

OCULAR HAZARDS OF LIGHT

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BACKGROUND

The eye is protected against bright light by the natural aversion response to viewing bright light sources. The aversion response normally protects the sun against injury from viewing bright light sources such as the sun, arc lamps and welding arcs, since this aversion limits the duration of exposure to a fraction of a second (about 0.25 s).

There are at least five separate types of hazards to the eye and skin from optical sources:¹

- (a) Ultraviolet photochemical injury to the skin (erythema and carcinogenic effects), and to the cornea (photokeratitis) and lens (cataract) of the eye (180 nm to 400 nm).
- (b) Thermal injury to the retina of the eye (400 nm to 1400 nm).
- (c) Blue-light photochemical injury to the retina of the eye (principally 400 nm to 550 nm; unless aphakic, 310 to 550 nm)²
- (d) Near-infrared thermal hazards to the lens (approximately 800 nm to 3000 nm).
- (e) Thermal injury (burns) of the skin (approximately 400 nm to 1 mm) and of the cornea of the eye (approximately 1400 nm to 1 mm).

The principal retinal hazard resulting from viewing bright light sources is photoretinitis, e.g., *solar retinitis* with an accompanying scotoma which results from staring at the sun. Solar retinitis was once referred to as "eclipse blindness" and associated "retinal burn." Only in recent years has it become clear that photoretinitis results from a photochemical injury mechanism following exposure of the retina to shorter wavelengths in the visible spectrum, i.e., violet and blue light. Prior to conclusive animal experiments at that time (Ham, Mueller and Sliney, 1976), it was thought to be a thermal injury mechanism. However, it has been shown conclusively that an intense exposure to short-wavelength light (hereafter referred to as "blue light") can cause retinal injury.

The product of the dose-rate and the exposure duration always must result in the same exposure dose (in joules-per-square centimeter at the retina) to produce a threshold injury. Blue-light retinal injury (photoretinitis) can result from viewing either an extremely bright light for a short time, or a less bright light for longer exposure periods. This characteristic of photochemical injury

mechanisms is termed *reciprocity* and helps to distinguish these effects from thermal burns, where heat conduction requires a very intense exposure within seconds to cause a retinal coagulation; otherwise, surrounding tissue conducts the heat away from the retinal image. Injury thresholds for acute injury in experimental animals for both corneal and retinal effects have been corroborated for the human eye from accident data. Occupational safety limits for exposure to UVR and bright light are based upon this knowledge. As with any photochemical injury mechanism, one must consider the *action spectrum*, which describes the relative effectiveness of different wavelengths in causing a photobiological effect. The action spectrum for photochemical retinal injury peaks at approximately 440 nm.

CALCULATING RETINAL EXPOSURE

From knowledge of the optical parameters of the human eye and from radiometric parameters of a light source, it is possible to calculate irradiances (dose rates) at the retina. Exposure of the anterior structures of the human eye to ultraviolet radiation (UVR) may also be of interest; and the relative position of the light source and the degree of lid closure can greatly affect the proper calculation of this ultraviolet exposure dose. For ultraviolet and short-wavelength light exposures, the spectral distribution of the light source can also be important.

Quantities and units

Two sets of light-measurement quantities and units are useful in defining light exposure of the retina: *radiometric* and *photometric*. Radiometric quantities such as radiance--used to describe the "brightness" of a source [in $\text{W}/\text{cm}^2\cdot\text{sr}$] and irradiance--used to describe the irradiance level on a surface [in W/cm^2] are particularly useful for hazard analysis. Radiance and luminance are particularly valuable because these quantities describe the source and do not vary with distance. Photometric quantities such as luminance (brightness in cd/cm^2 as perceived by a human "standard observer") and illuminance in lux (the "light" falling on a surface) indicate light levels spectrally weighted by the standard photometric visibility curve which peaks at 550 nm for the human eye (Figure 1). To quantify a photochemical effect it is not sufficient to specify the number of photons-per-square-centimeter (photon flux) or the irradiance (W/cm^2) since the efficiency of the effect will be highly dependent on wavelength. Generally, shorter-wavelength, higher-energy photons are more efficient.

Photometric quantities are hybrid quantities which are defined by an action spectrum for vision--a photochemically initiated process. Photometric quantities may not have much value in describing retinal effects other than vision or in research relating to neuroendocrine effects mediated by the visual system. Unfortunately, since the spectral distributions of different light sources vary widely, there is no simple conversion factor between photometric (either photopic or scotopic) and radiometric quantities. This conversion may vary from 15 to 50 lumens/watt (lm/W) for an incandescent source to about 100 lm/W for the sun or a xenon arc, to perhaps 300 to 400 lm/W for a fluorescent source (Sloney and Wolbarsht, 1980).¹

HUMAN EXPOSURE LIMITS

A number of national and international groups have recommended occupational or public exposure limits (ELs) for optical radiation [i.e., ultraviolet (UV), light and infrared (IR) radiant energy]. Although most such groups have recommended ELs for UV and laser radiation, only one group has recommended ELs for visible radiation (i.e., light). This one group is well known in the field of occupational health--the American Conference of Governmental Hygienists (ACGIH). The ACGIH refers to its ELs as "Threshold Limit Values," or TLVs and these are issued yearly, so there is an opportunity for a yearly revision³⁻⁴. The current ACGIH TLV's for light (400 nm to 760 nm) have been largely unchanged for the last decade, although they have been on a tentative list for much of that time. They are based in large part on ocular injury data from animal studies and from data from human retinal injuries resulting from viewing the sun and welding arcs. The TLVs also have an underlying assumption that outdoor environmental exposures to visible radiant energy is normally not hazardous to the eye except in very unusual environments such as snow fields and deserts.

On the international scene there are currently no limits for optical radiation except for the special case of laser radiation. The International Non-ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) published Guidelines on Limits of Exposure to Laser Radiation in 1985⁵ and revised them in 1988. INIRC guidelines are developed through collaboration with the World Health Organization (WHO) by jointly publishing criteria documents which provide the scientific data base for the exposure limits⁶.

THE ACGIH THRESHOLD LIMIT VALUES

Ultraviolet Radiation

The ACGIH TLV³ and the INIRC EL for exposure to the eye and skin to UVR is 3 mJ/cm²-effective, when the spectral irradiance E_λ at the eye or skin surface is mathematically weighted against the hazard sensitivity spectrum S_λ from 180 nm to 400 nm as follows:

$$E_{\text{eff}} = \sum E_\lambda \cdot S_\lambda \cdot \Delta \lambda \quad [1]$$

In addition to the above requirement, the ocular exposure is also limited to 1 J/cm² for periods up to 1000 s (16.7 min) and to 1 mW/cm² for greater periods. For this requirement, the total irradiance, E-uva, in the UV-A spectral region is summed from 315 nm to 400 nm:

$$E\text{-uva} = \sum E_\lambda \cdot \Delta \lambda \quad [2]$$

where E_λ is the spectral irradiance in W/(cm²-nm).

The permissible exposure duration, t_{max} , in seconds, to UVR is calculated by:

$$t_{\text{max}} = (3 \text{ mJ/cm}^2) / E_{\text{eff}} (\text{W/cm}^2) \quad [3]$$

and if the UV-A irradiance exceeds the 8-hour criterion of 1 mW/cm², the maximum exposure must also be less than:

$$t_{\max} = (1 \text{ J/cm}^2) / E_{\text{UVA}} \text{ (W/cm}^2\text{)} \quad [4]$$

Retinal Thermal Hazards

The ACGIH TLV derived to protect the human retina from *thermal injury* requires the use of another spectral weighting function, R_λ .¹⁸ The TLV for the hazardous radiance is termed L_{HAZ} , which is a function of the angular subtense α of the source (which is the light-source dimension D_L divided by the viewing distance r to give the angle in radians) and the exposure duration t (in seconds):

$$L_{\text{HAZ}} = 5 / \alpha \cdot t^{3/4} \quad [\text{in W}/(\text{cm}^2 \cdot \text{sr})] \quad [5]$$

The spectral radiance L_λ of the source is weighted against the retinal hazard function R_λ and the resulting effective radiance must not exceed L_{HAZ} :

$$\Sigma L_\lambda R_\lambda \Delta \lambda \leq L_{\text{HAZ}} \quad (\text{for } t < 10 \text{ s}) \quad [6]$$

For small sources such as an optical fiber source, the closest distance at which the human eye can sharply focus upon a small object is about 10 cm. The value of 10 cm is an exceptionally small value for the near-point of accommodation for the human eye. At shorter distances the image of a light source would be out of focus and blurred.

Blue-Light Photochemical Retinal Hazard

The ACGIH TLV³ to protect the human retina against photoreinitis,⁷ "the blue-light hazard" is an effective blue-light radiance L_B of 100 J/(cm²·sr), for $t < 10,000$ s, i.e.,

$$L_B = \Sigma L_\lambda \cdot B_\lambda \cdot \Delta \lambda \leq 100 \text{ J}/(\text{cm}^2 \cdot \text{sr}) \text{ effective} \quad [7]$$

and for $t > 10,000$ s (2.8 hrs.):

$$L_B \leq 10 \text{ mW}/(\text{cm}^2 \cdot \text{sr}) \quad [8]$$

To calculate the maximum direct viewing duration when [8] is not satisfied, this maximum "stare time," t_{\max} , is found by inverting Eqn. [7]:

$$t_{\max} = 100 \text{ J}/(\text{cm}^2 \cdot \text{sr}) / L_B \quad [9]$$

For very small sources that subtend a viewing angle less than α_{MIN} , which is 11 mrad = 0.011 rad. The blue light hazard is evaluated by mathematically weighting the spectral irradiance, E_λ , against the blue-light hazard function to obtain E_B to give:

$$E_B = \Sigma E_\lambda \cdot B_\lambda \cdot \Delta\lambda \leq 10 \text{ mJ/cm}^2 \text{ for } t \leq 10,000 \text{ s} \quad [10]$$

and for $t > 10,000 \text{ s}$ (2.8 hrs.):

$$E_B \leq 1 \mu\text{W/cm}^2 \quad [11]$$

To calculate the maximum direct viewing duration when [11] is not satisfied, this maximum "stare time," $t\text{-max}$, is found by inverting Eqn. [10]:

$$t\text{-max} = 10 \text{ mJ}/(\text{cm}^2\cdot\text{sr}) / E_B \quad [12]$$

Retinal Photochemical Hazard to the Aphakic Eye.

The third type of retinal hazard--the aphakic photochemical retinal hazard--is evaluated by spectrally weighting the radiance against the aphakic retinal hazard function A_λ .¹⁸ This photochemical retinal injury hazard is merely an extension of the blue-light hazard and must be analyzed only for individuals with at least one aphakic eye (i.e., an eye with the normal lens removed, as in cataract surgery). The approach is to substitute A_λ for B_λ in Eqns. [7] through [12]. For example, the aphakic hazard radiance $L\text{-aphake}$ is:

$$L\text{-aphake} = E\text{-aphake}/\Omega \quad [13]$$

$$L_A = \Sigma L_\lambda \cdot A_\lambda \cdot \Delta\lambda \leq 100 \text{ J}/(\text{cm}^2\cdot\text{sr}) \text{ effective for } t \leq 10,000 \text{ s (2.8 hrs.)}. \quad [14]$$

Infrared Radiation Hazards to the Eye

Any calculation of potential retinal thermal hazards to the eye normally includes a consideration of the contributions of IR-A (700-1400 nm) and IR-B (1.4 μm -3.0 μm). In contrast to blue light, IR-A is very ineffective in producing retinal injuries (Ham, et al., 1982, 1976).^{1,3} The data which could be used as the basis of an exposure limit for chronic exposure of the anterior of the eye to infrared radiation are very limited. Sliney and Freasier (1973) stated that the average corneal exposure from infrared radiation in sunlight was of the order of 1 mW/cm².⁸ Glass and steel workers exposed to infrared irradiances of the order of 80-400 mW/cm² daily for 10-15 years have reportedly developed lenticular opacities.⁸

The ACGIH guideline for IR-A exposure of the anterior of the eye is a time-weighted total irradiance of 10 mW/cm² for exposure durations exceeding 1,000 s (16.7 minutes). Pitts, et al. (1979) showed that the threshold radiant exposures to cause lenticular changes from IR-A were of the order of 5000 J/cm².⁷ Threshold damage irradiances were at least 4 W/cm². There is also a second ACGIH criteria to protect the retina against thermal injury from viewing specialized infrared illuminators which have visible light filtered out so that the aversion response stimulus is not present.¹

RADIOMETRIC MEASUREMENTS REQUIRED

To evaluate the potential optical radiation hazard to the eye, the ultraviolet spectral irradiance at from 200 - 400 nm would be determined at the nearest location of the eye. Spectral irradiance and radiance of the light emitted from the source in the 400 - 770 nm range (and sometimes to 1,400 nm) may also be required to analyze potential retinal hazards to an observer. Spectral irradiance at longer wavelengths could also be measured, although a measurement of total irradiance in this region is sufficient. The spectral radiance can be determined by measuring the spectral irradiance at a fixed distance (e.g., 30 cm) and dividing by the solid angle Ω subtended by the source.

$$L_B = E_B/\Omega \quad [15]$$

The spectral radiance is then independent of viewing distance because of the law of conservation of radiance.

Whenever spectroradiometric measurements are made for the purpose of a safety study, it is imperative that errors are not introduced. For this reason, it is useful to check measured spectroradiometric values with check-measurements made with illuminance and spot-luminance measurements. This is done by also calculating the illuminance E_v or luminance L_v from the spectral irradiance measurements, e.g.,

$$E_v = 683 \sum V_\lambda \cdot E_\lambda \cdot \Delta\lambda \quad [16]$$

The luminance L_v is then the illuminance divided by the angular subtense of the source Ω :

$$L_v = E_v/\Omega \quad [17]$$

where the luminance would be expressed in cd/cm^2 if the illuminance was expressed in lm/cm^2 .

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THE ENERGY POLICY ACT OF 1992

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As a consequence of the National Energy Strategy, which was conceived by the Bush Administration, Congress enacted and the President signed into law, the Energy Policy Act of 1992 on October 24, 1992, (EPACT 1992).

Of the thirty-three titles of EPACT, Title I - Energy Efficiency, is the longest and most comprehensive section. In concert with the goals of the International Lighting in Controlled Environments Workshop, this Section 103, Energy Efficient Lighting and Building Centers of EPACT, provides an opportunity for the nation to design, test and implement the most advanced, efficient lighting systems.

The purpose of Section 103 is to encourage energy efficiency in buildings through the establishment of regional centers to promote energy efficient lighting, heating and cooling, and building design.

EPACT provides for grants to nonprofit institutions, or to consortiums that may include nonprofit institutions, State and local governments, universities, and utilities, to establish or enhance one regional building energy efficiency center in each of the 10 regions served by a Department of Energy regional support office.

Each regional center established is permitted to accomplish the following:

Provide information, training, and technical assistance to building professionals such as architects, designers, engineers, contractors, and building code officials, on building energy efficiency methods and technologies, including lighting, heating and cooling, and passive solar;

Operate an outreach program to inform such building professionals of the benefits and opportunities of energy efficiency and the services of the center;

Provide displays demonstrating building energy efficiency methods and technologies, such as lighting, windows, and heating and cooling equipment;

Coordinate its activities and programs with other institutions within the region, such as State and local governments, utilities, and educational institutions in order to support their efforts to promote building energy efficiency;

Serve as a clearinghouse to ensure that information about new building energy efficiency technologies, including case studies of successful applications, is disseminated to end-users in the region;

Study the building energy needs of the region and make available region-specific energy efficiency information to facilitate the adoption of cost-effective energy efficiency improvements;

Assist educational institutions in establishing building energy efficiency engineering and technical programs and curricula;

Evaluate the performance of the center in promoting building energy efficiency;

Any nonprofit institution or consortium interested in receiving a grant under this section shall submit to the Secretary an application in such form and containing such information as the Secretary may require. A lighting or building energy center in existence on the date of enactment of this section which is owned and operated by a nonprofit institution or consortium as described in the subsection above shall be eligible for a grant under this section.

SELECTION CRITERIA: The Secretary shall select recipients of grants under this section on the basis of the following criteria:

The capability of the grant recipient to establish a board of directors for the regional center composed of representatives from utilities, State and local governments, building trade and professional organizations, manufacturers, and nonprofit energy and environmental organizations.

The demonstrated or potential resources available to the grant recipient for carrying out this subsection.

The demonstrated or potential ability of the grant recipient to promote building energy efficiency by carrying out the activities specified in the permitted activities.

The activities which the grant recipient proposes to carry out under the grant.

MATCHING FUNDS: The Federal share of a grant under this section shall be no more than 50 percent of the cost of establishing, and no more than 25 percent of the cost of operation of the regional center.

No grant may be made under this section in any fiscal year unless the recipient of such grant enters into such agreements with the Secretary, as the Secretary may require, to ensure that such recipient will provide the necessary non-Federal contributions. Such non-Federal contributions may be provided by utilities, State and local governments, nonlocal governments, nonprofit institutions, foundations, corporations, and other non-Federal entities.

TASK FORCE - The Secretary shall establish a task force to:

Advise the Secretary on activities to be carried out by grant recipients; Review and evaluate programs carried out by grant recipients;

Make recommendations regarding the building energy efficiency center grant programs.

LIGHTING APPLICATIONS

LAMPS

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