Environmental Health Criteria 23

Lasers and Optical Radiation

Executive Summary

Issued by the World Health Organization
in conjunction with the United Nations Environment Programm
and the International Radiation Protection Association

NOTE TO THE READER

Following the recommendations of the United Nations Conference on the Human Environment held in Stockholm in 1972, and in response to a number of resolutions of the World Health Assembly and a recommendation of the Governing Council of the United Nations Environment Programme, a programme on the integrated assessment of the health effects of environmental pollution was initiated in 1973. The programme, known as the WHO Environmental Health Criteria Programme, has been implemented with the support of the Environment Fund of United Nations Environment Programme. In 1980, the Environmental Health Criteria Programme was incorporated into the International Programme on Chemical Safety (IPCS), a joint venture of the United Nations Environment Programme, the International Labour Organisation, and the World Health Organization. The Programme is responsible for the publication of a series of criteria documents.

Each criteria document comprises an extensive scientific review concerning a specific environmental pollutant or group of pollutants, with information ranging from sources and exposure levels to a detailed account of the available evidence concerning their effects on human health and the environment. Drafts of these documents are prepared for WHO by individual experts or national institutions. They are then extensively reviewed by the approximately 25 Member States participating in this Programme and by one or more international groups of experts (*task groups*). A major objective of this programme is to assess existing information on the relationship between exposure to environmental pollutants (or other physical and chemical factors) and man's health and *to provide guidelines for setting exposure limits consistent with the protection of public health.*

To facilitate the application of these guidelines in national environmental protection programmes, it was decided to prepare "executive summaries" highlighting the information contained in the documents for those who need to know the health issues at hand, but not the scientific details.

An executive summary contains the exposure guidelines specified in the criteria documents as developed by the Task Group, together with the major supporting information on effects on health and the environment. New data published since the meeting of the Task Group, are not included in the Executive Summary but will be considered when the criteria documents and the summaries are reviewed and revised.

It would be appreciated if the reader would draw the attention of the International Programme on Chemical Safety to any difficulties encountered in using the information contained in the executive summaries. Comments should be addressed to:

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LASERS AND OPTICAL RADIATION[a]

1. Introduction

Optical radiation, which includes ultraviolet (UV), visible, and infrared (IR) radiation, forms part of the electromagnetic spectrum as shown in Fig. 1. These types of radiation are usually described in terms of wavelengths between 100 nm and 1 mm. Radiation with wavelengths shorter than 100 nm produces ionization in matter; radiation having wavelengths longer than 100 nm is normally termed non-ionizing.

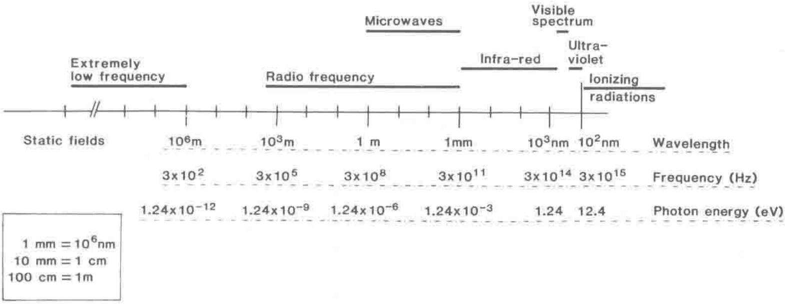

Fig. 1. The spectrum of electromagnetic radiation.

Ultraviolet and infrared radiation can be subdivided into UV-A (315 - 400 nm), UV-B (280 - 315 nm), and UV-C (100 - 280 nm) and IR-A (760 - 1400 nm), IR-B (1.4 - 3 m), and IR-C (3 m - 1 mm), respectively. The terms near, middle, and far are also used to describe these subdivisions and refer to the proximity to the visible part of the spectrum.

LASER is an acronym for "light amplification by stimulated emis-

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[a] Summary of *Lasers and optical radiation*, Geneva, World Health Organization, 1982, 154 pages (Environmental Health Criteria No. 23) (Published under the joint sponsorship of the United Nations Environment Programme, the World Health Organization, and the International Radiation Protection Association).

sion of radiation" and is a device that generates and/or amplifies coherent electro-magnetic waves within the optical spectrum. A laser oscillator consists of 2 basic elements, an amplifying (active) medium and a regeneration or feedback device (resonant cavity). Distinctive properties of laser light include monochromaticity (one or a few wavelengths), high radiance (i.e., high intensity leading to a small beam divergence), and phase coherence.

2. Sources

The sun remains the principal source of optical radiation exposure for man. The development of the laser in 1960 aroused great interest in potential hazards from exposure to lasers, but some other artificial sources of optical radiation pose similar hazards. It is often more difficult to evaluate the risks of non-laser sources since they typically emit over a broad-band of wavelengths. When sources emit in all parts of the optical spectrum, each potential hazard from the different bands must be considered separately and then collectively.

Sources of optical radiation exposure may be categorized as:

(*a*) sunlight (natural illumination);
(*b*) lamps;
(*c*) other incandescent (warm-body) sources; and
(*d*) lasers.

In industry, in addition to lasers, the optical radiation sources of concern include compact-arc lamps (as in solar simulators), quartz-halogen- tungsten lamps, gas and vapour discharge lamps, electric welding units, and pulsed optical sources, such as flash lamps used in laser research and photolysis, exploding wires, and super-radiant light. Some sources of optical radiation exposure and the potentially-exposed populations are listed in Table 1.

3. Biological effects

The interaction mechanisms of all optical radiation with biological tissues can be divided into three major categories: thermal (including thermo-mechanical), photochemical, and direct electric-field effects. At threshold levels, the predominant mechanism depends on maximal exposure rates (irradiance), total exposure, and on the wavelength(s) of the source. Thermal effects are characteristic of the IR region extending into the visible. Photochemical effects are mainly characteristic of the ultraviolet region, but also occur in the visible. Acoustic and other anomalous effects depend on acute thermal impulses of nanosecond (ns) duration, which may induce acoustic or mechanical transients, damaging the tissue. For sub-nanosecond exposures, direct electric field (non-linear) interactions with biological

Table 1. Some examples of optical radiation exposure

Sources	Principal wavelength bands of concern	Potential effects	Potentially exposed populations
sunlight	ultraviolet (UV), visible near-infrared	skin cancer; cataract; sunburn; accelerated skin aging; solar retinitis	outdoor workers (e.g., farmers, construction workers); sun-bathers; general population
arc lamps (Xe, Xe-Hg, Hg)	UV, visible, near-infrared	photokeratitis; erythema; skin cancer; retinal injury	printing plant camera operators; optical laboratory workers; entertainers
germicidal (low-pressure Hg)	far UV	erythema; photokeratitis; skin cancer	hospital workers; workers in sterile laboratories
medium-pressure Hg-HID lamps (broken envelope)	UV-A and blue light UVA	retinal injury photokeratitis; erythema	street lamp replacement personnel; gym-nasium users; general population
carbon arcs	UV, blue light	photokeratitis; erythema	certain laboratory workers; search light operators
He-Ne lasers (0.5-5-5.0 mW)	visible	retinal injury	construction workers; users of alignment lasers; some members of general population

Table 1 (contd).

Sources	Principal wavelength bands of concern	Potential effects	Potentially exposed populations
argon laser 1-20 W	visible	retinal injury, localized skin-burns	observers and operators of laser light shows; laboratory workers; medical personnel
metal halide UV-A lamps	near UV, visible	cataract; photosensitive skin reactions; retinal injury	printing plant maintenance workers; integrated circuit manufacturing workers
sunlamps	ultraviolet, blue light	photokeratitis; erythema, accelerated skin aging; skin cancer	suntan-salon customers; home users
welding arcs	ultraviolet and blue light	photokeratitis; erythema; UV cataract; retinal injury	welders' helpers; welders
ruby or neodymium laser rangefinders	visible near-infrared	retinal injury	scientific investigators; military personnel
industrial infrared sources	infrared	radiant heat stress; infrared cataract	steel mill workers; foundry workers; workers using infrared drying equipment

molecules appear to play a major role in the mechanism of injury.

The difference in the biological effects of laser radiation compared with those from conventional light sources of the same wavelength is due to the high radiance (''brightness'') and collimated beam of the laser. The other specific properties of lasers, such as coherency and monochromaticity, are not thought to influence the biological effects. The speckle pattern resulting from the interference effects of coherent laser light produces very fine gradations in irradiance but, within a few microseconds (μs), thermal conduction and physiological movements would smooth out the distribution of light and the localized temperature elevations resulting from the 1 – 10 - μm gradations of the speckle pattern.

4. Health effects on man

Beneficial effects of sunlight and UVR for man have been reported in the literature and are discussed in *Environmental Health Criteria 14: Ultraviolet radiation.* The reported beneficial effects of medical and environmental exposure are important for public health, but a careful benefit-versus-risk analysis must be carried out.

Optical radiation is mainly absorbed in superficial tissues, thus, the eye and the skin are the organs of concern in overexposure. The main acute effects are photokeratitis and thermal and photochemical retinal injury for the eye, and erythema and burns for the skin. Delayed effects include cataractogenesis and possible retinal degeneration for the eye, and accelerated aging and cancer for the skin.

However, though absorption is largely superficial, very small amounts of optical radiation can penetrate deeply into the body, where it may react with photosensitive cells. This may give rise to physiological reactions of great importance, e.g., cyclic lighting may influence circadian rhythms and annual rhythms. It has been alleged that constant, artificial illumination may suppress the natural circadian rhythms, giving rise to health problems.

Eye

The anterior structures of the eye are the cornea, conjuctiva, aqueous humor, iris, and lens. The cornea, aqueous humor, and lens are part of the optical pathway and, as such, must be transparent to light. Loss of transparency is serious. Because of the rapid turnover of corneal epithelial cells, damage limited to this outer layer can be expected to be temporary. Indeed, injury to this tissue by exposure to UV-B and UV-C, as occurs in ultraviolet photokeratoconjunctivitis or photoophthalmia (known also as "arc eye" or "welder's flash"), seldom lasts for more than one or two days. Unless deeper tissues of the cornea are also affected, surface epithelium injuries are rarely permanent.

Near-ultraviolet and near-infrared radiation (UV-A, IR-A, and possibly IR-B) are strongly absorbed in the lens of the eye (Fig. 2). Damage to this structure is of great concern in that the lens has a very slow turnover of cells. An acute exposure may result in effects that will not become evident for many years. This is probably the case in glass-blower's or steel puddler's cataract. Long-term exposure may also result in delayed effects.

The widespread use of sources that emit high levels of UVR in industry has been the cause of many corneal injuries. The UV-rich industrial sources circumvent the natural defences of the body by allowing direct exposure of the cornea at normal angles of incidence, unshielded by the brow or eyelids. Welding is a prime example of potentially-hazardous industrial exposure. The presence of possible photosensitizers makes the use of UVR in the chemical industry for

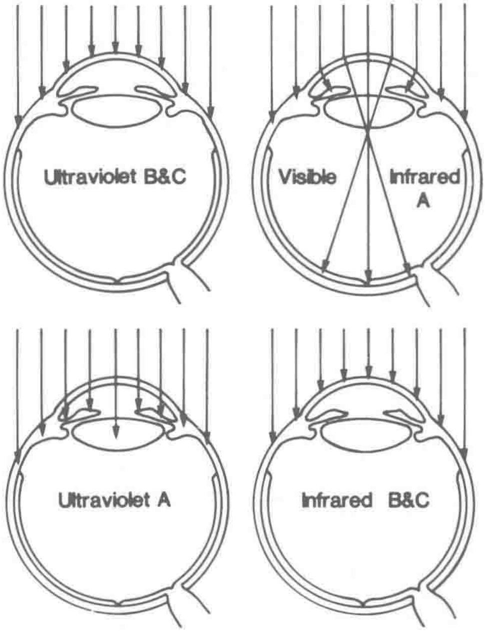

Fig. 2. Depth of penetration in the eye for different wavelengths

the manufacture of photosetting plastics potentially much more dangerous.

Until recently, it was felt that chorioretinal injury would not result from exposure to visible light in industrial operations. This is still largely true, since the normal aversion response to high brightness light sources (the blink reflex and movement of the head and eyes away from the source) provides adequate protection against most bright visual souces. However, the recent increased use of high-intensity, high-radiance optical radiation sources with output characteristics that differ significantly from those seen in the past may present a serious potential for chorioretinal injury. The recent findings of photochemically induced retinal injury following long-term exposures reinforce this conclusion.

Skin

Laser radiation injury to the skin is normally considered less important than injury to the eye, despite the fact that injury thresholds for the skin and eye are comparable, with the exception of the retinal hazard region (400 – 1400 nm). In the IR-C and UV-C spectral regions, where optical radiation is not focused on the retina, skin injury thresholds are approximately the same as corneal injury thresholds. Fortunately, functional losses associated with a laser burn of the skin are not as debilitating as a burn to the eye. Threshold injuries resulting from the short-term (i.e., less than 10 seconds) exposure of the skin to far-infrared (IR-C) and UV-C radiation are also very superficial and may only involve changes to the outer dead layer — the "horny layer" — of the skin cells (Fig. 3). A temporary injury to the skin may be painful, if sufficiently severe, but eventually it will heal, often without any sign of injury. Burns (thermal injuries) covering larger areas of skin are far more serious, as they may lead to serious losss of body fluids, toxaemia, and systemic infections.

Thermal injury of the skin has been the subject of many studies in this century. Severe pain could always be induced in human skin tissue, when the tissue temperature was elevated to 45 °C. This temperature also corresponds to an injury threshold, if the exposure to optical radiation lasts for many seconds.

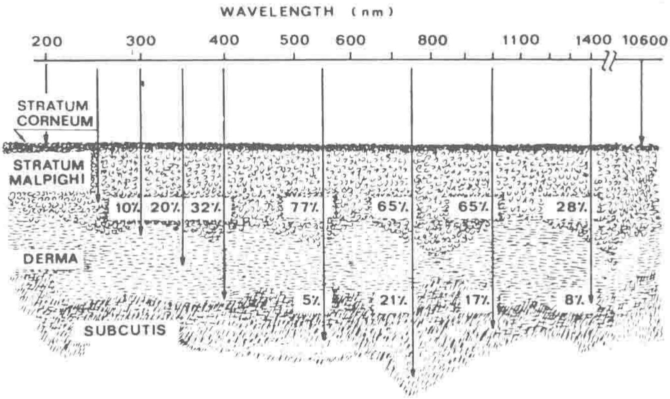

Fig. 3 Depth of penetration into the skin for different wavelengths. Values are percentages of incident radiation reaching a given layer.

Skin injuries resulting from momentary, but very intense, exposure to optical radiation are generally termed "flash burns". Flash burns of the skin following exposure to optical radiation in industry are rare. Most conventional sources such as open-arc processes and industrial furnaces do not cause skin injury as they do not create significant irradiance in work areas sufficiently fast to preclude a natural protective reaction to the intense heat.

The possibility of adverse effects from repeated or long-term laser irradiation of the skin is normally discounted, if scarring does not occur. Only UVR has been shown to cause long-term, delayed effects. These effects are accelerated skin aging and skin cancer. It is difficult to evaluate quantitatively the role of UVR in the induction of skin cancer. For solar radiation, the high-risk wavelengths are around 310 nm. At present, laser safety standards for exposure of the skin attempt to take into account all of these adverse effects.

Light-induced damage to the skin in the presence of certain chemicals (photosensitizers) may be considered phototoxic if an allergic mechanism is not involved. This can occur in any type of skin exposed to UVR of the proper wavelength and looks like a normal erythema. In some cases, the reaction may be delayed, but, in general, it will appear immediately after exposure. A number of systemic photosensitizers have been identified and examples are given in Table 2. Photoallergy is an acquired altered capacity of the skin to react to light (and UVR) alone or in the presence of a photosensitizer.

5. Protection standards

Both product performance safety standards and individual exposure (occupational and general population) limits for lasers have been developed. Separate environmental quality standards are unecessary, since it is sufficient to regulate the individual device. Several national standards have been promulgated and substantial progress has been made towards international agreement in these areas, since there appear to be only minor differences between the most recent national standards. Laser exposure limits are complex functions of wavelength, exposure duration, and viewing conditions and cannot be summarized without the use of complicated tables. On the basis of present knowledge, most of these extensive sets of laser standards appear adequate for the protection of the health of those potentially exposed. Several areas of concern still exist regarding exposure limits for ultrashort pulse, repetitive pulse, long-term, and multiwavelength exposures.

Most recent laser safety standards include a hazard classification scheme to simplify risk evaluation on which to base control measures. The safety procedures necessary for any laser operation vary according to three aspects: (a) the laser hazard classification; (b) the environment in which the laser is to be used; and (c) the people operating, or within the vacinity of, the laser beam. Hazard classification schemes differ only slightly, depending on which standard is being followed; a brief explanation of the most commonly used hazard classification system follows.

Class 1 lasers are the lowest powered lasers. These lasers are not considered hazardous, even if the output laser beam is directed into the pupil of the eye.

Class 2 lasers, often termed "low-power" or "low-risk" laser systems, are those that are only hazardous if the viewer overcomes the natural aversion response to bright light and stares continuously into the source — an unlikely event. Class 2 lasers have a caution label affixed to indicate that purposeful staring into the laser should

Table 2. Systemic photosensitizers: chemicals that induce photosensitivity[a]

Uses	Name
Antibacterial	nalidixic acid
Anticonvulsant	carbamazepine
Antimycotic	griseofulvin
Artificial sweeteners	cyclamates, calcium cyclamate, sodium cyclohexylsulfamate
Broad spectrum antibiotic	antibiotics
Chemotherapeutic, antibacterial	sulfonamides
Diuretics, antihypertensive	chlorthiazides
Hypoglycaemic or antidiabetic drugs	sulfonylurea
In vitiligo for sun tolerance and increased pigment formation	furocoumarins
Laxative	triacetyldiphenolisatin
Oral contraceptives	estrogens and progesterones
Tranquillizer, nematode infestation control; urinary antiseptic, antihistamine	phenothiazines
Tranquillizer, psychotropic	chlordiazepoxide

[a] Adapted from: Fitzpatrick et al. (1974).

be avoided. Since the aversion response only occurs for light, the Class 2 category is limited to the visible spectrum from 400 to 700 nm.

Class 3 "moderate-risk" or "medium-power" lasers are those that can cause eye injury within the natural aversion response time, i.e., during the blink reflex (0.25 seconds). Class 3 lasers do not cause serious skin injury or hazardous diffuse reflections under normal use. However, these must have danger labels and often require extensive safety precautions.

Class 4 lasers are the highest powered lasers and present the greatest potential for injury. They may also cause diffuse reflections that are hazardous to view or induce serious skin injury from direct exposure. They can induce combustion of flammable materials. More restrictive control measures and additional warnings are necessary.

Health and safety standards for lamps and other non-laser sources are almost non-existent. Progress has been made, in several countries, towards product performance safety standards for specific lamp products, such as high-intensity discharge (HID) lamps, sunlamps, and germicidal lamps. Occupational exposure limits have been proposed for ultraviolet radiation. Exposure limits for visible, and near-infrared radiation are only tentative. The spectrum of the source must be measured and weighted against several action spectra for risk analysis — a complex process.

6. Safety procedures

Lasers

A list of control measures recommended for Class 3 and Class 4 lasers is given in Table 3. Not all of the listed measures apply to each laser.

Because of the risk associated with exposure to Class 4 high-risk lasers, the safety precautions for indoors generally include the installation of door interlocks to prevent exposure of unauthorized or transient personnel entering the laboratory, the use of baffles to terminate the primary and any secondary beams, and the use of safety eyewear by personnel within the interlocked facility.

At one time, it was recommended that ambient light levels should be sufficient to constrict pupils. However, since a constricted pupil provides only a small additional safety factor, the recommendation for good illumination, which remains in present safety standards, meets the need for good general visibility, as the wearing of eye protectors reduces visual capability. Light-coloured, matt surfaces in the room minimize glare, and thus promote visibility.

The ability to analyse potential risks from any laser system is enhanced by a broad knowledge of optics, general laser technology, and the imaging process of the human eye. A laser safety specialist

Table 3. Control measures for general population and occupational exposure

I	Engineering control measures:
	protective housing enclosure and service panel requirements; interlocks on the protective housing; door interlocks and remote control connector; beam attenuator or beam shutter; key switch or padlock over aperture cover; filtered viewing optics and windows; warning lights; emission indicators (audible or visible); enclosed area or room; beam enclosure; remote firing and/or monitoring;
II	Personal protective equipment:
	eyewear; clothing; gloves;
III	Administrative and procedural controls:
	laser safety officer; standard operating procedures (SOPs); limitations on use by class; education and training; maintenance and servicing manuals; marking of protective devices; warning signs and labels; entry limitations for visitors, etc.; accident procedures.

should have a general background knowledge of optics with the basic knowledge necessary to perform risk analysis. It has been shown that risk analysis depends on at least three aspects - the laser sytem and its potential hazards, the persons who may be exposed, and, finally, the reflective materials and other optically important materials in the environment that can influence the risk analysis.

It is necessary to establish a safety programme that assures the safe use of lasers and other radiation sources. To assure knowledge of, and compliance with, applicable standards, a certain amount of formalized teaching is often necessary.

In the work-place, a specific individual should be assigned to maintain and enforce the safety programme (in some countries this individual is termed a laser safety officer (LSO)).

All workers occupied with, or working near, the radiation source should be included in the teaching programme.

The object is to make users and supervisors aware of the risks of exposure to lasers, how to avoid the hazards, how to use protective devices, and how to recognise overexposure.

Non-laser optical sources

Until the advent of the laser, the principal hazard recognized in the use of optical sources was the potential for injury of the skin and eye from exposure to UVR at wavelengths of less than 320 nm. The spectral band of less than 320 nm is often called the "actinic ultraviolet" and consists principally of the 2 bands known as UV-B and UV-C. The high attenuation in the spectral range of 100 – 300 nm, afforded by many optical materials, such as glass, generally resulted in the empirical safety approach in which optical sources were enclosed in glass, plastic, or similar materials to absorb this actinic radiation. If injurious effects were noted, the thickness of the material enclosing the source or the filter protecting the eye was increased.

The optical radiation emitted by a conventional light source can be evaluated against applicable exposure limits or guidelines. However, before making exhaustive measurements and safety calculations, it may be worthwhile to determine the need for a comprehensive risk evaluation. Many categories of lamps or other types of light sources can be excluded from all or several of the evaluations. The following multi-step scheme may be useful in this regard.

STEP 1 — Categorization of the lamp. Certain hazards are specific for certain types of lamp or light source. The following grouping is useful:

(a) incandescent lamps and incandescent heating sources;

(b) low-pressure discharge lamps;

(c) fluorescent lamps;

(d) high-intensity discharge (HID) lamps;

(e) short-arc (compact arc) lamps;

(f) carbon arcs;

(g) solid-state sources (light-emitting diodes, etc.);

(h) cathode-ray tubes (CRTs).

STEP 2 — Determination of the source envelope. Any glass between the actual source of radiation (e.g., the arc or tungsten filament) and the point of access can greatly influence the potential hazard. Soft (lime) glass of any reasonable thickness will greatly attenuate UV-B and UV-C radiation.

(a) *Incandescent lamps,* other than quartz-halide lamps, normally have a sufficiently thick glass envelope to completely preclude a UVR hazard. The blue-light hazard does not appear to be theoretically possible at black-body temperatures below 2000 K, but most filaments operate at effective temperatures exceeding 2000 K.

(b) *Low-pressure discharge lamps.* Low-pressure discharge lamps do not normally present a retinal hazard, because of the relatively low radiance. Only lamps with quartz envelopes can transmit sufficient UV-B and UV-C to be of concern. Of the common low-pressure lamps, only mercury lamps can create a severe UV hazard. Many may be quite hot to the touch.

(c) *Fluorescent lamps.* In almost all cases, low-pressure tubular lamps have a thin glass envelope, but could often present a potential UV hazard at the surface. They do not represent a thermal retinal injury hazard and seldom a blue-light hazard.

(d) *HID lamps.* These lamps may present both blue-light and thermal retinal hazards, and possible UVR hazards. Since most lamp envelopes are glass, there is little UV-B leakage. Nevertheless, the UV-B leakage may be of concern at very short distances. Quartz-mercury HID lamps require a UVR risk evaluation. If the outer glass envelope of an

HID lamp breaks, hazardous UVR levels will be emitted. Government regulations in Canada and the USA require HID lamps to have a self-extinguishing feature to prevent this hazard, unless the lamp packaging clearly warns against use without adequate shielding.

(e) *Short-arc lamps.* Of all the electric lamp categories, this group will require the most extensive risk evaluation. All potential hazards may be present (retinal thermal injury, skin thermal injury, and exposure to UV-B/C, UV-A, blue-light). Because of the high temperature of the arc, a quartz lamp envelope (which transmits UV-B and C) is characteristic. These lamps are often used in UV photocuring processes in industry.

(f) *Carbon arcs.* Unless a glass lens or filter plate exists between the open arc and a point of access, the carbon arc, like the short-arc lamp, is potentially injurious.

(g) *Solid-state lamps (e.g., LEDs).* The present solid-state lamps including LEDs, which emit visible radiation, do not present any health risk, regardless of the type of envelope.

(h) *Cathode-ray tubes (CRTs).* Present CRTs do not emit optical radiation at levels that could pose a potential health hazard.

STEP 3 — Review the available manufacturers' radiometric and photometric data and lamp descriptions. Any radiometric or photometric specification may be of value either for calculation or for direct intercomparison with measurements. Spectral data are most useful. The dimensions of the emitting area of the lamp will be required for retinal hazard evaluation.

STEP 4 — Comparison of lamp specifications with those of previously evaluated lamps. From experience, it is often possible to complete the risk evaluation with this step.

STEP 5 — Performance of detailed spectroradiometric measurements,