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Method of determining photobiological safety of contemporary light sources

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Key words: photobiological hazard, ultraviolet radiation, infrared radiation, visible radiation, blue light hazard, risk group, safe exposure time, lighting source, light emitting diode (LED)

Abstract

The article presents a method of evaluating irradiance, spectral irradiance, and spectral radiance, for purposes of determining risk groups of sources of light. The description of the method of measurement of radiance incorporates standard and alternative methods. Measurement methods were developed on the basis of general requirements and diagrams incorporated in the standard PN-EN 62471: 2010. The paper classifies risk groups of sources of light in terms of photobiological hazards and exposure limits when skin is at risk of being damaged by visible and infrared radiation. Threshold values of emissions for the continuous sources of radiation studied are presented. The article describes environmental conditions under which the measurements are to be taken, and requirements applicable to the process of light source aging. In addition, technical assumptions are presented, and the design of the test stand for measuring optical radiation parameters is described.

Introduction

The main task of all sources of white light is to generate visible radiation with specific spectral characteristics. When selecting a light source for a specific visual task or type of workstation, certain visible radiation parameters must be taken into account, such as: luminous flux, colour rendering index or colour temperature. The efficiency of the light source, related to its energy efficiency, is also an important parameter. The remaining radiation components, such as ultraviolet and infrared radiation, are not desired and may even negatively affect the health and productivity of exposed people. Visible radiation with excessive amounts of blue spectrum light has a similar impact on humans.

Given that all traditional light bulbs rated over 7 W will be withdrawn by September 01, 2016, various replacement products have been offered in the lighting market for several years. These may be halogen light bulbs, compact fluorescent lamps (CFL), or light emitting diode (LED) sources. Still, the characteristics of radiation of the newly introduced lighting devices, especially of LEDs, differ from that of the traditional incandescent sources due to their different ways of generating light. Hence, a question arises as to whether the spectral characteristics of LED sources or CFL allows them to replace traditional light bulbs. These concerns are raised mainly by people whose eyes and skin are particularly sensitive to certain types of radiation, mainly to the ultraviolet and blue parts of the spectrum.

The evaluation of photobiological hazards generated by optical radiation emitted by light sources is a complex metrological task, as measurements must be made over a wide spectral range (200–3000 nm), while taking into account effective values (Pietrzykowski, 2009). This requires special, calibrated measuring equipment, and the development of methods of examination of parameters of optical radiation emitted by electrical sources of optical radiation. First of all, all such methods must be based on criteria set forth in the standard PN-EN 62471: 2010 Photobiological safety of lamps and lamp systems, and take into account conditions resulting from the application of specific measuring equipment. These methods must also describe the way of determining light hazard groups of photobiological hazards caused by optical radiation, as per standard requirements (Pietrzykowski, 2012).

Classification of groups of hazards of light sources in terms of photobiological hazards

The standard PN-EN 62471: 2010 specifies photobiological safety criteria of optical radiation sources, and methods of measuring irradiation and radiance. According to this standard there are four risk groups, defined as follows:

- Free from risk group 0 (RG0) – sources of light pose no photobiological hazard;
- Risk group 1 (low risk) (RG1) – sources of light pose no hazard under normal operating conditions;
- Risk group 2 (moderate risk) (RG2) – sources of light pose no hazard related to ocular reaction to very bright sources of light;
- Risk group 3 (high risk) – sources of light pose hazard even during brief exposures. The use such sources of light is prohibited in general lighting.

This classification is based on maximum permissible exposure (MPE) assumed for the exposure of workers to hazards arising from artificial optical radiation, as specified in the Directive 2006/25/EC of the European Parliament and Council of April 05, 2006 on the minimum health and safety requirements regarding the exposure of the workers to hazards arising from physical agents (artificial optical radiation). The classification also takes into account the level of radiation emitted by a source of light, the spectral range of radiation, and access by humans. In the assumed classification, the only difference is that for purposes of determining the classification criteria for individual risk groups separate assumptions are made related to permissible times of safe exposure for each of the five photobiological hazards in a given category (Marzec & Nowicka, 2012). The no risk group is a group that poses no hazard of the following kinds of risks:

- No actinic ultraviolet within 8 hours after exposure, and no near ultraviolet after 1,000 s exposure;
- No risks to the retina attributable to photochemical factors after 10,000 s of exposure, and no thermal risks to the retina after 10 s;
- No risks to the cornea and lens from infrared red radiation after 1,000 s.

In addition, the no risk group includes sources of light that emit infrared radiation without strong luminous impulses (whose luminance is lower than 10 cd/m^2) and which do not endanger the retina with near infrared after 1,000 s of exposure. In the assumed classification, risk group 3 includes sources of light that may pose hazards even with temporary or brief exposure, and whose parameter values, determined on the basis of measurements, serving to evaluate the hazard, exceed the limits of risk group 2. As per the standard PN-EN 62471: 2010, a different method should be used to determine threshold emission values for the retina's

Table 1. List of limiting values of emission for continuous operation light sources, drawn up on the basis of the standard PN-EN 62471: 2010

Type of photobiological hazard	Wave-lengths [nm]	Function of biological efficiency	Sym-bol	Denomi-nation	Risk group 0 (RG0)		Risk group 1 (RG1)		Risk group 2 (RG2)	
					Safe exposure time	Emission limits	Safe exposure time	Emission limits	Safe exposure time	Emission limits
Actinic UV	200–400	$S_{UV}(\lambda)$	E_s	W·m^{-2}	8 hrs	**0.001**	10 000 s	**0.003**	1000 s	**0.03**
UV-A	315–400	–	E_{UVA}	W·m^{-2}	1000 s	**10**	300 s	**33**	100 s	**100**
Blue light	300–700	B(λ)	L_B	W·m^{-2}·sr^{-1}	10 000 s	**100**	100 s	**10,000**	0.25 s[3)]	**4,000,000**
Blue light – small source[1)]	300–700	B(λ)	E_B	W·m^{-2}	10 000 s	**1.0**	100 s	**1.0**	0.25 s[3)]	**400**
Retina thermal hazard	380–1400	R(λ)	L_R	W·m^{-2}·sr^{-1}	10 s	**28,000/α**	10 s	**28,000/α**	0.25 s[3)]	**71,000/α**
Retina thermal hazard – weak visual stimulus[2)]	780–3000	R(λ)	L_{IR}	W·m^{-2}·sr^{-1}	1000 s	**6000/α**	10 s	**6000/α**	10 s	**6000/α**
Cornea and lens thermal hazard	780–3000	–	E_{IR}	W·m^{-2}	1000 s	**100**	100 s	**570**	10 s	**3,200**

α – angular subtense in radians.
[1)] Small source of light defined as a source with angular subtense α < 0.011 radians.
[2)] Weak visual (light) stimulus: L < 10 cd·m^{-2} the requirement is that the source is to be evaluated as a source that is not used in general lighting.
[3)] 0.25 s is accepted as the time of the defensive (aversive) reflex of the eyes.

thermal hazard when a given source is a strong luminous stimulus, and a different method should be applied when it is a weak luminous stimulus.

The relationship among the type of photobiological hazard, the function of biological efficiency, and the time of safe exposure assigned to various risk groups for continuous operation sources is presented in Table 1. By this classification scheme, risk group 3 (RG3) includes sources of light that may represent a hazard even with temporary or brief exposure, and whose parameter values, determined on the basis of measurements that assess the hazard, exceed the limits of risk group 2 (RG2). Table 1 does not mistakenly present the same values of safe exposure times and emission threshold values for the no risk group and risk group 1 when evaluating the thermal hazard for the retina from a strong luminous stimulus. This is because the standard's PN-EN 62471: 2010 authors applied the same time criterion to both of these groups. However, the same emission threshold values apply to all risk groups but group 3 for retinal thermal hazards associated with a weak visual stimulus. This is because the same formula for a threshold value is used to evaluate the thermal hazard to the retina from a weak luminous stimulus, and the fact that, for exposure times of over 10 s, the impact does not depend on time but rather on the viewing angle (α) of the source (Wolska, Latała & Pawlak, 2012).

The highest of the risk level assessments is assumed to represent the general risk for the light source examined (covering all listed photobiological hazards).

Exposure limits for skin affected by hazardous visible and infrared radiation

The standard PN-EN 62471: 2010 gives information about the presence of thermal hazard to the skin, but fails to specify threshold values. However, a formula (1) is given, according to which the radiant exposure of skin in the visible spectrum and in infrared light (380 nm to 3000 nm) should be limited:

$$E_H \cdot t = \sum_{380}^{3000} \sum_{t} E_\lambda(\lambda, t) \cdot \Delta t \cdot \Delta\lambda \leq 20000 \cdot t^{0.25} \ [\mathrm{J \cdot m^{-2}}] \quad (t \leq 10 \ \mathrm{s}) \qquad (1)$$

where:
$E_\lambda(\lambda, t)$ – spectral irradiation in $\mathrm{W \cdot m^{-2} \cdot nm^{-1}}$;
$\Delta\lambda$ – spectral bandwidth in nm;
t – exposure time in seconds.

The exposure limit, determined by Eq. (1) is based on skin damage caused by increased temperature of the tissue, and only applies to small areas of radiant exposure. Exposure limits for periods exceeding 10 s are not specified. Usually, the acute pain experienced below the temperature at which the skin is damaged limits the exposure to the comfort zone. Larger areas of radiant exposure and thermal loading are not evaluated, because they require consideration of the exchange of heat between the person and the environment, physical activity, and various other factors that may not be used in the safety standard, but should be evaluated with the use of environmental criteria relating to thermal stress. In order to evaluate risk groups for this threat, thresholds in the range of 1–10 s were applied, namely, for RG0 and RG1 a threshold of $E_H = 20{,}000 \ \mathrm{W \cdot m^{-2}}$ was assumed, and for RG2, a threshold of $E_H = 35{,}566 \ \mathrm{W \cdot m^{-2}}$ was used (Wolska, Latała & Pawlak, 2012).

Method of evaluating the photobiological safety of light sources

The method of evaluating optical radiation parameters to determine the risk group of a light source was developed on the basis of the criteria laid out in the PN-EN 62471: 2010 standard. The standard specifies general requirements and reproducible layouts of irradiation and radiance measuring systems. Depending on the intended use of sources of light and luminaires, the following criteria of measuring the irradiation or radiance are applied:

- In case of sources for general lighting purposes used in such environments as offices, schools, apartments, production plants, on roads and in vehicles, the measurement should be made at a distance for which illuminance is equal to 500 lx (a typical illuminance value for general lighting used in offices, schools, etc.);
- For all other sources, including sources for special purposes such as displaying video images, reprographic processing, tanning bed salons, industrial processes, medical treatment and searching applications, the criterion is based on measuring the photobiological safety at a distance of 200 mm from the light source.

This difference is quite significant, as is evident in the fact that no-one in an office environment would looks at ceiling-mounted lights from a distance of only 200 mm. Still, in some industrial scenarios, such as quality control stations, employees may have to look at a light source from such small distances. In such cases, additional instructions protecting the eyes from damage are necessary. One should also remember that if sources of light are placed in a luminaire, the risk group classification may be changed by the luminaire's optics. Consequently, if the original parameters of the light source are modified in any way by the luminaire, new measurements must be made to re-classify the luminaire (Bąk, 2012).

Scope of evaluation for photobiological safety of light sources

The kinds of measurements of irradiation, spectral irradiation and spectral radiance depend on the type of light source and the kinds of photobiological hazard being assessed. Irradiation measurements are taken in order to evaluate the following hazards:

- Eye lens hazard caused by near ultraviolet 315–400 nm, E_{UVA};
- Cornea and lens hazard caused by infrared light 780–3000 nm, E_{IR};
- Skin thermal hazard 380–3000 nm, E_H.

Spectral (effective) irradiation measurements are taken in order to evaluate the following hazards:

- Ocular and skin hazard caused by UV radiation 200–400 nm, E_S;
- Retinal hazard caused by blue light 300–700 nm, E_B – small source.

Spectral (effective) radiance measurements are taken for the following hazards:

- Hazards to the retina caused by blue light 300–700 nm, L_B;
- Thermal hazards to the retina for light at 380–1400 nm, L_R;
- Thermal hazards for the retina for light at 780–1400 nm, L_{IR}.

Methodology of irradiation measurements

For purposes of measuring broadband and spectral irradiation, a measuring device must be used that features a detector with the following features:

- Flat and circular areas;
- Spatial angular sensitivity changing in the manner of cosine of the angle created with the normal to the detector's area;
- Constant spectral sensitivity for the examined range of wavelengths.

The standard PN-EN 62471: 2010 assumes that the minimal diameter of input aperture should be 7 mm, while the maximum diameter of input aperture should be equal to 50 mm. Most often, small integrating spheres, recommended as input devices for monochromators, have flat circular apertures whose diameter is 25 mm. Apertures whose diameter is 25 mm are recommended for sources of light with homogenous spatial distribution of optical radiation. It is also recommended that the measured irradiation not be averaged within a field of view that is smaller than the determined one, as this may lead to a reappraised hazard. The minimal size of averaging aperture is related to physiological and behavioral factors that result in the averaging of radiation incident to a certain area.

Figure 1 presents a schematic measuring system for measuring irradiation or spectral irradiation. The figure also shows the aperture applied in order to limit the field of view, with a half-angle (A), that may, if necessary, be applied for the distance (H), provided that it is large in relation to the detector's diameter (D). The measurement should be made when the light beam is in a position where the maximum reading is taken.

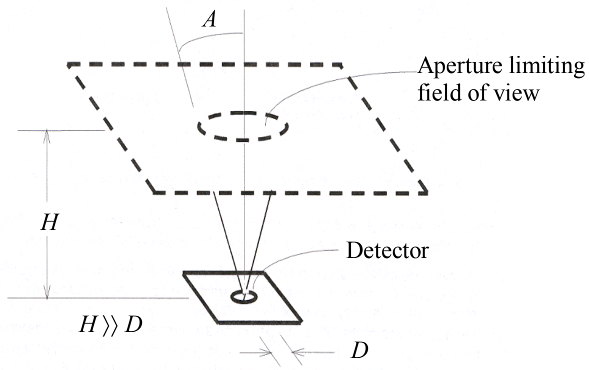

Figure 1. Diagram of irradiation measurements (PN-EN 62471: 2010)

Methodology of measuring radiance

Measurements of radiance are more complicated than measurements of irradiation.

Standard method

The requirements of the optical system for broadband and spectral measurements of radiance are as follows (see Figure 2):

- The radiation source is reproduced on the detector;
- The radiation source should have a circular area limiter for setting a specific angular subtense of the averaged viewing area a_{eff};
- The radiation source should have a circular input aperture that works like an averaging aperture when taking irradiation measurements, and satisfies the same requirements as specified for irradiation measurements. For smaller angles, the relationship between the detector's diameter (d) and the focal distance of the reproducing system (H) (Figure 2) should take the following form:

$$d = \alpha_{\text{eff}} \cdot H \quad (2)$$

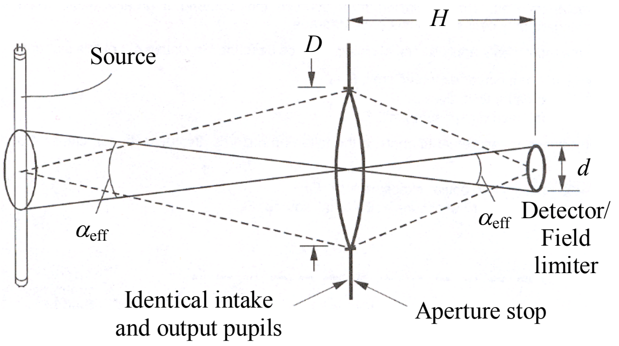

Figure 2. Example of a reproducible system for measuring radiance (PN-EN 62471: 2010)

As for irradiation measurements, the minimal diameter of the limiting aperture (*D;* see Figure 2) corresponds to a diameter of 7 mm for continuous operation sources. The diameter could be lower in this case, but movements of the eye and the head allow for such an averaging aperture.

It is also recommended that the measured radiance not be averaged within a viewing area that is smaller than specified, as this would lead to reappraisal of the hazard. The area of the averaging field of view is related to the range of the eye's movements that distribute the energy beam of the source's image across a larger area of the retina. The size of the averaging field of view a_{eff} is independent of the size of the source α. For sources corresponding to an angle α that is lower than the angle a_{eff} determined by the field of view, the value of average radiance is lower than the real, physical radiance of the source. However, this biologically effective value is suitable for comparing exposure with the exposure limit.

Alternative method

The alternative method of measuring radiance, described in the standard PN-EN 62471: 2010, may be beneficial in certain cases. In this method, radiance measurements may be specified as measurements of irradiation made with a well-specified field of view, if the measured value of irradiance is divided by the measured field of view in order to calculate the radiance value.

A test stand for measuring irradiance, with a circular limiter of field of view located at the source (Figure 3) may be used for measuring radiance. The size of the circular limiter of the field of view (F) and its distance (r) from the limiting aperture determine the field of view as in the following equation:

$$\gamma = F / r \tag{3}$$

The relation between the measured irradiation (E) and the source's radiance (L), with normal detection to the source's area (the angle between the normal and the beam's direction $\theta = 0$, for small angles) is presented as:

$$E = L \cdot \Omega \tag{4}$$

where the angle Ω in sr corresponds to the measured field of view. This means this is a spatial angle related to the flat angle (γ) in radians (Figure 3). Moreover, for smaller angles, the relation between the flat angle (γ) and the spatial angle (Ω) has the following form:

$$\Omega = \frac{\pi \cdot \gamma^2}{4} \tag{5}$$

Given the relations discussed above, the irradiance represented by the source's radiance may be determined as follows:

$$E = L \cdot \frac{\pi \cdot \gamma^2}{4} = L \cdot \frac{\pi \cdot F^2}{4r^2} \tag{6}$$

When measuring irradiance to obtain radiance values for comparison with specific hazard values, the diameter of the area limiter F should be determined so that the following relationship obtains:

$$\gamma = \alpha_{eff} \tag{7}$$

A correct assessment of the photobiological safety of a light source must account for the environmental conditions under which the measurements were made. Correct assessments must also include a properly completed process of aging of light sources, and a properly completed process of measuring the illuminance.

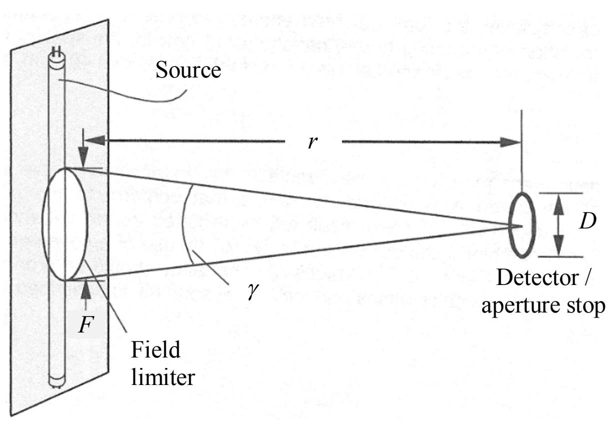

Figure 3. Alternative method of measuring radiance (PN-EN 62471: 2010)

Testing environment

Measurements should be done in a photometric darkroom that eliminates the impact of optical radiation of natural light and direct radiation originating from sources other than the one examined, and of radiation reflected from equipment, the room's walls and the measuring devices. Pursuant to Item 5.1.2 of the standard PN-EN 62471: 2010, the ambient temperature should have no effect on the emission of light sources, and should be constant. Consequently, measurements should be made in an air-conditioned room where the ambient temperature can be maintained at a constant level. This is important with regard to maintaining stable operation light sources examined, and to limiting measurement errors, especially when measuring infrared radiation emitted by sources of light. Moreover, as per Item 5.2.1 of the standard PN-EN 62471: 2010, it is recommended that the power supply of the examined sources of light conforms to information provided by their manufacturers. Therefore, the supply voltage should be checked with a voltmeter during examination of the light sources.

Aging of light sources

To ensure stable emission of the beam of energy emitted by a light source during the measuring process, and to ensure repeatable results, new sources of light should be properly aged (pretreated or seasoned). Aging for fluorescent lamps should be at least 100 hours, and 20 hours for halogen light bulbs (Item 5.1.1 of the standard PN-EN 62471: 2010). Aging for LED sources should be at least 100 hours. Before making the measurements, fluorescent lamps should be turned on at least 20 minutes in advance, and LED sources at least 60 minutes in advance. These times are related to stabilisation of the luminous flux emitted by these sources.

Measurement of illuminance

The measurement of illuminance should be made with a lux meter with a measuring probe whose relative sensitivity is adapted to the relative sensitivity of the human eye, V_λ. The measurement should be made in a vertical plane at the location of the measuring detector.

Test stand for measuring optical radiation parameters

The test stand for measuring optical radiation parameters used for determining risk groups of radiation sources should satisfy the following criteria:

- The device allows for the stable fixing of various types of light sources in vertical and horizontal positions;
- The device allows for stepless vertical and horizontal position adjustment of the light source;
- The device allows for stable fixing of the lux meter's probe, broadband measuring device detector, and spectroradiometer measuring head;
- The device has the ability to obtain a measuring distance between the source of light and the detector of 3–4 m;
- The device has the ability to level the central point of the measuring detector, and the central point of the illuminating area of the source of light;
- The device allows for the installation of sources of light with standard fittings: GU 10, G 9, GU 5.3, G 4;
- The device has the ability to install sources of light with standard threaded fittings E 27 and E 14;
- The device has the ability to install in-line fluorescent lamps, particularly 18 W, 36 W and 58 W models, or their LED equivalents;
- The device has the ability to install in-line halogen light bulbs with R7s fittings, 78 mm and 114 mm long;
- The device has the ability to install small flood lights and luminaires.

Description of the test stand design

The test stand was built with a duralumin profile made by *item*, with a square section, 40 × 800 mm. The profile is 3.5 m, the longest profile of this type. The large section and the ribbed shape of the profile, ensures that the element is not subject to any horizontal deformations. This guarantees that the location of the central point of the illuminated source of light and the central point of the measuring detector are precisely aligned axially on the profile. Figure 4 presents the test stand used during the leveling procedure of an LED light source installed horizontally in a sliding holder with a fixture with E 27 threads and a measuring detector. Both elements were leveled with a Bosch PLL 360 self-leveling line laser. The holder, as pictured on the left, can be used to smoothly travel horizontally along the entire profile, and to smoothly position the installed source of light vertically, at a distance ranging from 0 to 0.20 m.

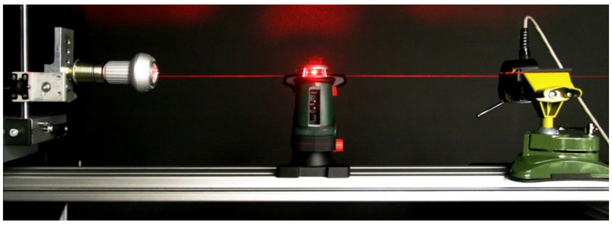

Figure 4. The test stand during the leveling procedure of MASTER LED NR 63, 7 W light source and the measuring detector of a broadband measuring device

Figure 5 shows the LED source installed vertically in a fitting with an E 27 thread, in an adjustable holder, during the leveling procedure and aligning to the aluminum profile axis.

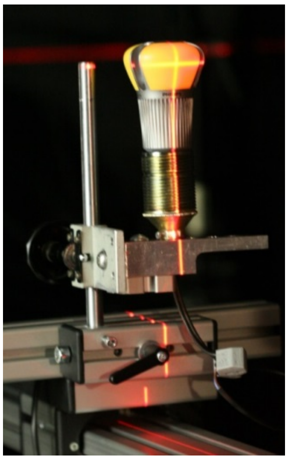

Figure 5. MASTER LED bulb MV, 12 W installed vertically in a fitting with E 27 thread, in an adjustable holder, during the leveling procedure and aligning to the aluminum profile axis

Figure 6 shows an example of a MASTER SPOT MV, 7 W source of light with GU 10 fitting, installed through the E 27/GU 10 reducing element, in a fitting with E 27 thread.

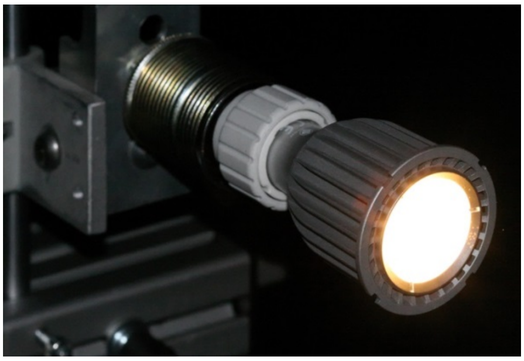

Figure 6. MASTER LED SPOT MV, 7 W source of light with GU 10 fitting, installed through the E 27/GU 10 reducing element, in a fitting with E 27 thread

Figure 7 shows various types of fittings for halogen and LED sources, adapted for installation in the sliding holder: GU 5.3, GY 6.35 – 12 V, G 9, GU 10 – 230 V.

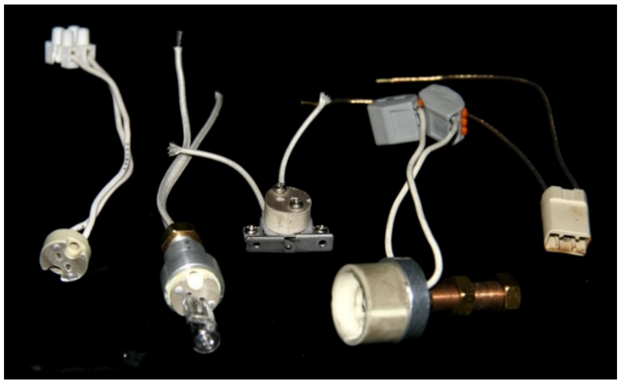

Figure 7. Examples of types of fittings for halogen and LED sources, adapted for installation in the sliding holder: GU 5.3, GY 6.35 - 12 V, G 9, GU 10 - 230 V

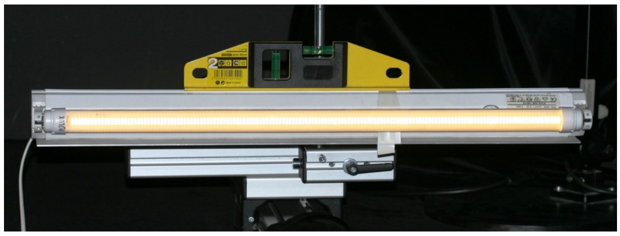

Figure 8. An LED replacement element for an 18 W in-line fluorescent lamp is shown installed on the sliding holder, during leveling procedure

Conclusions

Complaints from workers concerning various ailments, especially ailments affecting the eyes, are traceable to the improper lighting of work stations, and more specifically, to the use of various types of replacement light bulbs. The use of replacement light bulbs is not always the source of complaints; rather, it is the use of poor quality replacement parts. Most of the existing ambiguities are related to the potential harmful nature of LED sources, which also depends on the quality of products and their manufacturers. In addition, luminaires should be properly selected for the type of visual activity performed. Nevertheless, one must avoid looking directly at bright, spot-like sources of light, especially LEDs, transparent light bulbs, or discharge sources. Still, even when one randomly looks at a bright source of light, a natural reflex appears (a blink or an involuntary aversion of the eyes). Replacing in-line fluorescent lamps with LED tubes is not permitted, especially in luminaires without lampshades. Pursuant to the Directive 2006/25/EC, the workers' sight should be protected against visible radiation emitted by LEDs to the same extent as it should be protected against laser radiation. Consequently, every light emitting diode should have its own light and optical system, or it should be covered with a light dispersing lampshade.

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