Environmental Health Criteria 23

LASERS AND OPTICAL RADIATION

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NOTE TO READERS OF THE CRITERIA DOCUMENTS

While every effort has been made to present information in the criteria documents as accurately as possible without unduly delaying their publication, mistakes might have occurred and are likely to occur in the future. In the interest of all users of the environmental health criteria documents, readers are kindly requested to communicate any errors found to the Division of Environmental Health, World Health Organization, Geneva, Switzerland, in order that they may be included in corrigenda which will appear in subsequent volumes.

In addition, experts in any particular field dealt with in the criteria documents are kindly requested to make available to the WHO Secretariat any important published information that may have inadvertently been omitted and which may change the evaluation of health risks from exposure to the environmental agent under examination, so that the information may be considered in the event of updating and re-evaluation of the conclusions in the criteria documents.

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ENVIRONMENTAL HEALTH CRITERIA FOR LASERS AND OPTICAL RADIATION

Further to the recommendations of the Stockholm United Nations Conference on the Human Environment in 1972, and in response to a number of World Health Assembly resolutions (WHA23.60, WHA24.47, WHA25.58, WHA26.68) and the recommendation of the Governing Council of the United Nations Environment Programme, (UNEP/GC/10, 3 July 1973), 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 the United Nations Environment Programme.

A joint WHO/IRPA Task Group on Environmental Health Criteria for Lasers and Optical Radiation met in Paris from 1-5 June 1982. Dr E.I. Komarov, Division of Environmental Health, WHO, opened the meeting on behalf of the Director-General, and Dr H. Jammet, Chairman of IRPA/INIRC made some introductory comments. The Task Group reviewed and revised the draft criteria document, made an evaluation of the health risks of exposure to lasers and optical radiation, and considered rationales for the development of exposure limits.

In November 1971, the WHO Regional Office for Europe convened a Working Group meeting in The Hague which recommended, inter alia, that protection of man from laser radiation hazards should be considered a priority activity in the field of non-ionizing radiation protection. To implement these recommendations, the Regional Office has prepared a publication on "Nonionizing radiation protection", which includes a chapter on laser radiation (Suess, ed., 1982). In October 1974, the Regional Office convened a Working Group in Dublin, hosted by the Government of Ireland, to discuss laser radiation hazards. This provided one of the first opportunities for the exchange of information on the biological effects of laser radiation and threshold data, at an international level.

The International Radiation Protection Association (IRPA) became responsible for NIR activities in 1974 by forming a Working Group on Non-Ionizing Radiation which became the International Non-Ionizing Radiation Committee (IRPA/INIRC) at the IRPA meeting in Paris in 1977 (IRPA, 1977). Dr M. Faber, Dr J. Marshall, Mr D. Sliney (members of IRPA/INIRC) and Dr L. Court, all acting as WHO temporary advisers, prepared the draft criteria document on lasers and optical radiation during 1980-81, and revised it after receiving comments from the national focal points for the Environmental Health Criteria Programme and individual experts. Dr Marshall and Mr Sliney were responsible for the final scientific editing. The Secretariat gratefully acknowledges the work of these experts without whose help the document could not have been completed.

The document is based primarily on original publications listed in the reference section. Additional information was obtained from a number of general reviews, monographs, and proceedings of symposia including: Urbach, ed. (1969), Goldman & Rockwell (1971), Wolbarsht (1971, 1974, 1977), Sliney & Freasier (1973), Fitzpatrick (1974), Magnus (1976), Rubin (1977), Parrish et al. (1978), Lerman (1980a), Pratesi & Sacchi, ed. (1980), Sliney & Wolbarsht (1980), Williams & Baker, ed. (1980), Goldman, ed. (1981), and Goldman et al. (1982). Radiometric terms, units, and spectral band designations used in this criteria document are in accordance with the SI recommendations (Lowe, 1975) and those recommended by the Commission Internationale de l'Eclairage (CIE, 1970).

Modern advances in science and technology have changed man's environment, introducing new factors which, besides their intended beneficial uses, may also have untoward side effects. Both the general public and health authorities are aware of the dangers of pollution by chemicals, ionizing radiation, and noise, and of the need to take appropriate steps for effective control. The rapid growth of electro-optics and laser technology and the increasing use of electro-optical devices and lasers, including optical scanning equipment, high-intensity lamps, welding arcs, and UV photo-curing equipment, alignment lasers, and medical lasers have increased the possibility of human exposure to optical radiation and, at the same time, concern about health effects.

This document provides information on the physical aspects of electromagnetic radiation in the optical spectrum, within the wavelength range of 100nm-1mm. Optical radiation includes ultraviolet radiation (UVR) from approximately 100 nm to 400 nm, light (visible radiation) from approximately 400 nm to 760 nm, and infrared radiation from approximately 760 nm to 1 mm. Each of these spectral regions can be arbitrarily divided into subregions. Lasers are capable of producing optical radiation in all three major divisions of the optical spectrum. A brief survey of lasers and other man-made sources of optical radiation is presented. It is known that optical radiation interacts with biological systems and a summary of knowledge on biological effects and health aspects has been included in this document. In a few countries, concern about occupational and public health aspects has led to the development of radiation protection guides and the establishment of exposure limits for laser radiation and UVR. Several countries are considering the introduction of recommendations or legislation concerned with protection against untoward effects from non-ionizing radiation in the optical spectrum. In others, efforts are being made to revise and update existing standards. It is hoped that this criteria document may provide useful information for the development, at a national level, of protection measures against non-ionizing radiation.

Details of the WHO Environmental Criteria Programme, including definitions of some of the terms used in the documents, may be found in the general introduction to the Environmental Health Criteria Programme, published together with the environmental health criteria document on mercury (Environmental Health Criteria I - Mercury, Geneva, World Health Organization, 1976), now available as a reprint.

1. SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES

1.1 Summary

1.1.1 Scope

The potential hazards of optical radiation from wavelengths between 100 nm and 1 mm, i.e., ultraviolet radiation (UVR), visible light, and infrared radiation (IR) are considered in this document, and known adverse health effects, standards, and control measures are reviewed. Emphasis is placed on the health risks of laser radiation, but those of other sources are also covered. The health effects of UVR are discussed only briefly, as UVR has already been considered in depth in the WHO Environmental Health Criteria 14 (1979). Risks to the general population are considered as well as those of occupational exposure.

The clinical treatment of different disorders or non-medical problems, such as cosmetic surgery, where risk versus benefit must be addressed, is outside the scope of the document. However, it should be emphasized that the doses used in such exposures are entirely the responsibility of the persons authorized to give such treatment.

Although a certain amount of light is necessary for human health, this document does not attempt to determine a lower exposure limit or whether certain wavelengths are more necessary than others.

1.1.2 Optical radiation exposure

Despite the great increase in the use of man-made optical sources, the sun remains the principal source of optical radiation exposure for man. Though the development of the laser in 1960 aroused great interest in the potential hazards of optical radiation, many other artificial sources pose similar hazards. It is often more difficult to evaluate the risks of non-laser sources since, typically, they emit over a broad band of wavelengths. When broad-band sources emit in all parts of the optical spectrum, each of the potential hazards must be considered separately, as well as collectively.

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

Because optical radiations are not very penetrating, the eye and the skin are the organs of concern. 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.

The biological effects of all optical radiation 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, total exposure, and on wavelength regimes. The thermal effects are characteristic of the IR region extending into the visible. The 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 nanoseconds (ns) duration, which may induce acoustic or mechanical transients, damaging the tissue. For sub-ns exposures, direct electric field (non-linear) interactions with biological molecules appear to play a major role in the mechanism of injury.

Sources of optical radiation exposure may be categorized as:

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

In industry, in addition to lasers, there are continuous optical radiation sources, such as compact arc lamps (as in solar simulators), quartz-iodide-tungsten lamps, gas and vapour discharge tubes, electric welding units, and pulsed optical sources such as flash lamps used in laser research and photolysis, exploding wires, and super-radiant light. Common lasers and their applications are listed in Table 1 and some sources of optical radiation exposure and potentially exposed populations in Table 2. In most applications, maintenance and evaluation workers may be exposed. The general population may also be exposed on occasion, and it is the responsibility of the operator to minimize this exposure.

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 afforded by many optical materials, such as glass in the spectral range 100-300 nm, 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 widespread use of sources that emit high levels of UV-C/B in industry has been the cause of many corneal injuries. The UVR-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. In many cases, the hazards of these UVR-rich sources are greater as they are incorporated into optical systems, the elements of which are selected for either high transmission or high reflection in the UVR. 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 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. Indeed, 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 sources. 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.

Since organic macromolecules absorbing the radiant energy would have broad spectral absorption bands, the monochromatic nature of laser radiation would not be expected to create any different effects from those of radiation emitted by conventional sources; this conclusion is strongly supported by experimental evidence. The coherence of laser radiation is also considered not to affect the hazard potential for thermal or photochemical chorioretinal injury. Though a speckle pattern resulting from the interference effects of laser light at the retina does exist, the very fine gradations in retinal irradiance resulting from this effect (Considine, 1966; Fried, 1981) would certainly be lost, as soon as the pulse duration was greater than a few microseconds (μs). Both thermal

Table 1. Common laser devices and applications

Type	Wavelength(s)	Applications
argon (Ar)	458-515nm + 350 nm	instrumentation; holography; retinal photocoagulation; entertainment
carbon dioxide (CO_2)	10.6 µm	material processing; optical radar/ranging; instrumentation; surgery techniques
dye(s)	variable 350 nm 1 µm	instrumentation
excimer lasers	180-250 nm	laser pumping; spectroscopy
gallium arsenide (GaAs)	850-950 nm	instrumentation ranging; intrusion detection; communications; toys
helium cadmium (HeCd)	325, 442 nm	alignment; surveying
helium neon (HeNe)	632.8 nm	alignment; surveying; holography; ranging; intrusion detection; communications; entertainment
neodymium glass (Nd-glass) neodymium yttrium-aluminium garnet (Nd-YAG)	1.06 µm	material processing; instrumentation; optical radar/ranging; surgery
ruby	694.3 nm	material processing; holography; photocoagulation; ranging

Table 2. 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); sunbathers; 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)	actinic, far UV	erythema; photokeratitis; skin cancer	hospital workers; workers in sterile laboratories
medium-pressure Hg-HID lamps (broken enevelope)	UV-A and blue light actinic UVA	retinal injury photokeratitis; erythema	street lamp replacement personnel; gymnasium users; general population
carbon arcs	UV, blue light	photokeratitis; erythema	certain laboratory workers; search light operators
He-Ne lasers (0.5-5.0 mW)	visible	retinal injury	construction workers; users of alignment lasers; some members of general population
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

Table 2. (contd).

Sources	Principal wavelength bands of concern	Potential effects	Potentially exposed populations
sunlamps	ultraviolet, blue light	photokeratitis; erythema, accelerated skin aging; skin cancer	suntan-parlour customers; home users
welding arcs	ultraviolet and blue light	photokeratitis; erythema; UV cataract; retinal injury	welders' helpers; welders
ruby or neodynium 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

conduction and ocular tremor would smooth out the distribution of light and localized temperature elevations resulting from the 1-10 µm gradations of the speckle pattern and these non-uniformities would be blurred. Chorioretinal injury from either a laser or a non-laser source should not differ, therefore, if image size (retinal irradiance distribution), exposure duration, and wavelength are the same.

1.1.3 Present health and safety standards

Because of widespread concern regarding laser hazards, substantial progress has been made towards the development of both product performance standards and human (both occupational and general population) exposure limits. Separate environmental quality standards are unnecessary. 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. The laser exposure limits are complex functions of wavelength, exposure duration, and viewing conditions and cannot be summarized, without the use of complex tables. Based on 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.

Health and safety standards for lamps and other non-laser sources are almost non-existent. Some exposure limits have been proposed for ultraviolet, visible, and near-infrared radiation, but these are quite tentative. The spectrum of the source must be measured and weighted against several action spectra for risk analysis - a complex process. 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.

1.2 Recommendations for Further Studies

The following comments cannot hope to be comprehensive in an area of such rapidly expanding technology and whilst many of the listed problems may be currently of importance or under investigation in various research laboratories, others hitherto unsuspected may assume paramount importance. Current problems are discussed in the same order as the list of contents of this criteria document, beginning after the background information sections 1-5; the order does not assert priority ratings.

(a) Radiometric and photometric measurement

Further development of simplified, inexpensive laser or broad-band survey instruments is desirable for monitoring the health risks of optical radiation.

(b) The eye

The transmission characteristics of the ocular media are based on averaged data from relatively few eyes. The variations with age, in transmission and absorption in individual ocular components, have not been clearly defined. Present understanding of the effects of UVR on the cornea and the lens is poor, particularly of the role, if any, of UV-A in the exacerbation of cataracts. Further studies, especially in the field of epidemiology, are needed to establish the possible involvement of short-wavelength optical radiation in accelerating senile degenerative conditions in the retina. The special problems of the aphakic (lens-less) eyes or eyes with intraocular lens implants require attention in relation to the increased retinal exposure to UVA and short-wavelength visible radiation, particularly in the elderly. Some further work is required concerning the spectral dependence of both retinal damage and changes induced in the vitreous between 750 and 950 nm. It would also be of benefit to obtain a better understanding of the role of the choroid in both the absorption of optical radiation and production of damage and its involvement in the healing process. In conclusion, further studies must be undertaken on the quantification of the upper limits of flash blindness and persistent after-image production and the lower limits for oedema and irreversible damage.

(c) The skin

The optical properties of the skin require further study on the relationship between penetration depth and absorptivity and wavelength, skin pigmentation, and the angle of incident radiation. Epidemiological studies should be undertaken to further clarify the involvement and wavelength dependence of chronic exposure to optical radiation in the induction of skin cancers. Such studies should be encouraged in areas where direct comparison can be made between negroid indigenous and Caucasian immigrant populations in tropical and sub-tropical countries. Work is also required on the possible additive or synergistic effects of different wavebands, for example UVB, and UVB plus UVA. Finally a better understanding is required of the additional protective factors that must be applied to counteract the effects of specific photosensitizers (WHO, 1979).

(d) Exposure limits (ELs)

To date, the exposure limits and various recommended standards have been based mainly on empirical studies of acute effects on animals and extrapolation of limited epidemiological information. While these figures represent the best current knowledge, it should be emphasized that standards should be sufficiently flexible to enable the rapid incorporation of new data. Information is lacking in many fields, especially with regard to the long-term health risks associated with the adoption of present standards.

Further information on chronic effects is required and should be obtained from multicentre epidemiological studies. Such studies could be either retrospective or prospective but should clearly isolate ethnic, environmental, sociological, and age-related variations within participating populations. The systemic effects of optical radiation have not been adequately studied. These investigations should also take into account the effects of progressively increasing exposure to artificial sources in industry and the home. Active liaison is required between architects, illumination engineers, and health physicists to establish exposure limits and recommended lighting levels in relation to a variety of visual tasks.

The large number of variable parameters associated with repetitively pulsed exposures means that present ELs have been established in relation to a limited number of research studies. Further studies are needed and should include the problems of repeated exposures to a single system and repeated exposures to several sources within a relatively short period, i.e., a working day.

The difficulties involved in measurement of ultra-short (sub-ns) pulses have resulted in few bioeffect studies being undertaken and thus a large degree of extrapolation in establishing ELs. More work is required and a better understanding is needed of the bioeffects related to non-linear optical effects.

(e) Evaluation and control measures

In many countries, more than one executive office has some responsibiities for regulating optical radiation exposure and optical sources. Lack of clearly defined division of responsibilities between different agencies has created confusion for manufacturers and users of lasers and lamp sources. National agencies should make every effort to work towards uniform and compatible standards. Clear-cut criteria are needed to define conditions under which lasers can be used in public places.

Current efforts to achieve international harmonization of laser classification and control of health risks should be encouraged and extended.

Radiation product performance and user standards should be developed for lamps and lighting systems.

(f) Laser accidents

With the exception of a few published cases, medical and biophysical details relating to laser accidents are difficult to obtain. It would be helpful if individual countries established national accident-reporting protocols together with a central referral agency, in order to provide statistical evaluation of problems in safety procedures.

(g) Eye protection

The investigation of new types of eye protection filters should be undertaken and further attempts should be made to standardize existing filters on an international basis (e.g., welding filters, laser safety goggles).

(h) Medical surveillance and epidemiological studies

Occupational medical surveillance of workers may be necessary in certain cases; of great importance is the need for epidemiological studies on workers exposed for long periods to UVR and visible radiation. A study of central visual function and colour vision in comparison with an age-matched control group would be very informative. An epidemiological study of workers exposed over long periods to infrared radiation is also needed.

(i) Education

Since control measures for unenclosed lasers rely largely on the laser operator, training programmes must be instituted for such individuals. Education of the general population is also required both to allay unwarranted fears of accidental laser exposure and to give some background information against which elective optical radiation exposures (medical and paramedical, e.g., cosmetic) may be assessed.

2. DEFINITIONS OF OPTICAL RADIATION

2.1 The Electromagnetic Spectrum

Electromagnetic radiation consists of oscillating electric and magnetic fields. Radio frequency (including microwave), infrared, visible (light[a]), ultraviolet, X, and gamma radiation are all electromagnetic radiation and are propagated in both free space and matter. Collectively, this electromagnetic radiation forms the electromagnetic spectrum, when arranged according to frequency or wavelength. A chart of the spectrum is shown in Fig. 1.

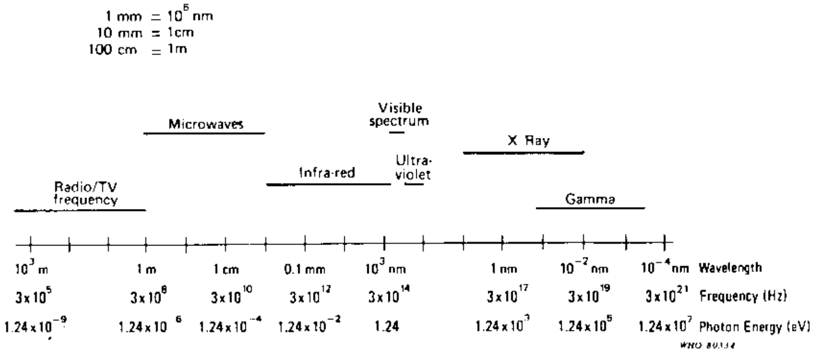

Fig. 1. The spectrum of electromagnetic radiation.

Equation 1 can be modified for electromagnetic radiation by giving the velocity of the radiation the value of the velocity of light, usually written as c. In a vacuum:

$$c_o = \lambda \nu \qquad \text{Equation (1)}$$

The velocity ρ_o has been set as 299792458 m/s or about 3×10^8 m/s = 3×10^{10} cm/s.

The ratio of the velocity of light c_o in a vacuum to the velocity c in a medium is termed the refractive index n of that medium ($n = c_o/c$). Equation 1 can also be expressed as

$$\lambda = c/\nu, \text{ or } \nu = c/\lambda \qquad \text{Equation (2)}$$

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[a] Light by definition is visible radiation; hence, it is incorrect (but commmon) to speak of "ultraviolet light" or "infrared light".

The inverse relationship between frequency and wavelength is clearly evident in Fig. 1. If n is constant at all points within the medium, then the medium is called optically homogeneous; if n is independent of direction, the medium is termed isotropic. If n is considered independent of the amplitude or intensity of the optical field, the interaction with the medium is termed "linear"; if not, it is "non-linear".

As the frequency increases from microwave radiation through the optical radiations to gamma radiation, the wavelength becomes shorter and shorter. The electromagnetic radiations have a characteristic energy associated with each photon and the photon energy increases with an increase in frequency. Reference to one region or another as the "γ-radiation region" or the "microwave region" is arbitrary and no internationally accepted set of terms exist for specifying all of the spectral regions.

The spectral bands represent wavelength intervals within which a common state of the art and technology exists in sources, detectors, or in modes of interaction with matter. The upper and lower limits of the entire electromagnetic spectrum have not been defined at present. The units used to describe energy, wavelength, and frequency often differ between spectral regions, as a matter of convention.

Ultraviolet, visible (light), and infrared radiation, collectively known as optical radiation are described in terms of wavelength. Sometimes, the spectral region of wavelengths shorter than approximately 100 nm is termed ionizing radiation, and wavelengths longer than 100 nm are placed in the non-ionizing radiation spectrum. These terms are useful for those who wish to distinguish between the biological effects of different types of radiation, but divisions between adjacent spectral bands vary according to different disciplines. For the physicist, the optical spectrum generally consists of 5 decades of wavelengths between 10 nm and 1 mm. On the other hand, photobiologists and health specialists, who are not concerned about vacuum ultraviolet radiation, begin at approximately 180-200 nm (which is the approximate long-wave edge of the vacuum ultraviolet) and go to far-infrared radiation at 1 mm. The Commission Internationale de l'Eclairage (CIE) Committee on Photobiology has provided spectral band designations that are quite convenient in discussing biological effects. Three common schemes of dividing the optical spectrum are given in Table 3 (CIE, 1970).

Table 3. Several schemes for dividing the optical spectrum

Physical No. 1	Physical No. 2	Photobiological (CIE)[a]
extreme UVR (1-10 nm to 100 nm)	vacuum or extreme UVR (1-10 nm to 180 nm)	UV-C (100 nm to 280 nm)
far UVR (200 nm to 300 nm)	middle UVR (180 nm to 300 nm)	UV-B[b] (280 nm to 315 nm)
near UVR (300 nm to 400 nm)	near UVR (300 nm to 400 nm)	UV-A[b] 315 nm to 380-400 nm)
light (380 nm to 760 nm)	light (400 nm to 700 nm)	light (380-400 nm to 760-780 nm)
near IR (760 nm to 4000 nm)	near IR (700 nm to 1200 nm)	IR-A (760-780 nm to 1400 nm)
middle IR (4 µm to 14 µm)	middle IR (1.2 µm to 7 µm)	IR-B (1.4 µm to 3 µm)
far IR (14 µm to 100 µm)	far IR (7 µm to 1 mm)	IR-C 3 µm to 1 mm)
submillimetre (100 µm to 1 mm)		

[a] Based on the recommendation of the Committee on photobiology of the Commission Internationale de l'Eclairage (CIE, 1970). The scheme was originally proposed by W.W. Coblentz of the US National Bureau of Standards in the 1930s.

[b] The dividing line between UV-B and UV-A is often taken as 320 nm, but may be taken as 315 nm. For the purposes of this document, 315 nm is used unless otherwise stated.

2.2 Interaction of Electromagnetic Radiation with Matter

Electromagnetic radiation interacting with matter is absorbed, transmitted, reflected, scattered, and diffracted. In most instances, one of these effects dominates, almost to the exclusion of others. However, all effects are always present to some extent. For instance, if a beam of light passes through a sheet of transparent glass, at least 4% of the incident light is reflected from each surface. On the other hand, only a very small percentage (less than 1%) is usually absorbed within the clear glass, even when marked refraction or bending of the light takes place. Similar effects occur in all spectral regions including the radiofrequency and gamma-radiation bands.

2.2.1 Interaction at an interface

2.2.1.1 Reflection

Reflection takes place at an interface. There are two basic types of reflections that are of interest, i.e., specular (mirror-like) and diffuse. Specular reflection is sometimes referred to as regular reflection. With specular reflection from a mirror or other very smooth surface, light obeys the law of reflection, which states that the angle of reflection equals the angle of incidence.

Specular reflection can occur, when the size of surface irregularities or roughness is less than the wavelength of the incident radiation. This description of specular reflection is important to keep in mind. Diffuse reflection occurs, when the surface irregularities are randomly oriented and are much greater than the wavelength of the incident radiation; for example, when light is reflected from chalk or a rough granite surface. Perfect diffuse reflection obeys Lambert's Law, i.e., the Cosine Law of Reflection. A useful formula in radiometry is:

$$E = \Phi \ \rho \cdot \cos \Theta \ / \pi r_1^{\,2} \qquad \text{Equation (3)}$$

where E is the irradiance reflected from the surface at angle θ (theta) relative to the surface's normal, ϕ (phi), the optical beam power upon the surface, ρ (rho), the diffuse reflection coefficient of the surface for the wavelength, r^1 the distance from the beam spot on the diffuse target to the detector, and π equals 3.14159.

It is important to remember that diffuse and specular reflections are strongly dependent on wavelength. A given surface may produce a reflection that is specular at one wavelength but may or may not be specular at a different wavelength.

The fraction of incident radiation specularly reflected from the surface of a transparent medium depends on the index of refraction, the polarization of the incident beam, and the angle of incidence. This is illustrated for glass in Fig 2.

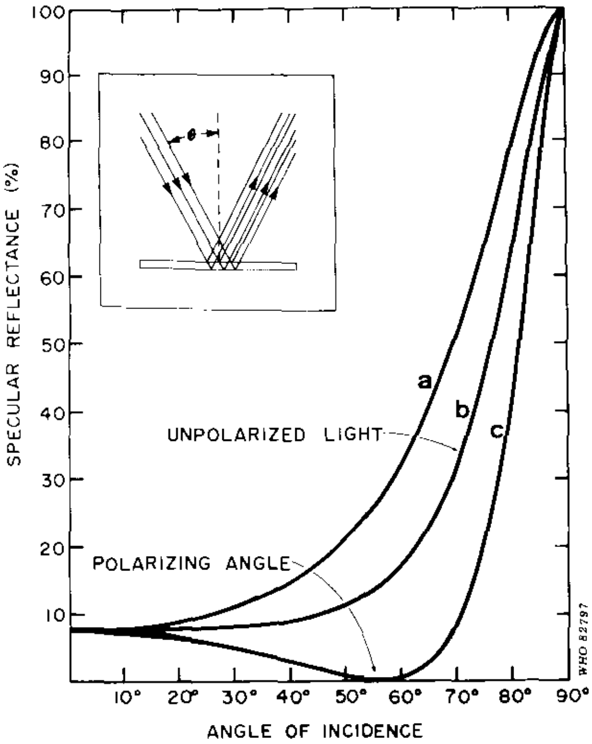

Fig. 2. The specular reflectance for plate glass. Specular reflectance depends on the polarization of the incident light and the angle of incidence. Light with the electric vector polarized perpendicularly (a) to the plane of incidence is reflected more than light that is polarized parallel (c) to the plane of incidence. Curve (b) refers to unpolarized light. The curves are for both surfaces of clear glass with an index of refraction of 1.5.

2.2.1.2 Refraction

Refraction also takes place at an interface. Refraction occurs, whenever a beam of light passes from one transmitting medium to another having a different refractive index (n). For example, refraction is the bending of light at air-water and air-glass interfaces. The law of refraction, which is also known as Snell's Law, states that the angle of incidence (θ_1) and the angle of refraction (θ_2) are related by the equation:

$$\sin \theta_1 / \sin \theta_2 = n_2/n_1 \qquad \text{Equation (4)}$$

where n_1 and n_2 are the indices of refraction of the first medium and the second medium respectively.

Lenses and prisms are optical components that depend principally on the phenomenon of refraction. The variation in the index of refraction with wavelength is termed dispersion. Thus a simple prism bends blue light and red light differently for the same angle of incidence, the two angles of refraction differ, and blue light can be separated from red light. In lenses, this effect is called chromatic aberration. It can be reduced by choosing a glass with very little dispersion or by combining two lenses that have complementary dispersion characteristics.

2.2.2 Interaction with a medium

2.2.2.1 Transmission

The nature of transmitted light that emerges from a medium depends on the phenomena of absorption and scattering and also on the reflection of some of the light at the interfaces between media. The transmittance of a medium is usually represented by τ (tau) and specified at a certain wavelength and for a certain path length at normal incidence. The transmittance of most materials varies markedly across the optical spectrum.

2.2.2.2 Attenuation

The absorption and transmission of a beam of optical radiation in any homogenous, isotropic medium is expressed in terms of the following equation:

$$\Phi = \Phi_0 e^{-(\alpha+\rho)x} = \Phi_0 e^{-\mu x} \qquad \text{Equation (5)}$$

where Φ is the radiant power (radiant flux) leaving the medium, Φ_0 the initial radiant power in the beam entering the absorbing medium, x the thickness of the medium (path length of the beam), α the absorption coefficient, ρ the scattering coefficient, and μ (Greek "mu") the attenuation coefficient of the absorbing medium.

In the Exponential Law of Absorption (Beer's Law), the constant α (Greek "alpha") is the absorption coefficient. The law shows that the radiant power diminishes exponentially with distance during transmission through a uniformly absorbing medium. For a scattering medium, the same approach may be applied with the absorption coefficient α being replaced by a scattering coefficient σ (Greek "sigma"). The attenuation coefficient varies with wavelength as does the scattering coefficient σ. Equation 5 is only an approximation for weak scattering. It can be rewritten to the base 10 instead of to the base e of natural logarithms and the constants μ, ρ, and α will then be different. "Attenuation depth" and "absorption depth" are useful terms to describe attenuation and absorption in tissue. The most popular convention is to define this depth as the distance into the tissue at which the incident irradiance is reduced to 1/e (37%) of its initial value. Another convention sets the value at 1/10.

Absorption in all substances is strongly dependent on the wavelength of the incident radiation. Atoms or molecules become excited when they absorb a quantum of radiant energy. Following absorption, this energy may be released in a variety of ways. When the energy is released as more photons of radiant energy, it is known as luminescence.

At very high irradiances, non-linear effects can occur as a result of the direct interaction of the high electric-field intensities with matter. Saturable absorption and enhanced absorption are examples that alter the absorption coefficient.

2.2.3 Interference, diffraction, and scattering effects

2.2.3.1 Interference and diffraction

When considering interference and diffraction effects, it is convenient to use the wave description of light. The bending or spreading of waves after passing an edge or passing through a small aperture is a wave phenomenon termed diffraction. The diffraction effects result from the constructive and destructive interference of adjacent waves. When the size of the barrier is comparable or smaller in size than the incident wavelength, the wave is bent around the barrier considerably. Thus, particles diffract light most dramatically, when they are approximately the size of the wavelength of the incident radiation. In this case, the sum of the diffraction effects is known as scattering.

In the treatment of plane waves impinging on an aperture such as a circular aperture, Huygens principle may be employed. Each point within the area of the aperture is regarded as a source of wavelets to explain the interference effects that produce a diffraction pattern on a screen some distance away.

2.2.3.2 Scattering

Small particles, the size of which approaches that of a wavelength of light, scatter light, as do atoms, and molecules. If the particles are much smaller than the wavelength of light (e.g., gas molecules), Rayleigh scattering takes place. For Rayleigh scattering, the fraction of scattered radiation from a beam is inversely proportional to the fourth power of the wavelength of the radiation. That is to say, that this type of scattering increases dramatically for shorter wavelengths. Rayleigh scattered, non-polarized light goes in all directions and becomes polarized to some extent. If light is scattered by particles the size of the order of the wavelength of light or greater, this strong wavelength preference is not seen in the scattered light. The type of large-particle scattering is termed Mie scattering. Unlike Rayleigh scattering, Mie scattering is strongly directional. Normally, the forward component of Mie scattered radiation is much greater than the backscatter.

The scattering of a beam of light passing through a homogeneous medium can be expressed in terms of the exponential function (Equation 5).

3. SOURCES OF RADIATION

Sources of optical radiation can be grouped according to the type of emitting material, the type of apparatus, or the manner in which the radiation originates.

Incandescent bodies are probably the most common sources of optical radiation. When the temperature of a body is elevated, more photons are emitted. If the temperature of the body is approximately that of the human body (37 °C or 310 K), most of the emitted photons have wavelengths in the far infrared, in the vicinity of 10 µm. If a material body is heated to incandescence, e.g., to 2000 K, the material may be described as "red hot". The higher the temperature, the greater the percentage of high energy photons released. But, in all cases, a wide range of photon energies is associated with the emitted incandescent radiation. A theoretically perfect incandescent source has a characteristic "black-body" spectrum. Fig. 3 shows the black-body spectra for several different temperatures. In practice, no material actually emits a perfect black-body spectrum, but some materials such as solid tungsten or molten metals approach this distribution.

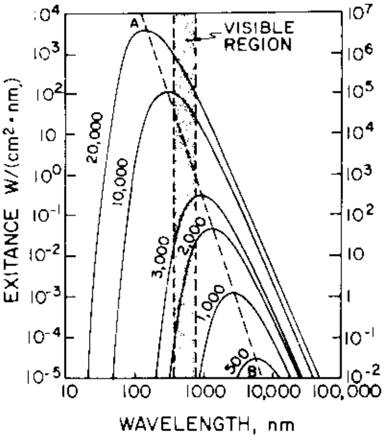

Fig. 3. Black-body spectra. Line AB shows Wien's Displacement Law for the shift of the peak wavelength with change in temperature (From: Sliney & Wolbarsht, 1980).

The ratio of the theoretically possible spectral emittance to the actual emittance of a grey body is the emissivity. For instance, the emissivity of tungsten throughout the visible is approximately 0.4.

A useful relation for black-body sources is the Stefan-Boltzmann Law, which states that the radiant exitance W integrated over all wavelengths of a black body is proportional to the fourth power of the absolute temperature of the body, i.e.:

$$W = \sigma T^4$$

3.1 Molecular and Atomic Transitions

Other sources of light such as carbon arcs, gas-filled arc lamps, or gas discharge lamps, depart widely from black-body characteristics, i.e., vary greatly with the wavelength in the visible region. In these cases, a stream of electrons flowing through a gas induces an emission of photons, characteristic of that particular gas. If gas has a low pressure and the current is not great, a line spectrum is emitted. Line spectra are the result of atomic transition. As the gas pressure and the current density increase, the gas temperature increases and a continuous spectrum appears. At high current densities and gas pressures, this type of emission (a continuum) predominates.

The energy Q_q of a single photon, emitted because of an atomic transition, is determined by the frequency of the emitted radiation as defined by the condition:

$$Q_q = \xi_1 - \xi_2 = h\nu \qquad \text{Equation (6)}$$

where ξ_1 and ξ_2 are energies corresponding to the initial and final energy states, h is the Plank constant (6.625×10^{-34} J·s), and ν is the frequency of radiation (in Hz).

Energy transitions in molecular systems can result in a radiation emission according to rules similar to those that apply to atomic systems. The energies (0.001-0.1 eV) of molecular vibrational or rotational transitions are, typically, less than those characteristic of electron transitions in atoms or molecules (1-100 eV). In addition to the electron "orbital" potential and kinetic energies, part of the energy of molecular systems is associated with rotational and vibrational modes. Emissions of this type occur in the infrared and microwave regions of the electromagnetic spectrum. Heat is the vibrational energy of molecular systems.

4. LASERS

All lasers have three basic components: (a) a laser (active) medium; (b) an energy source (pumping system); and (c) a resonant optical cavity. Lenses, mirrors, shutters, saturable absorbers, and other accessories may be added to the system to obtain greater power, shorter pulses, or special beam shapes, but only the three basic components (a, b, and c) are necessary for laser action.

4.1 The Laser Medium

Laser action depends on the ability of the laser (active) medium to undergo population inversion (i.e., more atoms or molecules in the excited state than in the lower state). Once population inversion occurs, an avalanche of photons can be generated by stimulated emission. Initial, spontaneously emitted photons stimulate other excited atoms to emit photons of the same energy in phase with one another. This process is Light Amplification by Stimulated Emission of Radiation, with the acronym, LASER.

Fig. 4 shows a simplified 3-level energy diagram for a laser material. This is just one of the many possible systems of energy levels. Though laser action is possible with only 3 energy levels, most such actions involve 4 or more levels.

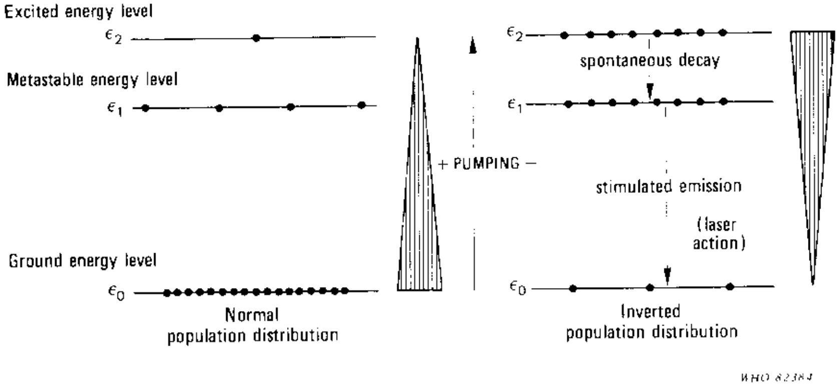

Fig. 4. Simplified 3-level energy diagram for a laser material. Population inversion of a set of atoms is produced by pumping electrons from a lower energy state to a higher energy state, so that the higher state has more electrons (larger population) than the lower state.

4.2 The Pumping System

Pumping systems are necessary to raise electrons to a higher energy level in lasers. These systems pump energy into the laser material, increasing the number of atoms or molecules trapped in the metastable energy level, until a population inversion exists large enough to make laser action possible (Fig. 4). Several different pumping systems are available including optical, electron collision, and chemical reaction.

In optical pumping, a strong source of light is used, such as a xenon flashtube or another laser (e.g., an argon or nitrogen laser), generally of a shorter wavelength than that emitted by the medium.

Electron collision pumping is accomplished by passing an electric current through a laser medium, usually a gas (e.g., helium-neon laser) or a semiconductor junction (e.g., gallium-arsenide laser), or by accelerating electrons in an electron gun to impact on the laser material, as in some semiconductor or gas lasers.

Chemical pumping is based on energy released in the making and breaking of chemical bonds. For example, some hydrogen fluoride (HF) or deuterium fluoride (DF) lasers are pumped in this manner.

4.3 The Resonant Optical Cavity

A resonant optical cavity is formed by placing a mirror at each end of the laser medium so that a beam of UVR, light, or IR radiation may be reflected from one mirror to the other. Lasers are constructed in this way so that the beam passes through the laser medium one or more times and the number of emitted photons is amplified at each passage. One of the mirrors is only partially reflecting and permits part of the beam to be transmitted out of the cavity at each reflection (Fig. 5). The alignment, curvature, and separation distance of the mirrors determine the shape (mode structure) of the emitted laser beam.

4.4 Types of Lasers

Lasers can be categorized in a variety of ways, e.g., according to the active medium or temporal mode of operation.

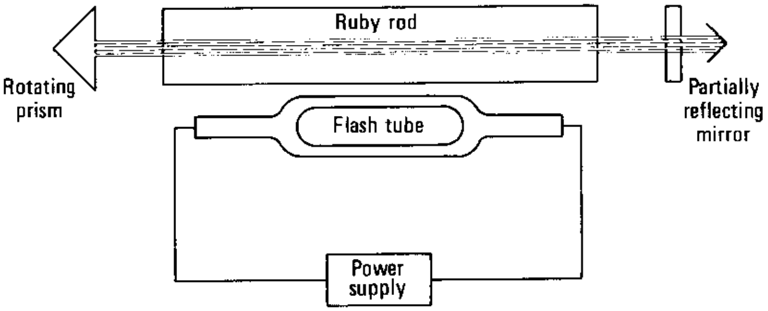

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Fig. 5. Schematic of "solid-state" ruby laser with a xenon flash tube as optical pump. A rotating prism serves both as a mirror and as a "Q-switch" (From: Sliney & Wolbarsht, 1980).

4.4.1 Active media

Lasers are often designated according to the type of laser medium, as follows:

(a) Solid-state lasers: a glass or crystalline medium into which active atoms are introduced;
(b) Gas lasers: a medium of pure gas or a mixture of gases; this category also includes metal vapour lasers;
(c) Semi-conductor lasers: a medium of n-type and p-type semiconducting element material;
(d) Liquid lasers: a liquid medium containing an active material, such as an organic dye, in solution or suspension.

Optical pumping (both coherent and incoherent) is usually used in the production of solid-state and liquid lasers while collision pumping is usually employed to produce gas lasers. However, chemical-reaction pumping is also used for some types of liquid and gas lasers. Semiconductor lasers may be optically pumped by an electric current, another laser beam, or electron-collision from an electron beam. Table 4 provides an abbreviated list of commercially available laser wavelengths.

4.4.2 Temporal modes of operation

Some lasers operate continuously, and are termed continuous wave (cw). In this type of operation, the peak power is equal to the average power output; that is, the beam irradiance is constant with time. Many lasers that appear to be cw may actually have a temporal structure that can only be resolved with very sophisticated systems of measurement.

The different temporal modes of operation of a laser are distinguished by the rate at which energy is delivered. In general, lasers operating in the normal pulse (or "long pulse") temporal mode have pulse durations of a few tens of µs to a few ms (Descomps, 1981).

Table 4. Common lasers

CIE band	Wavelength (nm)	Medium	Typical operation
Excimer	UVC + B	XeCl, XeFl, etc.	pulsed
UV-A	325	He-Cd	cw
UV-A	337	Nitrogen	pulse train
UV-A	350	Argon	cw
Light	441.6	He-Cd	cw
Light	458, 488, 514.5	Argon	cw
Light	458, 568, 647	Krypton	cw
Light	530 or 532	Nd frequency-doubled	pulsed
Light	632.8	He-Ne	cw
Light	694.3	Ruby	pulsed/Q-pulsed
Light	560-640	Rhodamine 6G dye	cw/pulsed
IR-A	850	GaAlAs	pulse train
IR-A	905	GaAs	pulse train
IR-A	1060	Nd: glass	pulsed/Q-pulsed
IR-A	1064	Nd: YAG	cw/pulsed/Q-pulsed
IR-C	5000	CO	cw/pulsed
IR-C	10 600	CO_2	cw/pulsed

Pulsed lasers can be operated to produce repetitive pulses. The pulse repetition frequency of a laser is the number of pulses that a particular laser produces per unit time duration. Lasers are now available with pulse repetition frequencies as high as several million pulses per s (MHz).

The resonant quality of the optical cavity of a laser can be altered by rotating one mirror or by placing a shutter between the mirrors. The shutter may be active (e.g., pockels cell) or passive (a saturable absorber). This enables the beam to be turned on and off rapidly and normally creates pulses with a duration of a few ns to a few µs. This operation is normally called Q-switching (or Q-spoiling or giant pulsing) (Fig. 6). The "Q" refers to the resonant quality of the optical cavity. A Q-switched laser usually emits less energy than the same laser emitting normal pulses, but the energy is emitted in a much shorter period of time. Thus, Q-switched lasers are capable of delivering very high peak powers of several megawatts or even gigawatts. Fig. 6 shows a variety of oscilloscope traces including a normal pulse and a Q-switched pulse.

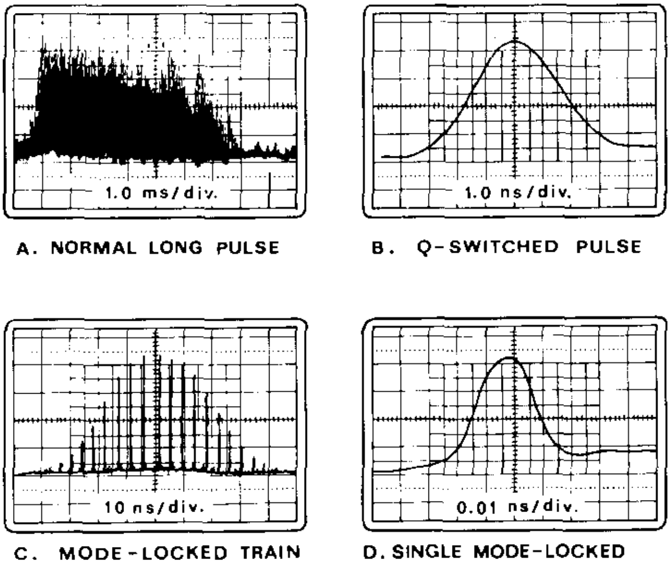

Fig. 6. Oscilloscope traces of a long-pulse (normal-pulse) laser (A), a Q-switched pulse (B), and mode-locked laser outputs (C and D)(From: Sliney & Wolbarsht, 1980). Note change in time scales in each trace (1 ms = 10^6 ns).

When the phases of a number of oscillating modes in a laser resonator are forced to maintain a fixed relation to one another through a non-linear absorber placed in the resonator, the laser output observed is a train of regularly spaced ultra-short pulses. This is termed a mode-locked laser. In a train of pulses, each pulse has a duration of a few picoseconds (ps) to a few ns. A mode-locked laser can deliver higher peak powers than the same laser when Q-switched (Dautray & Watteau, 1980). Fig.6 also shows a mode-locked pulse train from a pulsed Nd-YAG laser.

4.5 Spatial (TEM) Modes

A cross-sectional wave pattern is characteristic of all laser beam geometries (transverse electromagnetic wave or TEM). These wave patterns across the beam are identified with TEM mode notation. Fig.7 illustrates how some of the more common modes would appear in cross section. The TEM_{01} mode is similar to the TEM_{10} mode rotated through 90°.

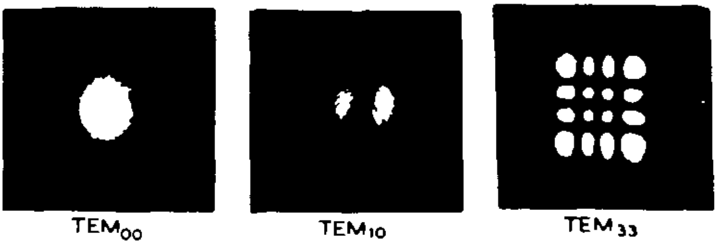

Fig. 7. Typical transverse electromagnetic (TEM) mode patterns as revealed in the beam cross-sectional patterns at some distance (i.e., in the far field) from a He-Ne laser (Adapted from: Kogelnik & Li, 1966).

Longitudinal (or axial) modes do not influence the emergent beam profile, but influence the degree of coherency of the spatial and the temporal frequency spectrum and are, therefore, of no great significance in the consideration of biological effects (unless they are intentionally or accidentally mode-locked to produce ps pulses).

4.6 Beam Characteristics

4.6.1 Beam diameter

The beam diameter of a laser operating in the TEM_{00} mode has been variously defined as the circle where the irradiance or radiant exposure is 1/2, 1/e, $1/e^2$, or 1/10 of the maximum (Fig.8). In almost all discussions in the health and safety literature, the edge of the beam is defined as 1/e or 0.37 of the maximum, whereas the beam diameter is almost always defined at $1/e^2$ points in the laser industry.

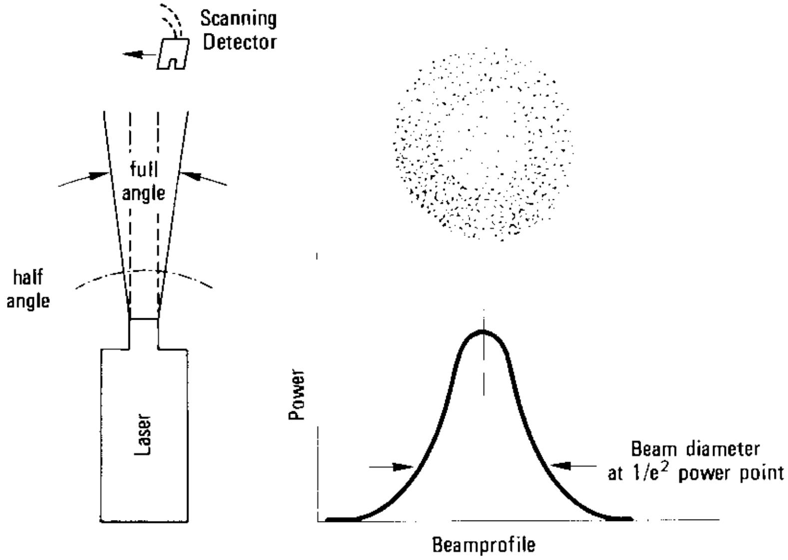

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Fig. 8. Gaussian profile of a single-mode laser beam plotted by scanning across the centre of the beam pattern above. The beam divergence of a laser should be expressed at the full-angle and not at the half-angle (From: Sliney & Wolbarsht, 1980).

4.6.2 Beam divergence

The wave nature of light prevents lasers from producing perfectly collimated beams. However, the divergence or beam spreading is much smaller than that of a searchlight or other conventional sources of optical radiation.

4.6.3 Beam irradiance versus range for a circular beam

To define potential exposure conditions, it is necessary to characterize the beam emitted from a laser. The beam's characteristics may be required near the output of the laser or at some considerable distance from the laser, after it has been collimated or focused. The optical radiation emitted by most lasers is confined to a rather narrow beam that slowly diverges or fans out as the beam propagates. The beam diameter D_L increases from an initial diameter a at the laser exit port as a result of the divergence ϕ:

$$D_L = a + r\phi \qquad \text{Equation (7)}$$

where r is the range (distance from the laser).

With the beam diameter defined as a function of distance from the laser, it is a simple matter to derive a formula to estimate the beam irradiance or radiant exposure at any distance r. The beam irradiance E (in W/m^2 or W/cm^2) would be the total power Φ in the beam (in watts) divided by the area of the cross section of the beam (usually expressed in m^2 or cm^2). For health risk assessment, a defining aperture of irradiance measurement is normally specified (e.g., 7-mm circular aperture).

The effect of atmospheric attenuation may become a major factor in evaluating the irradiance or radiant exposure at distances greater than a few kilometres. This attenuation is the result of three effects: (a) Mie (or large particle) scattering; (b) Rayleigh (or molecular) scattering; and (c) absorption by gas molecules. Rayleigh scattering is the most wavelength dependent; shorter wavelengths are predominantly scattered. The atmospheric attenuation may best be expressed by an exponential function. The attenuation of optical radiation could be described by a term ($e^{\mu r}$) where μ is termed the attenuation coefficient of the medium. It is the sum of scattering coefficients and absorption coefficients of the medium through which the laser beam propagates. One equation that is a close approximation for calculating the axial beam irradiance is:

$$E = 1.27\,\Phi\, e^{-\mu r}/(a + r\phi)^2 \qquad \text{Equation (8)}$$

and a corresponding equation for radiant exposure H from a pulsed laser of output energy Q is:

$$H = 1.27\,Qe^{-\mu r}/(a + r\phi)^2 \qquad \text{Equation (9)}$$

These equations can be adjusted for other beam profiles using simple geometry. The emergent beam diameter term, a, may be dropped at distances where a << rϕ. Equations 7, 8, and 9 are close approximations to rigorous formulations of Gaussian optics.

4.6.4 Hot spots

Hot spots are defined as areas of the beam, where the localized beam irradiance is much greater than the average across the beam. As the irradiance of hot spots may be many times higher than the average beam irradiance, they are of considerable concern in relation to health. There are several sources of hot spots: inhomogeneities in the laser cavity or areas of the active medium, where more energy is emitted than in other areas; imperfections in the mirrors and lenses of the laser system; and changes caused by atmospheric conditions. Atmospheric inhomogeneities along the beam path produce lenticular effects (scintillation) that are responsible for atmospheric hot spots. Fog, rain, snow, dust, smoke, or haze absorb and/or scatter the laser beam but do not cause hot spots. Such scattering reduces the severity of hot spots.

4.6.5 Coherence

Two types of coherence are characteristic of laser light: spatial and temporal. The term spatial coherence indicates that the optical radiation is spatially in phase, i.e., electromagnetic waves at different points in space oscillate in synchronism. Laser speckle is a consequence of spatial coherence. Temporal coherence indicates that the radiation is strictly monochromatic (of one wavelength). No light source is either totally coherent or totally incoherent; the differences between individual lasers and, for that matter, non-laser sources are merely a matter of degree. The term "coherence length" is used to describe the degree of spatial coherence.

5. RADIOMETRIC CONCEPTS

5.1 Radiometric and Photometric Terminology

Two systems of quantities and units are used to describe optical radiation. One is a physical system called the radiometric system. The other, the photometric system, attempts to describe the optical radiation in terms of its ability to elicit the sensation of light by the eye. Table 5 gives the most commonly used quantities and the preferred units for each system. There are generally analogous units in each of the 2 systems. The table is arranged to illustrate these similarities. Though the radiometric system of units may be used across the entire spectrum, the photometric system is limited to describe light (i.e., electromagnetic radiation that is visible) from approximately 380-400 nm to 760-780 nm.

It is important to remember that some terms refer only to extended sources (e.g., radiance) and other terms (e.g., radiant intensity) refer only to "point" sources.

5.2 Extended Sources Versus Point Sources

Lasers are often treated as "point" sources, whereas most conventional light sources are considered to be extended sources, at least at close distances. An extended source is one that appears to have some angular extent as seen by the viewer. The moon is an extended source; a star is a "point" source. Apart from lasers, a light source can be considered a point source only at a great distance, or if a pinhole diaphragm is placed in front of the light source. All other light sources are considered to be extended sources.

5.3 Inverse Square Law

The inverse square law for calculating the irradiance or radiant exposure at a distance from a source applies only to a point source. For example, the ratio of irradiance E_1, at one distance r_1 to E_2 at another distance r_2 is:

$$\frac{E_1}{E_2} = \frac{r_2^2}{r_1^2} \qquad \text{Equation (10)}$$

For practical purposes, extended sources can be considered as "point" sources at a distance many times greater than the source dimension. Both r_1 and r_2 should be at least as great as 10 source diameters for a diffuse lambertian source. This also applies to equation 3. The irradiance E at a distance r from a point source is:

$$E = I/r^2 \qquad \text{Equation (11)}$$

This equation applies to collimated extended sources (e.g., searchlights) or lasers, only at considerable distances from the source.

Table 5. Useful CIE radiometric and photometric quantitities and units [a,b]

RADIOMETRIC

Term	Symbol	Defining equation	Quantity applicable[c]	SI units & abbreviations
Radiant energy	Q_e		S, R	joule (J)
Radiant energy density	W_e	$W_e = \frac{dQ_e}{dV}$	F	joule per cubic metre (J/m^3)
Radiant power (radiant flux)	$\Phi_e P$	$\Phi_e = \frac{dQ_e}{dt}$	S, R	watt (W)
Radiant exitance	M_e	$M_e = \frac{d\Phi_e}{dA}$ $= \int L_e \cdot \cos \cdot d\Omega$	S	watt per square metre (W/m^2)
Irradiance or flux density (dose rate in photobiology)	E_e	$E_e = \frac{d\Phi_e}{dA}$	R	watt per square metre (W/m^2)
Radiant intensity (W/sr^1)	I_e	$I_e = \frac{d\Phi_e}{d\Omega}$	S	watt per steradian
Radiance [d]	L_e	$l_e = \frac{d^2\Phi_e}{d\Omega \cdot dA \cdot \cos\theta}$	S, F, R	watt per steradian and per square metre ($W/sr/m^2$)

Table 5 (contd.)

Term	Symbol	Defining equation	Quantity applicable[c]	SI units & abbreviations
Radiant exposure (dose in photobiology)	H_e	$H_e = \frac{dQ_e}{dA}$	R	joule per square metre (J/m^2)
Radiant efficiency [e] (of a source)	η_e	$\eta_e = \frac{P}{P_i}$	S	unitless
Optical	D_e	$D_e = -\log_{10} \tau_e$	R	unitless

PHOTOMETRIC

Term	Symbol	Defining equation	SI abbreviations & units
Quantity of light	Q_v	$Q_v = \int \phi_v dt$	lumen-second ($lm \cdot s$)
Luminous energy density	W_v	$W_v = \frac{dQ_v}{dV}$	lumen-second per cubic metre ($lm \cdot s/m^3$)
Luminous flux	Φ_v	$\Phi_v = 680 \int \frac{d\phi_e}{d\lambda V(\lambda) d\lambda}$	lumen (lm)
Luminous exitance	M_v	$M_v = \frac{d\phi_v}{dA}$ $= \int I_v \cdot \cos\theta \cdot d\Omega$	lumen per square metre (lm/m^2)
Illuminance (luminous density)	E_v	$E_v = \frac{d\phi_v}{dA}$	lumen per square metre (lm/m^2)
Luminous intensity (candlepower)	I_v	$I_v = \frac{d\phi_v}{dr}$	lumen per steradian ($lm \cdot sr$) or candela (cd)
Luminance [d]	L_v	$L_v = \frac{d^2\phi_e}{dr \cdot dA \cdot \cos\theta}$	candela per square metre (cd/m^2)

Table 5 (contd).

Term	Symbol	Defining equation	SI abbreviations & units
Light exposure	H_v	$H_v = \frac{dQ_v}{dA} = \int E_v dt$	lux-second (lx·s)
Luminous efficacy (of radiation)	K	$K = \frac{\phi_v}{\phi_e}$	lumen per watt (lm/W)
Luminous efficiency (of a broad band radiation)	V(*)	$V(*) = \int \frac{K}{K_m} = \frac{K}{680}$	unitless
Luminous efficacy [e]	η_v	$\eta_v = \frac{\phi_v}{P_i}$	lumen per watt (lm/W)
Optical density [f]	D_v	$D_v = -\log^{10}\tau_v$	unitless
Retinal illuminance (in trolands)	E_t	$E_t = L_v \cdot S_p$	Troland (td) = luminance of 1 cd/m² times pupil area in mm²

[a] The quantities may be altered to refer to narrow spectral bands, in which case the term is preceded by the word spectral, and the unit is then per unit of wavelength and the symbol has a subscribt λ. For example, spectral irradiance H_λ has units of $W/(m^2 \cdot m)$ or more often, $W/(cm^2 \cdot nm)$.

[b] While the metre is the preferred unit of length, the centimetre is still the most commonly used unit of length for many of the above terms and the nm or µm are most commonly used to express wavelength.

[c] Some radiometric quantities refer only to the source, field, or receiver. This noted in this column.

[d] At the source, $L = \frac{dM}{d\Omega \cdot \cos\theta}$; at a receptor, $L = \frac{dE}{d\Omega \cdot \cos\theta}$

[e] P_i is electrical input power in watts.

[f] τ is the transmission; D_v is also abbreviated as O.D.

6. RADIOMETRIC AND PHOTOMETRIC MEASUREMENT

6.1 Introduction

Reliable radiometric techniques and instruments are available that make it possible to analyse risks for the skin and eye from exposure to lasers and other sources of optical radiation. However, the cost of accurate equipment remains relatively high compared with that of survey equipment now available to evaluate many other environmental risks. Radiometric formulae and manufacturers' specifications of lasers will often be an adequate substitute for measurement.

There are many types of measurements for defining conditions or characterizing a source's output . The types of measurements considered in this section fall under the broad term of "radiometric". For characterizing a conventional light source, radiance is generally the most useful. For laser output measurements, radiant power and radiant energy are by far the most important. Irradiance and radiant exposure are of greater importance in defining hazardous exposure conditions from all optical sources.

In any discussion of the measurement of laser radiation for purposes of evaluating health risks, it is important first to clarify the conditions and requirements for such measurements. Industrial and environmental health specialists and health physicists usually rely heavily on instruments to detect or estimate a chemical or physical agent that their own human senses cannot detect. The presence of a laser beam can generally be detected by the human eye or through the use of an image converter, thus raising the question "Why should the laser beam be measured?". It soon becomes evident that, in most cases, even routine monitoring of either a work area or an individual by instrumentation is a hopeless task. A more logical approach to risk assessment is to develop a means of analysing the potential risk of a laser, based on the laser's output parameters.

As a general rule, present standards require only measurement of the laser-output characteristics for laser risk classification. Routine monitoring is seldom considered necessary and all measurements are normally performed only once, by (or for) the manufacturer of the laser equipment. Periodic measurements may be considered worthwhile for certain lasers that are near the borderline between two classes in the hazard classification and field measurements of outdoor laser propagation paths have often been found useful. Unlike most noxious agents, a high-powered laser beam is almost always hazardous for a considerable distance and its hazard generally exceeds exposure limits by orders of magnitude. Diagnostics of the beam profile and measurement of beam divergence have been discussed.

The evaluation of more conventional broad-band sources is more complex, since spectral characteristics and source size must be considered. To evaluate a broad-band optical source, it is normally necessary to determine the spectral distribution of optical radiation emitted from the source at the point or points of human access. The spectral distribution of the accessible emission, which is of interest for a lighting system, may differ from that actually being emitted by the lamp alone because of apertures or filtration by any optical elements in the light path. Secondly, the size, or projected size, of the source must be characterized in the retinal hazard spectral region. Thirdly, it may be necessary to determine the variation of irradiance and radiance with distance. The necessary measurements are normally complex. The spectrum of an arc lamp, a gas discharge lamp, or a fluorescent lamp consists of both line structure and a continuum. Significant errors can be introduced in the representation of the spectrum and in the weighting of the spectrum against a biological- or a safety-action spectrum, if the fraction of energy in each line is not properly added to the continuum.

6.2 Measurement Instrumentation

The radiometric instruments of interest in this discussion generally consist of detectors that produce a voltage, a current, a resistance change, or an electronic charge, one of which is measured by a sensitive electronic meter. The type of read-out meter for the radiometric instrument is not normally of great concern and seldom determines the selection of the instrument. There are both advantages and disadvantages associated with each type of detector and each has certain characteristics that may be useful for measuring a specific level of optical radiation in a wavelength range of interest. No single detector is best for measuring all wavelengths and radiant powers of optical radiation. A very sensitive detector can be readily damaged or its response distorted by a high-powered laser beam, whereas a detector designed to measure very high-powered laser radiation is normally insensitive to low-power radiation. Narrow-band detectors have the advantage of being insensitive to extraneous radiation, though their usefulness is limited to measurement of lasers operating in that particular spectral band.

In many countries, national physical standards laboratories exist, which offer calibration services for some radiometric instruments. Examples are: Laboratoire National d'Essais (France); National Physical Laboratory (United Kingdom); Assistance Committee for Measures and Standards (USSR); National Bureau of Standards (USA); and Physikalisch-Technische Bundesanstalt (Federal Republic of Germany).

6.2.1 Thermal detectors

Thermal detectors are mainly used for measuring the output power or energy of lasers and total irradiances from broad-band optical sources, in particular infrared sources. Some of these detectors are particularly useful for absolute measurements.

Thermopiles, bolometers, disc calorimeters, and pyroelectric detectors are characterized by a relatively flat response as a function of wavelength. The spectral response of these detectors is dictated by the "black" absorbers that are normally used to coat the detector's metal or crystalline substrate. As optical energy falls on the detector, the temperature increases. The temperature rise in the substrate is then converted into an electrical voltage or current. Because of the thermal mass of the metal, the time required to heat or cool the detector element limits the response time of the instrument. The absorber in a disc calorimeter may be a black painted disc or a glass volume absorber (James, ed. 1976). In recent years, the response time of thermopiles has been shortened by using thin-film techniques. Low powers (typically 0.01-100 mW) can be measured and the response time reduced. Pyroelectric detectors measure the rate of temperature change in a crystalline material rather than the final temperature elevation in a metal. Radiometric calorimeters can be used to measure cw radiation over the power range from 1 mW to over 1 kW, depending on the detector and wavelength. Pulsed radiant energy can be measured over the range from 10 mJ to 10 kJ.

The detector may be covered by a window, which limits spectral response. Quartz windows are necessary for UVR, but there is probably no window material that is universally flat from 200 to 20 000 nm.

6.2.2 Quantum detectors

Quantum detectors operate normally at room temperature and offer by far the most sensitive means of measuring optical radiation, therefore, their principle use is in spectroradiometers and detectors required for the measurement of lower powers and irradiances or for temporal resolution of pulses. The spectral sensitivity of photoemissive detectors depends on the photo-cathode material used in vacuum photodiodes or photomultiplier tubes, or in the characteristics of (doped) silicon. All detectors that operate by means of the photoelectric effect have a characteristic cutoff wavelength. At wavelengths greater than this cutoff, photons are largely ineffective in producing photoelectrons and the resulting photocurrent.

Because of the strong spectral dependence of the photodiode, these instruments are often not direct reading and the meter reading may have to be multiplied by one of several calibration factors.

Simple silicon-detector instruments can be quite useful, when the natural spectral response of silicon (approx 200-1100 nm) is changed by an appropriate input filter to yield a flat spectral response from 450 to 950 nm (Marshall, 1980).

6.2.3 Detectors to resolve short pulses

A variety of techniques have been developed to resolve the temporal behaviour of short laser pulses. An ultrafast oscilloscope with a solid-state silicon detector or biplanar vacuum photodiode is most often used to display the pulse shape of a Q-switched (1.0-100 ns) pulse. For temporal domains of less than 1 ns, streak cameras and some non-linear optical techniques are used to resolve the structure of a train of mode-locked laser pulses.

The techniques used in photometry and radiometry are far too numerous and complex to detail here (see for example: Grum & Becherer, ed. 1979; Le Bodo, 1976; or Sliney & Wolbarsht, 1980). Differences in measured values for the same source from each of two different laboratories may arise through a problem of "geometry" or incorrect allowance for extraneous light.

6.2.4 Safety meters

At present, inexpensive, portable radiometric measuring instruments that have been designed specifically for the risk analysis of a great variety of lasers, are not available. Indeed, it is unlikely that such instruments will be made in the future, because of the great variation in exposure criteria for different wavelengths and different exposure durations. The same holds true for non-laser optical source survey instruments. However, some relatively expensive, microprocessor-based instruments have been developed to cover a wide range of measurements. Simple instruments are possible for the purpose of measuring one type of laser or optical source.

Because of the great interest in photometry, there are many satisfactory photometers that measure both luminance and illuminance and follow the CIE photopic function V_λ quite well. This is not always the case for the other weighting functions. Direct reading UVR instruments are a case in point. The principal difficulty in developing a suitable UVR instrument is the rejection of unwanted wavelengths. It is difficult to measure only the UV-B and UV-C radiation with sufficient sensitivity, while still rejecting all of the UV-A and visible light.

6.2.5 Spectroradiometers

As well as broad-band measurements, it is often necessary to measure the spectrum of a conventional source. A grating or prism monochromator is used to resolve the spectrum.

An important part of measuring the spectral distribution of a broad-band lamp source or an arc process is the specification of the desired bandwidth, and the intervals at which data will be recorded. One of the most useful approaches is to scan through a spectrum and record the detector output in analogue fashion on an X-Y recorder, rather than to record digitized data.

An X-Y recorder can indicate the bandwidth of the monochromator and may quite often indicate the regions of the spectrum in which problems may arise from stray light or extraneous signals.

The required bandwidth and sampling interval are determined by comparing the so-called "slit function" of the monochromator system with the need for sufficient spectral resolution to make possible accurate weighting against action spectra used in risk analysis.

Two common difficulties are encountered in obtaining an accurate radiometric description of a broad-band, extended source. The first problem is to achieve adequate rejection of unwanted wavelengths from the passband of the monochromator (e.g., rejecting "stray light"). The second is the proper definition of the actual or effective source size of an arc or a discharge lamp. Several other special problem areas (such as background isolation, wavelength calibration, and the proper separation of line and continuous values) are also encountered in specific situations.

6.3 Biological Weighting of Spectroradiometric Data

Many of the calculations that are useful in risk analyses require weighting of the measured spectrum against a biological action spectrum. There are several, including the erythemal and the photokeratitic action spectra, the photopic response V_λ of the eye, and the retinal photochemical injury action spectrum B_λ (Ham, et al., 1976; ACGIH, 1981; Sliney & Wolbarsht, 1980) (Fig. 9).

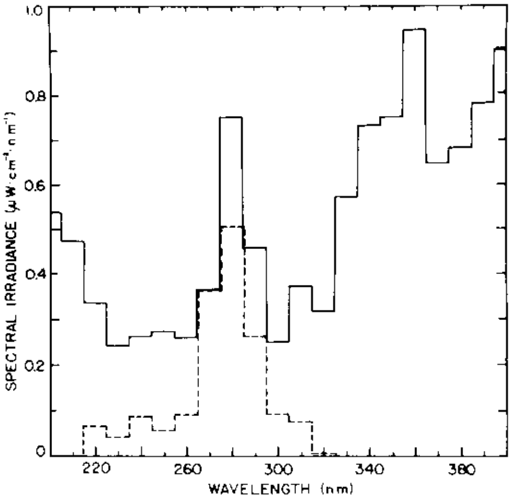


Fig. 9. Spectral irradiance of a welding arc. The arc's spectral irradiance is the solid line. The dashed line is the final, photokeratitic/erythemic-weighted spectrum used for risk analysis (From: Sliney, 1972).

7. BIOLOGICAL EFFECTS

For biological effects to take place, some of the incident radiation must be absorbed. This is known as Draper's Law (Smith, 1977).

The primary effects can be related to two general mechanisms, thermal and photochemical injury. In some special instances (as with ps pulses), non-linear effects related to the direct electric field of photons may be important. The observable biological effects are the result of secondary events. Under certain circumstances, these effects can be changed in size and direction. A number of these modifying factors are treated in the text such as pigmentation, increased body temperature, and photosensitizing substances.

7.1 Thermal Injury

Thermal injury mechanisms all require that sufficient radiant energy is absorbed in a tissue, sufficiently fast, to create a substantial increase above normal tissue temperature (typically 10 - 25 °C for short periods of a min or less). There is no dependence on photon energy, though energy must be absorbed. Heat conduction away from an irradiated area is of great importance. Thus, the presence of blood vessels and the size of the irradiated volume, as well as spectral absorption, influence the threshold of injury (Marshall, 1970).

For every short exposure, changes of state may occur so rapidly that micro-explosions (Hanson & Fine, 1968) or thermo-mechanical effects may become important (Vos, 1966a; Ham et al., 1970).

7.2 Photochemical Injury

Significant adverse effects have now been shown to result initially from a photochemical reaction rather than through a thermal damage mechanism. A photochemical reaction takes place when single photons have sufficient quantum energy to convert individual molecules to one or more different chemical molecules. A photochemical injury mechanism is demonstrated, when a reciprocity relation between irradiance (dose-rate) and exposure duration exists. That is, a constant radiant exposure (dose) is required to elicit the response over a wide variation of exposure durations, up to durations at which biological repair comes into play. An additional characteristic of any photochemical reaction is a rather steep drop-off of the action spectrum in the long wavelength end. The yield of the photochemical reaction products is propotional to the photon flux and each photon must have the amount of energy required for the reaction. At the long-wavelength end of the induced response (action spectrum), the energy of a single photon coupled with available thermal energy is generally insufficient to induce an effect.

Most photochemical effects of radiation are still not understood in detail. The relative spectral effectiveness of radiation in eliciting any particular biological effect is referred to by photobiologists as an "action spectrum". The steep slopes of many ultraviolet action spectra demonstrate the importance of not routinely extrapolating biological data concerning injury occurring at one wavelength to another wavelength, and of not assuming that any smooth curve does not have fine structures.

There are some instances where both photochemical and thermal effects contribute to the final biological effect. In general, they will enhance one another.

7.3 Threshold of Injury

All thermal injury has a macroscopically apparent threshold. Individual photons in the long-wavelength range do not have sufficient energy, normally, to cause more than temporary biological change at the molecular level. Acute pathological changes can only be demonstrated, when a sufficient thermal photon flux exists to cause temperature rises so rapid that normal heat dissipation and molecular repair are overwhelmed. In the case of photochemical injury, individual photons may alter or damage an individual molecule. However, it has been shown that many critical biomolecules have repair mechanisms to correct such damage (Smith, 1978). For very high photon flux densities the repair processes may be overwhelmed and macroscopic damage will be apparent. Occupational exposure limits can thus be set for any type of radiation in which the reciprocal relation of progressively lower power levels and longer exposure duration seems to show a marked deviation from linearity (non-reciprocity). At this irradiance level, any increases in the exposure duration may not be followed by pathological changes in the exposed tissues. This would not be accepted as a true threshold of injury by some investigators, since it could always be argued that a repair mechanism could fail. Thus, it must be admitted that there may be some finite, albeit extremely slight, risk of injury or delayed effects in a small population (Sliney & Wolbarsht, 1980).

7.3.1 Means of determining thresholds of injury

There are several different criteria that have been used in studying potential injury in tissue (Beatrice & Velez, 1978). Examples are:

(a) direct observation of irradiated tissue at low magnification
  (i) without special techniques
  (ii) with special visualization techniques such as fundoscopy or fluorescein angiography (eye) (Borland et al., 1978);

(b) histology
  (i) light microscopy
  (ii) electron microscopy (EM)
  (iii) histochemical studies;

(c) biochemical studies;

(d) electrophysiological tests (e.g., the eye) (Court et al., 1978);

(e) functional studies;

(f) epidemiological studies (i.e., skin cancer).

In setting exposure limits, all of these studies must be taken into account. In studies of skin reaction to optical radiation, the first criteria of direct observation of erythema mainly has been used, though histological and histochemical techniques have been used in a few studies. The threshold criteria just listed will be discussed briefly, as they apply to studies of injury from optical radiation.

8. EFFECTS OF OPTICAL RADIATION ON THE EYE

The attendant hazards of optical radiation vary greatly depending on the type of the source and its application. Generally, the effects of laser radiation are not different from the effects of optical radiation from a conventional source with the same wavelength, exposure duration, and given irradiance.

The effects of optical radiation on the eye vary significantly with wavelength. For this reason, the subject will be discussed in three sections. First, the effects of UVR, which are generally photochemical, on the lens and cornea will be considered. The main discussion will relate to the retinal hazard region (the visible and IR-A) where the eye is particularly vulnerable to injury, because of its imaging characteristics. Finally, IR effects on the anterior structures of the eye will be discussed.

There are many end points that can be used in establishing injury. Damage to the retina of the eye from visible radiation can appear as an altered light reflex or a white patch on the retina, visible during ophthalmoscopic examination. This criterion has been used in most injury studies. The end point could also be any histologically-defined injury seen with the light microscope; or, it could be consistently observed ultrastructural changes only visible with an electron microscope (transmission or scanning EM). Histochemical techniques can also serve to document an end point for injury. There is also the detection of functional alterations in sensory (behavioural) responses of task-oriented animal subjects, e.g., visual acuity, colour vision, dark adaptation. Often, these functional changes can also be detected by electrophysiological recordings of altered neural function within the visual system. A problem arises, when different investigators define the "threshold" for any one of these end points in different ways. The most meaningful thresholds for health criteria are those related to a persistent functional decrement.

8.1 Anatomy and Physiology of the Human Eye

In the human eye, light passes through the various ocular structures (Fig. 10) to fall on the retina, where it triggers a photochemical process that evokes the neural impulses that lead to vision. The light first passes through the structures in the anterior portion of the eye - the cornea, the aqueous humor in the anterior chamber, the pupil (and sometimes the iris), the somewhat pliable crystalline lens, then into the posterior part, the vitreous humor and the numerous layers of the retina. Only the three structures of the eye that are critical in relation to the subject of optical radiation hazards will be discussed, i.e., the cornea, the lens, and the retina.

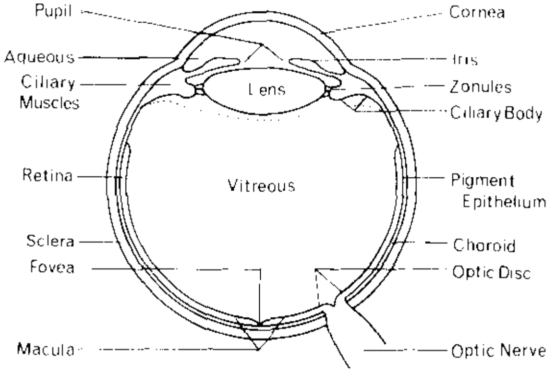


Fig. 10. Diagram of the eye showing the principal structures referred to in this text. This is a horizontal cross-section through a left eye viewed from the top of the head. (Drawing by courtesy of J. Marshall, Institute of Ophthalmology, London).

8.1.1 The cornea

The cornea and the conjuctiva of the eye are exposed directly to the environmental elements. These structures are protected from drying by the tear film, which is 6-10 μ in thickness.

The cornea and conjuctiva are tissues rich in sensory receptors and nerve endings serving as triggers of protective reflexes for mechanical and thermal agents.

As the epithelial cells must survive a harsh environment, they have a very short life span of approximately 2-5 days. If the cell death rate increases (as in photokerititis) and replacement is not in step with the loss, small erosions will develop that elicit a pain sensation.

The corneal stroma is built in a very regular fashion, which accounts for its transparency. If this regularity is distorted, i.e., by an oedema, the cornea will be less transparent or even opaque. A disturbance of the epithelium, or, more important still, of the inner cell layer of the cornea (the endothelium) will result in an oedema. Any scar formation will also alter the regular construction and hence will result in an opaque cornea. Thus serious visual handicap will be the result of irreversible corneal damage.

8.1.2 The lens

The lens is a tissue built up from cells that progressively deform to produce the lens fibres. These are arranged in an onion-like way and are covered with an elastic capsule. The capsule is attached through fine ligaments to the cilary muscle which alters the shape of the lens.

As new cells are formed, older cells become fibres and are progressively displaced towards the centre of the lens. The more superficial fibres form the cortex while the central fibres constitute the nucleus.

The lens fibres are transparent, ribbon-like cells, each of which runs completely around from the front of the lens to the back. Injury to any single fibre will, in time, extend throughout the entire fibre cell and will be more apparent in the thicker posterior part of the lens (posterior subcapsular cataract).

The lens, like the cornea, is not optically homogeneous but it is transparent in the visible range of the spectrum. However, increasing absorption of short-wavelength light occurs with age (Wolbarsht et al., 1977). The transparancy is the result of a precise relation of the various minute, optically well ordered, constituents. A disturbance of the cell elements or the fibre will result in the hydration of the fibre. Damage to the lens disturbs this relation resulting in increased light scattering. The lens becomes milky (a cataract).

8.1.3 The retina and choroid

The retina is divided into two major components - a pigmented monolayer - the retinal pigmented epithelium (RPE) and a multilayered lamina of neural cells called the neural retina. The light-sensitive cells are adjacent to the RPE.

There are two types of photoreceptor cells: rods and cones, named according to the shape of the distal (away from the synaptic end) extension of the photoreceptor cells. Light entering the eye must first pass through all of the neural retina before striking the receptor cells. In the retina, there are probably 120 million rods approximately 60 μm long and 2 μm in diameter and 6 million cones approximately 50 μm long and 3-5 μm in diameter. These receptor cells are interconnected by other specialized cells. Rods are mainly concerned with vision at low light levels and are predominant in the periphery of the retina. Cones are responsible for colour vision and high acuity visual tasks. They are most concentrated in a specialized central region of the retina, the fovea. The fovea is responsible for central vision used for reading. The anatomical aspects of the retinal pigment epithelium (RPE) and adjacent layers are of particular importance in a study of retinal injury from light sources. The outer segments of the rods and cones (the light-sensitive section of the cell) are immediately anterior to the RPE.

There are very small protrusions (microvilli) of the RPE that extend upward around the outer segments (Fig. 11). As the cones do not extend as near to the RPE as the rods, the microvilli extend out further to the cone outer segments. It is known that the RPE plays a critical role in the retinal metabolism and photochemistry, hence proper functioning of the REP is essential for normal vision. The outer segments of both rods and cones contain a stack of coin-like membranes on which their visual pigments are oriented. These discs are in a continuous state of flux. In rods, 10 - 30 new discs are made each day, while a similar number are phagocytized by the RPE cells (Fig. 11); the rate of shedding is greatest in the early morning. The life span of a disc is two weeks. The cone lamellar membranes do not form complete discs and do not appear to shed in the same manner as in the rods. The renewal activity of the cones is slower than that of the rods and it occurs at night.

Bruch's membrane separates the RPE from the blood supply in the capillary layer of the choriocapillaries which is the innermost layer of the choroid, and is where the smallest vessels are found. The choroid is an extremely vascular spongy tissue with many pigmented cells scattered throughout it. The thickness is variable; the average is about 250 μm. The blood vessels progressively increase in size towards the scleral surface. It has been suggested by Ernest & Potts (1971) that the primary function of the blood in the choroid is to keep the eye warm and at a uniform temperature. Because of this extreme vascularity, heat from laser exposures introduced in this region under steady-state conditions will do little to elevate the temperature unless high power levels are used.

Fig. 11. The outer segment of the rods. Notice the discs (made up of two lamellar membranes) stacked in the outer segments of the rod. The outermost discs are shed daily and are consumed by the pigment epithelium. The microvilli reach up from the retinal pigment epithelium to assist in this process. (Drawing by courtesy of J. Marshall & M. Rainor, Institute of Ophthalmology, London).

8.2 Spectral Properties of the Eye

To understand the biological effects of different optical spectral bands on different ocular structures, it is first necessary to consider the relative spectral absorption of the different ocular media. Fig. 12 shows the spectral absorption for each of the media.

Essentially all incident optical radiation at very short wavelengths in the ultraviolet and long wavelengths in the infrared is absorbed in the cornea. Clearly an ocular structure cannot be damaged unless optical radiation is absorbed. In some instances, particularly in the UV region, less than 1% of the total incident radiation absorbed in a structure can be significant, if the radiation contains critically effective wavelengths.

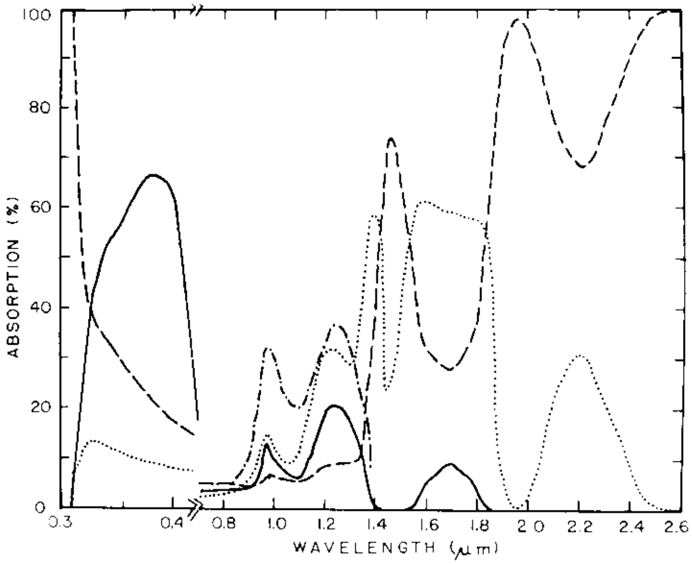


Fig. 12. The spectral absorption of the ocular media in the human eye. Each portion of the ocular media, the cornea (----), the aqueous humor (····), the lens (——) and the vitreous humor (-.-), absorb different portions of the incident optical radiation at different wavelengths. Very little is absorbed in the visible region, hence, the break in the curves. Note the strong absorption of the lens in the near-ultraviolet region and the absorption of the vitreous in the 0.86-1.35 μm infrared region (From: Sliney & Wolbarsht, 1980).

8.3 Injury to the Anterior Portion of the Eye

The anterior structures of the eye are the cornea, conjunctiva, 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 a particular keratoconjuntivitis, the ultraviolet photokeratitis or photoophthalmia (known also as "arc eye", or "welder's flash"), seldom lasts 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. Damage to this structure is of great concern in that the lens has a very slow turnover of cells. A one-day exposure may result in effects that will not become evident for many years. This is probably the case of glass-blower's or steel puddler's cataract and in cataracts caused by ionizing radiation. Long-term exposure may also result in delayed effects (Tengroth et al., 1980).

8.3.1 Effects on the cornea

UV-B and UV-C radiation are absorbed in the cornea and conjunctiva and sufficiently high doses will cause keratoconjunctivitis. The initial effect of UVR exposure is damage to, or destruction of, the epithelial cells. Under normal conditions, the corneal epithelial layer is completely replaced in a matter of a day or so. After exposure, there is a latent period, generally shorter than 12 h, which varies inversely with the exposure dose. Healing of the corneal and conjuctival epithelium takes 1-2 days. In severe exposures, damage to Bowman's membrane and the stroma may occur and is commonly followed by scar formation (usually of a milky appearance) and sometimes by invasion of the entire cornea by blood vessels. Some limited recovery of moderate damage may occur in months or years.

The action spectrum and threshold dose for ultraviolet keratoconjunctivitis (Fig. 13) have been generally agreed on by several groups of investigators.

The reciprocity or irradiance and exposure duration probably hold for time periods similar to those for ultraviolet erythema (reddening) of the skin. Specifically, it matters little whether radiant exposure of the cornea occurs in 1 µs or in 2 h. The product of the irradiance and the duration of exposure required for the same effect is a constant for periods up to several h.

The cornea is quite transparent in the IR-A. In the IR-B, there are some fairly narrow water absorption bands at 1430 nm and 1959 nm. Above 2000 nm, absorption is very high, making the cornea very susceptible to far-infrared radiation. Thus, as might be expected, the threshold for damage corresponds to the absorption bands. Radiation in the IR-C band can induce a burn on the cornea similar to that on the skin.

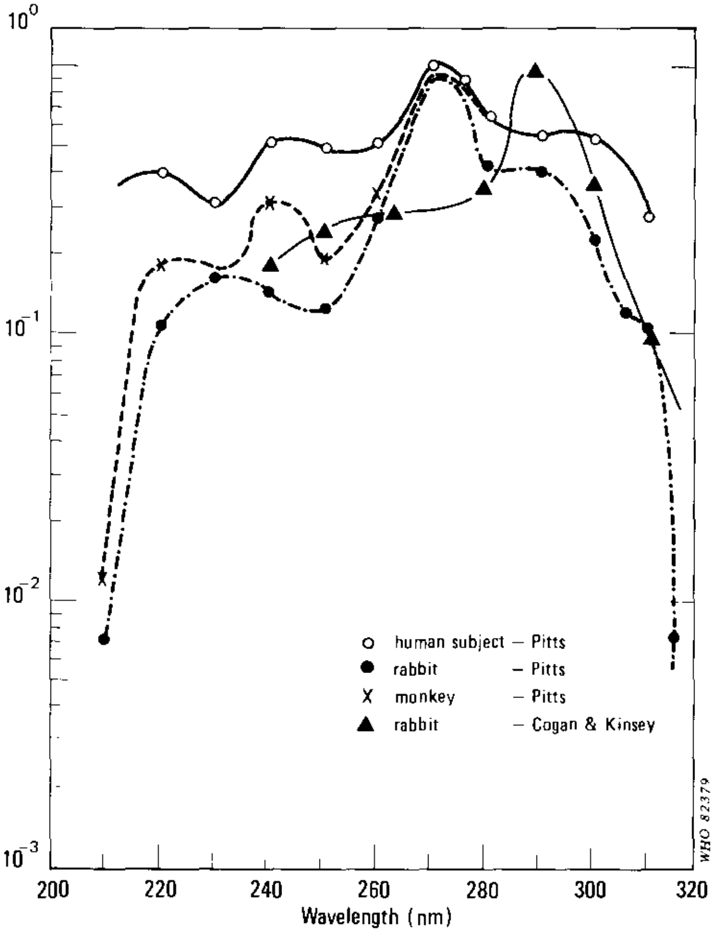


Fig. 13. Action spectra for photokeratitis by UVR. Data replotted from Pitts (1974) and Cogan & Kinsey (1946). The abscissa shows the relative sensitivity of the cornea to ultraviolet injury for human beings and monkeys. The sensitivities are not significantly different from 270-300 nm.

The nerve endings of the cornea are quite sensitive to all temperature elevations and an elevation of 10 °C causes a pain response. With full-face exposure, a temperature rise can be felt before corneal pain appears.

Infrared lasers such as CO_2 lasers (10.6^9 µm), HF, and DF lasers (2.7-4.0 µm) or CO lasers (5 µm), having cw output irradiances of the order of 10 W/cm^2 or more can produce corneal lesions by delivering at least 0.5-10 J/cm^2, before the blink reflex is operative (Fig. 14).

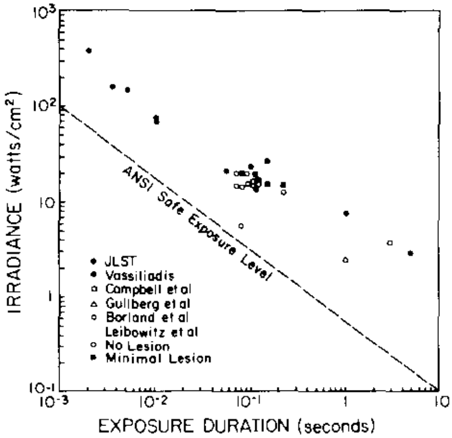


Fig. 14. Threshold for corneal injury from CO_2 laser radiation. The collected data of Stuck & colleagues of the US Army (JLST), much of it unpublished, are compared with the published data of Gullberg et al. (1967), Liebowitz et al. (1969), Borland et al. (1971), and Vassiliadis (1971). The range of scatter in the data for a specific exposure duration is thought to be mainly due to the use of different corneal image sizes, and the 2 lowest points are believed to be the result of hot spots in a multimode laser irradiance pattern (Collation of data by courtesy of Mr Bruce Stuck, Letterman Army Institute of Research, USA).

8.3.2 UVR lenticular effects

The lens has much the same sensitivity to UVR as the cornea. With exposure to UV-A, there is substantial transmission in the cornea and high absorption in the lens (Fig. 12).

Acute exposures of the order of 10^5 to 3×10^6 J/m^2 (10 to 300 J/cm^2) to radiation in the 320-400 nm region cause corneal opacities, but only exposure to radiation in the

UV-B region appears to be strongly effective in causing lenticular opacities under acute exposure conditions (Pitts et al., 1977; Zuchlich & Kurtin, 1977) (Fig. 15). The lenticular opacity may only last for a few days at low exposures.

On the other hand, since long-term exposure to UVR at ambient outdoor levels may be associated with a reduction in the ability of the lens to transmit short-wavelength light (Lerman, 1980b) and with senile cataracts (Weale, 1982), the effects of UVR on the lens may be cummulative. In addition, there is experimental evidence that UV-A radiation can induce photosensitized oxidation of the ocular lens (Zigler & Goosey, 1981).

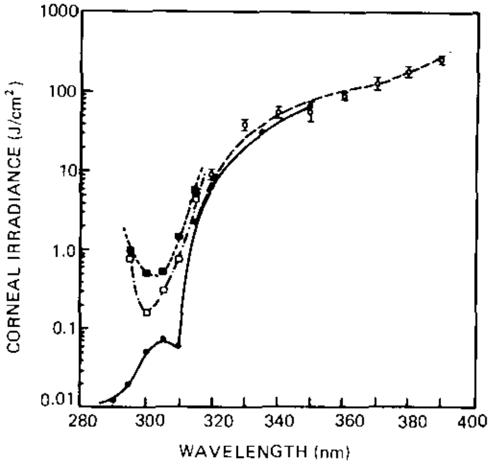


Fig. 15. Action spectra for injury to the lens and cornea by near-UVR. Lower solid curve is the data of Pitts et al. (1977), for photokeratitis; upper dashed line is the data for permanent lenticular opacities; intermediate dot-dash line with open squares is the threshold for temporary lenticular opacities. The open circles with dashed lines represent the threshold for corneal epithelial injury by Zuchlich & Kurtin (1977).

8.3.3 Infrared cataract

As explained earlier, the ocular media absorb an increasing amount of the radiant energy incident upon the cornea for increasing wavelengths in the near infrared

(IR-A). For infrared wavelengths greater than 1400 nm (IR-B and IR-C), the cornea and aqueous absorb essentially all of the incident radiation, and, beyond 1900 nm, the cornea is considered to be the sole absorber (Fig. 12). This absorbed energy may be conducted to interior structures of the eyes elevating the temperature of the lens, as well as that of the cornea itself. Heating of the iris by absorption of visible and near-infrared radiation is considered to play a role in the development of opacities in the lens, at least for short exposure times (Goldmann, 1933). Hence, it would be expected that the spectral absorption and reflectance of the iris would determine the action spectrum for this effect, for such exposure times. However, radiation of the lens alone, at lower levels for longer exposures induces cataracts in the part of the lens not covered by the iris (Vogt, 1919; Wolbarsht, 1978b). Most IR-B and IR-C lasers cause damage only to the cornea (Andeev et al., 1978; Stuck et al., 1981).

8.4 Retinal Injury

The retina is particularly vulnerable to visible and near-infrared radiation, a spectral domain known as the retinal hazard region. In most real situations, the refractive power of the cornea and lens leads to a dramatic increase in irradiance between the cornea and the retina. When an object is viewed directly, the light forms an image on the fovea, the centre of the macula, which, in man, is approximately 0.25 mm in diameter. The typical result of a retinal injury is a blind spot (i.e., a scotoma) within the irradiated area. A peripheral scotoma, unless very large, may go unnoticed. However, if the scotoma results from a lesion located in the fovea, severe visual handicap results. A central scotoma could result from looking directly at a hazardous source. The size of the scotoma depends on the irradiance relative to threshold, the angular extent of the source, and the extent of accommodation.

Laser lesions of the retina resulting from exposures to light cause many alterations in structure that can only be seen histologically (Marshall, 1973). Fig. 16 shows two typical lesions in the macula of a human being.

The subjective loss of vision associated with laser-induced retinal injury may be immediate or may develop progressively over a period of hours or days (Gabel & Birngruber, 1981). The extent to which visual function recovers depends on the size of the initial injury and the types of retinal cells involved, as well as the presence and extent of retinal haemorrhages and their subsequent degree of resorption (Boldry, et al., 1981). Retinal neurons do not undergo cell division so repair by cell replacement does not occur. In small lesions, recovery may result from either growth of new parts of damaged cells such as photoreceptor outer segments, or by migration of viable cells into the damaged site. Severe damage is irreversible and visual loss is permanent.

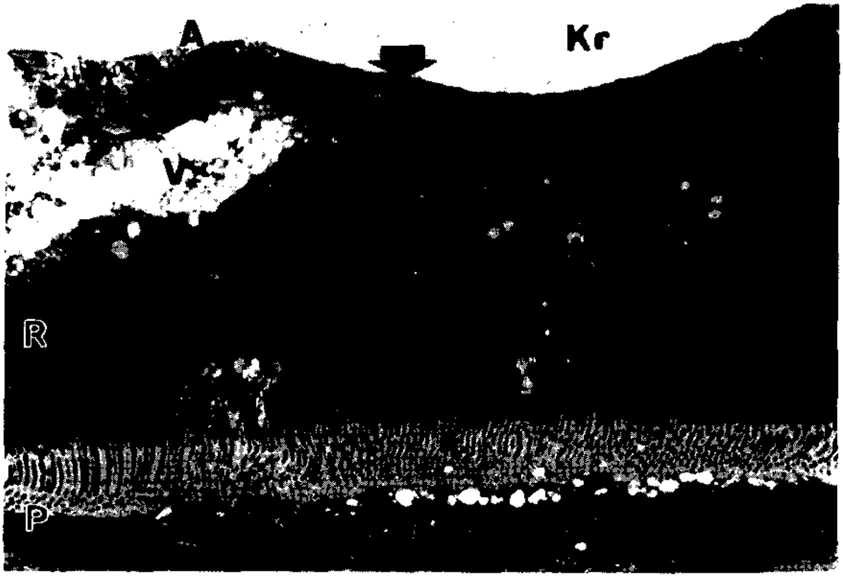


Fig. 16. Light micrograph of a histological cross-section of human retina and choroids at the fovea, 14 h after irradiation with both an argon (A) and a krypton (Kr) laser. Both laser exposures were for a 0.1-mm image size and a 0.2-s exposure duration. The estimated ocular exposure power at the cornea was 60 mW (A) at 488 nm and 110 mW (Kr) at 647.1 nm. In both lesions, there is a marked disturbance of the retinal pigmented epithelium (P) and receptor cells (R). In the argon-laser-induced lesion, there is a region of damage in the inner retinal layers (V) as a result of absorption of the blue argon laser light by the yellow macular pigment. The arrow shows the direction of incoming laser light (From: Marshall & Bird, 1979).

Only an extremely small fraction of UVR incident on the cornea reaches the retina. Nevertheless, the fraction of a percent of UV-A that reaches the retina can have adverse effects, as has been demonstrated by Zuchlich & Taboada (1978). Retinal lesions were seen following exposure to a He-Cd laser at 325 nm. Because of the strong scattering of UV-A in the ocular media, it is difficult to estimate the retinal exposure. Young rhesus monkeys were used; hence, the transmission of the ocular media was still relatively high (perhaps 1%), whereas, in adult human beings this transmission is much less.

Aphakics (persons with the lens removed) are special exceptions to this rule and would be expected to be extremely susceptible to UV-A injury of the retina, particularly as their corrective lenses will usually transmit UV-A radiation very well.

8.4.1 Determining the retinal exposure

The optical properties of the eye play an important role in determining retinal injury. Such factors as the image quality, pupil size, spectral absorption, and scattering by the cornea, aqueous, lens, and vitreous, as well as the spectral reflectance of the fundus and absorption and scattering in the various retinal layers, must be known for a definitive description of retinal exposure. These factors will be considered separately.

8.4.1.1 Pupil size

The limiting aperture of the eye determines the amount of radiant energy entering the eye, and thus reaching the retina. It is therefore proportional to the area of the pupil. For the normal, dark-adapted eye, pupil sizes range from approximately 7 to 8 mm; for outdoor daylight, the normal pupil constricts to approximately 1.6 - 2.0 mm. The ratio of areas between a 2-mm and an 8-mm pupil is: 1:16; hence, a 2-mm pupil permits the entry of one-sixteenth of the light admitted by a 8-mm pupil. The angle subtended by the source also plays a role; thus a light source of a given size and luminance causes a different pupil size, depending on the viewing distance (i.e., the image area on the retina), and the luminance of the surrounding field.

The pupilomotor reflex will constrict the pupil on exposure to a bright light source within a period of the order of 20 ms (Davson, ed., 1962). Some medications and drugs will create an abnormal pupil size. Therefore, in a large population, the pupil size may vary greatly under the same environmental exposure conditions.

8.4.1.2 Spectral transmission of the ocular media and spectral absorption by the retina and choroid

The transmission of the ocular media between 300 nm and 1400 nm has been studied by several investigators and results vary (Geeraets & Berry, 1968; Gabel et al., 1976). Fig. 17 shows a representative spectral transmission of the human ocular media.

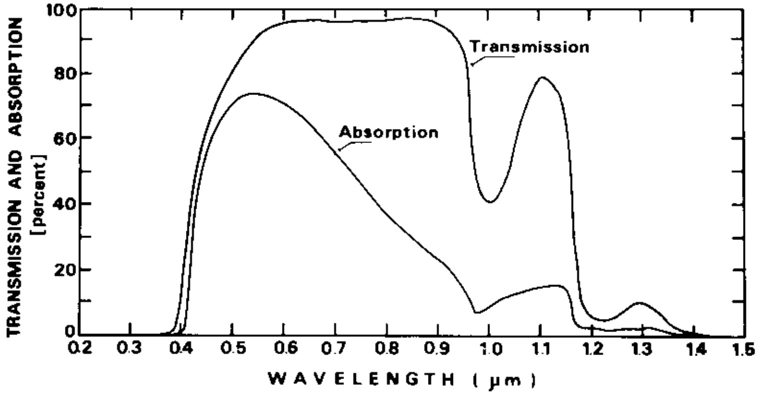


Fig. 17. Optical spectral transmission of the transparent media of the human eye and absorption of light energy in the retina and choroid as a function of equal corneal spectral irradiance. The upper curve of spectral transmission would be used in calculating a retinal irradiance. The lower curve would be used to calculate retinal absorbed dose (From: Geeraets & Berry, 1968).

There is considerable individual variability in these spectral quantities and this must be remembered when using the data in an accurate calculation. The other factor that must not be forgotten is the shift of the short-wavelength cutoff at 390-410 nm with age. The lens transmits less UV-A and blue light with increasing age as it yellows. With the above factors taken into account, it is possible to multiply the spectral absorption data of the retina and choroid by the spectral transmission data for the ocular media to arrive at an estimate of the absorbed spectral exposure dose in the retina and choroid, relative to the spectral radiant exposure at the cornea. This spectral effectiveness curve for retinal thermal injury is applicable, at least, to exposure durations of less than approximately 10 s (Fig.17).

8.4.1.3 Optical image quality

The retinal image size can be calculated for most extended sources by geometrical optics. As shown in Fig. 18, the angle subtended by an extended source defines the image size. The effective focal length of the relaxed normal eye f_e is approx 1.7 cm. With f_e known, the retinal image size d_r can be calculated, if the viewing distance r and the dimension of the light source D_L are known:

$$d_r = D_L f_e / r \qquad \text{Equation (12)}$$

From this, the quantitative relation can be obtained of retinal irradiance E_r to source radiance L (or retinal illuminance to source luminance) for small angles:

$$E_r = (\pi \cdot d_p^2\ L \cdot \tau)/4f_e^2$$

$$= 0.27\ d_p^2 \cdot L \cdot \tau (\text{for } d_p \text{ in cm}) \qquad \text{Equation (13)}$$

where d_p is the pupillary diameter and τ is the spectral transmission of the ocular media.

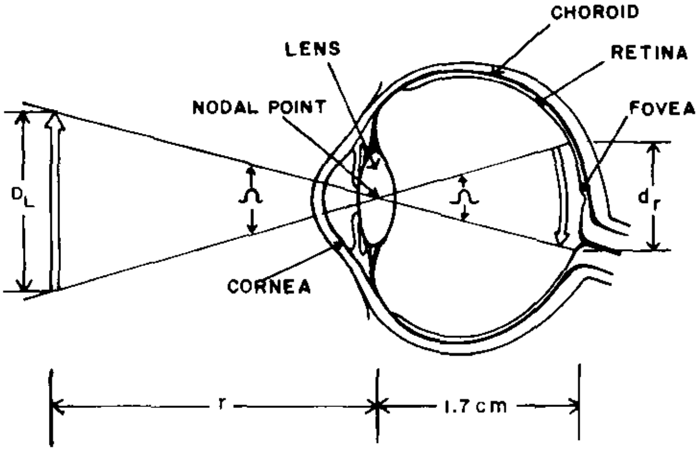


Fig. 18. The source angle at the eye. An extended source is imaged at the retina; the approximate size of the image is determined using the simple geometric relation that both the object and image subtended an angle (Ω) measured at the eye's nodal point (approximately 1.7 cm in front of the retina (From: Sliney & Freasier, 1973).

From equation 13, it is possible to define a permissible radiance (luminance) from a permissible retinal irradiance for any source of known radiance or luminance, without taking into account the viewing angle or viewing distance.

Each source point has a corresponding image point, hence, the retinal irradiance in an incremental area of the image is related to the radiance of a corresponding incremental area of the source (Hartman & Kleman, 1980).

8.4.1.4 Small images

Equation 13 breaks down for very small images (or for very small hot spots in an image), where the source or source element in question subtends an angle of less than 10 minutes-of-arc (i.e., image size is less than 50 µm).

The diffraction theory can be applied to estimate the minimal retinal image size for viewing a point source such as a laser. However, scattering in the ocular media and corneal aberations limits this image diameter to approximately 10-20 µm (Sliney, 1971).

It would be expected that, in the case of small-sized images, the retinal hazard would increase in proportion to the area of the pupil. Therefore, night-time viewing of a point source would be expected to be far more dangerous than day-time viewing; however, this is not the case, since the image blur increases with larger pupil sizes. It is worthwhile noting that the increase in irradiance from cornea to retina, when the relaxed eye views a point source, is about 10^5 (100 000 times) (Sliney & Freasier, 1973). Almost any directly viewed laser can appear as a point source.

8.4.1.5 Retinal pigment epithelium (RPE) absorption

As previously indicated, visible and near-infrared radiation is transmitted through the ocular media and is absorbed principally in the retina. The radiation passes through the neural layers of the retina before reaching the RPE and choroid. The visual pigments in the rods and cones absorb only a small fraction of light to initiate the visual response, perhaps only 5% of the total energy entering the eye. The RPE absorbs a substantial fraction of the light (about 50% in the green) and is optically the most absorbent layer. As the absorption takes place in a highly concentrated layer of melanin granules approximately 3-6 µm thick, the greatest temperature rise occurs in this layer (Bergquist et al., 1978; Birngruber, 1978). The actual size, shape, distribution, and physical characteristics of individual melanin granules become quite important for a thermal model adequate to describe the behaviour of this layer, during very short pulse exposures (Wolbarsht, et al., 1980). The granules may be heated to incandescence during Q-switched exposures, and this incandescence can be seen, if viewed during a 1064-nm (neodymium-YAG) laser experiment (Mueller & Ham, 1980, private communication).

8.4.2 Chorioretinal thermal injury

The retinal injury mechanism is considered to be largely thermal for accidental exposures from arc lamps, cw lasers, or optically aided viewing of the sun, for durations of the order of 1 ms to ≈10 s. Since injury appears to result principally from protein denaturation and enzyme inactivation, the variation in retinal temperature during and following the insult must be considered (Beatrice & Velez, 1975). Several efforts to develop mathematical models for light absorption, heat flow, and the rate-process injury mechanisms within the complex structure of the retina have been moderately successful, over periods of exposure lasting from 1 ms to 10 s (Vos, 1966a; Mainster et al., 1970; Allen, 1980).

The tissue surrounding the absorption site can much more readily conduct away the absorbed heat for images, 10-50 µm in diameter, than it can for large images of the order of 1000 µm (1 mm). Indeed, retinal injury thresholds for the same time range of 0.1-10 s are very closely related to image size, as would be expected from calculations of heat flow in the retina. For example, exposure to irradiances of 10-100 kW/m^2 (i.e., 1-10 W/cm^2) results in a minimal retinal injury threshold for a 1000-µm image, whereas an irradiance of 10 MW/m^2 (1 kW/cm^2) is required to produce the same type of threshold lesion in a 20-µm image (Ham et al., 1970).

For short-pulse durations, the reason for the spot-size dependence of the threshold is not clear (Frisch et al., 1971). The expectation, when exposure durations are of the order of 1 ms, is that injury will take place before there is significant heat flow. Indeed, the variation of threshold with pulse duration itself is also rather puzzling, especially the increase in threshold for 20-ns, Q-switched pulses over those of 1-µs duration (Hansen & Fine, 1968; Harlen, 1978; Anderson, 1980b). Obviously, the Q-switched pulse energy is being dissipated in some mechanism such as a mechanical displacement of tissue (an acoustic transient), which does not contribute to the normal thermal injury process that determines the minimum threshold.

In studies conducted by Beatrice & Lund (1979) with image distributions that were non-circular, such as line images on the retina, circular lesions were produced after long-term exposures. This would be predicted by thermal injury and heat flow calculations. Very short, Q-switched exposures with similar line image distributions produced lesions that were very elongated, as, again, would be predicted by a simple thermal model or injury. It might be thought that the contribution of acoustic transients from such a short exposure would have been to enlarge the lesion. Photoacoustic effects should certainly make a considerable contribution; but whether the acoustic transient adds to, or subtracts from the injury mechanism is not yet clear.

For short-term exposures (< 1 μs) resulting from Q-switched lasers, exploding wires, super-radiant light, and mode-locked lasers, the exposure thresholds of injury are lowest. Although it is believed that, for a Q-switched exposure, the injury mechanism is largely thermal, the effect of acoustic transients due to rapid heating and thermal expansion in the immediate vicinity of the absorption site (individual melanin granules) may play a role. For still shorter durations of exposure, direct electric field effects, Raman and Brillouin scattering, and multi-photon absorption could play a role in the damage mechanism (Greisemann & Marti, 1978; Rockerolles, 1978).

8.4.3 Location of retinal burns

As previously explained, the different regions of the retina play different roles in vision. Thus, the significance of functional loss of all or part of any one of these regions, because of retinal injury, varies. The loss of foveal vision seriously reduces visual performance. Limited peripheral loss could be unnoticed, subjectively (Kaufman, 1970; Holzinger et al., 1978).

8.5 Photochemical Retinal Injury

8.5.1 Very long-term exposure

The human retina is normally subjected to irradiances below 1 W/m^2 (10^{-4} W/cm^2), as shown in Fig. 19, except for occasional momentary exposure to the sun, welding arcs, and similar bright sources. The retinal images resulting from viewing such sources are often quite small (for example 0.15 mm for the sun) and the duration of exposure is normally limited to the duration of the blink reflex (0.15-0.2 s). Natural aversion to bright light usually limits further retinal exposures above 10^{-4} W/cm^2. Until recently, few studies of adverse retinal effects existed for the irradiance range of 10^{-4}-1 W/cm^2. Studies in this range have generally centred on flash blindness effects following light exposures lasting up to 1 s.

Exposure of large areas of the retina to moderately high luminance light of the order of 10^5 cd/m^2 (~100 μW/cm^2, i.e., 1 W/m^2 at the retina) for durations of one to several hours has been investigated in experimental animals. Generally, the light sources employed in these studies were fluorescent lamps. A thermally-enhanced photochemical mechanism of injury or a phototoxic effect appears to be most likely (Kuwabara, 1970; Noell & Albrecht, 1971). More recently, similar fluorescent light exposure of rhesus monkeys with dilated pupils showed that this effect was not limited to nocturnal animals but could conceivably be related to very lengthy direct-viewing by man (Sykes, et al., 1981). Collectively, the results of these studies suggest that abnormally high environmental levels of retinal illumination cause retinal degeneration for any species. This is particularly marked in albinos (LaVail, 1980). The effects are most dramatic when the normal, diurnal cycle of light and dark is eliminated by constant illumination (Williams & Baker, 1980). The levels and durations of these retinal exposures exceed those encountered during normal human behaviour. Only rarely have investigators reported that continual exposure to high luminance levels in the natural environment (or work environment) has elicited significant functional changes in the human retina (Livingston, 1932; Smith, 1944; Peckham & Harley, 1951; Medvedovskaja, 1970; Roger, 1973).

It has been shown that short-wavelength exposures are most effective in inducing photochemical retinal injury (Ham et al., 1976, 1978; Lawwill et al., 1977). The adverse effect is normally centralized in the pigment layer and adjacent outer receptor layer. Other retinal layers may be affected, but this generally follows changes in the RPE. The effect appears first where pigment is located.

Results of studies of photochemical retinal injury in experimental rhesus monkeys (Ham et al., 1978; Moon et al., 1978) agree with clinical experience reviewed by Sliney (1978) concerning the development of eclipse-burn photoretinitis after staring at the sun. Until recently, it was generally

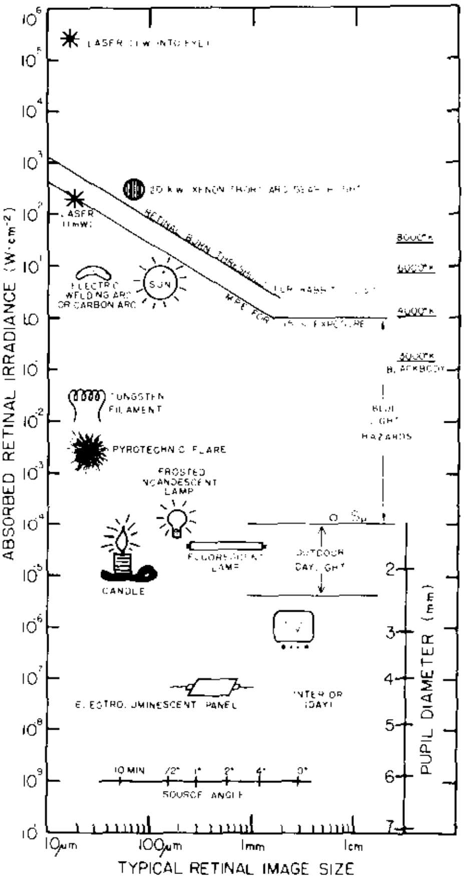


Fig. 19. Range of retinal irradiances from a variety of conventional optical sources. The eye is exposed to light souces having radiance varying from approximately 10^{-4} W/(sr·cm²) to approximately 10^{-6} W/(sr·cm²) and even less for reflected lights. The resulting retinal irradiances vary from approximately 200 W/cm² down to 10^{-7} W/cm² or less. Retinal irradiances are shown for typical image sizes for a variety of sources. The minimal pupil size was assumed for intense sources except for the searchlight (7-mm pupil). The retinal burn threshold for a 10-s exposure of the rabbit retina is shown as the upper solid line (Ham et al., 1966). The threshold for permanent shift of blue cone sensitivity in monkeys obtained by Harworth & Sperling (1975) is shown as a short-solid line labelled O-Sp, at 3 x 10^{-4} W/cm². The approximate pupil sizes are shown at the lower left based on exposure of most of the retina to light of a given irradiance (From: Sliney & Wolbarsht, 1980).

accepted that solar retinal injury was permanent; however Hatfield (1970) and Penner & McNair (1966) reported significant numbers of patients who recovered within 30 days.

Repeated exposure of large retinal areas in trained monkeys to incoherent light at retinal irradiances just above those experienced in a bright natural outdoor environment, showed a permanent decrease in functional sensitivity to blue light (Harwerth & Sperling, 1975). Exposure of the monkeys to narrow bands of wavelengths from the green to the red elicited a similar, but not lasting, reaction. These types of studies, repeated by Zwick & Beatrice (1978), showed more dramatic changes with coherent light having a speckle pattern. Prolonged erythropsia (red vision) in aphakics has also been reported following exposure to large-area, high-luminance sources with large amounts of ultraviolet such as snow fields.

Follow-up studies conducted during the 1940s showed the effects on vision of the prolonged exposure of beach lifeguards to bright outdoor environments. Temporary reductions in sensitivity for both daylight and night vision lasting for periods of several days were reported (Peckham & Harley, 1951).

There is growing concern among some investigators, who have studied the adverse retinal effects of intense light sources, that life-long exposure to light plays a role in retinal aging (Marshall, 1978). Certain age-degenerative retinal effects may be light-initiated. This opinion is prompted by the strong similarity between histological and ultrastructural changes in aged retinae and those in retinae exposed to intense light sources including disorganization of the outer receptors; depigmentation of the RPE, and a decrease in the total number of receptors. Clearly, considerably more research will be required before this opinion can be confirmed.

8.6 Flash Blindness

Flash blindness is a normal physiological process, being a transitory loss of visual function. This phenomenon is a function of the preadaptive state of the subject, the nature of the visual task (i.e., task luminance, position in the visual field, and acuity), and the luminance of the stimulating source. The mechanism is complex and not fully understood, as it involves both biochemical and neural processes. The recovery time is a measure of the degree of flash blindness.

Flash blindness has been intensively investigated, both in predicting functional loss that might be expected from a given exposure and in the design of protective devices. The response times of present-day protective devices range from a few ms down to several µs. Even within this long delay, great difficulty has been encountered in producing a device that can attenuate the luminance of the source by a factor of more than 1000.

In dealing with the data on flash blindness and attempting to relate it to retinal mechanisms, it is well to keep in mind the ideas originally expressed by Brown (1973), who showed that recovery from flash blindness did not involve a single, simple mechanism. It involves both dark adaptation and neurophysiological effects not usually seen in studies of dark adaption.

8.7 Discomfort Glare

If a very bright light source is suddenly switched on after the eye has adapted to a luminance much lower than that of the source, the viewer experiences discomfort, blinks, and tends to turn the head or eyes. This effect is much more dramatic when the ambient luminance is low. Out-of-doors, in full daylight, the luminance of a large extended source required to elicit this phenomenon is of the order of 100 000 cd/m^2 (10 cd/cm^2 or 29 000 foot-lamberts); however, the luminance of this source must be far greater to elicit a response, if the source subtends an angle of less than about 4.5 mrad (0.25 degree).

8.8 Flashing Lights

Classical studies of vision suggest that a strobe operating at 10 Hz can appear subjectively brighter than a cw source of the same peak brightness, due to the Bartley Effect for flashing light sources. Similarly, the brightness of a single pulse appears brighter than it really is; this phenomenon is termed the Broca-Sulzer Effect (Cornsweet, 1966).

Strobe light sources produce little annoyance during daylight hours. However, at night, if a strobe illuminates an area that would otherwise be dark, at a frequency of 5-10 Hz, the static objects illuminated by the strobe appear to float around, because of loss of a fixation point during off-periods of the light.

The medical literature suggests that epileptic seizures in susceptible individuals represent the only well-documented health hazard from exposure to low-frequency intermittent light. The most sensitive frequency range is from 8 to 16 Hz. Various estimates indicate that approximately 1.0% of the epileptic population, which itself constitutes less than 1.0% of the general population, will experience these "flicker-induced" seizures.

9. THE SKIN

9.1 Anatomy

The skin is normally of less interest than the eye as far as optical radiation hazards are concerned. However, under certain conditions, it may be more vulnerable than the eye, which can be protected by the blink reflex or by eye protectors.

The outermost layer, the stratum corneum or horny layer, consists of flattened, epidermal cells. They originate in the germinative layer (a single cell layer of collumnar germinative basal cells) at the bottom of the epidermis, grow, and are gradually pushed outward until they die and are flattened to form a protective layer over the living cells.

The stratum corneum is approximately 10-20 μm thick over most parts of the body, except the soles of the feet and the palms of the hand, where it is much thicker (500-600 μm).

The epidermis is relatively uniform in thickness throughout the body (50-150 μm) and can be separated into a number of layers with the growing cells in the lowest level toward the basal membrane.

Melanocytes, specialized cells that produce melanin pigment granules, are located in the basal layer of the epidermis. The melanocytes send out dendritic processes that interdigitate within the keratinocytes. Melanosomes (the pigment granules) are then transferred into the keratinocytes. The pigment is thus distributed throughout the epidermis and stratum corneum by migration of the keratinocytes.

The dermis, or corium, is thicker than the epidermis, and consists largely of connective tissue which gives the skin its elasticity and supportive strength. The sweat glands extend into the corium.

9.2 Body Heat Regulation

The skin plays a major role in the thermoregulatory system of the human body. At incident irradiances less than those that cause thermal skin burns, the body can be subjected to heat stress. Several physical means are employed by the skin for cooling (conductive, convective, and radiative cooling).

The sweat glands produce sweat, which permits evaporative cooling as well as conductive cooling. The reflectance of human skin in the far infrared is very low with a correspondingly high emissivity for wavelengths in the 8-13 μm infrared region. The high emissivity at these wavelengths permits highly efficient radiative cooling of the skin at body temperature.

Comparison of the reflectance spectrum of the human skin with the solar emission spectrum shows a striking similarity. The skin reflects largely in the visible part and near-infrared parts of the spectrum, where solar radiation is greatest, and absorbs heavily in the ultraviolet and far infrared, where there is very little solar radiation. Any good radiator of infrared energy (a black body) must have very high absorption, hence very low total reflection. The skin does indeed have low reflectance in the far infrared, and seems well adapted to the natural environment. The skin both reflects direct solar radiation and reradiates internally generated infrared radiation with the greatest possible efficiency. However, the human body is less capable of reflecting the infrared radiation from man-made sources such as fire, or more specifically from molten steel in a steel mill (Hardy, 1968; Sliney & Freasier, 1973; Stolwijk, 1980).

9.3 Optical Properties

The stratum corneum strongly absorbs actinic UVR, which causes sunburn. This layer also strongly absorbs far-infrared radiation. Melanin granules are small (1 μm diameter) and not only protect the dermis by absorption of UVR, but also by scattering optical radiation. Melanin scatters rather than absorbs radiation in the near-infrared region. For this and other reasons, near-infrared radiation penetrates deeply into the tissue. Since the index of refraction of the stratum corneum is about 1.5, the Fresnel reflective component is somewhat similar to that of glass (Fig. 2). Optical radiation incident on the skin at grazing angles of incidence is hardly absorbed at all. The relative effectiveness of optical radiation in penetrating the epidermis (and dermis) varies approximately as the cosine of the angle of incidence. Since light penetrates the outermost layers of the skin, undergoes multiple scattering, and some light is scattered back out of the skin, the skin has an appearance that cannot easily be duplicated by a non-translucent surface (Anderson & Parrish, 1981).

9.4 Penetration Depth and Reflection

Studies of the effects of pulsed visible and IR laser radiation on pig skin, performed in the 1960s, provided single-wavelength thresholds for injury for very short-term exposures of the order of 1 ms and 20 ns. For such short durations of exposure, the influence of heat flow from the absorbing site is not a major factor. For this reason, these studies aptly showed that the threshold of injury depended on the reflectance of the skin and the depth of penetration of the optical radiation into the skin (Fig. 20).

The reflectance of the skin also plays a role in determining how much radiation can effectively be absorbed. The skin's spectral reflectance varies with pigmentation and is significant only in the visible and near-infrared spectrum. The skin's reflectance at wavelengths of less than 310 nm and above 2.5 µm is less than 5%.

It must be remembered that small amounts of optical radiation penetrate deeply into the body, where it may react with photosensitive cells. This may give rise to physiological reactions of great importance, such as circadian rhythms and annual rhythms. Artificial constant irradiation may suppress the circadian rhythms, giving rise to health problems.

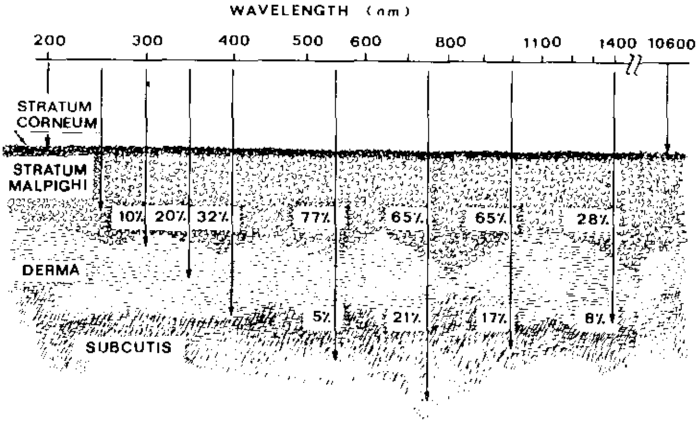


Fig. 20. Depth of penetration into the skin for different wavelengths. Values are percentages of incident radiation reaching a given layer (From: Urbach, 1969).

9.4.1 Injury to the 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, except in 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. The probability of exposure is greater for the skin than for the eye, because of the skin's greater surface area, and yet injury to the eye is still considered to be of greater significance. For a comparable area of tissue destruction, the functional losses associated with the eye are more debilitating than with the skin. Threshold injuries resulting from the short-term (i.e., less than 10 s) 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. A temporary injury to the skin may be painful, if sufficiently severe, but eventually it will heal, often without any sign of the injury. Burns (thermal injuries) to larger areas of skin are far more serious, as they may lead to serious loss of body fluids, toxaemia, and systematic infections.

Thermal injury of the skin has been the subject of many studies in this century. Hardy et al. (1956) found that 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.

Skin injury resulting from momentary but very intense exposures 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 create significant irradiances in work areas where skin injury could occur sufficiently fast to preclude a natural protective reaction to the intense heat. The flash burns that do occur are more often the result of conductive heating of the skin by exceedingly hot gases or steam. Though the eye is protected from most flash burns, the eye lid may be injured with resulting complications in vision. The threshold depends on the area of irradiated tissue. Heat conduction in tissue is far more efficient for small than for larger irradiated areas (e.g., 1 mm^2) and exposure to higher levels of irradiance would be possible before injury occurred. With extensive irradiation, injury would occur at a far lower level of irradiance. Hazardous exposure of large areas of skin is unlikely to be encountered in the normal work environment, as the heat alone from a source that could produce heat stress due to elevation of deep body temperature, would require protective measures at lower irradiance levels.

The threshold of injury obviously depends also on the duration of exposure. The previously mentioned thresholds are for just one exposure duration of 0.5 s. For exposures lasting less than 0.5 s the irradiance required for an injury would significantly increase as the duration of exposure decreased.

Studies of the process of thermal injury in skin show that the longer the length of exposure, the lower the temperature required to coagulate proteins and destroy tissue by elevated temperature. Fig. 21 shows this time dependence of threshold for white-light, arc-source burns (upper curve), and for far infrared laser radiation ,(lower curve). The explanation for these threshold differences lies in the fact that thermal injury depends on energy absorbed per unit volume (or mass) to produce a critical temperature elevation. Skin reflectance and penetration greatly influence this absorption. Skin disorders are common and may change the reaction of the skin to irradiation. Some disorders may be aggravated while, in others, healing may be enhanced by optical radiation.

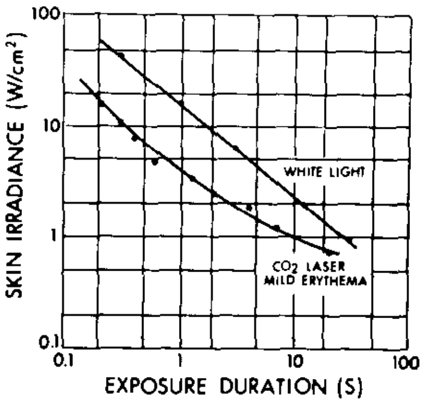


Fig. 21. Thresholds for injury for pig skin. Lower curve is for mildest erythema for 10.6-µm infrared laser radiation (Parr, 1969). Upper curve is for white-light first-degree burn thresholds based on studies by Davies (1959).

9.4.2 The sensation of warmth and heat flow

The sensation of warmth, resulting from the absorption of radiant energy, normally provides adequate warning for avoiding action to prevent thermal injury of the skin from almost all sources except the nuclear fireball and some high-powered, far-infrared lasers. The spot size dependence of this sensation is illustrated by irradiating human skin with a beam of CO_2-laser radiation at 10.6 µm. An irradiance of 0.1 W/cm^2 produces a definite sensation of warmth for beam diameters larger than 1 cm. On the other hand, one-tenth this level (0.01 W/cm^2) can readily be sensed, if the whole body or a larger portion of the body is exposed. The dependence on the size of the irradiated area results from conduction of heat away from the absorbing area, thus limiting surface temperature rise, the sensation of heat being a function of temperature rise. As noted previously, the skin temperature elevation required to elicit persistent pain (as well as thermal injury after several s) is approximately 45 °C (Hardy et al., 1956; Hardy, 1968).

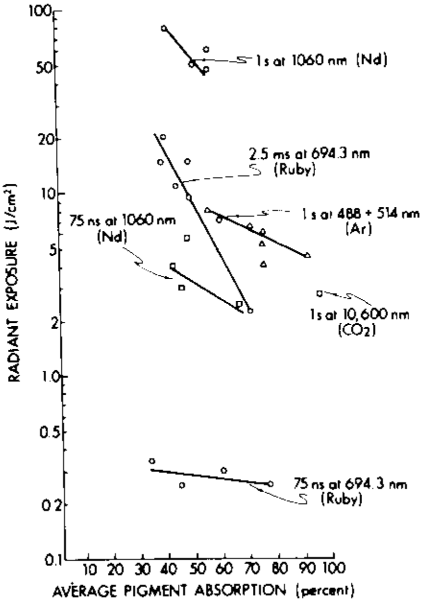


Fig. 22. Collection of laser injury threshold data for skin (From: Rockwell & Goldman, 1974).

9.4.3 Thermal injury threshold for the skin

Fig. 22 presents data reported by Rockwell & Goldman (1974), which illustrate that for some wavelengths, the threshold depends on skin pigmentation. In the far-infrared, however, all tissue absorbs heavily, not just melanin pigment granules.

9.4.4 Delayed effects

The possibility of adverse effects from repeated or long-term laser irradiation of the skin is normally discounted, if scarring does not occur (Goldman et al., 1971). Only UVR has been shown to cause long-term, delayed effects. These effects are accelerated skin aging and skin cancer. It is difficult to quantitatively evaluate the role of UVR in the induction of skin cancer. For solar radiation, the high-risk wavelengths are around 310 nm. Some attempts to calculate the dose-effect relationship have now been made (de Gruijl & van der Leun, 1980). At present, laser safety standards for exposure of the skin do attempt to take into account all of these adverse effects.

9.4.5 Ambient environment and heat stress

The temperature of the ambient environment can play a role in adding to or subtracting from, the temperature rise through continuous exposure of the skin to optical radiation, particularly if full-profile exposure is possible. Though full-profile exposure to laser radiation is uncommon, it is not impossible. Just as full-profile exposure to far-infrared radiation from furnaces can cause heat stress, so also can exposure to far-infrared laser radiation. Radiant absorption is, however, only one factor in defining heat stress (WHO Scientific Group ..., 1969; Stolwijk, 1980). Increased body temperature due to fever or other causes generally lowers the irradiance threshold of the effects of optical radiation.

Man in his natural environment is already exposed to significant optical radiation out-of-doors. The sun's irradiance on a clear day may vary from 0.5 to 1.1 kW/m^2 (50 to 110 mW/cm^2) at midday. The human body is well designed to reflect direct solar radiation. In the far-infrared region of the spectrum, the skin's low reflectance and high emissivity make it possible for the body to both radiate and strongly absorb 10-μm radiation. The ambient radiant exitance of surrounding structures and the ground may vary from 10 to 400 W/m^2 (1 to 40 mW/cm^2).

9.4.6 UVR effects on the skin

UVR gives rise to acute and delayed visible effects. The acute effects are erythema (skin reddening), thickening of the stratum corneum and pigmentation through melanogenesis (Van der Leun, 1965). The delayed effects are accelerated skin aging and carcinogenesis (Urbach, 1980).

Threshold levels for the acute effects from UV-A are generally of the order of 1000 times greater than those of UV-B or UV-C. The effects depend, to a large extent, on skin pigmentation at the time of exposure. These subjects have been dealt with in detail in the WHO Environmental Health Criteria document on ultraviolet radiation (WHO, 1980).

9.4.7 Photosensitization

Light-induced damage to the skin in the presence of certain chemicals (photosensitizers) may be considered phototoxic if an allergic mechanism is not ivolved. It 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 6.

9.4.8 Photoallergy

Photoallergy is an acquired altered capacity of the skin to react to light (and UVR) alone or in the presence of a photosensitizer. This subject has been treated in detail in WHO (1979).

Table 6. 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).

10. LASER SAFETY STANDARDS: RATIONALE AND CURRENT STANDARDS

10.1 Introduction

Laser safety standards may take several forms. The standard may be simply a list of guidelines concerning laser operation or equipment design with no mention of exposure limits or a list of personnel exposure limits (ELs) or product emission limits. Today, most safety standards incorporate all of these aspects, to some extent. This section explains the scientific and philosophical problems encountered in the development of today's standards. The distinction between occupational exposure standards and equipment performance standards will also be discussed.

Exposure limits may be applied in three general categories of standards, i.e., occupational safety and health standards, environmental quality standards and equipment performance standards. ELs for laser radiation for general population and occupational exposure were developed in many countries during the late 1960s and throughout the 1970s. A general consensus for many of these limits can be found in the 1982 draft international standard of the International Electrotechnical Commission (IEC, in preparation).

10.2 Laser Hazard Classification

It was recognized during the early development of laser safety standards that some form of risk classification was necessary. This resulted from many complaints from research scientists in the 1960s that they were being needlessly constrained in their use of small He-Ne lasers by safety specialists, who were attempting to apply guidelines originally drafted for high-power ruby and neodymium lasers.

Most recent laser safety standards therefore include a hazard classification scheme to simplify risk evaluation on which to base control measures (Harlen, 1978).

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 used, and (c) the people operating or within the vicinity of the laser beam. Hazard classification schemes differ only slightly, depending on which standard is being followed; and a brief explanation of the most commonly used hazard classification system follows.

Class 1 lasers are the lowest powered lasers. This group is normally limited to certain gallium-arsenide lasers or enclosed lasers. These lasers are not considered hazardous, even if the output laser beam can be collected by 80-mm collecting optics and concentrated into the pupil of the eye. An infrared or ultraviolet laser is Class 1 if the radiation concentrated on the skin or eye will not cause injury within the maximum exposure duration possible during one day of laser operation. Most lasers are not Class 1, however, when they are incorporated into consumer or office machine equipment, the resulting system may become Class 1. If a Class 1 system contains a more dangerous laser, the access panel to it must be interlocked or contain a warning to alert the user of the hazardous laser radiation that may be encountered, when the panel is removed.

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. This could just as readily occur by forcing oneself to stare at the sun for more than a minute or to stare into a film projector source for several minutes. This hazard, though rare, is as real as eclipse blindness, hence Class 2 lasers should have a caution label affixed to indicate that purposeful staring into the laser should 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" laser systems are those that can cause eye injury within the natural aversion response time, i.e., during the blink reflex (0.25 s). Class 3 lasers do not cause serious skin injury or hazardous diffuse reflections under normal use. However, these must have danger labels and the safety precautions required are often considerable.

Class 4 laser systems are the highest powered lasers and present the greatest potential for injury or combustion of flammable materials. They may also cause diffuse reflections that are hazardous to view or induce serious skin injury from direct exposure. More restrictive control measures and additional warnings are necessary (Clevet & Mayer, 1980).

Fig. 23 summarizes the most typical classification scheme. Some standards further refine the above classification scheme to include special subclasses referred to as Class 2a, Class 3a, and Class 4a. Relaxed restrictions may apply to these subclasses.

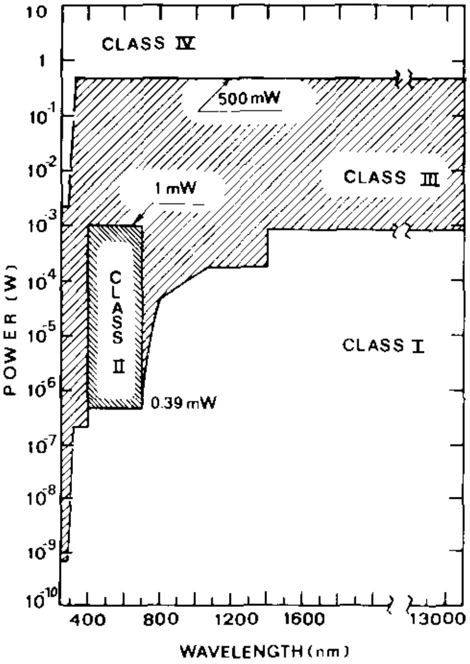


Fig. 23. Accessible emission limits (AELs) of cw lasers in perspective. The ANSI (1980) limits are the same, except for slight differences for upper limits of Class 1 cw lasers at wavelengths between 550 nm and 1400 nm; ANSI limits also exist between 200 and 250 nm and 13 μm and 1 mm (From: Sliney & Wolbarsht, 1980).

11. EXPOSURE LIMITS

11.1 Rationale

Exposure limits for lasers and optical radiation cover a wide range of wavelengths and exposure conditions, and biological effects may apply to both the eye and skin. For this reason, no single rationale can apply to all of the specific ELs. It is first important to distinguish between acute and chronic (or delayed) effects. For acute effects, thresholds exist and statistical (probit analysis) techniques can indicate this threshold with a degree of uncertainty. The method of assessing the acute effect may not always be the most sensitive, but is often chosen for reasons of simplicity and repeatability. However, this approach is feasible only because the relationship between this assessment threshold and the onset of irreversible damage is known from more rigorous studies using the most sensitive techniques for damage assessment. While a threshold for most chronic effects can be expected on theoretical grounds, this threshold can best be estimated from careful evaluation of epidemiological data. ELs are set by considering both types of effects and the degree of uncertainty in thresholds.

Scientists working in the field of ionizing radiation are used to the problems of cumulative doses and total lifetime exposure. In describing the adverse biological effects of optical radiation at wavelengths greater than 320 nm, few scientists would argue that a linear hypothesis applies with total integration of the lifetime exposure.

Optical radiation is usually absorbed in a thin layer of tissue and its effects are thermal in nature, except for the ultraviolet and visible photochemical processes. For both of these acute effects, there is a definite threshold; that is, an exposure level exists below which no adverse change will occur and no real risk exists. Of course, the threshold can vary with the individual and with environmental conditions. However, if the safety level is set well below these variations, then the exposure conditions are not hazardous.

To establish a rationale for developing exposure limits from the biological data requires careful analysis of the spread of the empirical data. These include the variables influencing potential for injury in exposed individuals, the increase in severity of injury for suprathreshold exposure doses, and the degree of repair of injury.

The accuracy of available measuring instruments and the desire for simplicity in expressing the limits have also influenced the exposure limits. It is difficult to interrelate all these factors; however, most specialists agree on the final limits, even though they may have derived them in different ways.

Separate high risk occupational limits - in contrast to exposure limits for the general population - have not been developed. Unlike ionizing radiation, there has been little debate as to whether a threshold of injury actually exists. However, there can be a debate concerning the exact "threshold values" for specific wavelengths and exposure durations. UV-B and UV-C laser radiation could, in theory, have delayed effects with no real threshold, but has nevertheless been treated like longer wavelength laser radiation. Long-term effects of low-level exposure have been indicted as a possible contributing agents in senile degenerative processes in the retina (Marshall, 1978; Young, 1981). If true, a simple threshold for these effects probably does not exist.

11.2 Assessment of the "Safety Factor"

It is very difficult to decide on the margin that should be introduced, to account for individual variation in experimental error, in deriving the ELs. This margin is sometimes loosely termed the safety factor; however, this is not correct. The threshold of injury is actually the result of considering the probit analysis of many data points.

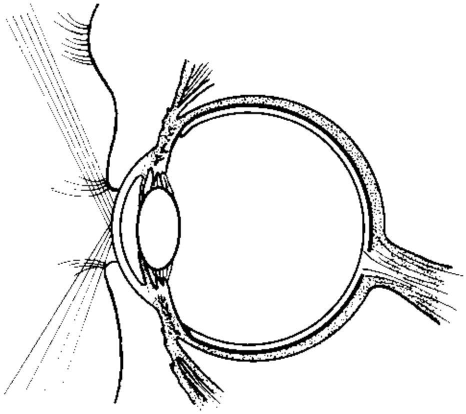
The most reliable statistical method for describing any biological threshold is probit analysis. One point on the curve, the 50% damage probability, is often assigned a special significance. This point is known as the ED_{50} and is the exposure dose required, for example, to produce an ophthalmoscopically visible (or an otherwise measurable) lesion in 50% of the exposures in a group of animals or in a single animal, where several exposures have taken place. The ED_{50} point has in the past been termed a threshold point by some investigators, though clearly the use of the term threshold in describing a 50% probability of injury seems rather inappropriate. In toxicological studies of the effects of chemicals on biological systems, the term threshold has often been used to define a 10% probability of a biological response.

Probit analysis is a powerful tool in determining safety information but was not originally applied, e.g., to retinal damage from laser exposure. In the early studies on retinal damage, the experimental design was usually such as to facilitate calculations of only the ED_{50} point.

When the data are plotted on probit paper, a line results that can easily be extrapolated to the clinical damage probability. Indeed, studies should be designed to give the slope with maximum precision. For this, two points at low and high probability, e.g., the 20% and 80% probability points are more important than the ED_{50} point. Once this information is available together with the criterion for injury and the accepted degree of safety, it is possible to determine the exposure limit. Present-day laser ELs are typically a factor of 5–20 below an ED_{50} for observable acute injury, this ratio varying as a result of functional-loss, histological, and suprathreshold-severity studies.

11.3 Environmental Considerations

Though laboratory studies of the adverse effects of optical radiation provide the basic insight into thresholds, locations, and mechanisms of tissue injury, it is difficult to extrapolate these findings to protection standards. Of special importance, is the separation of acute temporary effects from those leading to delayed permanent detrimental effects.



WHO 82805

Fig. 24. Reflection of illumination from the cornea. Oblique rays of direct sunlight are largely reflected from the cornea and are not absorbed significantly in comparison with UVR incident directly along the visual axis. This explains why ultraviolet photokeratitis occurs when the UV irradiation is nearly normal to the visual axis but not when far higher levels originate from the sun or lamps overhead (From: Sliney, 1972).

In this regard, it will also be necessary to take the actual exposure conditions of man into consideration - both from natural environmental sources or from artificial sources. It must be remembered, for instance, that terrestrial solar radiation changes, both in total irradiance and in spectral distribution, throughout the day. Furthermore, the direction of illumination is of great importance because of the reflection from the cornea, as seen in Fig. 24.

11.4 Limiting Apertures

One difficulty in developing ELs is the specification of the limiting aperture over which the values must be either measured or calculated. For the skin, where no self-focusing effect takes place, the smallest feasible aperture is most desirable. Unfortunately, the smaller the aperture, the higher the sensitivity required for the measuring instrument and the greater the inaccuracy that will result from calibration problems associated with diffraction and other optical effects. Since various biological effects are influenced differently by the size of an incident beam, the limiting aperture varies for different conditions.

11.4.1 The 1-mm aperture

A 1-mm aperture has been typically considered the smallest practical aperture size for specifying ELs. Under continuous exposure conditions, heat flow and scattering within the layers of the skin tend to eliminate any adverse effects from hot spots smaller than 1 mm in diameter.

11.4.2 The 11-mm aperture

Wavelengths greater than 0.1 mm present a further difficulty. At these far-infrared, submillimetre wavelengths, a 1-mm aperture creates significant diffraction effects and calibration becomes a problem. Hot spots predicted by physical optics are larger than at shorter wavelengths. For these reasons, a 1-cm square, or 11-mm diameter (1 cm^2) circular aperture has typically been chosen as the limiting aperture for wavelengths between 0.1 mm and 1 mm.

11.4.3 The 7-mm aperture

For ocular ELs in the "retinal hazard region", from approximately 400 nm to 1400 nm, the averaging (sampling) aperture is determined by the pupil of the eye. A pupil size of 7-mm has been decided as typical, though not without a great deal of debate.

11.4.4 The 80-mm aperture

A still larger measuring aperture of 80 mm is conventionally used for power and energy measurements to account for intrabeam viewing conditions with optical telescopes or binoculars.

11.5 Spectral Dependence of Exposure Limits

Eye and skin injury thresholds vary considerably with wavelength. To establish the spectral dependence of ELs, it is generally accepted that the biological data can only be followed approximately. The ELs have been adjusted for variation in wavelength, but do not precisely follow the empirical biological data. Fig. 25 shows an example of theoretical variation of susceptibility modified to provide a spectral correction factor, useful for calculating the EL.

Fig. 25 provides the reciprocal of the product of the relative spectral transmission of the ocular media with the retinal absorption (Fig. 17). This indicates the relative effectiveness of different wavelengths for causing retinal thermal injury. However, this curve still does not show the relative spectral hazard to the lens of the eye in the near infrared. Also plotted in this graph is the spectral modification factor used for pulsed retinal exposure limits in the American National Standards Institute standard (ANSI, 1980). This modification factor is used for other limits for protection against thermal injury. Because of variation of threshold with image size and variation of image size with wavelength, a further increase in the ratio between IR-A and visible ELs is given in the ANSI Z-136.1 standard for IR-A wavelengths between 1050 nm and 1400 nm, but only for durations of exposure of less than 0.05 ms.

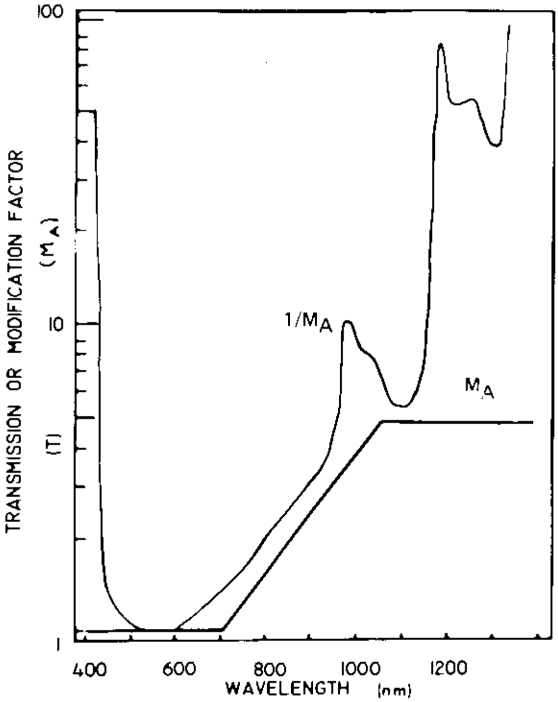


Fig. 25. Retinal absorption (A) and the spectral modifying or correction factor (M_A or C_A). The upper curve is the reciprocal of the retinal absorption (1/A) spectrum relative to corneal irradiance. It may also be thought of as the reciprocal of the action spectrum for retinal thermal injury. A more useful spectral modifying factor, M_A, is the lower function composed of straight-line segments to approximate (1/A) (Adapted from: Suess, ed., 1982).

11.6 Repetitively Pulsed Laser Exposure

The values in the present standards for repetitive ocular exposure have been based on limited data and developed from purely empirical extrapolations. The cumulative effect of repetitive pulses was considered to be a function of the duration of the individual pulse in a pulse train. For short pulses (duration less than 10 μs), the EL for a single pulse was multiplied by a correction factor to provide a reduced exposure on a per-pulse basis. This value was then compared with the EL values for the total energy and for a total exposure of the duration of the entire train of exposures, to determine which limit would apply. For a train of pulses, where the individual pulse duration exceeded 10 μs, a criterion based on total on-time T_t of the train of pulses was applied to each individual pulse. This resulted in a reduced EL for each pulse. However, all of these approaches were based largely on studies in which the eye of the rhesus monkey was exposed to single pulses of "minimal image size".

More recent studies (Greiss et al., 1980) suggest that the pulse thresholds add as a function of $N^{-1/4}$ for small image sizes, but not for large image sizes. The letter N refers to the number of pulses in the train.

11.7 Restrictions for Special Applications (Class 3a)

The low risk of Class 2 lasers differs little from the lack of risk of Class 1 lasers, in practice. Class 2 lasers emit a power of 0.4 μW - 1 mW, a light level difficult to stare into because of the aversion response. The risk increases significantly, when the eye is unable to protect itself, as occurs when a visible laser beam irradiance exceeds 2.5 mW/cm^2 (i.e., a total of 1 mW entering the 7-mm pupil of the eye by either unaided or optically-aided viewing). The laser classification denotes risk, when the laser is viewed under worse-case conditions. In practice, if worst-case conditions are seldom experienced, further relaxations can be applied for certain limited applications. An example of this is the 5 mW limit applied to the total power for surveying/alignment of lasers. This recognizes that "moderate-risk" (Class 3) lasers are sometimes needed in this application but that the benefit in this application outweighs the moderate risk of the 1-5 mW visible laser group (US DHEW, 1979).

11.8 Present Standards of Exposure

11.8.1 Laser standards

A number of national and international standards have been promulgated that show only minor differences, some of which may be partly resolved, when future editions of the American National Standards Institute (ANSI), British Standards Institute (BSI), GOST, and the International Electrotechnical Commission (IEC) appear.

Table 7. Exposure limits for direct ocular exposures (intrabeam viewing) from a laser beam

Spectral region	Wavelength	Exposure time (t) seconds (s)	Exposure limits
UVC	200 nm to 280 nm	10^{-9} to $3x10^{4}$	3 mJ/cm^{2}
UVB	280 nm to 302 nm	10^{-9} to $3x10^{4}$	3 mJ/cm^{2}
	303 nm	10^{-9} to $3x10^{4}$	4 mJ/cm^{2}
	304 nm	10^{-9} to $3x10^{4}$	6 mJ/cm^{2}
	305 nm	10^{-9} to $3x10^{4}$	10 mJ/cm^{2}
	306 nm	10^{-9} to $3x10^{4}$	16 mJ/cm^{2})
	307 nm	10^{-9} to $3x10^{4}$	25 mJ/cm^{2})
	308 nm	10^{-9} to $3x10^{4}$	40 mJ/cm^{2}) not to
	309 nm	10^{-9} to $3x10^{4}$	63 mJ/cm^{2}) exceed
	310 nm	10^{-9} to $3x10^{4}$	100 mJ/cm^{2}) $0.56t^{1/4}$
	311 nm	10^{-9} to $3x10^{4}$	160 mJ/cm^{2}) J/cm^{2}
	312 nm	10^{-9} to $3x10^{4}$	250 mJ/cm^{2})
	313 nm	10^{-9} to $3x10^{4}$	400 mJ/cm^{2})
	314 nm	10^{-9} to $3x10^{4}$	630 mJ/cm^{2})
	315 nm	10^{-9} to $3x10^{4}$	1.0 J/cm^{2})
	315 nm to 400 nm	10^{-9} to 10	$0.56t^{1/4}$ J/cm^{2}
UVA	315 nm to 400 nm	10 to 10^{3}	1.0 J/cm^{2}
	315 nm to 400 nm	10^{3} to $3x10^{4}$	1.0 mW/cm^{2}
Light	400 nm to 700 nm	10^{-9} to $1.8x10^{-5}$	$5x10^{-7}$J/cm^{2}
	400 nm to 700 nm	$1.8x10^{-5}$ to 10	$1.8(t/\sqrt[4]{t})$ mJ/cm^{2}
	400 nm to 549 nm	10 to 10^{4}	10 mJ/cm^{2}
	500 nm to 700 nm	10 to T_1	$1.8(t/\sqrt[4]{t})$ mJ/cm^{2}
	550 nm to 700 nm	T_1 to 10^{4}	$10C_B$ mJ/cm^{2}
	400 nm to 700 nm	10^{4} to $3x10^{4}$	C_B µW/cm^{2}

Table 7. (contd).

Spectral region	Wavelength	Exposure time (t) seconds (s)	Exposure limits
IR-A	700 nm to 1049 nm	10^{-9} to $1.8\text{x}10^{-5}$	$5\ C_A\text{x}10^{-7}$ J/cm^2
	700 nm to 1049 nm	$1.8\text{x}10^{-5}$ to 10^3	$1.8C_A(t/\sqrt[4]{t})$ mJ/cm^2
	1050 nm to 1400 nm	10^{-9} to $5\text{x}10^{-4}$	$5\text{x}10^{-6}$ J/cm^2
	1050 nm to 1400 nm	$5\text{x}10^{-4}$ to 10^3	$9(t/\sqrt[4]{t})$ mJ/cm^2
	700 nm to 1400 nm	10^3 to $3\text{x}10^4$	$320\ C_A$ μW/cm^2
IR-B & C	1.4 μm to 10^3 μm	10^{-9} to 10^{-7}	10^{-2} J/cm^2
	1.4 μm to 10^3 μm	10^{-7} to 10	$0.56\ \sqrt[4]{t}\ )$ J/cm^2
	1.4 μm to 10^3 μm	10 to $3\text{x}10^4$	0.1 W/cm^2

The formula for Correction Factor C_A (Fig. 25) is

$C_A = 1$ for wavelength (λ) of 400 nm - 700 nm;
$C_A = 10^{(0.002[\lambda-700\ \text{nm}])}$ for 700 nm $< \lambda <$ 1050 nm; and
$C_A = 5$ for $1050 < \lambda < 1400$ nm.
$C_B = 1$ for $\lambda = 400 - 550$ nm;
$C_B = 10^{(0.015[\lambda-550])}$ for $\lambda = 550 - 700$ nm.
$T_1 = 10$ s for $\lambda = 400 - 550$ nm; $T_1 = 10 \text{ x } 10^{(0.02[\lambda-550])}$ for $\lambda = 550 - 700$ nm.

For $\lambda = 1.5$ to 1.6 μm increase EL by 100 for periods of less than 1 μs.

Table 11. Selected values of the minimum angle of an extended source that may be used for applying extended source ELs

Exposure duration (s)	Angle α (mrad)
10^{-9}	8.0[a]
10^{-8}	5.4[a]
10^{-7}	3.7[a]
10^{-6}	2.5[a]
10^{-5}	1.7[a]
10^{-4}	2.2
10^{-3}	3.6
10^{-2}	5.7
10^{-1}	9.2
1.0	15
10	24
10^{2}	24
10^{3}	24
10^{4}	24

[a] For exposure durations of less than 0.05 ms α_{min} is less for λ = 1050 to 1400 nm.

Tables 7-11 present the most recent set of occupational ELs, those promulgated by the ANSI Z-136.1 Standard (ANSI, 1980) and the threshold limit values (TLVs) of the American Conference of Governmental Industrial Hygienists (ACGIH, 1981), those given in the draft International Electrotechnical Commission standard (IEC, in preparation), and the values mentioned as "best available" in Suess, ed. (1982).

11.8.1.1 Exposure limits

The tables and figures presented in this section are from the ACGIH booklet Threshold limit values for chemical substances and physical agents in the workroom environment with intended changes for 1981 (ACGIH, 1981). For this criteria document, the term "exposure limit" is used.

While the concept of an EL (or TLV) is that neither the general population nor workers should be intentionally exposed above the limit, accidental over-exposure may not always result in injury. It is helpful to quote the TLV preamble given by ACGIH: "The threshold limit values are for exposure to laser radiation under conditions to which nearly all workers may be exposed without adverse effects. The values should be used as guides in the control of exposures and should not be regarded as fine lines between safe and dangerous levels. They are based on the best available information from experimental studies".

11.8.1.2 Repetitively pulsed lasers

Since the additive effects of multiple pulses are not fully understood, caution must be used in the evaluation of such exposures. The exposure limits for irradiance or radiant exposure in multiple pulse trains have the following limitations:

(a) The exposure from any single pulse in the train is limited to the exposure limit for a single comparable pulse;

(b) The average irradiance for a group of pulses is limited to the EL (as given in Tables 7, 8, and 9) of a single pulse of the same duration as the entire pulse group;

(c) When the instantaneous Pulse Repetition Frequency (PRF) of any pulses within a train exceeds 1, the EL, applicable to each pulse, is reduced by a factor (C_p), as shown in Fig. 26 for pulse durations of less than 10^{-5} s. For pulses of greater duration, the EL of a pulse in the train is found by dividing the EL of a longer pulse of duration Nt by N, where N is the number of pulses in the train, t is the duration of a single pulse in the train, and the EL of Nt is the exposure limit of one pulse having a duration equal to Nt s. The "pulse" duration Nt is known as the TOTP (total on time pulse), T_t in the ANSI standard. For a short group of N pulses, the reduced EL will not be less than the single pulse EL divided by N.

Repeated exposures at repetition rates of less than 1 Hz should be considered additive over a 24-h period.

Table 8. Exposure limits for viewing a diffuse reflection of a laser beam or an extended source laser.

Spectral region	Exposure limits	Wave-length	Exposure time (t) (s)
UV	200 nm to 400 nm	10^{-9} to $3x10^{4}$	Same as Table 7
Light	400 nm to 700 nm	10^{-9} to 10	$10\ \sqrt[3]{t}\ J/(cm^2 \cdot sr)$
	400 nm to 549 nm	10 to 10^{4}	$21\ J/(cm^2 \cdot sr)$
	550 nm to 700 nm	10 to T_1	$3.83\ (t/\ \sqrt[4]{t}\ )\ J/(cm^2 \cdot sr)$
	550 nm to 700 nm	T_1 to 10^{4}	$21/C_B\ J/(cm^2 \cdot sr)$
	400 nm to 700 nm	10^{4} to $3x10^{4}$	$2.1/C_B x10^{-3} W/(cm^2 \cdot sr)$
IR-A	700 nm to 1400 nm	10^{-9} to 10	$10C_A\ \sqrt[3]{t}\ J/(cm^2 \cdot sr)$
	700 nm to 1400 nm	10 to 10^{3}	$3.83C_A(t/\sqrt[4]{t})J/(cm^2 \cdot sr)$
	700 nm to 1400 nm	10^{3} to $3x10^{4}$	$0.64C_A\ W/(cm^2 \cdot sr)$
IR-B & C	1.4 µm to 1 mm	10^{-9} to $3x10^{4}$	Same as Table 7

C_A, C_B, and T_1 are the same as in footnote to Table 7.

Table 9. Exposure limits for skin exposure from a laser beam

Spectral region	Wave-length	Exposure time (t) (s)	Exposure limits
UV	200 nm to 400 nm	10^{-9} to $3x10^{4}$	Same as Table 7
Light &	400 nm to 1400 nm	10^{-9} to 10^{-7}	$2C_A$ x $10^{-2}\ J/cm^2$
IR-A	400 nm to 1400 nm	10^{-7} to 10	$1.1C_A\ \sqrt[4]{t}\ J/cm^2$
IR-B & C	1.4 µm to 1 mm	10^{-9} to $3x10^{4}$	Same as Table 6

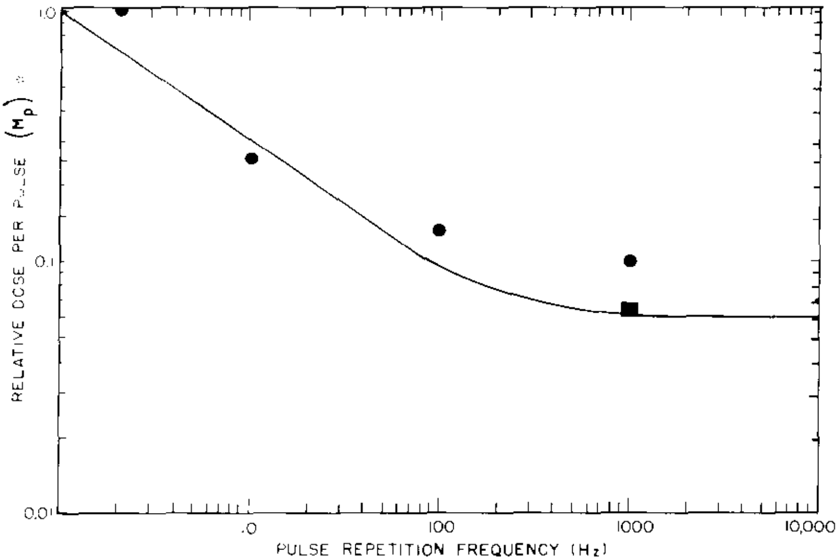
C_A = 1.0 for $\lambda = 400 - 700$ nm; see Fig. 25 for value at greater wavelengths.

NOTE: To aid in the determination of ELs for exposure durations requiring calculations of fractional powers, Fig. 25 may be used.

Table 10. Additivity of effects on eye and skin from different spectral regions[a]

Spectral region	UV-C and UV-B 200-315 nm	UV-A 315-400 nm	Visible and IR-A 400-1400 nm	IR-B and IR-C 1400-10^6nm
UV-C and UV-B 200-314 nm	eye skin			
UV-A 315-nm		eye skin	skin	eye skin
Visible and IR-A 400-1400 nm		skin	eye skin	skin
IR-B and IR-C 1400-10^6nm		eye skin	skin	eye skin

[a] Some synergism is expected when 2 spectral bands illuminate the same tissue simultaneously. Exact formulae to treat these additive effects have not been developed for most standards.



* MF for PRF >1000 Hz is 0.06

Fig. 26. Modifying factor. Modification factor C_p (ordinate; line) is used for calculating the reduced single-pulse EL of a pulse in a train of pulses, if the pulse duration is less than 10^{-5} s. C_p (solid line) is 0.06 for a PRF (F) greater than 1 kHz. Experimental biological data for argon (o) and neodymium (□) repetitive pulse trains of 0.5-s total exposures by Skeen et al. (1972) are shown for comparison.

11.8.1.3 Extended source laser exposure

The ELs for "extended sources" apply to sources that subtend an angle greater than α_{min} (Table 11), which varies with exposure duration (t). This angle is not the beam divergence of the source. Limits expressed as either radiance or integrated radiance may be averaged over an angle as great as α_{min} or sampled over a source area as small as 1 mm in diameter.

Table 8 should be used to calculate the EL (as a brightness) for an extended source such as a holographic display or a screen illuminated by a static or scanning laser beam. The values in Table 8 apply to viewing a diffuse reflection from a laser beam, where a truly extensive retinal image occurs. Some laser devices are intentionally designed as diffuse sources (e.g., beacons) to radiate monochromatic optical power and still remain Class 1. The extended source ELs of Table 8 apply to the direct output of the laser system if the source is diffuse. As a further example, a low-quality semiconductor diode laser or a semiconductor laser diode array may be "extended". In this case, the average radiance of the diode array might be applied against the extended source EL. It must be emphasized that, in almost all instances, a laser source is still a "point source" within definitions used by the standards.

To aid in determining when extended-source ELs are applicable, the concept of α_{min} was invented. The value of α_{min} is a linear angle expressed in mrads and is the minimum viewing angle at which extended-source ELs apply. For viewing distances beyond the location where the source angle subtends an angle less than α_{min}, the source is considered from a safety standpoint to be a "point source" and the intrabeam viewing criteria of Table 7 apply. Because the extended source ELs and the point source ELs do not vary in exactly the same way as a function of pulse duration (or exposure duration) (t), this limiting angle α_{min} varies with exposure duration (Table 11). Indeed α_{min} is nothing more than:

$$\alpha_{min} = (4/\pi)\ (\text{EL [point source]/EL [extended source]})^{1/2}$$

Equation (14)

11.8.1.4 Restriction on ELs

The ELs were developed for conditions of occupational exposure and the underlying assumption is that nearly all workers may be exposed to the levels without adverse effects. However, some photosensitive individuals may experience adverse effects at lower levels for wavelengths of less than 500 nm.

11.8.2 Standards for non-laser sources

11.8.2.1 Introduction

The most commonly occurring hazardous effects from arcs and high-intensity lamps are ultraviolet erythema and photokeratitis. Retinal injury from such sources is seldom recognized though it is not unheard of. Considering that much was known about optical radiation hazards prior to the development of the laser, it seems somewhat surprising that ELs and safety standards for lamps and arcs did not exist prior to laser safety standards. Standards were developed empirically for eye protective filters for welders, but were not based on ELs.

Bright sources emitting cw light elicit a normal aversion or pain response that serves to protect the eye and skin from injury. Visual comfort has often been used as an approximate hazard index. Eye protection baffles and other controls have been provided on this basis. The determination of shade number for welding goggles is one example. The present standards for welding goggle specifications were simply based on a comfort index for viewing the arc. Since UVR and infrared radiation were considered to be of no value in viewing welding arcs, they were deliberately filtered out. UV and IR filtration factors exceeding those for light were specified as the best that could be achieved with readily available glass materials.

Quantitative guidance is often sought with regard to both eye and skin safety in relation to new sources of radiation. Though several safety limits for optical radiation have been proposed in the literature within recent years, it is only for the ultraviolet spectral region that there have been any widely accepted limits, but even these have provoked controversy.

ELs applicable to broad-band sources such as open-arc processes, arc lamps, incandescent lamps, and gas discharge lamps may differ considerably from laser ELs for two main reasons. The first is that the source normally emits in a broad spectral band. Therefore, effects due to narrow wavelength absorption or coherence, which are potentially of concern with laser exposure, are not likely to have a substantial impact on the hazards from a broad-band source. All of the composite optical spectral bands for conventional sources must be evaluated separately. For instance, ultraviolet hazard criteria differ completely from light hazard criteria.

The second major difference between laser and non-laser health criteria results from the fact that most hazardous laser exposures result from viewing a point source, whereas hazardous lamps and arcs are usually extended sources. In the development of a new lamp, any unwanted ultraviolet radiation should be filtered out by the choice of an appropriately thick glass envelope, based on computation, and assessments of both acute and chronic risks and actual UVR measurements. In the past, manufacturers have watched for acute effects in people exposed to prototype lamps.

The radiance from a conventional source is generally physically limited compared with that of a laser source. The exposure of an individual from a lamp source is seldom likely to exceed that under normal operating conditions. Laser output powers can change enormously with slight changes in the laser cavity.

11.8.2.2 UVR Criteria

As previously noted, the health hazards associated with UV-B + C exposure of the eye and skin are often considered separately from those associated with UV-A.

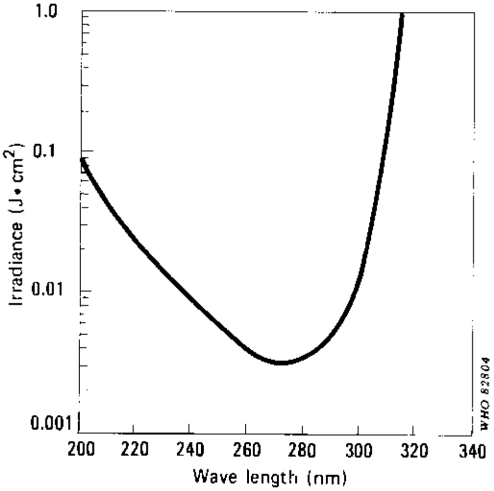


Fig. 27. Threshold limit values for UVR.

In the development of health criteria for industrial UVR exposure, the prime consideration must be ELs that would prevent unwanted acute and chronic effects. At the same time, simplicity of measurement and application are important. If a single instrument having a spectral response weighted against the envelope action spectrum for UV-B and UV-C injury were developed, then a direct measurement could be made of the UVR risk. Without a spectrally integrating instrument, the spectral irradiance from the source of interest can be measured at the point of greatest concern (normally the nearest point of access). This spectral irradiance E_λ is then weighted by the ACGIH envelope action curve S_λ (Fig. 27, Table 12 and 13) for wavelengths of less than 320 nm.

Table 12. Relative spectral effectiveness for selected wavelengths

Wavelength (nm)	E_λ (mJ/cm²)	Relative spectral effectiveness S_λ
200	100	0.03
210	40	0.075
220	25	0.12
230	16	0.19
240	10	0.30
250	7.0	0.43
254	6.0	0.5
260	4.6	0.65
270	3.0	1.0
280	3.4	0.88
290	4.7	0.64
300	10	0.30
305	50	0.06
310	200	0.015
315	1000	0.003

Table 13. ACGIH ultraviolet exposure limits

Duration of exposure per day	Effective irradiance, E_{eff} ($\mu W/cm^2$)
8 h	0.1
4 h	0.2
2 h	0.4
1 h	0.8
30 min	1.7
15 min	3.3
10 min	5
5 min	10
1 min	50
30 s	100
10 s	300
1 s	3000
0.5 s	6000
0.1 s	30 000

All the preceding ELs for ultraviolet energy apply to sources that subtend an angle less than 80°. Sources that subtend a greater angle need to be measured only over an angle of 80°.

ACGIH recommended values: The threshold limit values for occupational exposure to UVR incident on skin or eye, where irradiance values are known and exposure time is controlled, are as follows:

1. For the near ultraviolet spectral region (320-400 nm), total irradiance incident on the unprotected skin or eye should not exceed 1 mW/cm^2 for periods greater than 10^3 s (approximately 16 min) and for exposure times less than 10^3 s should not exceed one J/cm^2.
2. For the actinic ultraviolet spectral region (200-315 nm), radiant exposure incident on the unprotected skin or eye should not exceed the values given in Table 10, within an 8-h period.
3. To determine the effective irradiance of a broad-band source weighted against the peak of the spectral effectiveness curve (270 nm), the following weighting formula should be used:

$$E_{eff} = \sum E_\lambda S_\lambda \Delta\lambda \quad \text{where:}$$

E_{eff} = effective irradiance relative to a monochromatic source at 270 nm in W/cm^2 ($J/s/cm^2$)

E_λ = spectral irradiance in $W/cm^2/nm$

S_λ = relative spectral effectiveness (unitless)

$\Delta\lambda$ = band width (nm)

4. Permissible exposure time in seconds for exposure to actinic ultraviolet radiation incident on the unprotected skin or eye may be computed by dividing 0.003 J/cm² by E_{eff} in W/cm². The exposure time may also be determined using Table 13, which provides exposure times corresponding to effective irradiances in μW/cm².

Conditioned (tanned) individuals can tolerate skin exposure in excess of the TLV without erythemal effects. However, such conditioning may not protect persons against skin cancer.

For the UV-A, ACGIH considered it reasonable to propose a guideline for ocular exposure so low that no conceivable thermal or photochemical injury mechanisms were likely to be demonstrated. To prevent thermal injury, it was assumed that, for exposure durations of less than 100 s, the eye should be protected against exposures above 10 kJ/m² (1 J/cm²). Because of the lack of adverse effects reported in individuals working with ultraviolet "black light" sources at levels of 1 mW/cm² (or above), it was presumed that a level of 1 mW/cm², the approximate level of exposure of the eye to UVA-A in outdoor reflected sunlight, would be a reasonable upper limit for exposures lasting 1000 s or more. The skin exposure limit could presumably be increased by a factor of 5 for the longer exposure durations. To avoid thermal effects at very short exposure durations, the total UVR corneal irradiance was also limited to 1 W/cm². It is now known that photochemical effects occur in both the eye and skin and that total daily doses of 20-100 J/cm² cause acute corneal opacities (Pitts et al., 1977; Zuchlich & Kurtin, 1977) and skin erythema from the UV-A (Parrish et al., 1978). Hence, these UV-A criteria must be applied with great caution for conditions of very long (exceeding 4 h) exposure.

11.8.2.3 Retinal health criteria

Laser protection standards incorporate several simplifications that depend on the single-wavelength and point-source characteristics of the laser. These standards may provide a too conservative estimate of the real risk, if laser criteria are applied to broad-band sources. No official standards exist for the retinal risk evaluation of a broad-band source. Tentative guidelines exist from ACGIH. To use these guidelines, both a blue-light hazard function $B\lambda$ and a retinal thermal injury function $R\lambda$ must be used. The source spectrum may be weighted to indicate comparative levels of risk from the two types of retinal injury mechanisms. Using equation 13 (section 8.4.1.3), in which the retinal irradiance E_r is directly proportional to the radiance L of the source, the square of the pupil diameter d_p, and the transmission τ of the ocular media. The retinal spectral irradiance distribution can be calculated from the spectral radiance distribution L_λ and knowledge of the spectral transmission of the ocular media τ_λ. In the absence of a radiance standard, this approach can be used to calculate retinal levels directly and to compare them directly with thresholds of injury (Sliney & Freasier, 1973). However, the present approach is to establish ELs for the spectrally weighted radiances. These safety weighting functions are given in Table 14. Spectral factors weighted against the spectral radiance are then applied as shown in sections 11.8.2.4 and 11.8.2.5.

Table 14. Spectral weighting functions for assessing retinal risks from broad-band optical sources[a]

Wavelength (nm)	Blue-light hazard function B_λ	Thermal hazard function R_λ
400	0.10	1.0
405	0.20	2.0
410	0.40	4.0
415	0.80	8.0
420	0.90	9.0
425	0.95	9.5
430	0.98	9.8
435	1.0	10
440	1.0	10
445	0.97	9.7
450	0.94	9.4
455	0.90	9.0
460	0.80	8.0
465	0.70	7.0
470	0.62	6.2
475	0.55	5.5
480	0.45	4.5
485	0.40	4.0
490	0.22	2.2
495	0.16	1.6
500-600	$10^{[(450-\lambda)/50]}$	1.0
600-700	0.001	1.0
700-1049	0.001	$10^{[(700-\lambda)/500]}$
1050-1400	0.001	0.2

[a] From: ACGIH (1981).

11.8.2.4 Retinal thermal risk evaluation

To protect against thermal retinal injury from short-term exposures, the spectral radiance of the lamp weighted against the function R_λ (Table 14) should not exceed:

$$\sum_{400}^{1400} L_\lambda \; R_\lambda \; \Delta\lambda \quad L(Haz) = \surd t/(\alpha t) \; W/(cm^2 \cdot sr) \qquad \text{Equation (15)}$$

where L_λ is given in $W/(cm^2 \cdot sr)$, t is the viewing duration (or pulse duration if the lamp is pulse limited) which is limited to 1 ms - 10 s, and α is the angular subtense of the source in radians. The angle α should be limited to approximately 0.1 radian. If the lamp is oblong, α refers to the longest dimension (l) that can be viewed. For instance, at a viewing distance (r) of 500 cm from a tubular lamp 50 cm long, the viewing angle α is l/r or 0.1 rad. Spectral radiance (L_λ) measurements must be made at frequent wavelength intervals (Δλ) to preclude serious error. The Δλ should be less than 5 nm in the UV and blue end of the visible spectrum.

11.8.2.5 Retinal blue-light risk evaluation

To protect against retinal injury from blue-light exposure, the integrated spectral radiance of the lamp weighted with the blue-light hazard function (B_λ of Table 14) should not exceed 100 $J/cm^2 \cdot sr$ for a duration of less that 10^4 s or exceed 10 $mW/(cm^2 \cdot sr)$ for $t > 10^4$ s:

$$\sum_{400}^{1400} L_\lambda \cdot t \cdot B_\lambda \cdot \Delta\lambda \leqslant 100 \; J/(cm^2 \cdot sr) \text{ for } t < 10^4 \text{ s} \qquad \text{Equation (16)}$$

or

$$\sum_{400}^{1400} L_\lambda \cdot B_\lambda \cdot \Delta\lambda \leqslant 10 \; W/(cm^2 \cdot sr) \text{ for } t > 10^4 \text{ s} \qquad \text{Equation (17)}$$

and for a point source (α < 11 mrad)

$$\sum_{400}^{1400} E_\lambda \cdot t \cdot B_\lambda \cdot \Delta\lambda \leqslant H(Haz) = 10 \; mJ/cm^2 \text{ for } t < 10^4 \text{ s} \qquad \text{Equation (18)}$$

or

$$\sum_{400}^{1400} E_\lambda \cdot B_\lambda \cdot \Delta\lambda \leqslant E(Haz) = 1 \; \mu W/cm^2 \text{ for } t > 10^4 \text{ s} \qquad \text{Equation (19)}$$

These levels assume a constricted pupil, as would occur with fixed viewing of any type of extended source with a radiance approaching the EL. For a spectrally weighted source radiance (L) that exceeds 10 mW/(cm² •sr) in the blue-light spectral region, the permissible exposure duration t_{max} in s is simply:

$$t_{max} = 100\ \mathrm{J/(cm^2 \cdot sr)}\ \ /\ \sum_{400}^{1400} L_\lambda \cdot B_\lambda \cdot \Delta\lambda \text{ for } t < 10^4 \text{ s} \qquad \text{Equation (20)}$$

The extended-source limits are greater than the 198. ELs for a 440-nm laser radiation source given by either ANSI or ACGIH, which assume a 7-mm pupil rather than the 3-mm used for the broad-band source analysis.

11.8.2.6 IR-A risk analysis

The proposed ACGIH EL also limited the IR-A and IR-B infrared radiation beyond 770 nm to 10 mW/cm² to avoid possible cataractogenesis (the appearance of which may be delayed). For an infrared heat lamp or other source that lacks a strong visual stimulus, the radiance for wavelengths between 700 and 1400 nm for long-term viewing should be limited to:

$$\sum_{700}^{1400} L_\lambda \cdot \Delta\lambda < L(Haz) = [0.6/\alpha]\ \mathrm{W/(cm^2 \cdot sr)} \qquad \text{Equation (21)}$$

This limit is also based on a 7-mm pupil diameter.

NOTE: Equations 16 to 21 are empirical and are not, strictly speaking, dimensionally correct. To make these formulae correct, a dimensional correction factor must be inserted into each formula. It is, therefore, important to use only the units specified.

11.8.3 Infrared standards

There are no established non-laser, infrared (IR) health standards. However, the laser ELs can be applied for broad-band sources, if, in addition, the whole-body irradiation is evaluated. Even irradiances as low as 100 W/m² (10 mW/cm²) can place an uncomfortable thermal load on the human body, especially when the irradiation is not confined to one side of the body and this radiant heat load occurs along with high ambient air temperatures. In contrast, the IR laser EL for periods exceeding 10 s is 1 kW/m^2 (100 mW/cm^2), assuming that the total irradiated area of the skin or the eye will be small. For laser exposure the irradiated area is generally small, but this is not so likely when the body is exposed to optical radiation from non-laser sources; and heat stress must be evaluated.

The determination of the wet-bulb-globe-temperature (WBGT) index requires a combination of a dry-bulb temperature with a wet-bulb (WB) temperature (which involves humidity, air movement, etc.) and a black-globe (BG) temperature (which includes the radiant (predominantly infrared) contribution). These three temperatures are weighted differently in two equations used for evaluating heat stress - one for outdoor workers exposed to sunlight, another for indoor workers exposed to infrared sources. The nature of the skin's reflectance is such that much of the visible and IR-A are reflected, whereas IR-B and IR-C are almost totally absorbed. The spectral reflectance of most clothing is somewhat similar to that of skin in the infrared. Obviously the second formula would be used in any IR risk evaluation. The ACGIH formula for indoor heat stress is:

$$WBGT = 0.7\ WB + 0.3\ GT \qquad \text{Equation (22)}$$

A heat-stress condition exists when this WBGT value exceeds 25-30 °C depending on work load.

A major problem in any infrared safety standard concerned with wavelengths beyond 1.4 μm is ambient IR-C. The black-body radiant exitance at 273 K (0 °C) is 32 mW/cm^2; at 300 K (27.2 °C), it is 46 mW/cm^2. A whole-body irradiance of 20-50 mW/cm^2 from radiant warmers on a cold (0 °C) winter day is comfortable; but the same irradiance on a hot summer day could bring on heat stress. Therefore any IR safety standard should distinguish between all the IR bands, and IR-C limits would have to vary with ambient conditions.

12. RISK EVALUATION

There are three broad areas of concern for any potentially hazardous optical source: (a) the potential of the source for causing personal injury; (b) the environment in which the laser or optical source is used; and (c) the individuals who operate and those who are potentially at risk from exposure to the emitted optical radiation. For both lasers and lamp systems, it is possible to develop a hazard classification scheme that would greatly assist the health and safety professional in evaluating the risk from an optical source in a particular environment (Anderson, 1980a).

It is important to understand that the laser classification system was developed to aid the user in establishing a safety programme for a particular laser device to relieve the user' and also the health and safety professional of the burden of detailed and often complex measurements or calculations. The unique risks and control measures applicable to specific environments depend on the personnel potentially exposed and vary with each laser application. However, fortunately, many of the protection measures depend entirely, or to a great extent, on the laser hazard classification.

Since the control measures required for Class 1 and Class 2 laser systems are minimal or nonexistent for the user, it is the applications of Class 3 and Class 4 lasers that require careful study of the risks, and the development of detailed control measures. There are several protective methods, which can apply to a Class 3 or a Class 4 laser product. The total enclosure of the source is certainly the most desirable control measure. However, since total enclosure with proper interlocks would result in a Class 1 laser product, there is normally a reason why a laser system was not originally designed as a Class 1 device. There are a few instances where a specific enclosure must be developed for each application. Where the enclosure approach is feasible, this solution is strongly recommended.

Where the laser beam is operated without being enclosed - either indoors or out-of-doors - the laser safety officer (a health or safety professional or other special trained individual) has great need of reference material and technical data. These data include the reflective properties of materials found in the environment, attenuating properties of filters, windows, or other enclosures, and a working knowledge of several aspects of optical systems.

Several system-safety items should be considered for incorporation in laser system design, including:

- beam attenuators;
- interlocks;
- manual switches;
- the enclosure;
- emission indicators;
- accidental laser firing;
- beam diffusers;
- multiple wavelengths;
- mode locking;
- beam hotspots.

12.1 Laser Hazard Classification

For the classification of a laser, the following variables concerned with output should be known: (a) the wavelength or wavelength range; (b) the classification duration (i.e., in the ANSI standard: how long is it possible for a person to be exposed to an applicable EL); (c) average power output (for cw or repetitively-pulsed lasers); and (d) total energy per pulse (or peak power, pulse duration, PRF, and emergent beam radiant exposures) for all pulsed lasers. The laser source radiance or integrated radiance and the maximum viewing angular subtense is required, if the source is an extended laser source and is operating in the retinal hazard region (400-1400 nm).

If the laser is modified, after manufacture, in a way that could affect the hazard classification, then the user or the individual performing the modification should reclassify the modified system.

12.2 Environmental Considerations including Reflection and the Probability of Exposure

Environmental considerations probably play a greater role in determining the control measures for Class 3 and Class 4 laser systems, and these can only be evaluated by the user. These environmental considerations include the possibility of reflections (Gorodetski et al., 1968).

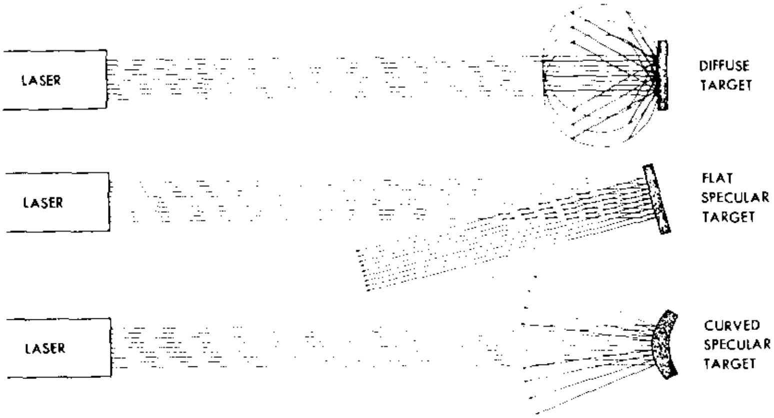


Fig. 28. Reflections. Three general types of reflections are illustrated. Diffuse reflections (top) are generally not hardous (except for Class 4), since the collimated nature of the beam is destroyed. Specular reflections (below) are most dangerous, since the beam's collimation or point-source character is retained (From: Suess, ed., 1982).

12.2.1 Reflections

The three general types of reflection that may be encountered in many environments are shown in Fig. 28. Diffuse reflections normally greatly reduce the hazards of the primary beam, though, for Class 4 visible and near-infrared lasers, hazardous diffuse reflections are likely (Komorova et al., 1978). The dividing line between Class 3 and Class 4 visible and IR-A lasers is defined by diffusely reflective hazard conditions. Reflections from flat mirrors produce substantial risks of hazardous exposure at considerable distances from the reflector as can be seen in Fig. 28. Where random orientation of the reflectors can occur, the potentially hazardous area can be quite large. Curved surface specular reflections,on the other hand, are normally hazardous only at relatively short distances of the order of magnitude of the radius of curvature from the reflector surface. Though specular surfaces are of greatest concern in open laboratory situations, they are not unheard of in the outdoor use of lasers and in medical applications.

Absolute values of spectral reflectance are relatively unimportant because such values vary only by a factor of 10-20, whereas the laser beam irradiance may exceed the applicable EL by orders of magnitude above this factor.

Most reported laser accidents have occurred, when the probability of exposure was very high. No discussion of reflection hazards is therefore complete without the consideration of the probability of exposure. It must be remembered that the underlying philosophy of the classification system is that control measures should increase with increasing risk of exposure as well as with increased severity of exposure.

12.2.2 Retroreflection

Some materials exhibit a property known as retrodirective reflection. The reflection does not obey either the law of regular (specular) reflection, or the cosine dependence of Lambertian reflection. A collimated indigent beam may remain collimated and be redirected along the original axis of propagation, regardless of the angle of incidence at the retroflector. Corner cubes and some specialized highway signs are examples of retroflectors.

12.2.3 Optically aided viewing

Nearly all laser workers know that viewing a laser source with a telescope may substantially increase the risk. This increase in risk is most dramatic for intra-beam viewing of a collimated source. In this case, an increase in the power entering the eye is possible, because the diameter of the objective (D_o) of the telescope or binocular is much larger than the pupil of the eye d_p. The actual increase in risk (G) depends on whether the pupil of the eye is larger or smaller than the exit pupil (D_e) of the optical system, the spectral transmittance (τ_λ) of the optical system at the laser wavelength(s), and the beam diameter relative to the objective (collecting aperture) diameter.

When a bright object, larger than a point source, is viewed through a well-designed optical system, the radiant power reaching the retina (visible and IR-A) is theoretically increased by the square of the instrument's magnifying power.

However, since there is a commensurate increase in the area of the retinal image, the retinal irradiance remains unchanged, except for a slight reduction because of reflective loss and the absorption of light in the optical system. The retinal hazard in this case may increase in some instances, since the thermal retinal injury threshold decreases with increasing image size.

13. ACCIDENTAL INJURIES

At present, retinal injuries with loss of sight following exposure to visible and IR-A laser radiation have been the most catastrophic of all effects from laser radiation (Boldry et al., 1981; Zhokov, 1981). Though the relatively high-powered, far-infrared lasers such as the cw, carbon-dioxide laser, have caused numerous burns to the hands and clothes, these are considered inconsequential in comparison with the serious retinal injuries. One postal survey conducted several years ago (Rockwell & Goldman, 1974) appeared to indicate that there had been at least 100 injuries to the eye from laser radiation in the USA. One subjective account in this regard was that of Decker (1977).

Despite such reports, surprisingly few serious injuries of the eye have been reported in the last 15 years in relation to exposure to pulsed lasers. This low accident rate cannot be accounted for by assuming that the ocular ELs are too conservative. The explanation is probably that accidental exposure of the eye to a collimated beam is normally an extremely remote possibility, if precautions are taken to keep the eye out of the beam. One of the few situations in which the probability of hazardous exposure is great is during work in the laboratory and, each year, several retinal injuries are reported under these conditions. However, it is difficult to ascertain the exposure conditions in sufficient detail for useful threshold or injury data to be derived. Concern may also exist regarding the potential bias in an individual's description of the accidental exposure conditions to support a claim of compliance with safety measures. It is not clear whether laser exposures are always detected by the exposed individual, and this may be a particular problem with IR lasers (Kašuba & Akifev, 1977). It is known that retinal injury outside the macula may have little or no effect on everyday visual performance and therefore may not be detected subjectively.

14. CONTROL MEASURES

Risk control guidelines are not mutually exclusive. Following one or two guidelines may reduce the risk to such an extent that other recommended control measures, in that particular class, are no longer essential. For example, if the beam path of a Class 4 laser were enclosed, then it would hardly be necessary to remove all glass objects, or other specular surfaces near the beam path but outside the enclosure, nor would it seem necessary to wear eye protectors. However, the eye protection might be necessary if the enclosure were being modified or during initial alignment.

Table 15. 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;
emission delay (BRH);
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.

The decision to use any particular set of controls depends on use conditions and whether general population exposure is likely.

Table 15 provides a brief list of the most commonly recommended laser control measures.

Because of the risk associated with exposure to Class 4 high-risk lasers, the safety precautions associated with these laser installations 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 (Klost, 1971).

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 safety factor, the requirement for good illumination, which remains in present safety standards, is related to good general visibility, as the wearing of eye protectors reduces visual capabilities. Light-coloured, matt surfaces in the room minimize glare, and thus promote visibility.

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

15. HAZARDS OF LAMP SOURCES AND PROJECTION SYSTEMS

The optical radiation emitted by a conventional light source, either a bare lamp, a luminaire, or a projection system, can be evaluated using the previously mentioned tentative exposure limits or guidelines.

Prior to 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 (Sliney & Wolbarsht, 1980) 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 (LEDs 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 (Sliney & Wolbarsht, 1980), 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 UVR hazard. Many may be quite hot to the touch.

(c) Fluorescent lamps. Low-pressure tubular lamps in almost all cases have a thin glass envelope, but could often present a potential UVR 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 UV levels will be emitted. Governmental regulations in Canada and the USA require HID lamps to have a self-extinguishing feature to preclude this hazard, unless the 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 (UV-B/C, UV-A, blue-light, retinal thermal injury, and skin thermal injury). Because of the high temperature of the arc, a quartz envelope (which transmits UV-B and C) is characteristic. These lamps are often used in UV photocuring processes in industry (Moss, 1980).

(f) Carbon arcs. Where a glass lens or filter plate does not exist 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 emit optical radiation at levels that could pose a potential health hazard (Wolbarsht et al., 1980).

STEP 3 - The obtaining of 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, when necessary. In addition, where feasible, measurements of luminance, illuminance, and total irradiance should be performed. These will provide confirmation of the spectroradiometric measurements. The pulse duration must be measured for a pulsed source.

STEP 6 - Determination of the source dimensions. A photograph and microdensitometer scan of the negative may be necessary for a non-uniform source. The maximum angular subtense α of the source should be calculated at the point of human access or at 15 cm from the source, whichever is closer.

STEP 7 - Estimation of the exposure and comparison with the exposure limits to determine the degree of risk.

STEP 8 - Consideration of potentially hazardous failure modes. For example, breakage of the outer envelope of some high-intensity discharge (HID) lamps can create a serious UVR hazard (Anderson, 1980b).

16. PROJECTION OPTICS

Broad-band sources involving projection optics are most difficult to evaluate. Besides the problems encountered in evaluating exposed lamps, the projected beam and projected source size must be characterized. When viewing a collimated light source from within the beam (other than a laser), a magnified view of the actual source will be seen. The source is generally a high-brightness lamp. The brighter the lamp, the greater the maximal irradiance in the projected beam. This is a consequence of the Law of Conservation of Brightness (Radiance) (see, for example, Kline, 1970; or Sliney & Wolbarsht, 1980). Some usually safe lamps become hazardous to view through projection optics, despite the fact that the optics cannot make the lamp brighter. The risk increases because of the dependence of retinal injury on image size. Besides the obvious projection sources - such as spotlights, searchlights, slide projectors, and film projectors - solar concentrators and other non-imaging light collectors may also require risk evaluation. From the Law of Conservation of Radiance, it is possible to evaluate the retinal risks from projector systems. Collimating optics may consist of refracting elements (lenses), reflecting elements (curved mirrors), or both.

17. SAFETY GUIDELINES FOR HIGH-INTENSITY SOURCES

Since lamp or arc sources may be hazardous from several aspects, it may be helpful to develop a safety classification scheme, similar to the one applied to laser products. The following scheme of Sliney & Wolbarsht (1980) illustrates this approach to evaluate the retinal risks from projector systems.

Both lamps and total lighting systems could be included. The categories could be as follows:

Safety Group 1: Safe sources. These lamps are considered safe to view throughout the day. No warning label would be required. Examples: a frosted 15-W filament lamp or a TV-display, cathode-ray tube.

Safety Group 2: Low-risk sources. These lamps are safe for momentary 0.25-s, unintentional viewing. Examples: most spotlights and film-projector lamp bulbs. A caution label should be required on the lamp base, and possibly on the projection system itself. No ultraviolet or infrared hazard would exist at distances of more than 10 cm from the lamp or projected beam.

Safety Group 3: Moderate-risk sources. These lamps would be unsafe to view at close range, even momentarily. Presumably, skin injury could also occur from ultraviolet radiation as from germicidal lamps, sun lamps, and high intensity UV-A lamps. A danger-label, clearly visible on the equipment, could be required. A common lamp that might fit into this category would be a 600-1000-W tungsten-halogen lamp without a Fresnel lens, such as is used for a home cine film spot lamp. The emergent beam irradiance is far in excess of that required to ignite paper within half a metre of the source. Obviously, the basis for the determination of a hazard classification would differ according to whether the hazard classification criteria were based on retinal or skin injury. Each measurement for classification would be for a specified accessible approach distance, using a standard aperture and solid angle of acceptance. The minimum approach distance could vary with application. Other examples that might be included in this category are some very high intensity, short-pulse, laser flash tubes, and 20 kW xenon-arc searchlights.

Safety Group 4: High-risk sources. These sources would cause skin burns and/or erythema within a standardized period of exposure (e.g., within 10 s) at a standardized distance at which the effective UV irradiance would exceed 3 W/m^2 (0.3 mW/cm^2), or the total irradiance across the entire spectrum would exceed 2 kW/m^2 (0.2 W/cm^2). Examples of such sources are an open carbon-arc spotlight or an open 1-kW mercury lamp. It may be that safety groups 3 and 4 are so similar in degree of risk, that they could be combined.

18. WELDING ARCS

The most common high-intensity arc is probably the welding arc. These arcs vary in brightness and in UVR content, primarily according to the arc current, type of shielding gas, and the metals being welded.

The greatest population exposed to intense sources of optical radiation are welders and their assistants. The American Welding Society estimated that there may be as many as 500 000 welders in the USA alone (Emmett & Horstman, 1976). The two broad categories of welding equipment are gas (acetylene) welding equipment and electric-arc welding equipment. A gas welding torch or cutting torch has a luminance not much greater than a candle flame, typically ranging from 10 to 200 kcd/m^2 (1-20 cd/cm^2), and the UVR emission is quite small. The optical radiation hazards of such torches are virtually nonexistant. Welding filter goggles used with such torches are to reduce glare, and are little darker than very dark sunglasses having a shade number of the order of 3-5 (visual transmittance of 5-15 %). On the other hand, electric welding arcs may be 1000 times brighter than gas torches and emit UVR at proportionately higher levels (Sutter et al., 1972).

Protective shields, curtains, screens for bystanders, and welders' goggles are the standard protective equipment used in welding (Mayer et al., 1979; Sliney et al., 1981). Protective procedures and protective equipment for the welder have been developed empirically over the last three-quarters of a century. Only very recently have detailed measurements of the radiometric output of welding arcs been available. When these measurements were carefully compared with exposure limits being developed for protection against bright light sources, it was shown that the empirically-developed protective equipment standards were adequate.

19. EYE AND SKIN PROTECTION

19.1 Laser Safety Eyewear

From a safety point of view, the most desirable laser hazard control measure is complete enclosure of the laser or laser system; however, this may not always be practical and laser eye protectors are generally the best alternative. Though most industrial laser applications do not require the use of eye protectors, this is not always true for laser applications in the research laboratory. Eye protectors provide the simplest solution to the laser safety problem for a constantly changing experimental arrangement. Several factors play a role in determining whether eyewear is necessary in any situation. At least three output parameters of the laser must be known: maximum exposure duration, wavelength, and output power (or output irradiance, or radiant exposure, or energy), as well as the applicable safe corneal radiant exposure. In addition, some knowledge of such environmental factors as ambient lighting and the nature of the laser operation may also be required.

Laser eye protection generally consists of a filter (often composed of several individual filter plates) which selectively attenuates at specific laser wavelengths, but elsewhere transmits as much visible radiation as possible (Swope & Koester, 1965; Schreibeis, 1968; Scherr et al., 1969; Swope, 1969, 1970; Straub, 1970; Sliney, 1974). Eyewear is available in several designs - spectacles, coverall types with opaque side-shields, and coverall types with somewhat transparent filter side-shields. The selection of appropriate laser protective eyewear may be complex (Envall & Murray, 1979). Active electronic imaging devices have also served an additional role, as eye protection.

19.2 Welders' Filters

Eye protection filters, which were originally developed for welders, were based more on available materials than on knowledge of ocular protection requirements. The first organized study of glass filter materials was carried out by Sir William Crookes (1914) in England. Optical transmission characteristics are now standardized as "shades" and specified for particular applications (Coblentz et al., 1931; Stair, 1948; ANSI, 1978). Though maximum transmittances for ultraviolet and infrared radiation are specified for each shade, the mean photopic visual transmittance τ_v, or visual optical density D_v, has traditionally been used to define the shade number S:

$$S = (7/3)\ D_v + 1 = -\ln \tau_v + 1 \qquad \text{Equation (23)}$$

or $$D_v = (3/7)\ (S - 1) \qquad \text{Equation (24)}$$

where $$D_v = -\log_{10} \tau_v \qquad \text{Equation (25)}$$

19.3 Eye Protection for Furnace Radiation

As well as protective clothing and equipment, many industrial methods now used probably reduce the level of glass furnace radiation to which the eye is exposed. For instance, the openings to higher temperature furnaces are a great deal smaller than they have been in past years; this would reduce the total irradiance of the eye from infrared radiation. There are sufficient data and cases of a very specific form of cataract in workers to suggest that infrared does, indeed, cause glass-blower's or furnaceman's cataract (Duke-Elder, 1972).

19.4 Eye Protection Filters for Solar Radiation

Direct viewing of the sun, for whatever reason, requires protection against several different portions of the spectrum. A yellowish or reddish filter generally protects against ultraviolet radiation. Protection against intense visible rays should be weighted to filter out more of the blue-light than the rest of the visible spectrum. It is generally found that a shade 12 or 13 welder's filter is quite adequate to protect against ultraviolet radiation, infrared, and visible radiation. The protection afforded against the IR, however, is far greater than necessary.

The use of darkened coloured slides is not advisable, since these slides (usually made by developing unexposed colour film) use organic dyes that transmit in the near-infrared (IR-A) spectral band.

19.5 Skin Protecting Agents for UVR (Sunscreens)

A number of topical, physical, and chemical screening agents have been developed that provide nearly total or partial filtration of ultraviolet radiation. Since actinic UV-B and UV-C radiation are the most hazardous, efforts to develop topical agents have concentrated primarily on filtering out this type of radiation. The chemical agents in these "sunscreens" include para-aminobenzoic acids (PABA) and its esters, salicylates, and cyanamates. These materials are mixed in solution with substances that have good substantivity (i.e., adhere to the skin) (Dahling et al., 1970; Fitzpatrick et al., 1974).

19.6 Protective Garments

Aluminized fabrics were greatly improved during various manned space programmes (Stoll & Chiantra, 1971). Such fabrics, when used in thermal protective garments, have been shown to offer equivalent or superior reflective and mechanical properties compared with conventional aluminized asbestos garments (Wren et al., 1977). Aluminized rayon (basket weave) and certain aluminized cottons were shown to allow the least transmission of infrared radiation.

20. MEDICAL SURVEILLANCE (RATIONALE)

In the past two decades, many employees working routinely with lasers have been subjected to preplacement, periodic, and end-of-job eye examinations in order to obtain sufficient information concerning the risk of retinal damage. Many of these studies indicated that periodic eye examinations rarely located hitherto unsuspected retinal damage. In general, published reports of ophthalmic accidents have been those in which the acute over-exposure was sufficient to subjectively alert the individual (Hathaway et al., 1977). Thus, many authorities (Suess, ed., 1982) suggest that ophthalmic examinations are unnecessary for individuals routinely working with Class 1 and 2 lasers, and that, if requested, the examinations should be confined to those working with Class 3 or 4 systems only.

An examination is required within 24-48 h of any event in which the worker suspects, or knows, that the eye might have been exposed. Laser lesions change in appearance and may even tend to disappear within the heterogeneous appearance of the fundus within a period of time, so that ophthalmic examinations, some time after exposure, may be difficult to interpret.

21. FORMAL TRAINING FOR LASER WORKERS

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.

At work places, 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 workers and work leaders aware of the risks of lasers, how to avoid the hazards, the proper use of protective devices, and how to realize when overexposure has taken place.

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GLOSSARY

ACOUSTICO-OPTIC: involving the interaction of light and an acoustic wave. Acoustico-optic devices such as Q switches and modulators are used in manipulating laser beams.

ACTIVE MEDIUM: the atomic or molecular species which can provide gain for laser oscillation. Also called laser medium, lasing medium or active material.

ANGSTROM (A): a non-SI unit equal to 10^{-10} metre. Its use as a unit of optical wavelength has largely been supplanted in recent years by the nanometre (10^{-9} metre).

ARC LAMP: an electric lamp in which current passes through the ionized air between two electrodes, giving off light. Applications include laser excitation.

ATOMIC LASER: a gas laser in which the active material is an atomic species rather than a molecule.

ATTENUATION: reduction in intensity that results when optical radiation travels through an absorbing or scattering medium. In optical fibre, attenuation (in decibels) equals 10 log (P_o/P_{in}), where P_o is the power at the output end of the fibre and P_{in} is the power launched into the fibre.

AVERAGE POWER: in a repetitively pulsed laser, the energy per pulse times the repetition rate. When the energy per pulse is expressed in joules and the repetition rate in hertz, the average power is expressed in watts.

BEAM DIAMETER: the distance between the two opposing points at which the irradiance or radiant exposure is a specified fraction (typically 1/e or $1/e^2$) of the irradiance or radiant exposure of the emitted radiation.

BEAM DIVERGENCE: the increase in beam diameter with distance from the laser's exit aperture. Measured in milliradians at specified points, usually where irradiance or radiant exposure is 1/e or $1/e^2$ the maximum value, and expressed as the "full-angle" divergence.

BOLOMETER: a type of detector which measures infrared radiation by the temperature-induced change of resistance in a metal foil exposed to the radiation and heated by it.

BREWSTER ANGLE: the angle between an incident beam of light and a dielectric reflecting surface at which none of the light polarized in the plane of incidence is reflected. Brewster's angle is $\tan^{-1}\underline{n}_2/\underline{n}_1$, where $\underline{n}_1$, and $\underline{n}_2$ are the indexes of refraction of the first and second media respectively. A window mounted at Brewster's angle with respect to an incident beam is often used as a window in laser cavities.

CALORIMETER: a type of detector that measures heat produced by absorption of radiation.

CHEMICAL LASER: a type of laser in which the population inversion is produced directly by an "elementary" chemical reaction (a collision prpcess in which one or more molecules undergo changes in their chemical bonds).

COHERENCE: a fixed phase relationship among various points of an electromagnetic wave in space (spatial coherence) or in time (temporal coherence).

COLLIMATOR: an optical device for converting a diverging or converging beam of light into a collimated or parallel beam, or for expanding or reducing the cross-sectional area of an incident collimated beam. A target collimator projects a parallel beam from its own light source such that, viewed from any distance, the light source appears to be at infinity.

CONTINUOUS WAVE (cw) LASER OPERATION: laser operation in which radiation is emitted continuously.

CORE: the central region of an optical fibre. The core must have a higher refractive index than the cladding for light to be transmitted through the fibre via total internal reflection

CORNER CUBE: an optical component with three mutually perpendicular faces and a hypotenuse face. Because light entering through the hypotenuse is totally internally reflected at each perpendicular face, the cube acts as a retroreflector. Also known as corner reflector.

CRYSTAL LASER: a type of laser in which the active medium is an atomic species in a crystal such as ruby, YAG (yttrium aluminium garnet), or YALO (yttrium aluminate).

DETECTOR: see PHOTODETECTOR.

DIFFRACTION: deviation of light rays from the paths predicted by geometical optics.

DIODE LASER: see SEMICONDUCTOR LASER.

DISPERSION: variation of the refractive index of an optical material with change in wavelength, as in a prism; in an optical fibre, the temporal spreading of a light pulse due to the fibre's different propagation speeds for different wavelengths and modes of light. Such spreading limits the fibre's information-carrying capacity of bandwidth.

DIVERGENCE: see BEAM DIVERGENCE.

DYE LASER: a type of laser in which the active medium is an organic dye, generally in solution with the liquid either flowing or encapsulated within a cell. Experimental solid and gas dye lasers also have been built. Also called organic-dye, tunable-dye or liquid laser.

ELECTRON-BEAM-SUSTAINED LASER: a molecular-gas laser in which the electrical discharge is sustained with a beam of high-energy electrons. Usually injected transversely to the laser cavity's optical axis, the electron beam permits laser operation at pressures and cross-section-to-length ratios higher than possible with an unsustained discharge. This technique is often used in commercial carbon-dioxide lasers with very high continuous-wave output power.

ELECTRO-OPTIC: applying to modulators, Q switches and other beam-manipulating devices in which operation relies on modification of a material's refractive indices by an applied electrical field. In a Kerr cell the index change is proportional to the square of the electrical field, and the material is usually a liquid. In a Pockels cell the material is a crystal whose index change is linear with the electric field.

EMISSIVITY: ratio of radiant exitance of a thermal radiator to that of a full radiator (black body) at the same temperature - (ISO 31/VI 1980).

EXCIMER LASER: a laser in which the active medium is an excimer, a molecule which is chemically unstable except in its excited state. The term often is applied to lasers in which the active medium is a rare-gas halide (or monohalide) excimer such as KrF^* or XeF^*.

GAS LASER: a type of laser in which the active medium is a gas. The category is subclassified according to the active medium into atomic (such as helium-neon), molecular (carbon dioxide, hydrogen cyanide and water vapour), ionic (argon, krypton, xenon, and the metal-vapour types such as helium-cadmium and helium-selenium), and excimer (typically rare-gas halides). Loosely applied, "ion" means argon and krypton.

GLASS LASER: a type of solid-state laser in which the active medium is a glass rod doped with rare-earth atoms, usually neodymium.

HERTZ (Hz): the SI unit of frequency of periodic phenomena. It replaces the non-SI unit "cycles per second". The number of pulses per second that a laser can produce may be expressed in hertz.

HOLOGRAM: a recording of the interference of coherent light reflected from an object with light direct from the same source or reflected from a mirror. Illumination of the hologram reproduces the object's three-dimensional image.

IMAGE CONVERTER: an electron tube which produces a visual replica of an image formed on its cathode by some form of electromagnetic radiation. In an image converter camera, the image formed by the electron tube is focused on to photographic film for a permanent record.

INFRARED: electromagnetic radiation with wavelength between 0.76 micrometre and about 1 millimetre. Wavelengths at the shorter end of this range are frequently called "near" infrared, and those longer than about 20 micrometres, "far" infrared.

INTEGRATED OPTICS: devices in which several optical components are "integrated" on to a single substrate; analogous to integrated electronic circuits. Although still in the research phase, integrated optics has potential for use in optical signal processing and in fibre-optic communications.

INTERFERENCE FILTER: an optical component which depends on interference in a series of thin films deposited on a substrate to limit transmission to a desired spectral band.

ION LASER: a type in which the active element is an ionized gas, generally argon or krypton.

IRRADIANCE (E): radiant flux per unit area, expressed in watts per square centimetre.

LASER: acronym for "light amplication by stimulated emission of radiation." A device which generates or amplifies electromagnetic oscillations at wavelengths between the far infrared (submillimetre) and ultraviolet. Like any electromagnetic oscillator, a laser oscillator consists of two basic elements: an amplifying (active) medium and a regeneration or feedback device (resonant cavity). A laser's amplifying medium can be a gas, semiconductor, dye solution, etc; feedback is typically from two mirrors. Distinctive properties of the electromagnetic oscillations produced include monochromaticity, high intensity, small beam divergence, and phase coherence. As a description of a device, "laser" refers to the active medium plus all equipment necessary to produce the effect called lasing.

LASER DIODE: see SEMICONDUCTOR LASER.

LED: abbreviation of light-emitting diode. A semiconductor emitting incoherent light into a broad field of view, used in low-speed or short-haul fibre-optic links. Most LEDs used in fibre-optic applications emit in the near infrared.

LIDAR: acronym for "light detection and ranging," a system employing a laser beam to gather ranging information as well as intelligence on reflection and scattering of light by clouds and atmospheric pollutants.

LIQUID LASER: a type in which the active element is either an organic dye or an inorganic liquid. See also DYE LASER.

MULTIMODE: emission at several frequencies simultaneously, generally closely spaced, each frequency representing a different mode of laser oscillation inthe resonant cavity.

Nd-GLASS: neodymium-doped glass, used in some solid state lasers. The neodymium atoms are the active medium.

Nd-YAG: neodymium-doped yttrium-aluminium-garnet (YAG), a crystal which is used in some solid state lasers. The neodymium atoms are the active medium.

NEUTRAL DENSITY FILTER: a filter which reduces the intensity of light without affecting its spectral character.

NONLINEAR EFFECTS: changes in a medium transmitting electromagnetic waves that are proportional to the second, third or higher powers of external electric field. Nonlinear optical effects include harmonic generation and the electro-optic effect. See electro-optic.

OPTICALLY PUMPED LASER: a laser whose active medium is excited by another light source to produce a population inversion. For solid-state and some dye lasers this source usually is an incoherent type such as a flash- or arc-lamp. For gas and other dye lasers, coherent laser sources generally provide such optical pumping.

PARAMETRIC OSCILLATOR: a nonlinear device, usually a crystal, which produces tunable laser oscillations at the sum or difference frequency of mixed laser beams. Also called tunable parametric oscillator or optical parametric oscillator. Loosely applied to the complete instrument containing the pump laser and the tuning crystal.

PHOTODETECTOR: any device which detects light, generally producing an electronic signal with intensity proportional to that of the incident light.

PHOTON: a massless "particle" of electromagnetic radiation, with energy equal to hc/λ where h is Planck's constant (6.6×10^{-34} joule second) and c/λ is the frequency of the radiation (speed of light divided by wavelength).

POLARIZER: an optical component which only transmits lightwaves that oscillate in a given plane.

POPULATION INVERSION: a condition in which most atoms of a species are in an excited, metastable state. Collision of a photon with such an atom causes the atom to relax to a lower energy state, and to emit a second photon, amplifying the light signal. Population inversion is required for lasing to occur.

PULSELENGTH: the duration of the burst of energy emitted by a pulsed or Q-switched laser. Expressed in seconds and usually measured at the half-power (half the full height of a voltage or current pulse). Also called pulsewidth.

PULSED LASER: a laser that emits light in pulses rather than continuously.

PUMP: the energy source (such as flashlamp, electron beam or current supply) that drives the amplification in the active medium of a laser by creating a population inversion.

PYROELECTRIC CRYSTAL: a type of crystal that shows electrical effects when its temperature is changed; these effects are used to detect infrared radiation.

Q SWITCH: essentially a "shutter" which prevents laser emission until opened. Q stands for "quality factor" of the laser's resonant cavity. "Active" Q switching is achieved with a rotating mirror or prism, Kerr or Pockels cell, or acoustico-optic device; "passive" Q switching is achieved with a saturable absorber such as a gas or dye. In a pulsed laser a Q switch increases pulse power by shortening pulse duration while not significantly decreasing the energy; in a continuous wave laser the device provides shorter and more intense pulses at a higher repetition rate than could be achieved by pulsing the laser directly.

RADIANCE (L): At a point of a surface and in a given direction, the radiant intensity of an element of the surface, divided by the area of the orthogonal projection of this element on a plane perpendicular to the given direction (ISO 31/6-1980). Expressed in watts per steradian square centimetre.

RADIANT FLUX: the rate of flow of radiant energy, measured in watts.

RADIOMETER: an instrument for measuring incident radiation in radiometric units (watts). Radiometric measurements can be made at any wavelength, but the spectral range of a particular instrument may be limited to a narrow range.

RADIOMETRIC UNITS: units defined for measurement of the intensity of electromagnetic radiation; the basic unit is the SI unit watt.

RAMAN EFFECT: the appearance of additional weak lines in the spectrum of light that has been scattered by a transparent substance. The extra lines result from rotational or vibrational transitions of the molecules in the scattering medium. If the medium is illuminated with laser light of sufficient intensity, the emission at the Raman frequencies is amplified, exhibiting characteristics of stimulated emission (i.e., stimulated Raman effect.).

REFLECTANCE: the ratio of wave energy reflected from a surface to the wave energy incident on a surface.

SEMICONDUCTOR LASER: a type in which the active material is a semiconductor, either a diode or homogeneous. Commercial types are generally diodes in which lasing occurs at the junction of n-type and p-type semiconductors, usually gallium-arsenide or gallium-aluminium-arsenide. Homogeneous types are made of undoped semiconductor material and are pumped by an electron beam.

SOLID-STATE LASER: a type the active medium of which is an atomic species in a glass or crystal. The atomic species may be added to the glass or crystal, as neodymium is added to glass, or may be instrinic, as chromium is in ruby. This term is generally not applied to semiconductor lasers.

SUPER-RADIANT: applying to coherent optical amplification of spontaneous emission that occurs without relaxation processes. Commonly used to describe a laser whose gain is high enough to permit amplification without mirrors; examples are nitrogen and molecular hydrogen. Beam quality of a super radiant laser is generally inferior to that of a laser with a complete optical cavity. "Super-fluorescent" has been proposed as a more precise description of this type of laser.

TEA LASER: acronym for transversely excited, atmospheric pressure laser. A gas laser in which excitation of the active medium is transverse to the flow of the medium. Because of shorter breakdown length, this type operates in a gas-pressure range higher than that for longitudinally excited gas lasers (but not necessarily atmospheric) and offers a potentially higher power output per unit volumes because of a greater density of lasing molecules.

TUNABLE LASER: a laser or a parametric oscillator whose emission can be varied across a broad spectral range.

ULTRAVIOLET: electromagnetic radiation with wavelengths between about 40 and 400 nanometres. Radiation between 40 and 200 nm is termed "vacuum ultraviolet" because it is absorbed by air and travels only through a vacuum. The "near" ultraviolet has wavelengths close to those of visible light; the "far" ultraviolet has shorter wavelengths.

YAG: yttrium aluminium garnet, a crystal host which can be doped with an active laser medium, usually neodymium.

YALO: yttrium aluminate ($YAlO_3$), a crystal host doped with an active laser medium, usually neodymium.

YLF: yttrium lithium fluoride, a crystal host which can be doped with an active laser ion, usually holmium.