ILSC ® 2013 Conference Proceedings

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Reference information for this proceedings paper

Title: *Simplified method to assess the UV and blue light hazard of lamps*

Author: *Schulmeister K, Buberl A, Weber M, Kitz E*

Proceeding of the International Laser Safety Conference, March 18-21 2013, Orlando, Florida
Page 357-365

Published by the Laser Institute of America, 2013
Orlando, Florida, USA www.lia.org

SIMPLIFIED METHOD TO ASSESS THE UV AND BLUE LIGHT HAZARD OF LAMPS

Paper #P104

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Abstract

The UV-emission, as well as emission in the visible wavelength range, was measured for about 100 lamps of various types used for lighting. It can be concluded, that at the distance where the illuminance equals 500 lx, the UV- and Blue light ICNIRP/ IEC 62471 /ACGIH exposure limits are not exceeded. By relating the UV emission with the visible emission, it was further possible to derive a factor for each lamp with which it is possible to measure the UV emission with a lux-meter, or to express the UV exposure limits in terms of permitted illuminance, for instance 4000 lx. Similarly, it was possible to derive such a transformation factor for the blue-light weighted emission and to express the blue-light hazard exposure limits in terms of illuminance. It is seen that this value is closely related to the color temperature of the lamp, and that for white lamps, the blue-light hazard exposure limit at the distance where the illuminance is 500 lx, is not exceeded.

Introduction

Lamps used for lighting emit a varying degree of radiation in the ultraviolet part of the spectrum (200 nm to 400 nm). If exposure limits for the eye or skin are exceeded, UV radiation can result in acute and chronic injuries [1,2]. Also the blue component of the emission, for very bright sources and continued staring into the lamp for some time can exceed the blue-light exposure limit that is defined to protect the retina regarding photochemically induced injury (known from staring into the sun, or welding arcs). The corresponding exposure limits for exposure at the workplace are defined by ACGIH [3] in the US and in Europe by the European Directive for Artificial Optical Radiation AORD [4]; directly adopting the ICNIRP exposure limits [5]. According to the principles of the Directive and the respective national work place safety legislation in the European member states, each source of optical radiation at the workplace needs to be analyzed to characterize if the exposure limits can be exceeded or not; there is no "white list" of sources or applications which would not have to be analyzed at last to a minimal degree. However, product safety classification (such as according to IEC 62471 which specifies risk groups [6]) or results of research projects can be used to simplify this analysis and reduce it to a minimum effort.

In the framework of an AUVA research project we have measured over 100 different lamps in the UV and visible spectral range. The goal was to obtain data that would simplify the requirement for analysis of lighting at the workplace. Based on this work, a hazard analysis can be greatly simplified. Additionally, scaling factors were be derived with which effective exposure levels for UV-S(λ), UV-A, photochemical retinal and thermal retinal can be determined with a lux-meter.

Illuminance Reference Levels

Compared to other sources of optical radiation, lamps used for lighting have the advantage that the level of visible radiation that is incident in the area where humans are present, i.e. where the sources are used for lighting, is relatively well defined: on the one hand there are minimum required lighting levels, that depend on the task that is to be performed, on the other hand, the upper range of lighting levels is limited due to requirements to prevent glare as well as to limit cost. In many countries, there are recommendations and standards for the minimal level of lighting of indoor work places. In Europe, EN 12464-1 [7] can be seen to reflect the state of technology. According to EN 12464-1, for instance, locations for rough assembly tasks require illuminance levels of 200 lx, finer assembly tasks 500 lx, staircases 100 lx, cantinas 200 lx, regular offices 500 lx in the specific working area and for precision work in the respective local working area a higher level such as 1500 lx; outside of the working area, a level of 300 lx is required.

The level of 500 lx is used as reference level in several international and national product safety standards:

IESNA RP27, CIE S009, IEC 62471, IEC 60432-2, IEC 62035. In order to appraise this reference level as representative - even considering the possibility that locally or for some time during the day, the illuminance level can be higher than 500 lx - it is of key importance to recognize that the exposure limit for UV radiation is specified as radiant exposure, for instance 30 J/m^2 (3 mJ/cm^2) which is not to be exceeded over a period of 8 h 20 min (or 30 000 s). This exposure limit translates to an irradiance-exposure level for continuous exposure for a duration of 30 000 s (division of exposure limit by 30 000 s) of 10^{-3} W/m^2. Let us assume that for a given lamp, at the location where an illuminance level of 500 lx is measured, the UV effective exposure level just equals 10^{-3} W/m^2. If there is exposure for 30 000 s at that level, the exposure limit will just be reached. However, since the basic exposure limit is given as a radiant exposure (a dose value), if there are periods with lower exposure levels than 10^{-3} W/m^2 (or 500 lx), these compensate for periods with higher exposure levels than 10^{-3} W/m^2 (or 500 lx) and the dose limit is not exceeded as long as the **average irradiance**, averaged over 30 000 s is below 10^{-3} W/m^2 (or the average illuminance is at or a little below 500 lx for the above example). This situation is shown Figure 1 and is pivotal to appreciate that 500 lx is an appropriate reference level: while, locally, the illuminance can be higher for special tasks (and this is usually achieved with local task lighting additional to the general room lighting), there will be periods when there is reduced lighting, such as in breaks, in the bathroom, etc.

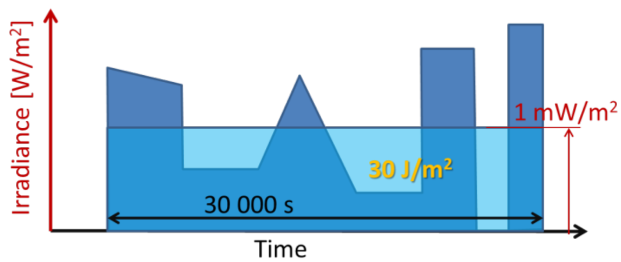

Fig. 1. Contrary to the laws of vision and lighting, for UV it is not the *momentary* irradiance that is relevant, but the accumulated dose, which is equivalent to the average irradiance (or illuminance); averaged over 30000 s, about 8 h

Another factor in the discussion on the relationship of illuminance levels and UV exposure is that part of the illuminance (at a desk for instance) is not originating directly from the ceiling luminaire, but from reflections from walls – white walls do reflect visible radiation well but UV radiation is reflected with a strongly decreased level [8].

Methods

Transformation of UV-Exposure Limits

The exposure limits for UV radiation promulgated by ICNIRP and adopted by the European Artificial Optical Radiation Directive are summarized in Table 1.

Table 1. UV-Exposure limits defined by ICNIRP and the European Directive for Artificial Optical Radiation, as well as differences for the UV-A ACGIH® exposure limit.

	Exposure limit in J m^{-2}	max. Integration-duration	Action spectrum	Symbol for effective (weighted) radiant exposure	Applies to	Irradiance Exposure limit for 30000 s exp. duration
Actinic UV	30	30 000 s	S(λ)	H_{eff}	Eye, Skin	0.001 W m^{-2}
UV-A	10 000	30 000 s ACGIH:1000 s	Limited to 315-400 nm	H_{UVA}	Eye	0.33 W m^{-2} ACGIH: 10 W m^{-2}

It is noted that according to the ACGIH exposure limits that apply at the workplace in the USA, the UV-A exposure limit has a maximum integration duration of only 1000 s, so that for longer exposure durations, the limit becomes a constant irradiance of 10 Wm^{-2}; a factor of 30 higher than for the ICNIRP /AORD maximum integration duration.

For a given lamp spectrum (a given lamp type), the absolute level of exposure changes with distance, but the relative ratio between visible and UV remains (to a good approximation) constant. It is therefore possible to determine a ratio factor for UV and the visible part for a given lamp that can be used to transform the UV exposure limit (for that lamp) into an exposure limit that limits the UV but is expressed as illuminance, i.e. in units of lux. One can then measure the illuminance at the relevant exposure distance with a lux-meter and determine in that simple way if the UV limits are exceeded or not. It is also possible to compare these “permitted lux values” (such as for a lamp emitting relatively little UV, 10 000 lx) with typical illuminance levels, where for many lamps it is clear from these high permitted lux levels that they would not be exceeded except when the luminaire is under maintenance. It is important to note that “permitted lux values” depend on the specific spectrum, i.e. are specific to the lamp, and can also be changed by reflectors in the luminaire or by diffusing covers.

The ratio between "UV-effective irradiance" and illuminance is the central quantity here, and this is referred to as "U-factor" in this work.

The UV-effective irradiance that is to be compared to the actinic-UV limit of 30 J m^{-2} is defined as

$$E_{eff} = \int_{\lambda=200\ nm}^{\lambda=400\ nm} E(\lambda) \cdot S(\lambda) \cdot d\lambda$$

To obtain the illuminance, the spectral irradiance is weighted with the luminous efficiency function V(λ) and integrated over the wavelength range of 380 nm to 780 nm, and multiplied with the factor K_m = 683 lm/W to link photometric quantities (1 cd is a SI unit) with radiometric quantities.

$$E_v\left[\frac{lm}{m^2}\right] = E_v\left[lx\right] = K_m \cdot \int_{380nm}^{780nm} E(\lambda)\cdot V(\lambda)\cdot d\lambda$$

The two U-factors for the two UV exposure limits are:

$$U_{eff}\left[\frac{W}{lm}\right] = U_{eff}\left[\frac{W/m^2}{lx}\right] = \frac{E_{eff}\left[W/m^2\right]}{E_v\left[lx\right]}$$

$$U_{UVA}\left[\frac{W}{lm}\right] = U_{UVA}\left[\frac{W/m^2}{lx}\right] = \frac{E_{UVA}\left[W/m^2\right]}{E_v\left[lx\right]}$$

The unit of the U-factors therefore is (W/m^2)/lx, or, since the /m^2 cancels out, W/lm. It is important to remember, however, that the "W/m^2" here belongs to a weighted quantity and these are effective values, and in the equations above two differently weighted values (such as the lx is a weighted value).

To have values in a practical range, we are using mW klm^{-1} (milliwatt per kilolumen). The unit mW/klm is also used in EN 60432-2 to define the permitted UV emission for quartz-halogen lamps in open luminaires (2 mW/klm). When the numerator as well as the nominator is divided by the unit for area, the value does not change, but the units change from W lm^{-1} to W m^{-2} lx^{-1}:

$$U\left[\frac{W/m^2}{lx}\right] = U\left[\frac{W}{lx\cdot m^2}\right] = U\left[\frac{\frac{W}{m^2}}{\frac{lm}{m^2}}\right] = U\left[\frac{W}{lm}\right]$$

since 1 lx = 1 lm m^{-2}.

The transformation of W lm^{-1} into mW klm^{-1} is affected by multiplication with 10^6.

It is noted that it is common practice to measure values that are given in units of lm as total emitted radiation, i.e. by placing the lamp in an Ulbricht sphere, while the values given as illuminance (in lx) are measured in front of the lamp with a specified averaging aperture with for instance 1 cm diameter. In this paper we generally use mW/klm even though the emission/exposure is measured in a certain distance from the lamp (where the lamp community would use the form of (mW/m^2)/lx).

For the reference illuminance value of 500 lx, and assuming an exposure duration of 30 000 s (resulting in a permitted effective irradiance value for UV actinic of 1 mW/m^2), the U factor equals:

$$\frac{0{,}001\ \frac{W}{m^2}}{500\ lx} = \frac{1\ \frac{mW}{m^2}}{0{,}5\ klx} = \frac{1\ \frac{mW}{m^2}}{0{,}5\ \frac{klm}{m^2}} = 2\,mW/klm$$

which is what is specified as maximum permitted ratio in IEC 62035 and IEC 60432-2 und -3.

These U-factors can then be used to transform UV exposure limits into "lx" exposure limits. The same can be done for the UV-A exposure limit:

$$\frac{0{,}33\ \frac{W}{m^2}}{500\ lx} = \frac{330\ \frac{mW}{m^2}}{0{,}5\ klx} = \frac{330\ \frac{mW}{m^2}}{0{,}5\ \frac{klm}{m^2}} = 660\ mW/klm$$

Where the mW here are not unweighted (normal radiometric) mW but „UV-A-mW".

For a given lamp, the U-factors are used to transform the UV-exposure limits EL_E_{eff} and EL_E_{UVA} into illuminance exposure limits in the following way:

$$E_{vMAX\_eff}\left[lx\right] = \frac{EL\_E_{eff}\left[\frac{W}{m^2}\right]}{U_{eff}\left[\frac{W/m^2}{lx}\right]}$$

$$E_{vMAX\_UVA}\left[lx\right] = \frac{EL\_E_{UVA}\left[\frac{W}{m^2}\right]}{U_{UVA}\left[\frac{W/m^2}{lx}\right]}$$

Is U_{eff} for example is equal to 0.5 mW/klm = $0.5 \cdot 10^{-6}$ $W/m^2/lx$, the UV-exposure limit for 30 000 s exposure duration is transformed as follows:

$$\frac{0,001\,\frac{W}{m^2}}{0,5\;mW\,/\,klm} = \frac{0,001\,\frac{W}{m^2}}{0,5\cdot 10^{6}\,W\,/\,lm} = \frac{0,001\,\frac{W}{m^2}}{0,5\cdot 10^{6}\,\frac{W/m^2}{lx}} = 2000\;lx$$

One can use this "lux-exposure limit" to compare it with the exposure level measured with a lux-meter. This is the same principle as to convert the measured illuminance value into an effective UV exposure value (multiplication of illuminance-value with U) and to compare it directly with the UV exposure limit. In that way it is possible to "measure" UV exposure with a lux-meter.

Above values are derived for the worst-case exposure duration of 30 000 s. If the exposure duration is shorter, the permitted illuminance value is increased correspondingly. Also, if the value is determined for the lamp, as in the project described here, any added luminaire will affect the U-factor by decreasing the relative UV-emission (as any reflector or diffusing cover plate is less effective in the UV as compared to the visible, as confirmed by measurements in the framework of the AUVA project [9]).

Also, even though the factor is determined for one lamp (or luminaire), the advantage is that it applies for the case of several lamps next to each other as long as they are of the same type. For several lamps next to each other, it is just the distance, where for instance an illuminance level of 500 lx exists, which increases.

An important figure of merit for a given lamp and exposure distance is the permitted exposure duration to reach the exposure limit (the permitted radiant exposure permitted for a 30 000 s period). For an effective actinic UV irradiance of 1 mW/m^2, the permitted exposure duration is 30 000 s, or 8 hours and 15 minutes. While the dose is not further added up beyond 8 h 20 min in the framework of a safety analysis according to ACGIH or the AORD, to calculate the permitted exposure duration is a well communicable value to express the UV emission/exposure: for instance, if the effective irradiance equals 0,5 mW/m^2 , the calculated permitted – exposure – duration – figure – of – merit equals 16 h 40 min.

Another figure of merit (all expressing the same ratio) is how high the illuminance level is permitted to be, to reach the exposure limit for an assumed exposure duration of 30 000 s. If the permitted (average) illuminance level for a given lamp for instance equals 1000 lx (this is independent of the distance), then the calculated permitted exposure duration at a level where the illuminance equals 500 lx is 16 h 20 min. The U-factor for that example would be 1 mW/klm. All these figure-of-merits express the same ratio that could also be expressed as "safety factor" relative to the 30 000 s UV exposure limit, which in the above example equals 2.

Measurements

110 lamps of different type and manufacturers were obtained from specialized lamp dealers as well as do-it-yourself shops at the beginning of 2011. The spectral irradiance was measured with a Bentham DM300 double-monochromator. The distance to the lamp was 20 cm in all cases; if the exposure limit for 30 000 s was exceeded, measurements at larger distances (1 m, 2 m) were also performed. For tubular lamp shapes, the measurement direction was radial, for lamps with reflectors, the measurement direction was perpendicular to the reflector (axial). For bare lamps, where the most restrictive measurement geometry was not clear, radial *and* axial directions were measured. The values for the distance, where the illuminance equals 500 lx were obtained by scaling of the 20 cm distance measurement. Comparison of data from difference distances showed that the U-factors have no significant distance dependence.

The number of lamps analyzed per type is given in Table 2.

Table 2. Types of lamps and numbers measured for each type.

	Number of lamps
CFL (Compact Fluorescent Lamp)	39
Incandescent lamp („soft-glass“, no halogen)	5
LED	6
Quartz-halogen incandescent lamp	35
Fluorescent lamp (tube)	27
Halogen-Metall vapor lamp (metal halide lamp)	15
Mercury vapor lamp	19
Sodium vapor lamp	3

Results

The complete list of spectra and figure of merits is published in the AUVA Report 55 [9]. Here we present tables of those lamps per lamp type with the highest relative UV component; Table 3 and Table 4.

Table 3. Figures of merit for the most critical lamp per lamp-type, for the S(λ) weighted spectra, i.e. for the actinic UV with the exposure limit of 30 J/m^2.

Lamp Type	safety factor	Permitted exposure duration in 500 lx distance [hh:min]	Permitted average illuminance (30 000 s integration)	U_{eff}-factor [mW/klm]
Mercury vapor lamp	1.04	8:40	520 lx	1.92
Quartz halogen lamp	1.4	11:56	717 lx	1.40
Fluorescent tube	3.0	25:22	1522 lx	0.66
CFL	3.1	26:39	1 599 lx	0.63
Sodium vapor lamp	28.0	242 h	14 557 lx	0.07
Metal halide lamp	40.0	355 h	21 300 lx	0.05
Incandescent lamp	100.0	830 h	49 800 lx	0.02
LED	23000	95 907 h	5.7 Mlx	0.0001

Table 4. Figures of merit for the most critical lamp per lamp-type, for the UV-A integrated spectra, i.e. for the UV-A limit of 10 000 J/m^2.

Lamp Type	safety factor	Permitted exposure duration in 500 lx distance [hh:min]	Permitted average illuminance (30 000 s integration)	U_{UVA}-factor [mW/klm]
Mercury vapor lamp	0.7	5:56	356 lx	935
Metal halide lamp	1.8	15:16	917 lx	364
Fluorescent tube	2.3	19:07	1147 lx	291
Quartz halogen lamp	5.5	45:22	2723 lx	122
CFL	5.7	47:43	2864 lx	116
Incandescent lamp	12.1	100 h	6020 lx	55
Sodium vapor lamp	19.0	157 h	9421 lx	35
LED	133.2	1144 h	68 klx	5

The tables list both the permitted exposure duration for the 500 lx distance as well as the permitted average illuminance level for 30 000 s averaging duration (where it is not known at what distance this illuminance is found). In Table 5 and Table 6, the values for 20 cm distance are given, which is a relevant distance for instance for maintenance of the luminaire as a worst-case distance. Table 5 lists lamps which even at 20 cm distance are not critical for 30 000 s exposure duration; Table 6 lists lamps which might be critical at that distance, depending on exposure duration.

Table 5. Permitted exposure duration at 20 cm distance; non-critical lamps.

	S(λ)		**UV-A**	
Lamp Type	*Lamp-number*	Permitted exposure duration *S(λ)* *[hh:min]*	*Lamp-number*	Permitted exposure duration *UV-A* *[hh:min]*
CFL	#68a	14:45	#31	8:55
Incandescent lamp	#72	60:53	#21	173 hours
LED	#88	10 820 hours	#88	129 hours
Fluorescent tube	#24	6:39 (2200 lx)	#24	9:10
	#89	9:41 (1300 lx)	#53	13:35
Sodium vapor lamp	#111	11:14	#111	7:16

Table 6. Permitted exposure duration at 20 cm distance; potentially critical lamps.

	S(λ)		UV-A	
Lamp Type	*Lamp-number*	Permitted exposure duration *S(λ) [hh:min]*	*Lamp-number*	Permitted exposure duration *UV-A [hh:min]*
Metal halide lamp	#96	1:07 (206 000 lx)	#96	0:02
Quartz halogen lamp	#55	4:32 (434 000 lx)	#55	0:06
Mercury vapor lamp	#107	0:08 (40 000 lx)	#109	0:10

Discussion of UV-Emission

The data in Table 3 show that none of the permitted average illuminance levels are below 500 lx. It should be kept in mind that the data given in the tables are for the most critical lamp found per group, and in some cases (for instance for the case of quartz halogen lamps), this data comes from one lamp while all the others of that type have a much less critical UV emission. Also the values are for bare lamps, and the relative UV emission is greatly decreased due to reflections or diffusing covers of a luminaire.

If the average illuminance level (averaged over 30 000 s) is below 500 lx, or below the given value in Table 3, one can conclude that the actinic UV exposure limit is not exceeded. As pointed out in the introduction, for most workplaces, an average illuminance level of 500 lx can well be assumed to be appropriate, since episodes of higher illuminance levels, if they exist, will be compensated by episodes of lower illuminance levels. Also, it is important to note that it is really only mercury vapor lamps which have - in a consistent way, i.e. not only an "outlier" - UV emission not far from the permitted 30 000 s value at 500 lx illuminance levels. However, these types of lamps, due to their long maintenance period are used in high-bay hall lighting where the higher price per lamp is compensated by the lower maintenance cost. The illuminance level on the (factory) floor can assumed not to exceed 500 lx. The quartz halogen lamp that had a permitted illuminance value of 717 lx is an outlier (not manufactured by the "big" lamp companies but a home-brand of a DIY shop), as all the other quartz halogen lamps have a minimum permitted illuminance level of 9000 lx for the actinic UV and 4000 lx for the UV-A limit.

Noteworthy is also that the white LED lamps have practically no UV emission, and would lend themselves for instance for lighting applications where any UV emission/exposure is to be avoided.

From the data it is possible to conclude that - unless for maintenance of the luminaire, or special cases of long term exposure to very high illuminance levels of critical lamps (which cannot be excluded for very special task lighting, but is certainly rare) - lighting, and particularly general lighting in schools, factories, shops, warehouses and offices, etc., can be assumed not to lead to a actinic exposure level of the eye or skin that exceeds the exposure limit defined by ICNIRP, ACGIH and the AORD of 30 J/m^2.

Regarding the UV-A exposure limit, it needs to be considered that this limit only applies to the eye and not to the skin. The values given in Table 4 are determined for direct axial or radial exposure, in an angle of 90° with respect to the axis. This would only apply for actual exposure scenarios if the direction of view is directly into the lamp. The most critical lamp-type is again the mercury vapor lamp. As noted before, this type of lamp is not used in regular office lighting, but for high-bay lighting of factories, warehouses and supermarkets. The luminaire has to be designed so that for the usual direction of view (not upwards into the lamp), the lamp is shielded sideways; otherwise the lamp would induce an unacceptable glare. A typical luminaire with a mercury vapor lamp is shown in Figure 2.

Fig. 2. A high-bay luminaire with a mercury vapor lamp.

It is thus possible to conclude that direct viewing upwards into the lamp will occur only occasionally, and the side view is either shielded by the luminaire (to prevent glare) or the lamp is sufficiently far away so that the exposure from that lamp is also negligible. Consequently, if the permitted exposure duration (per 30 000 s period) at the 500 lx distance for direct viewing equals about 6 hours for the most critical lamp, it can be assumed with good confidence that the UV-A exposure limit for normal lighting situations (where glare *has* to be avoided based on design guidelines, as well as at least in Europe, work place safety legislation) is not exceeded.

Maintenance

The data presented in Table 6 show that for exposure at very close distances, for the listed potentially critical lamp types, the exposure limits for the eye and the skin can be exceeded, and can be exceeded considerably for long exposure duration. The associated illuminance levels at that distance of more than 40 000 lx shows that this is far from any normal distance where the lamp would be used for lighting. However, for a situation where maintenance of the luminaire is performed for a respective total duration per day for the case that the lamp cannot be switched off, personal protection to protect the eyes and skin is necessary. It is also noted that the present study did for these lamps and distances not analyze potential risk for injury of the retina, i.e. application of the retinal photochemical limit, and it can be assumed that it is prudent to use eye protection that also filters the blue light component, also to prevent glare.

Damaged outer envelope

Also it should be noted that it is known that some high pressure discharge lamps (mercury vapor lamps and metal halide lamps) emit considerable amount of UV-radiation for the case that the outer envelope is broken and there is no inner shroud and the lamp is not switched of automatically by a protective internal fuse. A broken outer envelope is known to have caused inflammation of the cornea in some cases [10,11], usually in sports halls where the lamp probably was damaged by a ball. This can only be an issue for an open luminaire, i.e. a luminaire without cover glass (as shown in Figure 2), since a cover glass on the one hand protects the lamp and on the other, when intact, reduces the UV emission to a safe level.

For open luminaires and when a high pressure discharge lamp is used (that is not internally protected), it is therefore prudent to perform a visual check if the lamp is intact.

Blue-light Hazard

The concept discussed in the previous sections for UV emission/exposure, where the illuminance is characterized relative to the effective UV exposure, can also be applied for the blue light hazard (potential photochemical injury of the retina). The basic photochemical retinal limit is given as 10 J m^{2}sr^{-1}, but can be transformed into a permitted effective irradiance value of 1 W/m^2 for the worst assumption of 10 000 s exposure duration per day (the maximum integration duration) and a field of view for measurement of 110 mrad [12, 13]. The weighting function is here the blue-light hazard function $B(\lambda)$.

$$E_{BL} = \int_{\lambda=300\ nm}^{\lambda=700\ nm} E(\lambda)\ \cdot B(\lambda) \cdot d\lambda$$

When the measurement of the spectral irradiance is performed with an open field of view, as was the case in the project (and is also the case for lux-meters), then the obtained exposure level is a worst case value for those cases where the source is larger than 110 mrad. In this way, illuminance measurement can again be used to indirectly measure the blue-light effective irradiance. The respective U-factor is defined as:

$$U_{BL}\left[\frac{W/m^2}{lx}\right] = \frac{E_{BL}\left[W/m^2\right]}{E_v\left[lx\right]}$$

For a given U-factor, it is then possible to derive the permitted illuminance E_{v_crit} for the 10 000 s exposure limit of 1 W/m^2.

$$E_v\left[lx\right] = \frac{1\left[W/m^2\right]}{U_{BL}\left[\frac{W/m^2}{lx}\right]}$$

where the "1 W/m^2" is again not a normal radiometric W/m^2 but a photobiologically weighted one. As a numerical value, thus, the permitted illuminance in lx is equal to the inverse of the U-factor. A U-factor of 1/1000 W/m^2/lx means that for continued staring into the lamp at a distance where the illuminance equals 1000 lx, the blue light hazard exposure limit of 1 W/m^2 is just reached (for the worst case assumption of an open field of view). Or, in other words, for the distance where the illuminance level is 500 lx, for that lamp, the exposure level is a factor of 2 below the exposure limit for long term staring.

A plot the U-factors as function of associated color temperature (Figure 3) reveals that irrespective of the lamp type and therefore spectral distribution, the U-factors are highly correlated with the color temperature and are all very close to the factor that results for black-body radiation (the dashed blue line). The only exception, where the fit to the black-body radiator is not that close, is for mercury vapor lamps which compared to the V(λ) weigthed illuminance have a higher blue light weighted emission/exposure compared to a black-body radiation with the same color temperature (higher U-factor and therefore lower inverse factor plotted in Figure 3). The maximum difference is about a factor of 1.33.

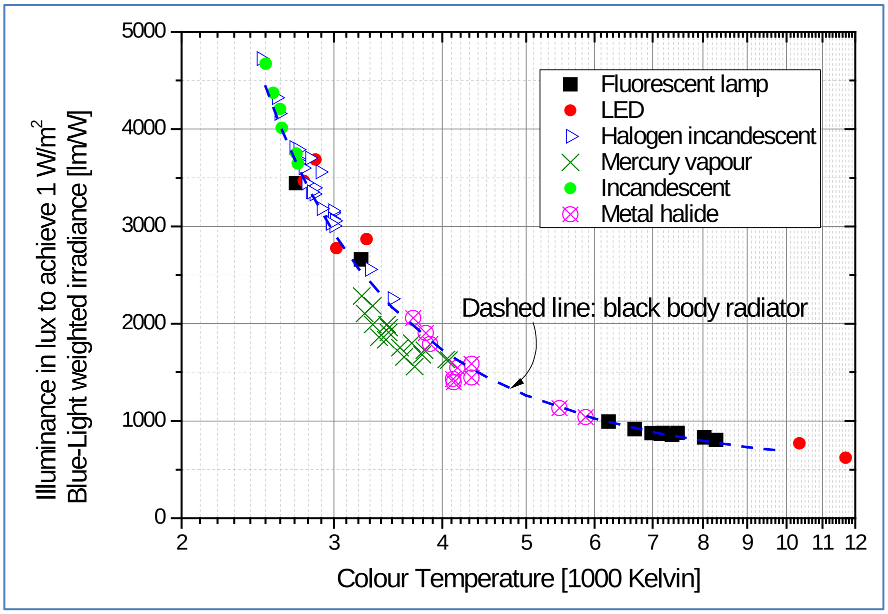

Figure 3. Illuminance levels that result in exposure of the eye at the blue-light exposure limit for 10 000 s exposure duration, as function of color temperature.

This is particularly valuable information when the reference distance is set to the distance where the illuminance equals 500 lx. The plot shows that for white light sources with color temperatures below 12 000 Kelvin and 500 lx reference distance, the blue light hazard exposure cannot generally be exceeded, and, for instance, according to IEC 62471, is "automatically" in the exempt group (RG0). For bluish-white lamps, which is possible for "cold-white" LEDs and emitters which use a blue laser as primary light source (for these the color temperature is so high that normal algorithms do not work), as well as for blue light sources (blue LEDs), this conclusion is not permissible and for these sources, the permitted illuminance level is correspondingly lower in order not to exceed the blue-light hazard exposure limit for continuous staring into the lamp. Assuming some worst-case spectral distributions for LEDs, we have derived a value of 27 lx for blue LEDs (peak above 450 nm) and a value of 2 lx for violet LEDs (peak below 450 nm) [14].

Summary and Conclusions

A representative selection of 110 lamps used for lighting was characterized in terms of UV-emission and emission in the visible wavelength range. The UV emission/exposure level at a distance where the illuminance is 500 lx is in no case above the 30 000 s exposure limit for actinic UV for the skin and the eye. Also, considering that direct vision of high-brightness lamp is not expected except for momentary episodes (due to glare effects), the UV-A exposure limit for the eye can also be assumed to be not exceeded. These findings form a basis for greatly simplifying the hazard analysis at the workplace in Europe, where each and every source of optical radiation needs to be assessed to characterize if the workplace safety exposure limits are exceeded or not.

The work also provides for lamp-specific transformation values to express the two UV exposure limits in terms of permitted illuminance levels. With this factor it is possible, for the case that specific measurements are to be performed, to measure the UV effective exposure level with a lux-meter.

As a third output of the project, it was possible to derive transformation factors for the blue-light hazard, with which it could be shown that at the reference distance of 500 lx illuminance level, the blue-light hazard exposure limit, for lamps emitting "white" light with color temperatures below 12000 Kelvin, cannot be exceeded, i.e. are always in the exempt group of IEC 62471 (RG0).

Acknowledgements

We would like to acknowledge that the project "UV-EVAL" to analyze the UV emission of lamps used for lighting and to develop a simplified hazard analysis strategy was funded by the AUVA.

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