non-human primates, the staring duration to reach the threshold is twice that, i.e. 6,8 seconds.

Regarding the potential risk for thermally induced injury following intentional staring into a projector, it was concluded that there is no relevant increased risk for prolonged exposure, due to the constriction of the pupil and the weak dependence of the injury threshold given as intraocular power on exposure duration.

Considering the brightness of the projector when a white image is emitted, and also that the irradiance in the beam of a projector emitting at the permitted levels for RG2 of between 800 W m^{-2} and 1000 W m^{-2} at half a meter distance will be felt as “hot” any exposure duration beyond the critical level can be seen as not relevant for product safety. A person who suffers from a medical disorder leading to non-reactive pupils, as well as a person coming from an eye exam with dilated pupils is aware of this condition and together with the high brightness of a projector and that the beam at levels of RG2 limits can even be felt as warm, it does not appear relevant to require that a product is “safe” for the case of intentional staring into a very bright source for several seconds when the pupils are known to be non-responsive.

6 ACKNOWLEDGEMENTS

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