OCCUPATIONAL SAFETY 68 AND HEALTH SERIES

THE USE OF LASERS IN THE WORKPLACE

A PRACTICAL GUIDE

Prepared by the International Non-Ionizing
Radiation Committee of the International Radiation
Protection Association in collaboration with the
International Labour Organization

INTERNATIONAL LABOUR OFFICE, GENEVA

The International Programme for the Improvement of Working Conditions and Environment (PIACT) was launched by the International Labour Organisation in 1976 at the request of the International Labour Conference and after extensive consultations with member States. PIACT is designed to promote or support action by member States to set and attain definite objectives aiming at "making work more human". The Programme is thus concerned with improving the quality of working life in all its aspects: for example, the prevention of occupational accidents and diseases, a wider application of the principles of ergonomics, the arrangement of working time, the improvement of the content and organisation of work and of conditions of work in general, a greater concern for the human element in the transfer of technology. To achieve these aims, PIACT makes use of and co-ordinates the traditional means of ILO action, including:

- the preparation and revision of international labour standards;
- operational activities, including the dispatch of multidisciplinary teams to assist member States on request;
- tripartite meetings between representatives of governments, employers and workers, including industrial committees to study the problems facing major industries, regional meetings and meetings of experts;
- action-oriented studies and research; and
- clearing-house activities, especially through the International Occupational Safety and Health Information Centre (CIS) and the Clearing-house for the Dissemination of Information on Conditions of Work.

This publication is the outcome of a PIACT project.

The use of lasers
in the workplace

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Preface

This publication is one of a series of practical guides on occupational hazards arising from non-ionizing radiation (NIR) carried out in collaboration with the International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA)[1] as part of the ILO International Programme for the Improvement of Working Conditions and Environment (PIACT).

The purpose of this book is to provide basic guidance on working conditions and procedures that will lead to higher standards of safety for all personnel engaged in the manufacture, maintenance and operation of laser devices. It is intended in particular for the use of competent authorities, employers and workers, and in general all persons in charge of occupational safety and health. The following topics are covered: the characteristics of laser radiation; the biological and health effects; occupationally related exposure type and effects; hazard evaluation; instrumentation and measurement techniques; occupational exposure limits and safety standards; control of and protection from exposure to laser radiation; and the principles of an administrative structure needed to ensure laser safety in the workplace. Emphasis is upon protective measures.

The manuscript was prepared by an IRPA-INIRC working group chaired by Dr D. H. Sliney and including Dr B. Bosnjakovic, Dr L. A. Court, Dr A. F. McKinlay and Dr L. D. Szabó. Following comments received from INIRC members, it was reviewed in detail during the annual meeting of the IRPA-INIRC in Rome (Italy), May 1991, in cooperation with Dr G. H. Coppée representing the International Labour Office.

This book is the result of a ILO/IRPA-INIRC activity and is published by the ILO on behalf of the two organizations. The ILO wishes to thank the International Non-Ionizing Radiation Committee of the IRPA, and in particular Dr D. H. Sliney and his working group, for their contribution and cooperation in the preparation of this practical guide on the use of lasers in the workplace.

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[1] Since May 1992 the INIRC of the IRPA has become an independent scientific body called the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and has responsibility for NIR protection in the same way as the International Commission on Radiological Protection (ICRP) has for ionizing radiation. (ICNIRP Secretariat: c/o Dipl.-Ing. R. Matthes, Bundesamt für Strahlenschutz, Institut für Strahlenhygiene, Ingoldstädter Landstrasse 1, D-85764 Oberschleissheim, Germany, Tel.: +49 89 31603237, Fax +49 89 31603111.)

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Introduction

Laser workers may be defined as persons engaged in the development, operation, manufacture, maintenance, service and use of laser devices. People taking medication and persons with various disabilities are included within this definition, and so account must be taken of this where necessary when preparing safety guidelines.

The rate of development and the number of new applications of lasers in the past few decades have been phenomenal. Lasers have fostered a revolution in the field of electro-optics and communications. There is every indication that the rapid growth of laser technology will continue and that laser use will become more widespread.

Despite the benefits of technology, it is axiomatic to say that improper use or design of any apparatus can produce undesirable effects. The laser is no exception. On the other hand, although technical achievement often moves in advance of a full understanding of the hazards, it has been encouraging to witness, from the inception, the serious attention given to the effects of laser radiation upon biological systems (Appendix B) and the development of protection guidelines and recommended limits of exposure (IRPA, 1985 and 1988).

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Characteristics of laser radiation

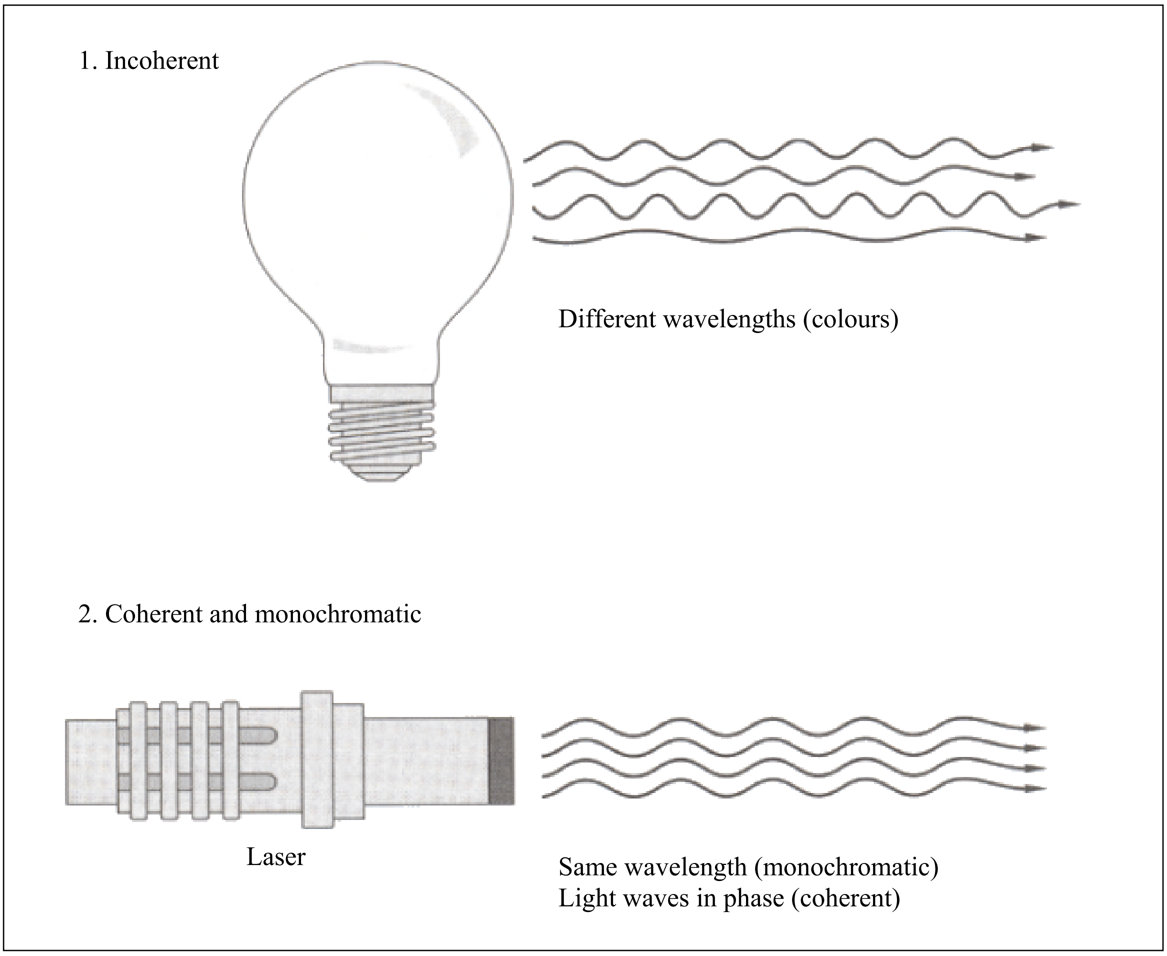
2.1 Radiometric quantities and units and terminology

The physical (radiometric) terms and units used in the optical region of the electromagnetic spectrum are standardized by the *Système International d'Unités* (SI). The International Commission on Illumination (Commission Internationale de l'Eclairage, CIE) together with the International Electrotechnical Commission (IEC) publishes a standardized vocabulary of lighting terminology that includes definitions of radiometric and photometric terms, quantities, and units (CIE, 1989) which are used in this document. There are only a few terms, quantities, and units in widespread use when specifying exposure limits for the health protection of workers, and these are discussed in detail in Appendix A.

2.2 Types of lasers

There are a number of methods to group or categorize lasers depending upon wavelength, pulse characteristics, active medium or pumping process. Lasers may be pulsed or continuous-wave (CW) depending upon the duration of excitation of the active medium by pumping. The duration of a pulse may vary from femtoseconds (10^{-15} s) or picoseconds (10^{-12} s) to larger fractions of a second. If the laser emits pulses of duration less than 1 nanosecond (10^{-9} s), it will normally be a "mode-locked" laser. If the laser emits pulses of the order of several nanoseconds (ns) to several 100 ns it is referred to as a "q-switched" laser. If the emission of an optically pumped laser follows the normal pulse emission of a flashlamp, then the laser is normally referred to as a "long-pulse" or "normal-pulse" laser. For safety purposes, lasers which emit continuously for periods greater than 0.25 s are referred to as "CW lasers." Lasers which emit groups or "trains" of pulses are referred to as "repetitively pulsed" and the frequency of pulses is referred to as the "pulse repetition frequency" (PRF). By contrast with conventional light sources, the laser is coherent, normally collimated and monochromatic, as shown in figure 1.

Figure 1. Laser source compared to conventional light source



3

Sources of occupational exposure to laser radiation

3.1 Industrial and scientific laser applications

3.1.1 Industrial laser use

Industrial lasers typically are used for cutting, welding or other type of material processing. These systems contain high power lasers, but are operated in a controlled environment.

3.1.2 Scientific laser applications

These types of applications are the hardest to categorize – almost any possible exposure wavelength or condition can occur. These applications are the hardest to control and most complaints about "overly restrictive" controls are received from scientists. However, scientists are also the most likely to be injured in laser accidents.

3.2 Medical and surgical laser applications

In medicine, lasers were first used in ophthalmology for retinal photocoagulation purposes and secondly in general surgery. They are a first class tool in microsurgery, including neurosurgery. Diagnostic and therapeutic laser techniques are presently being investigated in most medical fields, such as diagnostic transillumination of tissue, gynaecological and gastroenterological surgery, dermatology, and aesthetic (cosmetic) surgery.

3.3 Laser optical fibre communications

During operation, laser energy is confined to the optical fibre. Maintenance and service procedures may allow access to laser levels that may be hazardous.

3.4 Display and entertainment lasers

These lasers typically emit many watts of visible light. They are potentially very dangerous if system safety features fail during operation.

Some common laser devices and applications are given in table 1.

Table 1. Common laser devices and applications

Type	Wavelength(s)	Applications
Argon (AR) (ion)	458-515 nm +350 nm	Instrumentation; holography; entertainment; retinal photocoagulation
Carbon dioxide (CO_2) (gas)	10.6 µm	Material processing; optical radar/ranging; instrumentation; surgery techniques
Dye(s)	Variable 350 nm to 1 µm	Instrumentation; dermatology
Excimer lasers	193-351 nm	Laser surgery; material processing; laser pumping; spectroscopy
Gallium arsenide (GaAs) (semiconductor diode)	850-950 nm	Optical fibre communications; instrumentation; ranging; intrusion detection; toys
Helium cadmium (HeCd) (gas discharge)	325,442 nm	Alignment; surveying
Helium neon (HeNe) (gas discharge)	632.8 nm	Alignment; surveying; holography; ranging
Krypton (ion)	568,647 nm	Entertainment; instrumentation
Neodymium glass (Nd-glass) neodymium yttrium-aluminium garnet (Nd-YAG)	1.06 µm	Material processing; instrumentation; optical radar/ranging; surgery
Ruby	694.3 nm	Dermatology; holography; ranging

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Hazard evaluation and laser device classification

4.1 General concepts of hazard evaluation and risk assessment

Four aspects of the use of lasers need to be taken into account in the evaluation of possible hazards, the assessment of risk of injury and in the application of control measures:

(a) The capability of the laser or laser system to injure personnel determines its "hazard classification". This includes consideration of human access to the main exit port or any subsidiary port of the laser beam. Certain hazard controls are built into commercially manufactured lasers or laser systems (IEC, 1984, 1990). The concept of *risk* is included in the scheme of "hazard" classes.

(b) The environment in which the laser is used.

(c) The level of training of the personnel who operate the laser or who may be exposed to its beam.

(d) The intended use of the laser.

The practical means for evaluating laser radiation hazards and assessing risk of exposure is to first determine the hazard classification of each laser system. The hazard class indicates the laser's relative hazard potential and may also incorporate an assessment of risk of exposure to potentially hazardous levels of laser radiation. Appropriate controls are specified for each class. The use of the classification system will, in most cases, preclude any requirement for radiometric measurements and a detailed risk assessment by the user.

In the standardized laser classification scheme, aspect (a) (the potential hazard of the laser or laser system) is defined. Aspects (b) and (c) vary with each use and cannot be readily included in a general classification scheme. In total hazard evaluation and risk assessment procedures, all four aspects must be considered, although in most cases aspects (a) and (d) are sufficient to determine the control measures applicable.

4.2 Classification of laser devices

The hazard and risk classification scheme given below is based on the output parameters and accessible levels of radiation. This classification takes largely into account that of the IEC (1984) the US Food and Drug Administration (FDA, 1989) and that used by ANSI (1986). The laser device classification normally will appear on many commercial laser products manufactured subsequent to the adoption of these standards. This classification should be used unless the laser is modified so as to change its output power or energy significantly. The classes are:

1. laser systems that are not hazardous (without known biological hazards);

2. laser systems (visible only) that are normally not hazardous by virtue of normal aversion responses (low-risk);
3. laser systems where intrabeam viewing of the direct beam and specular reflections may be hazardous (moderate-risk), sometimes divided into two subcategories a and b, where Class 3a represents a low risk (similar to Class 2) and is hazardous only if the beam is re-collected or focused by an optical instrument;
4. laser systems where even diffuse reflections may be hazardous and where the beam produces a fire hazard or serious skin hazard.

The basis of the hazard and risk classification scheme is the ability of the primary laser beam or reflected beam to cause biological damage to the eye or skin.

A Class 2 laser or low-power system does not produce an immediate hazard when accidentally viewed directly, but must have a cautionary label affixed to the external surface of the device to advise against staring into the beam. Similar controls are required for a Class 3a laser.

The moderate-risk Class 3b category (or medium-power system) requires control measures to prevent viewing of the direct beam.

Class 4 high-risk (or high-power) systems require the use of controls that prevent exposure to the eye and skin to the direct and diffusely reflected beam. In addition to the possibility of eye damage, exposure to optical radiation from such devices could constitute a serious skin hazard.

4.3 Laser output parameters required for hazard classification

Accessible emission limits (AELs) have been established for each class of laser below Class 4; i.e. a laser product is in a given class only if the emitted laser radiation is below the AEL for its class. There are no AELs (i.e. upper limits) for Class 4. The following parameters are required for the classification of the different types of laser:

1. Essentially all lasers: wavelength(s) or wavelength range.
2. Continuous-wave (CW) or repetitively pulsed lasers: average power output is also required and, in some cases, a determination of the exposure duration depending upon the application.
3. Pulsed lasers: total energy per pulse (or peak power), pulse duration, pulse repetition frequency, and emergent beam radiant exposure.
4. Extended-source laser devices, such as injection laser diodes and those lasers having a permanent diffuser within the output optics: all of the above parameters, the laser source radiance or integrated radiance, and the maximum viewing angular subtense, α.

4.4 Definitions of laser device hazard classes

Class 1 – laser devices with no known radiation hazard.

A Class 1 laser device is defined as any laser, or laser system containing such a laser, that cannot emit laser radiation levels in excess of the AEL for Class 1 (see below) for the classification duration. The classification duration is the longest daily exposure duration expected. The exemption from hazard controls applies strictly to emitted laser radiation hazards and not to other potential hazards.

The AEL for Class 1 is defined by a "worst-case" analysis of a laser's potential for producing injury. In this "worst-case" risk assessment it is necessary to consider not only the laser output irradiance or radiant exposure, but also whether a hazard would exist if the total laser output were concentrated within the defining aperture for the applicable exposure limit. For instance, the unfocused beam of a CW, CO_2 laser of 10.6 μm would normally not be hazardous if the beam irradiance were less than 1 kW m^{-2}; however, if the output power were 10 W and the beam could be focused by a mirror at some location to a spot 1 mm in diameter, a serious hazard could exist. The AELs for class 1 must be defined in two different ways, depending on whether the laser itself is considered an "extended source" (an unusual case), or a "point source" (the normal case).

For most lasers, the AEL for Class 1 is the product of a × b, where a is the intrabeam (point-source) exposure limit for the eye for the exposure duration T_{max} and b is the circular area of the defining aperture.

For extended-source lasers (e.g. laser arrays, laser diodes and diffused-output lasers that emit in the spectral range 400 – 1,400 nm) the AEL for Class 1 is determined by a power or energy output such that the source radiance would not exceed the extended-source exposure limit if the source were viewed at the minimum viewing distance of 10 cm. An optical viewing system does not increase the hazard for extended sources. This AEL is seldom necessary to apply, and the point-source AELs can be applied to provide a conservative analysis.

Class 2 – low-risk, low-power visible laser devices which do not represent a hazard for momentary viewing, and are defined as follows:

(a) visible continuous-wave laser devices that can emit a power exceeding the AEL for Class 1 for the classification duration (0.4 μW for T_{max} greater than 0.25 second) but not exceeding 1 mW;

[NOTE: In some standards, some Class 2 lasers may be placed into a subcategory, Class 2a (which are not hazardous for viewing durations greater than 1,000 s)].

(b) visible scanning laser systems and repetitively pulsed laser devices that can emit a power exceeding the appropriate AEL for Class 1, but not exceeding the AEL for Class 1 for a 0.25 second exposure, are Class 2.

Any laser device in a low-risk classification by virtue of enclosure must have warning labels indicating higher-risk class "when access panels are removed". These labels may be covered by a separate enclosure which must be removed before the main access panels can be removed.

Class 3a – low-risk, medium-power laser devices are visible continuous-wave lasers, operating in a power range of 1-5 mW, which have an irradiance in the emergent beam of 25 Wm^{-2} or less. In some standards the class applies to non-visible lasers having an emission with less than five times the AEL for Class 1 which do not exceed the occupational exposure limit (EL) due to a large exit beam diameter.

Class 3b – moderate-risk, medium-power laser devices are defined as:

(a) UVR, IRB and IRC laser devices (ultraviolet radiation, infrared B and C radiation) that can emit a radiant power in excess of the AEL for the lower classes but cannot emit:

  - an average radiant power in excess of 0.5 W for T_{max} greater than 0.25 second; or
  - a radiant exposure of 100 Jm^{-2} within an exposure duration of 0.25 second or less;

(b) visible and IRA (near infrared) continuous-wave or repetitively-pulsed laser devices that exceed the limits for lower classes but cannot emit an average radiant power of 0.5 W for T_{max} greater than 0.25 second;

(c) visible and IRA pulsed laser devices that exceed the limits for lower classes but cannot emit a radiant exposure that exceeds either 100 Jm^{-2} or that required to produce a hazardous diffuse reflection from a perfect diffuser.

Class 4 – high-risk, high-power laser devices that can emit in access of AELs for Class 3b laser devices.

4.5 Classification of multi-wavelength and multiple-source lasers

The classification of laser devices that can potentially emit at numerous wavelengths should be based on the most hazardous possible wavelength combination. Usually the risk from one wavelength far outweighs the contribution of other wavelengths. Multiple sources are considered independent if separated by the appropriate limiting angle for an extended source.

4.6 Detailed risk assessment

Classification is the initial step in hazard analysis and risk assessment. However, it is not sufficient merely to classify the laser in terms of its power or energy output. The place and way that a laser is used, as well as the people who may operate it or be in the exposure zone, must also be considered. The additional safety measures that such environmental and personnel factors may require must be taken into account, and are discussed below.

4.7 Environment

Environmental factors require careful consideration after the laser device has been classified, as their importance in the total hazard evaluation and risk assessment depends on the laser classification. The decision to employ additional hazard controls not ordinarily required for moderate-risk and high-risk laser devices may depend largely on environmental considerations. The probability of exposure of personnel to hazardous laser radiation must be considered separately since it is influenced by the laser's use: indoors, as in a machine shop, a classroom, a research laboratory, or a factory production line; or outdoors, as at a highway construction site, on the open sea, on a military laser range, in the atmosphere above occupied areas, or in a pipeline construction trench. Other environmental hazards should also be considered.

If exposure of unprotected personnel to the primary or specularly reflected beam is expected, calculations or measurements of either irradiance or radiant exposure of the primary or specularly reflected beam, or radiance of an extended source, at that specific exposure location are required. It is important to consider that transmission and reflection properties of materials can vary significantly in the infrared and ultraviolet regions when compared to those properties in the visible region of the optical spectrum. For example, plastic curtains which appear very dark or opaque to visible light may be actually highly transparent in the near-infrared; many paints that are of low reflectance in visible light have a much higher reflectance in the near-infrared. Also, dull, non-specular metal surfaces as visualized under visible light are frequently highly specular (mirror-like) for the infrared wavelength of the CO_2 laser at 10.6 μm.

4.7.1 Indoor laser operations

In general only the laser source itself is considered in evaluating an indoor laser operation if the beam is enclosed or is operated in a controlled area. The following step-by-step procedure is recommended for evaluation of moderate-risk laser devices indoors when this is necessary, since unprotected personnel may potentially be exposed with this particular class of laser devices:

Step 1. Determine the applicable AEL considering the maximum exposure duration from the intended use.
Step 2. Determine the hazardous beam path(s).
Step 3. Determine the extent of hazardous specular (mirror-like) reflection as indicated in figure 2. The reflection hazard varies with the degree of focusing of the beam and the nature of the surface.
Step 4. Determine the extent of hazardous diffuse reflections (nominal hazard zone).
Step 5. Determine whether any non-laser hazards exist.

4.7.2 Outdoor laser operations over extended distances

The total hazard evaluation of a particular laser device depends on defining the extent of several potentially hazardous conditions. This may be done in a step-by-step manner as follows:

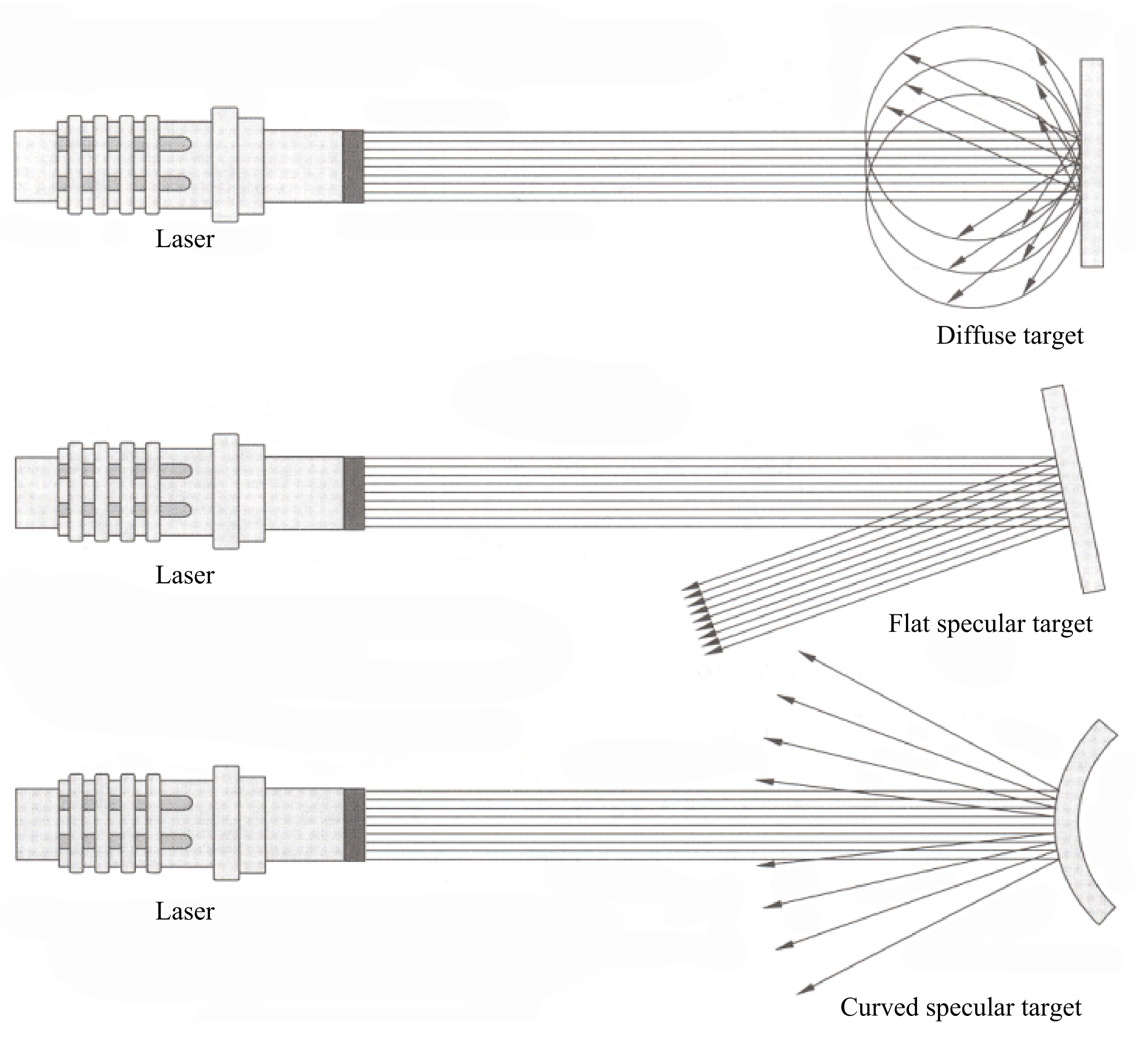
Step 1. Determine the applicable AEL considering the maximum exposure duration from the intended use.
Step 2. Estimate the nominal hazardous range of the laser.
Step 3. Evaluate potential hazards from specular-surface reflections, such as those from windows and mirrors in vehicles, and hazards from retroflectors.

Step 4. Determine whether hazardous diffuse reflections exist (nominal hazard zone), especially if the laser is operating in the 400 – 1,400 nm band.

Step 5. Evaluate the stability of the laser platform to determine both the extent of horizontal and vertical range control and which, if any, of the azimuth and elevation constraints need to be placed on the beam traverse.

Step 6. Determine the likelihood of people being present in the area of the laser beam.

Figure 2. Reflection of laser beams



4.8 Personnel

The individuals who may be in the vicinity of a laser and its emitted beam or beams can influence the decision to adopt additional control measures not specifically required for the class of laser being employed. This again depends on the classification. of the laser device.

If children or others unable to read or understand warning labels are exposed to potentially hazardous laser radiation, the hazard evaluation is affected and control measures could require appropriate modification.

The type of personnel influences the total risk assessment, especially with the use of moderate-risk, medium-power lasers. The principal means of hazard control for certain lasers or laser systems, such as military laser range-finders and some moderate-risk lasers used in the construction industry, is for the operator to keep the laser beam away from personnel or flat, mirror-like surfaces.

The factors to be taken into account with regard to personnel who may be exposed are summarized as follows:

(a) the maturity and general level of training and experience of the laser users (e.g. students, master machinists, soldiers and scientists);

(b) the maturity of onlookers, their awareness that potentially hazardous laser radiation may be present, and their knowledge and ability to apply relevant safety precautions;

(c) the degree of training in laser safety of all individuals involved in laser operation;

(d) the extent to which individuals can be relied on to wear eye protection;

(e) the number and location of individuals relative to the primary beam or reflections, and the probability of accidental exposure.

5

Instrumentation and measurement techniques

In any discussion of the measurement of laser radiation for the purpose of evaluating health hazards, one should first consider the necessity of measurement. As a general rule measurements are required only of the laser output for the purpose of determining the laser hazard classification. Routine monitoring is seldom considered necessary and measurements are performed by the laser developer or manufacturer. However, where exposure is intentional and in the outdoor environment, it is often necessary to measure laser beam irradiance or radiant exposure down range.

5.1 Laser parameters to measure

One can calculate the irradiance or radiant exposure at any distance from a laser. To do this the output power or energy, the initial beam diameter and beam divergence must be determined.

One can use a calorimeter or other types of energy or power meters to measure the output energy or power. The measurement of output beam diameter or divergence can be more difficult. Measurement of the beam divergence is critical for determining the potentially hazardous viewing distance (nominal ocular hazard distance (NOHD). Power-through-aperture measurements may be employed to determine the effective beam diameter and divergence.

From the standpoint of hazard analysis, it is necessary to know the maximal output radiant exposure of a pulsed laser to determine if a diffuse reflection hazard exists. The simplest technique for this purpose is the use of thermally or photochemically reacting surfaces (beam-profile paper). In other cases where the beam irradiance is insufficient to cause a surface change in the special beam-profile paper, conventional photography or a radiometric instrument which has a sufficiently small aperture must be used.

5.2 Types of radiometric instruments

Radiometric instruments of interest to this discussion generally consist of a detector which produces a voltage, a current, a resistance change, or a charge which is measured by a sensitive electronic meter.

The detector is the primary determining factor in selecting an instrument. Each type of detector has certain characteristics which may pose either an advantage or a disadvantage for measuring a certain level of optical radiation in a certain wavelength range. No one type of detector can serve for measuring all types of laser radiation. A very sensitive detector can be destroyed by a high-power laser beam.

5.2.1 Thermal detectors

Thermopiles and disc calorimeters are characterized by a relatively flat spectral response.

Response times of calorimeters and thermopiles may still be too great when measuring a short-pulse. Pyroelectric detectors, which respond to the rate of temperature change in a crystalline material, have response times of the order of nanoseconds.

Thermal detectors find their greatest application in the measurement of laser radiation which operate in the infrared region, where other detectors do not respond, or where quantum detectors require cryogenic cooling. For a single instrument to measure laser power between 10 mW and 100 W, disc calorimeters are considered reliable at all optical wavelengths. In many instances the radiant energy output of a pulsed laser can be measured using a disc calorimeter if the beam radiant exposure is below the damage threshold of the absorbing black – which may typically be of the order of 105 J m^{-2}. For higher energy pulsed lasers, ballistic thermopiles or volume-absorber disc calorimeters are often useful. The disc calorimeter and the ballistic thermopile are both more suitable for the laboratory than for the field, since several seconds or even minutes are required for the detector to cool between measurements of a pulsed laser or for stabilization in a CW measurement.

5.2.2 Quantum detectors

These detectors are by far the most sensitive detectors of optical radiation in the 200 nm to 1,100 nm spectral region. The spectral sensitivity of photoemissive detectors depends on the photocathode material used in vacuum photodiodes or photomultiplier tubes, or in the intrinsic characteristics of silicon or germanium. Silicon is employed in solid-state photodiodes which may operate as either photoconductive or photovoltaic detectors. The type of detector chosen normally depends on what wavelengths one wishes to measure and what wavelengths one may wish to exclude.

Response times of the order of 1 ns are possible with quantum detectors. One instrument that has been found particularly useful for hazard analysis of all types of UV, visible and IRA lasers uses a vacuum photodiode detector. With the appropriate selection of input optics and apertures, it is possible to measure radiance, integrated radiant exposure, radiant power or energy, and irradiance. The disadvantage of this type of instrument is that it can become quite expensive to have all these features with sufficient sensitivity. Because of the strong spectral dependence, these instruments are normally not direct reading and the meter reading must be multiplied by one or several calibration factors.

5.2.3 Hazard evaluation

At present no radiometric instruments are available which have been designed specifically for hazard analysis of a wide range of lasers. Indeed, it is unlikely that such instruments will be made in the near future because of the great variation in exposure critical for different wavelengths and different exposure times. Of course, such instruments could be made for each of the specific categories of lasers, but at present a set of these instruments would be quite expensive. Fortunately, most high-intensity light sources and modern lasers have fairly consistent maximum output parameters. Because of this consistency and the uncertainties of exposure limits, there is seldom a need for periodic monitoring of a source. Quite often an optical source can be determined to have a radiant output either greatly exceeding or far below the applicable exposure limits.

5.3 Photographic measurement techniques

Photographic radiometry can play a valuable role in some instances. Determination of the effective source size is of critical importance in making a hazard evaluation of a high-intensity extended source. The radiance is of principal interest in such an evaluation, and photographic techniques may be used to determine the radiance distribution of a source.

One of the most important criteria for evaluating the potential hazards from pulsed laser systems is the output radiant exposure. If the output is above the levels considered safe for viewing diffuse reflections, considerably more stringent (Class 4) controls must be instituted. A rough guideline for determining whether the output is at or above these threshold levels can be arrived at through the use of appropriate heat-sensitive papers or emulsions. If the beam reacts thermally with such paper, there is a possibility of hazardous diffuse reflections. If the beam does not thermally react with a specially chosen paper, it can generally be assumed that the beam does not produce hazardous diffuse reflections. Such paper can also indicate emergent beam profiles for high-energy lasers.

5.4 Calibration and measurement techniques

Calibration of all radiometric systems is required periodically. The preferred calibration method for the irradiance levels of interest (table 2) uses a reference disc calorimeter or pyroelectric radiometer. A stable optical source such as a standard lamp or CW laser is then employed to illuminate alternately the uncalibrated detector and the reference detector.

The calibration of radiant exposure meters is more complicated unless the instrument behaves linearly with changes in exposure duration. If it does, an irradiance standard and a calibrated shutter may be adequate for energy calibration. Several methods have been developed for measurement of radiant energy output of pulsed lasers. The many techniques used in radiometry are far too numerous and complex to detail here. Pitfalls exist and have been described (Sliney and Wolbarsht, 1980).

Table 2. Approximate radiometric range of interest for hazard analysis

Spectral region (CIE band designation)	Irradiance ($W m^{-2}$)	Radiant exposure ($J m^{-2}$)	Radiance ($W m^{-2} sr^{-1}$)	Integrated radiance ($J m^{-2} sr^{-1}$)
UV-B and UV-C 180 nm - 315 nm	10^{-3} to 10^{2}	1 to 10^{3}	N/A	N/A
UV-A 315 - 380 nm	1 to 10^{4}	10 to 10^{5}	N/A	N/A
Visible 380 nm - 760 nm	10^{-3} to 10^{2}	10^{-3} to 10^{2}	10^{3} to 10^{7}	10 to 10^{5}
Metavisible or near infrared, IR-A 760 - 1,400 nm	10^{-2} to 10^{3}	10^{-2} to 10^{2}	10^{3} to 10^{7}	10 to 10^{6}
IR-B and IR-C 1,400 nm - 1 mm	10^{2} to 10^{4}	10 to 10^{5}	N/A	N/A

N/A = not applicable.

5.5 Conclusions

Radiometric techniques and instrumentation are available to analyse hazards of exposure of the skin and eyes to laser and other high-intensity optical radiation sources. However, the cost for such equipment remains relatively high when compared to the survey equipment available to evaluate many other environmental hazards. Radiometric formulas and manufacturer's specifications, when carefully applied, can often be an adequate substitute for measurements. If detailed information is necessary, however, at least some measurements are generally required. However, measurements taken by untrained personnel may lead to invalid conclusions. A more detailed summary is to be found in Sliney and Wolbarsht, 1980, and Sliney, 1989.

6

Occupational exposure limits and safety standards

6.1 The IRPA/INIRC guidelines on limits of exposure to laser radiation

6.1.1 Background

The International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) first published guidelines on limits of exposure to laser radiation in 1985. Since that time, as a result of an expanded laser database, the guidelines were revised in 1988.[1] Prior to presenting the guidelines on laser exposure, it is worthwhile explaining the process by which IRPA/INIRC develops guidelines on non-ionizing radiation (NIR).

6.1.2 Exposure limits

Exposure limits in standards are expressed in terms of radiant exposure (J/m^2 or J/cm^2) or irradiance (W/m^2 or W/cm^2) for direct exposure or respectively integrated radiance ($J/m^2.sr$ or $J/cm^2.sr$) and radiance ($W/m^2.sr$ or $W/cm^2.sr$) for extended sources.

The development of exposure limits requires a valid assessment of the possible biological effects and of the exposure-response relationship as well as appropriate information on the various sources in use, the resulting levels of exposure and the people at risk. It also requires a protection philosophy which links the above knowledge with the general aims of occupational health protection. As noted above, the basic resource document used for the development of the laser exposure limits was the Environmental Health Criteria Document (WHO, 1982). The data base of laser biological effects upon the human eye and skin reviewed in the criteria document was the same as that used by other national and international organizations to derive exposure limits and, not surprisingly, the IRPA exposure limits are generally in agreement with those of the International Electrotechnical Commission (IEC, 1984, 1990), the American Conference of Governmental Industrial Hygienists (ACGIH, 1991), the American National Standards Institute (ANSI, 1986), the British Standards Institute (BSI, 1984), the Health Council of the Netherlands (HCN, 1979), the Deutsche Institut für Normung, (DIN, 1984) and others.

A summary of the IRPA exposure limits is given in tables 3(a), 3(b) and 3(c).

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[1] A. S. Duchêne et al. (eds.): *IRPA guidelines on protection against non-ionizing radiation* (New York, Pergamon Press, 1991), Ch. 4.

Table 3(a). Exposure limits for direct ocular exposures (intrabeam viewing) from a laser beam

Wavelength λ (nm)	Exposure duration *t* t (s)	EL limit EL (J/m^2 or W/m^2)	Restrictions
Ultraviolet			
180 to 302	1 ns to 30 ks	$3.0 \times 10^{1}\ \text{J/m}^2$	All ELs for λ less than 315 nm must be $< 5.6 \times 10^{3}\ t^{3/4}\ \text{J/m}^2$
303	1 ns to 30 ks	$4.0 \times 10^{1}\ \text{J/m}^2$	
304	1 ns to 30 ks	$6.0 \times 10^{1}\ \text{J/m}^2$	
305	1 ns to 30 ks	$1.0 \times 10^{2}\ \text{J/m}^2$	
306	1 ns to 30 ks	$1.6 \times 10^{2}\ \text{J/m}^2$	
307	1 ns to 30 ks	$2.5 \times 10^{2}\ \text{J/m}^2$	
308	1 ns to 30 ks	$4.0 \times 10^{2}\ \text{J/m}^2$	
309	1 ns to 30 ks	$6.3 \times 10^{2}\ \text{J/m}^2$	
310	1 ns to 30 ks	$1.0 \times 10^{3}\ \text{J/m}^2$	
311	1 ns to 30 ks	$1.6 \times 10^{3}\ \text{J/m}^2$	
312	1 ns to 30 ks	$2.5 \times 10^{3}\ \text{J/m}^2$	
313	1 ns to 30 ks	$4.0 \times 10^{3}\ \text{J/m}^2$	
314	1 ns to 30 ks	$6.3 \times 10^{3}\ \text{J/m}^2$	
315 to 400	1 ns to 10 ks	$5.6 \times 10^{3}\ t^{3/4}\ \text{J/m}^2$	
315 to 400	10 s to 30 ks	$1.0 \times 10^{4}\ \text{J/m}^2$	
Visible and IR-A			
400 to 700	1 ns to 18 µs	0.005 J/m^2	7 mm limiting aperture
400 to 700	18 µs to 10 s	$18\ t^{3/4}\ \text{J/m}^2$	
400 to 550	10 s to 10 ks	100 J/m^2	
550 to 700	10 s to T_1 s	$18\ t^{3/4}\ \text{J/m}^2$	
550 to 700	T_1 s to 10 ks	$100\ C_B\ \text{J/m}^2$	
400 to 700	10 ks to 30 ks	$0.01\ C_B\ \text{W/m}^2$	
700 to 1,050	1 ns to 18 µs	$0.005\ C_A\ \text{J/m}^2$	
700 to 1,050	18 µs to 1 ks	$18\ C_A\ t^{3/4}\ \text{J/m}^2$	
1,051 to 1,400	1 ns to 50 µs	$0.05\ C_C\ \text{J/m}^2$	
1,051 to 1,400	50 µs to 1 ks	$90\ C_C\ t^{3/4}\ \text{J/m}^2$	
700 to 1,400	1 ks to 30 ks	$3.2\ C_A \cdot C_C\ \text{W/m}^2$	
Far infrared			
1,400 to 1,500	1 ns to 1.0 ms	1,000 J/m^2	3.5 mm limiting aperture
1,400 to 1,500	1.0 ms to 10 s	$5{,}600\ t^{1/4}\ \text{J/m}^2$	
1,500 to 1,800	1 ns to 10 s	$10^{4}\ \text{J/m}^2$	
1,801 to 2,600	1 ns to 1.0 ms	1,000 J/m^2	
1,801 to 2,600	1.0 ms to 10 s	$5{,}600\ t^{1/4}\ \text{J/m}^2$	
2,601 to 106	1 ns to 100 ns	100 J/m^2	
2,601 to 108	100 ns to 10 s	$5{,}600\ t^{1/4}\ \text{J/m}^2$	
1,400 nm to 1 mm	10 s to 30 ks	1,000 W/m^2	

Notes: The limiting aperture for all ELs in the UV and for wavelengths from 1,400 nm to 0.1 mm is 1 mm for less than 0.25 s and 3.5 mm for longer durations, is 11 mm for wavelengths greater than 0.1 mm, and is 7 mm for all ocular ELs from 400 to 1,400 nm. For a 1 ks = 1,000 s, and 30 ks = 8 hours.

$C_A = 1$ for $\lambda = 400$ to 700 nm; $C_A = 10^{[0.02(\lambda - 700)]}$ if $\lambda = 700 - 1{,}050$ nm
$C_B = 1$ for $\lambda < 550$ nm; $C_B = 10^{[0.015(\lambda - 550)]}$ for $\lambda = 550$ nm to 700 nm
$T_1 = 10 \times 10^{[0.02(\lambda - 550)]}$ for $\lambda = 550$ nm to 700 nm. $C_C = 1$ for $\lambda < 1{,}150$
$C_C = 10^{0.0181(\lambda - 1150\ \text{nm})}$ for $1{,}150 < \lambda < 1{,}200$; $C_C = 8$ for $1{,}200 < \lambda < 1{,}400$

Source: IRPA.

Table 3(b). Extended source laser ocular exposure limits

Extended source ELS are determined by multiplying the intrabeam ocular ELs by correction factor C_E. The following corrective factor C_E shall be applied to the listed intrabeam exposure limits for source sizes greater than α_{min} where α_{min} is:

$\alpha_{min} = 1.5$ mrad for $t < 0.7$ s,
$\alpha_{min} = 10 \times t^{3/4}$ mrad for $0.7 \text{ s} < t < 10$ s, and
$\alpha_{min} = 11$ mrad for $t < 10$ s.

$C_E = \alpha / \alpha_{min}$ for $\alpha_{min} < \alpha < 100$ mrad.
$C_E = 10 \times \alpha^2 / \alpha_{min}$ for $\alpha > 100$ mrad.

Source: IRPA.

Table 3(c). Laser exposure limits for the skin

Wavelength λ (nm)	Exposure duration *t* t (s)	Exposure limit EL (J/cm² or W/cm²)	Restrictions
Ultraviolet			
200 to 400	1 ns to 30 ks	Same as eye EL	
Visible and IR-A			
400 to 10^6	1 ns to 100 ns	0.2 C_A kJ/m²	1 or 3.5 mm limiting aperture
400 to 10^6	100 ns to 10 s	11 C_A $t^{1/4}$ kJ/m²	
400 to 10^6	10 s to 30 ks	2.0 C_A kW/m²	
Far infrared			
1,400 to 10^6	1 ns to 30 ks	Same as eye EL for 2,601 nm to 1 mm	

Notes: The limiting aperture for all pulsed exposures ($t < 0.25$ s) is 1 mm, and is 3.5 mm for greater exposure durations.
1 ks = 1,000 s, and 30 ks = 8 hours.
$C_A = 1$ for $\lambda = 400$ to 700 nm; $C_A = 10^{[0.02(\lambda - 700)]}$ if $\lambda = 700 - 1{,}050$ nm

Source: IRPA.

Table 3(a) illustrates the IRPA exposure limits for direct ocular exposure (intrabeam viewing) to a laser beam. Table 3(b) shows the IRPA exposure limits for viewing a diffuse reflection of a laser beam or an extended source laser. Table 3(c) gives the IRPA exposure limits for skin. The correction factor C_A, mentioned in table 3(a), is given in figure 3 as a function of the laser wavelength. For a more comprehensive presentation and background of the IRPA exposure limits, the reader is referred to the complete guidelines which can be found in Health Physics (IRPA, 1985, 1988). In table 3(d) some representative exposure limits have been selected for the most commonly available lasers. One should also remember that because of the way most of the laser safety standards are organized, one makes use of a laser hazard classification (initially based upon exposure limits) to perform a hazard evaluation, rather than to perform measurements of beam exposure for comparison with exposure limits (IRPA, 1988). The exposure limits are actually used only in special instances where human exposure is intended and the laser beam irradiance or radiant exposure may actually be measured or calculated to determine if the exposure limit will be exceeded.

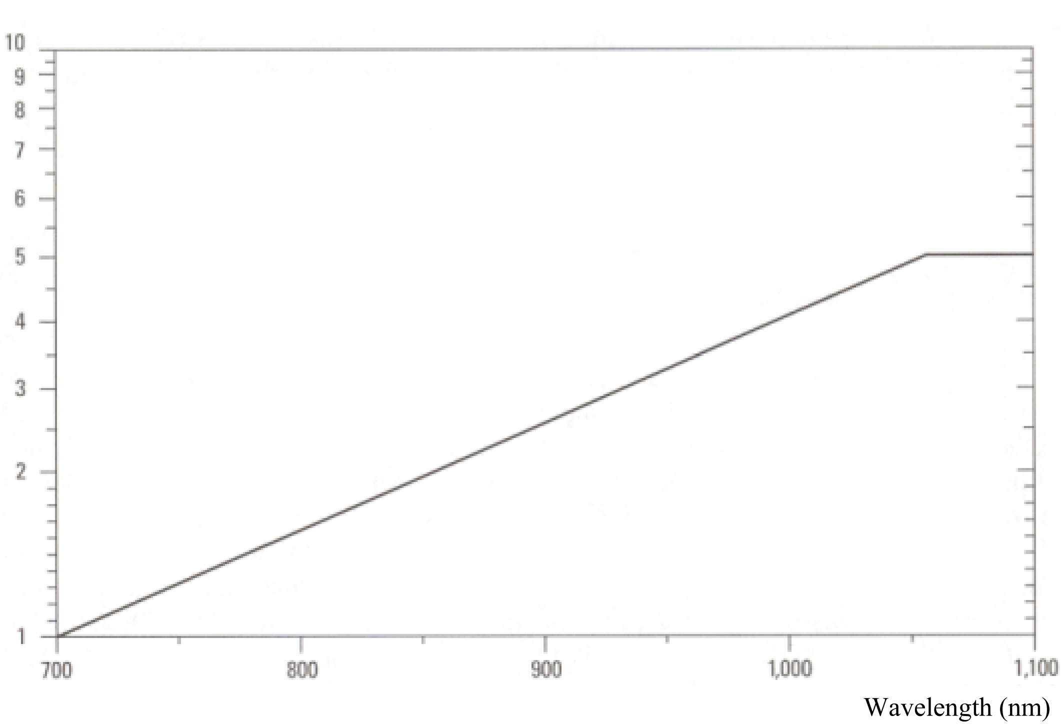
Table 3(d). Selected occupational exposure limits (ELs) for some common lasers

Laser	Wavelength	Exposure limit
Argon-fluoride laser	193 nm*	3.0 mJ/cm^2 over 8 hrs
Xenon-chloride laser	308 nm	40 mJ/cm^2 over 8 hrs
Argon ion laser	488, 514.5 nm	3.2 mW/cm^2 for 0.1 s 2.5 mW/cm^2 for 0.25 s
Helium-neon laser	632.8 nm	1.8 mW/cm^2 for 1.0 s
Krypton ion laser	568,647 nm	1.0 mW/cm^2 for 10 s
Helium-neon laser	632.8 nm	17 µw/cm^2 for 8 hrs
Neodymium-YAG laser	1,064 nm 1,334 nm	5.0 µJ/cm^2 for 1 ns to 100 µs No EL for t < 1 ns 5 mW/cm^2 for 10 s
Erbium glass laser	1,540 nm	1.0 J/cm^2 for 1 -1,000 ns
Erbium:YAG	2,940 nm	10 mJ/cm^2 for 1 -100 ns
Hydrogen-fluoride laser	2.7-3.1µm	10 mJ/cm^2 for 1 -100 ns
Carbon-dioxide laser	10.6 µm	100 mW/cm^2 for 10 s to 8 hrs, limited area 10 mW/cm^2 for >10 s for areas ≥ 1,000 cm^2

*Not all standards/guidelines have ELs below 200 nm.
Note: to convert ELs in mW/cm^2 to mJ/cm^2, multiply by exposure time *t* in seconds.

Source: IRPA/INIRC Guidelines (IRPA, 1985, 1988).

Figure 3. **Correction factor CA used to determine exposure limit values in the near-infrared spectral region.**



Source: IRPA, 1985.

6.1.3 The 1988 revisions

In 1988, IRPA published revisions to its 1985 guidelines (IRPA, 1985, 1988). None of these revisions affected the basic limits as outlined in table 3(a). The most significant change related to the method for determining the applicable exposure duration for CW lasers and for repetitive-pulse laser exposures. The previous method was simplified and clarified. Several previous rules for determining pulse additivity were reduced to one expression. All tables of exposure limits remained unchanged.

A correction for large-area illumination of the skin was also introduced. Among other things, that change minimized the transition between the guidelines for limits of exposure to microwave radiation at 300 GHz and the guidelines for infrared laser exposure at 1.0 mm (i.e. 300 GHz).

6.1.4 Infrared laser exposure limits

It may seem remarkable that with the variation of the spectral absorption properties of water in the IRB and IRC (wavelengths between 1,400 nm and 1 mm), that the exposure limits are all constant with wavelength with the exception of short-pulse, sub-microsecond exposures to 1.54 µm laser radiation. However, the available data are insufficient to define additional wavelength corrections (relative to the extensive data base at 10.6 µm) over the entire infrared range (1.4 µm to 1 mm). At 1.54 µm, the infrared exposure limits are increased by a factor of 100 for exposure durations shorter than 1 µs. No further extrapolation to other wavelengths is justified on the basis of presently available information.

A change in the exposure limits for the skin was made by INIRC in 1988. For beam cross-sectional areas between 100 cm^2 and 1,000 cm^2, the exposure limit for exposure durations exceeding 10 s is $10{,}000/A_s$ mW/cm^2, where A_s is the area of the exposed skin in cm^2. For exposed skin areas exceeding 1,000 cm^2, the exposure limit is 10 $mW\ cm^{-2}$ (IRPA, 1988).

6.1.5 Exposure duration

A significant clarification in the 1988 revision related to guidance for selecting the appropriate exposure duration to attribute to a CW laser exposure. Determining the applicable exposure limit for a specific continuous-wave or repetitively pulsed laser exposure requires a determination of the exposure duration. For a single pulse exposure, this duration is obvious; however, the following criteria should be followed where repeated exposures or lengthy exposures occur.

For any single-pulse laser exposure, the exposure duration is the pulse duration, t, defined at its half-power points. For all skin exposure limits and for ocular exposure to non-visible wavelengths (less than 400 nm or greater than 700 nm), the continuous wave exposure duration is the maximum time, T, of anticipated direct exposure. For exposure of the eye to any continuous wave laser, the exposure duration is the maximum time of anticipated direct viewing. However, if purposeful staring into a visible (400 to 700 nm) beam is not intended or anticipated, then the aversion response time, 0.25 s, should be used. For ocular exposures in the near-infrared (700 to 1,400 nm), a maximum exposure duration of 10 s provides an adequate hazard criterion for either unintended or purposeful staring conditions. In this case, eye movements will provide a natural exposure limitation and thereby eliminate the need for consideration of exposure durations greater than 10 s, except for unusual conditions. In special applications, such as intentional exposure from diagnostic medical instrumentation, even longer exposure durations may apply.

Exposure limits for pulse durations less than 1 ns were not provided by IRPA/INIRC because of a lack of biological data. However, a conservative interim guideline would be to limit peak irradiances to the exposure limit applicable to nanosecond pulses at the wavelength of interest.

6.1.6 Repetitive laser exposures

Repeated exposure within any one day to laser radiation can occur from multiple repeated exposures to a continuous wave beam, or from exposures to repetitively pulsed lasers and some scanning beam lasers. Scanning beams create repetitive-pulse exposures to the eye in the retinal hazard region (400-1,400 nm). Both the individual pulse duration and the total cumulative exposure duration must be determined. In this case, the total exposure duration of the train of pulses is determined in the same manner as is used for continuous wave laser exposures, i.e. the time T elapsed from the beginning of the exposure (first pulse) to the end (last pulse). The methods for determining the exposure limits for repetitive laser exposures are given in the following paragraphs:

(i) Ultraviolet laser radiation

For repeated exposures, the exposure dose is additive over a 24-hour period, regardless of the repetition rate. This rule is consistent with all experience on biological effects of ultraviolet radiation. The exposure limit for any 24-hour period should be reduced by a factor of 2.5 times relative to the single-pulse exposure limit if exposures on succeeding days are expected (Zuclich, 1980).

(ii) Visible and infrared laser radiation

Both scanned continuous wave lasers and repetitively pulsed lasers can create a series (train) of laser pulses entering the eye. The exposure limit per pulse for repetitively pulsed intrabeam viewing is $N^{-1/4}$ times the exposure limit for a single pulse of the same duration (t) where N is the number of pulses found from the product of the pulse repetition frequency (PRF) and the total exposure duration (T). The duration T is determined in the same manner as for a continuous wave laser of the same wavelength (see above). This exposure limit applies to all wavelengths greater than 700 nm where thermal injury predominates. For wavelengths less than 700 nm where photochemical damage mechanisms may also apply, the exposure limit as calculated on the basis of $N^{-1/4}$ also must not exceed the exposure limit calculated for Nt seconds when t is the duration of a single pulse in the train and Nt is greater than 10 s. For pulse repetition frequencies greater than 15 kHz, the average irradiance or radiant exposure (radiance or integrated radiance) of the pulse train shall not exceed the exposure limit for a continuous wave exposure for the viewing duration T. Average irradiance is the total radiant exposure delivered during time T, divided by T. The empirical relation of $N^{-1/4}$ was based upon several studies (Sliney and Marshall, 1991). The basis of the 0.25 s and 10 s viewing criteria are studies of eye movements (Sliney and Wolbarsht, 1980).

(iii) Repeated exposure of the skin

For repetitive-pulsed laser exposure of the skin, the exposure limit based upon a single-pulse exposure shall not be exceeded and the average irradiance of the pulse train shall not exceed the exposure limit applicable for the total duration T of the pulse train.

6.2 Future outlook

The only area of exposure limit guidelines being considered for possible revision relates to extended-source limits. This change would still not affect many applications, as one normally uses the more conservative intrabeam ("point-source") exposure limits in practice (Courant et al., 1989).

7

Control of and protection from exposure to laser radiation

This section recommends measures for the effective control of exposure to laser radiation and protection from occupational exposure to optical radiation from laser products. It applies to laser products which may consist of a single laser with or without a separate power supply or may incorporate one or more lasers in an optical, electrical or mechanical system. Such systems have been described in section 4.

7.1 Control measures – General concept

Approaches to laser safety vary greatly among individuals and groups who have an interest in the problem. Most programmes in industry, government and universities are still in the course of development. Some organizations have written policies and practices outlining the responsibilities of management and of technical supervision, environmental health, safety and medical personnel. Such policies are usually broadly defined, with specific provisions for individual problems. All such policies and procedures should emphasize the need to rely primarily on engineering controls. Appropriate education and training should be conducted both for the individual laser operator and for supervisory personnel for the safe conduct of laser operations. Engineering measures should take into account the need for interlocks, proper layout of room areas, shielding materials and warning signs. The criteria for selecting protective eyewear involve many interrelated factors. It should be noted that commercially available protective eyewear is designed for protection against a specific wavelength or group of wavelengths. Eye protection devices designed for protection against specific wavelengths and power from the laser system should be used when engineering and procedural controls are inadequate. For cases in which long-term exposure to the eye by visible lasers (only) is not intended, the applicable exposure limit may be based on a 0.25-second duration.

The International Electrotechnical Commission (IEC, 1984), the American Conference of Governmental Industrial Hygienists (ACGIH, 1990) and the Laser Institute of America (LIA, 1990) have prepared guides for laser installations, and the American National Standards Institute (ANSI, 1986) and other national bodies have developed a detailed personnel exposure standard for laser users. These documents give hazard controls for laser radiation that vary depending on the type of laser being used and the manner of its use. The control of laser operation should be entrusted to a knowledgeable laser operator under the supervision of personnel knowledgeable in laser hazards. A closed installation should be used when feasible.

In the above-mentioned guides and standards, only two general precautions are common to all laser installations:

(a) people should not look into the primary beam or at specular reflections of the beam, unless necessary, even if the exposure limit is not exceeded;

(b) the laser operator should be familiar with the type of laser used and act responsibly; provisions should be made for the appropriate education and training of all individuals using laser devices.

Consideration should be given to the operation of laser devices in a controlled area according to laser classification. Special emphasis should be placed on control of the path of the laser beam. Only authorized personnel should operate laser systems. Spectators should not be allowed to enter a controlled area unless appropriate supervisory approval has been obtained and protective measures taken.

Laser optical systems (mirrors, lenses, beam deflectors, etc.) should be aligned in such a manner that the primary beam, or a specular reflection (mirror-like) of the primary beam, cannot result in an ocular exposure above the exposure limit for direct irradiation of the eye.

Optical systems such as lenses, telescopes and microscopes may increase the hazard to the eye when viewing a laser beam, so that special care should be taken in their use. Microscopes and telescopes may be used as optical instruments for viewing, but should be provided with an interlock or filter, if necessary, to prevent ocular exposures above the appropriate exposure limit for irradiation of the eye.

With non-visible laser beams, extra vigilance is necessary to ensure that the beam path is properly positioned and that dangerous specular reflections do not occur.

Laser medical instrumentation for surgery or for diagnostic purposes should have built-in safety devices, including special firing mechanisms, and warning notices as to the need for eye protection and protection of the patient, including the use of nonflammable gas anaesthesia. The normal safety precautions for any electrical equipment should be included. Laser surgical devices for training purposes should have dual controls. A suitable training programme should be provided for all potential users and operating room personnel. The control measures should not restrict or limit in any way the use of laser radiation of any type that may be intentionally administered to an individual for diagnostic, therapeutic or research purposes, by or under the direction of qualified professionals engaged in the healing arts. Precautions should be taken to ensure that any unnecessary exposure of organs or tissues is minimized.

With the increase in medical and industrial applications of high-power laser systems, there is an increased probability of accidental exposure of the skin to levels of laser radiation above the exposure limit for skin. It is recommended that, for personnel working with such high-power (Class 4) laser systems, protection should be provided for the skin wherever possible.

The engineering control measures recommended for Class 3b and 4 lasers or laser systems, upon review and approval by the laser safety officer (LSO) may be replaced by procedural, administrative or other alternative engineering controls which provide equivalent protection. This situation could occur, for example in medical or research and development environments.

7.2 Laser radiation surveillance in the workplace

The objective of laser radiation surveillance and laser hazard evaluation is to determine from records whether the equipment or installation complies with recommended standards of performance and personnel exposure (i.e. whether or not excessive exposure has occurred), to delineate boundary areas requiring shielding and to identify controlled and uncontrolled areas in the workplace (before the source(s) is operational).

When conducting laser radiation surveys and laser hazard evaluation, the following procedure is recommended:

(a) laser radiation surveys or laser hazard evaluations should be carried out by a competent person, preferably the LSO;

(b) they should be conducted in the following situations:
   (i) before routine operation begins, for all new installations capable of producing laser radiation exceeding the recommended exposure limits;
   (ii) following any repairs or changes in working conditions, protective shielding and barriers that may affect the exposure levels, to ensure that the levels do not exceed the recommended exposure limits;
   (iii) when any malfunction is suspected that may affect laser radiation levels;
   (iv) at regular intervals at installations capable of exposing personnel in excess of the recommended limits.

Records should be kept of all formal laser radiation survey data and their evaluation, the number and types of devices in the area surveyed. Such records should also include a review of all known laser radiation incidents and their attributed causes.

7.3 Control of occupational exposure

7.3.1 Laser classification

The classification scheme relates specifically to the accessible emission from the laser system and the potential hazard based on its physical characteristics. Laser products should be classified by the manufacturer and labelled with that class in accordance with the appropriate national regulation and IEC 825 (IEC, 1984, 1990).

7.3.2 Manufactured laser products

This practical guide specifies safety precautions and control measures to be taken by the user of a laser system, in accordance with its hazard classification, and does not concern the duties and obligations of manufacturers. It is normally expected that users can apply the manufacturer's classification of the product for assessing the hazards of the laser product during operation, thus avoiding all or most radiometric measurements. Manufacturers are referred to Standard Publication 825 of the International

Electrotechnical Commission (IEC, 1984, 1990) which relates to classification and performance requirements for safety.

7.3.3 Research and developmental lasers

Since most injuries from laser radiation have occurred in research laboratory environments, it is of particular importance to control exposure in these environments. Developmental lasers are frequently "brass-board" prototypes constructed in-house without all of the system safety features common to manufactured products. It is therefore important to classify these lasers once operational, attempt to enclose the beam path as much as practicable and install system safety features if practical to minimize potentially hazardous exposure.

The hazard control methods for Class 3b and Class 4 experimental devices are then the same as for a manufactured laser product, and these controls are presented in the following sections.

7.3.4 Class 3b and Class 4 laser systems used indoors

The need to use personal protection against the hazardous effects of laser operation should be kept to a minimum by engineering safety design, beam enclosure and administrative controls.

When exposure to potentially hazardous laser radiation (Class 3b and Class 4) is likely, adequate eye protectors should be provided (see paragraph 7.4.12).

7.3.5 Class 3b and Class 4 laser systems used outdoors

The hazard potential for Class 3b and Class 4 lasers may extend over a considerable distance. The range from the laser at which the irradiance or radiant exposure falls below the appropriate exposure limits is termed the nominal ocular hazard distance (NOHD). The area within which the beam irradiance or radiant exposure exceeds the appropriate exposure limit is called the nominal ocular hazard area (NOHA), or in some countries the nominal hazard zone (NHZ). This area is bounded by the limits of traverse, elevation and pointing accuracy of the laser system and extends either to the limit of the nominal ocular hazard distance (NOHD) or to the position of any target or backstop. The exact nominal ocular hazard area (NOHA) will also depend on the nature of any material within the beam path, e.g. specular (mirror-like) reflectors.

The nominal ocular hazard distance (NOHD) is dependent on the output characteristics of the laser, the appropriate exposure limit, the type of optical system used, and the effect of the atmosphere on beam propagation.

A beam backstop is almost always needed. Control of the main beam is the most important consideration in devising control measures. Direct viewing of a visible laser beam will appear extremely bright even if the exposure levels are not exceeded. Persons may therefore believe that they have been overexposed, or they may be distracted and risk ancillary hazards.

The risk from the direct beam is increased if the possibility exists for persons viewing the beam with magnifying optics. The eye hazard at any distance is increased by the square of the magnifying power of the optics. The hazard distance is increased by the magnifying power of the optics over that for unaided viewing. Therefore, a laser with a 100 m hazard distance for unaided viewing would be hazardous at 700 m for someone using 7 × 50 binoculars. The possibility of persons using optics reinforces the need for a beam backstop. Outdoors, almost any diffuse material will serve as a beam backstop. Unlike laboratory situations, high-energy operations, which could damage a beam backstop, are not conducted outdoors.

Specular reflections are of concern in outdoor operations. Target materials may have specular surfaces which could redirect the laser beam into areas where unprotected persons not concerned with the test are situated. Target materials must be chosen carefully to eliminate the possibility of allowing hazardous specular reflections. Diffuse reflections from lasers generally used outdoors do not produce a hazardous reflection.

When pointing lasers into the sky, the hazards to aircraft must be considered. Even if the exposure limits are not exceeded, a brilliant light may distract pilots, especially at night, perhaps enough to lose control of their aircraft. Infrared lasers should only be used in situations where aircraft are not exposed above the exposure limits. Pilots are normally not assumed to be using magnifying optics.

Eye protection is generally considered as a last resort for outdoor operations. If the hazard is sufficient that the operators and personnel in the target area need eye protectors, then the optical density and wavelength need to be properly chosen. However, added concern is necessary for persons not associated with the testing to be informed of the hazards.

Warnings to persons in the area may include laser warning signs with specific instructions to protect personnel, or warning lights. For high traffic situations, areas may need to be roped off or guards posted to warn persons entering the area. Any type of warning should only be used during laser testing where failure of persons to heed the warning would put them at risk. Warnings left in place at a testing site cannot be relied on to be effective during actual testing.

7.4 Safety precautions

7.4.1 Types of control measures

The purpose of safety precautions and control measures is to reduce the possibility of exposure to hazardous levels of laser radiation and to other associated hazards. Control measures may be grouped into one of three categories: (a) engineering controls, (b) personal protective clothing and equipment, (c) administrative controls. In general, engineering control measures are considered more reliable and therefore preferable. If engineering control measures are not practicable, personal protective equipment (normally eye protectors) should be used. Administrative controls and procedures are additional measures which cannot be used as a substitute for engineering control measures.

7.4.2 Selection of control measures

It may not be necessary to implement together all of the control measures at a given time or for a specific laser operation. Whenever the application of any one or more control measures reduce the possible exposure to a level below the applicable exposure limit, then the application of additional control measures may become unnecessary for a given laser operation.

7.4.3 Modified laser products

If a modification by the user of a previously classified laser product affects the intended function or the emergent laser beam power or energy, the person or organization performing any such modification is responsible for ensuring the reclassification and relabelling of the laser product.

7.4.4 Specified environments

The following guidance relates to safe operation of laser products in:

(a) outdoor and construction environments where administrative controls often provide the only reasonable approach to safe operations;

(b) laboratory and workshop environments where engineering controls may play the greater role;

(c) display and demonstration environments, where pre-planning, delineation and control of access often provide the only reasonably practicable approach to safe operation.

7.4.5 Laser demonstrations, displays and exhibitions

Only Class 1, Class 2 or Class 3a laser products should be used for demonstration, displays or entertainment in unsupervised areas. The use of lasers of a higher class for such purposes should be permitted only when the laser operation is under the control of an experienced, well-trained operator and when spectators are prevented from exposure to levels exceeding the applicable exposure limits. Where appropriate, licensing of such displays should be based on an assessment of overall laser safety associated with the potential use of the laser.

Each demonstration laser system used for educational purposes in schools, etc., should be operated so as not to permit exposure to laser radiation in excess of the applicable exposure limit.

7.4.6 Laboratory and workshop laser installations

(i) Class 2 and Class 3a laser products

Precautions are only required to prevent continuous viewing of the direct beam; a momentary (0.25 s) exposure, as would occur in accidental viewing situations, is not considered hazardous. However, the laser beam should not be intentionally aimed at people. The use of optical viewing aids (e.g. binoculars) with Class 3a laser products is potentially hazardous.

(ii) Class 3b laser products

Class 3b lasers are potentially hazardous if a direct beam or specular reflection is viewed by the unprotected eye (intrabeam viewing).[1] The following precautions should be taken to avoid direct beam viewing and to control specular reflections:

(a) the laser should be operated only in a controlled area;

(b) care should be exercised to prevent unintentional specular reflections;

(c) the laser beam should be terminated where possible at the end of its useful path by a material that is light-diffusing and of such a colour and reflectivity as to make beam positioning possible while still minimizing the reflection hazards;

(d) eye protection is required if there is any possibility of viewing either the direct or specularly reflected beam, or of viewing a diffuse reflection through magnifying optics collecting energy within 20 cm;

(e) the entrances to areas should be posted with a standard laser warning sign.

(iii) Class 4 laser products

Class 4 laser products pose potential hazards from both the direct beam or its specular reflections and from diffuse reflections. They also present a potential fire hazard. The following controls should be employed in addition to those of section (ii) to minimize these risks:

(a) beam paths should be enclosed whenever practicable. Access to the laser environment during laser operations should be limited to persons wearing proper laser protective eyewear (and protective clothing in some instances);

(b) Class 4 lasers should be enclosed when operated whenever practicable, thus eliminating the need for personnel to be physically present in the laser environment;

(c) good room illumination is important in areas where laser eye protection is worn. Light-coloured and light-diffusing wall surfaces help to achieve this condition;

(d) a sufficient thickness of firebrick or other refractory material should be provided as a backstop for the beam since fire is a principal hazard associated with high-

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[1] Conditions for safe viewing of a diffuse reflection of Class 3b visible lasers are: minimum viewing distance of 13 cm between screen and cornea and a maximum viewing time of 10 s. Other viewing conditions, e.g. staring fixedly at a diffuse reflection, are considered unrealistic.

powered lasers (e.g. carbon dioxide, hydrogen fluoride, deuterium fluoride). Caution should be observed with these materials as surface glazing may occur with prolonged exposure and give rise to specular reflection. Adequately cooled non-flat metal targets, such as cones and absorbers, are preferred. Laser cutting and welding normally do not produce hazardous reflections at a distance except when beam power fails and ablation ceases;

(e) special precautions may be required to reduce unwanted reflections from farinfrared laser radiation, and the beam and target area should be surrounded by a material such as polymethylmethacrylate opaque to the laser wavelength (even dull metal surfaces may become highly specular at the CO_2 wavelength of 10.6 µm).

7.4.7 Outdoor and construction laser installations

(i) Class 2 laser products

Wherever reasonably practicable, the beam should be terminated at the end of its useful path, and the laser should not be aimed at the eyes of people or routinely operated at head height.

(ii) Lasers for surveying, alignment and levelling

Class 1 or Class 2 lasers should be used for surveying, alignment, and levelling applications whenever practicable. There may be situations, however, where high ambient light levels require the use of lasers of higher output power. If Class 3a lasers are used, the requirements of section (iii) should be followed. In those exceptional cases where Class 3b lasers are necessary, the requirements of section (iv) should be followed. In addition, human access should not be permitted to laser radiation in the wavelength range of 400 nm to 700 nm with a radiant power that exceeds 5 mW for any emission duration exceeding 0.38 ns, nor should human access be permitted to laser radiation in excess of the accessible emission level (AEL) for Class 1 for any other combination of emission duration and wavelength range.

(iii) Class 3a laser products used for surveying, alignment and levelling

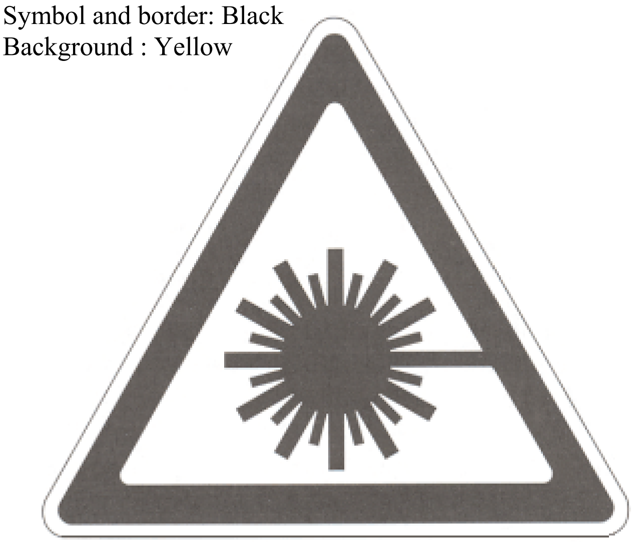
The following guidance applies to surveying operations using Class 3a laser products for alignment and levelling:

(a) Only qualified and trained employees approved by a laser safety officer should be assigned to install, adjust and operate the laser equipment.

(b) Areas in which these lasers are used should be posted with a laser warning sign (figure 4).

Figure 4. Standard laser warning sign (IEC)

Specific warning statement and information vary with the application



(c) Wherever practicable, mechanical or electro-optic means should be used to assist in the alignment of the laser.

(d) Precautions should be taken to ensure that persons do not look directly into the beam (prolonged intrabeam viewing is hazardous). Direct viewing of a totally collected beam above 2 mW through optical instruments (theodolites, etc.) may be hazardous and should not be permitted unless specifically approved by a laser safety officer.

(e) The laser beam should be terminated at the end of its useful beam path and should in all cases be terminated if the hazardous beam path (to the nominal ocular hazard distance) extends beyond the controlled area.

(f) The laser beam path should be located well above or below eye level wherever practicable.

(g) Precautions should be taken to ensure that the laser beam is not unconditionally directed at mirror-like (specular) surfaces (most importantly, at flat mirror-like surfaces).

(h) When not in use, the laser should be stored in a location where unauthorized personnel cannot gain access.

(iv) Class 3b and Class 4 laser products

Class 3b and Class 4 lasers in outdoor and similar environments should be operated only by people adequately trained in their use and approved by the laser safety officer. To minimize possible hazards, the following precautions should be employed in addition to those given in para (iii):

(a) People should be excluded from the beam path at all points where the beam irradiance or radiant exposures exceed the exposure limits unless they are wearing appropriate eye protectors. Engineering controls such as physical barriers, interlocks limiting in the beam traverse and elevation should be used wherever practicable to augment administrative controls.

(b) The intentional tracking of non-target vehicles or aircraft should be prohibited within the nominal ocular hazard distance.

(c) The beam paths should, whenever practicable, be cleared of all surfaces capable of producing unintended reflections that are potentially hazardous, or the hazard area should be extended appropriately.

7.4.8 Use of built-in engineering controls

(i) Remote interlock connector

The remote interlock connector installed in a Class 4 laser should be connected to an emergency master disconnect interlock or to room, door, or fixture interlocks. Door interlocks should be employed when a hazardous level of laser radiation may exist at the doorway.

(ii) Key control

When it is not in use each Class 3b or Class 4 laser product should be protected against unauthorized use, by removal of the key of the key control.

(iii) Beam stop or attenuator

In addition to the laser operating switch, Class 3b and Class 4 laser products should be provided with a permanently attached beam stop or attenuator mechanism capable of preventing output emission in excess of the appropriate level when the laser product is on stand-by.

7.4.9 Warning signs

The entrances to areas or protective enclosures containing Class 3a, Class 3b, and Class 4 laser products should be posted with appropriate warning signs (see figure 4 for an example).

7.4.10 Beam paths

The beam emitted by each Class 3b or Class 4 laser product should be terminated at the end of its useful path by a diffusely reflecting material of appropriate reflectivity and thermal properties or by absorbers.

Open laser beam paths should be located above or below eye level (for standing and seated persons) where practicable.

Laser beams should be enclosed within an appropriate protective enclosure (e.g. within a tube) where practicable.

7.4.11 Specular reflections

Care should be exercised to prevent the unintentional specular reflection of laser beams from Class 3b or Class 4 laser products. Optical elements such as mirrors, lenses and beam splitters should be rigidly mounted and subject to controlled movements.

7.4.12 Eye protection

(i) Protective eyewear specifications

The following should be considered when specifying suitable protective eyewear:

(a) wavelength(s) of operation;

(b) maximum expected radiant exposure or irradiance;

(c) applicable exposure limit;

(d) required optical density of eyewear at laser output wavelength, which is normally the logarithm of the ratio of (b)/(a);

(e) visible light transmission requirements;

(f) radiant exposure or irradiance at which damage to eyewear occurs;

(g) need for prescription glasses;

(h) comfort and ventilation;

(i) degradation or modification of absorbing media, even if temporary or transient;

(j) strength of materials (resistance to shock);

(k) peripheral vision requirements;

(l) any relevant national regulations.

Eye protection which is designed to provide adequate protection against specific laser radiations should be used in all hazard areas where Class 3b or Class 4 lasers are in use. Exceptions to this are:

(a) when engineering and administrative controls are such as to eliminate potential exposure in excess of the applicable exposure limit;

(b) when, due to the unusual operating requirements, the use of eye protectors is not practicable. Such operating procedures should only be undertaken with the approval of the laser safety officer.

(ii) Identification and labelling of laser eye protectors

All laser protective eyewear shall be clearly labelled with information adequate to ensure the proper choice of eyewear with particular lasers.

(iii) Required optical density

The optical density (OD) of laser protective eyewear is normally highly wavelength-dependent. Where protective eyewear is required to cover a band of radiation, the minimum value of D within the band shall be quoted. The value of D required to give eye protection can be calculated from the formula:

$$D = \log_{10} (H_O / EL)$$

where H_O is the expected exposure level at the unprotected eye expressed in the same radiometric units as the EL (exposure limit).

(iv) Eyewear selection

Protective eyewear should be comfortable to wear, provide as wide a field-of-view as possible, maintain a reasonably close fit (if the required D is greater than 1.5) while still providing adequate ventilation to avoid problems of misting and to provide adequate visual transmittance. Care should be taken to avoid, as far as is possible, the use of eye protectors employing flat reflecting surfaces which might cause hazardous specular reflections. The frame and any side-pieces should protect against exposures up to 0.03 of that afforded by the lenses.

7.4.13 Protective clothing

Where personnel may be exposed to levels of laser radiation that exceed the exposure limit for the skin, suitable protective clothing should be provided. This is primarily of importance with UV laser radiation. Class 4 lasers especially are a potential fire hazard, and protective clothing worn should be made from a suitable flame- and heat-resisting material if exposure is expected, although engineering controls should be relied upon rather than resorting to protective clothing.

7.5 Hazards incidental to laser operation

Depending on the type of laser used, associated hazards involved in laser operations may include the hazards listed in the following paragraphs.

7.5.1 Atmospheric contamination

Appropriate local-exhaust ventilation should be employed if hazardous levels of airborne contaminants are released during laser use. Examples are:

(a) vaporized target materials and reaction products from laser cutting, drilling, welding operations, and from laser surgical procedures. These materials may well include asbestos, carbon monoxide, carbon dioxide, ozone, lead, mercury, other metals, and biological material;

(b) gases from the flowing gas laser systems or from the by-products of laser reactions, such as fluorine, bromine, chlorine, and hydrogen cyanide;

(c) gases or vapours from cryogenic coolants.

7.5.2 Collateral radiation hazards

Collateral radiation is any other radiant energy emitted by a laser as necessary for its performance. Examples are the broad-band white light from a pump light used to excite crystal lasers, or ultraviolet radiation from a gas-discharge laser.

(i) Ultraviolet collateral radiation

There may be a considerable hazard from the ultraviolet radiation associated with flashlamps and continuous wave laser discharge tubes, especially when ultraviolet transmitting tubing or mirrors (such as quartz) are used. Normally, the protective housing of laser products will protect against such hazards.

(ii) Visible and infrared collateral radiation

The visible and near-infrared radiation emitted from flashtubes and pump sources and target re-radiation may be of sufficient radiance to produce a potential retinal hazard. Eye protective filters suitable for conventional arc cutting and welding are needed to view the optical plasma produced in laser cutting and welding.

7.5.3 Electrical hazards

Many lasers make use of high voltages (greater than 1 kV) and pulsed lasers are especially dangerous because of the stored energy in the capacitor banks.

Unless properly shielded, circuit components such as electronic tubes working at anode voltages greater than 5 kV may emit X-rays.

The manufacturing requirements for electrical safety are detailed in IEC standard 824 (IEC, 1984). Workers should not alter these protective features, such as safety interlocks. All current-carrying conductors should be shielded from personal contact.

7.5.4 Cryogenic coolants

Cryogenic liquids may cause burns and require special handling precautions.

7.5.5 Other hazards

The potential for explosions at the capacitor bank or optical pump systems exists during the operation of some high-power laser systems. There is a possibility of flying particles from the target area in laser cutting, drilling, and welding operations. Explosive reactions of chemical-laser reagents or other gases used within the laboratory are also possible.

7.6 Training

All workers potentially exposed to laser radiation should be informed of any potential hazards and appropriate means of protection. This training should be presented in an understandable manner, and should indicate the consequences if protective measures are not used.

Operation of Class 3b or Class 4 laser systems can represent a hazard not only to the user but also to other people over a considerable distance. Because of this hazard potential, only persons who have received training to an appropriate level should be placed in control of such laser systems. The training which may be given by the manufacturer or supplier of the system, the laser safety officer, or by an approved organization, should include, but is not limited to:

(a) familiarization with system operating procedures;

(b) bioeffects of the laser upon the eye and the skin;

(c) the proper use of hazard control procedures, warning signs, etc.;

(d) the need, if any, for personal protection;

(e) the consequences, when appropriate, if means of protection are not used;

(f) accident-reporting procedures and where medical attention should be sought.

7.7 Health surveillance

In the absence of general national regulations, the following recommendations should be taken into consideration.

(a) A medical examination by a qualified specialist should be carried out immediately after an apparent or suspected injurious ocular exposure. Such an examination should be supplemented with a full biophysical investigation of the circumstances under which the accident occurred.

(b) Pre- and post-assignment ophthalmic examinations of workers using Class 3b and Class 4 lasers are recommended. Examinations which emphasize tests of visual function should be considered adequate in any case.

8

Administrative organization

This section details administrative aspects recommended for the safety of people using, and potentially exposed to, lasers.

The responsibility for the protection of workers and all other persons against the potentially adverse effects of exposure to lasers should be clearly assigned to a department, agency, committee or individual, as indicated in the following sections of this chapter.

8.1 Role of the competent authorities

The competent or regulatory authorities whose terms of reference and functions are concerned with protection against the harmful effects of laser radiation should cooperate with each other. This cooperation is necessary to ensure that each authority, or department within an authority, is well aware of the responsibilities of other bodies so as to avoid duplication of effort.

8.1.1 Setting of relevant rules, regulations, standards and codes

The competent authorities should formulate the necessary regulations for laser radiation protection. This should be undertaken in consultation with the representative organizations of the employers and workers concerned. In addition, the authorities should provide, as necessary, detailed specific guidance for the safety design and manufacture and use of laser radiation sources, including the occupational health surveillance of exposed workers, where considered appropriate.

8.1.2 Licensing, notification and/or registration systems

The competent authorities should adhere to the principle that exposure of people should be minimized and that the exposure limits should not be exceeded. The classification of lasers and consequent requirements of notification, registration, or licensing should be based on an assessment of the safety design of the system and its intended use. Whenever more rigid control is necessary, the authorities should specify the laser product requiring a licence, together with the procedures and conditions for obtaining one.

The licence permit should comprise follow-up methods to ensure compliance during plant construction, commissioning and operation, including future modification of design or working procedures. Granting of a licence should not preclude a change during the period of its validity. A request for such a change may be initiated by the licensee, or the change may be desirable or necessary as a result of experience gained during operation at the workplace or elsewhere, or as a consequence of technological innovation or of safety research and development.

The licensing process should define the various responsibilities concerned with the planning, design, construction, commissioning and operation of the facility. The licensee on the other hand should submit and make available to the competent authorities all the information requested. Whenever a significant change in operation or use of the exposure source occurs relevant to the licensing process, the licensee should submit that information, preferably in accordance with a specified procedure, to the authorities.

8.1.3 Quality control requirements for the design, planning and construction of plant and equipment

Quality control programmes for each constituent area of activity in the design, planning and construction of any plant and equipment incorporating lasers depends on the potential hazards involved and may vary from a very extensive, multiphase and multi-step plan to a rather more simple and straightforward operational procedure. The basic responsibility for achieving quality in performing a particular task (e.g. in design, manufacturing, commissioning or operation) rests with those assigned to it and not with those seeking to verify that it has been carried out correctly.

The authorities should encourage manufacturers to undertake studies and research in order to improve the design, construction and performance of equipment incorporating lasers and of materials and facilities supplied so as to contribute to the minimization of occupational hazards.

8.1.4 Inspection and intervention

The competent authorities should establish a system of inspection to supervise safety precautions to ensure compliance with the relevant standards and with the requirements as specified in any licence. They should also assume the necessary power to intervene in cases of non-compliance with the standards. Any situation which has resulted or is expected to result in exposures in excess of appropriate exposure limits should be reported in an approved manner.

8.2 Responsibility of the employer

The owner of the device or installation emitting laser radiation has a number of responsibilities. These include:

(a) the radiation safety of employees;

(b) the purchase and provision of laser equipment which meets all appropriate standards when new and during its lifetime of use;

(c) ensuring that the laser equipment meets appropriate radiation safety standards and safety requirements as specified in this document;

(d) acting to reduce the exposure of workers to laser radiation and making the organizational arrangements required to prevent the risks associated with exposure;

(e) establishing and publicizing (preferably in writing) a general policy emphasizing the importance of prevention, and taking the decisions and the practical steps required to give effect to national regulations and for the implementation of the preventive measures.

Responsibility may be delegated by the owner depending on the size of the organization and the amount of radiation-emitting equipment used. Without prejudice to the responsibility of each employer for the health and safety of the workers in his employment, and with due regard to the necessity for the workers to participate in matters of occupational health and safety, one or more persons may be designated to carry out the role of responsible user and laser safety officer.

8.3 Duties of the laser safety officer

There should be one person designated by the owner or employer as the responsible person for laser safety if Class 3b and Class 4 lasers are in use. If the organization is sufficiently large, a Laser Safety Committee may exist to establish policy; however, the laser safety officer (LSO) would be the principal executive agent for laser hazard control. In the absence of a Laser Safety Committee, the LSO should have the following duties:

(a) ensuring that an effective safety programme is developed and instituted whenever there is a special hazard due to laser radiation;

(b) ensuring the proper briefing of workers, and to promote the cooperation between employer and workers in the reduction or prevention of laser exposure;

(c) establishing safe operating procedures for laser equipment and ensuring that all staff are made aware of them;

(d) ensuring that assigned laser equipment is maintained and used correctly by competent personnel;

(e) knowing the exposure levels in the vicinity of the equipment under normal conditions of use;

(f) defining areas where exposure in excess of the recommended limits may result, and posting warning signs that clearly indicate the permitted occupancy conditions;

(g) ensuring that appropriate laser radiation surveys and hazard assessments are performed when and as required, and maintaining records of such surveys and assessments;

(h) investigating and reporting laser exposures which may be in excess of the limits recommended;

(i) designating staff as laser workers and arranging for the medical examination and treatment of over-exposed workers in the case of accidental exposure;

(j) recording levels and duration of exposure for persons who have been exposed in excess of the recommended limits;

(k) reviewing the precautions listed herein designating the appropriate controls and assuring education and awareness of the potential hazard controls.

8.4 Duties of other occupational safety and health specialists

A safety engineer, industrial hygienist, occupational health nurse, health physicist or other health professional may be designated as the LSO, or may be delegated some of the responsibilities of the LSO. In small organizations, the user, LSO and health physicist may be the same person. This person should have direct access to the employer. The extent and nature of the responsibilities will depend on the size of the organization and the number of devices. In general, the health specialist provides technical support in the planning of the installation and the operation of laser devices. Health specialists should, where necessary, supervise compliance with the regulations and take part in the implementation of preventive measures.

8.5 Duties of the worker (user)

Laser users in charge of the day-to-day operation and maintenance of laser-radiation-emitting devices must:

(a) be aware of the hazards associated with operating the specific laser devices assigned to them and, in particular, the importance of any interlock systems and dangers associated with defeating such systems, and adherence to all occupancy restrictions;

(b) be able to recognize malfunctions of the specific devices assigned to them that might result in high laser exposures;

(c) be aware of and trained in normal safe operating practices and the procedures to be followed in the event of malfunction of the devices, or in an emergency situation arising from excessive laser radiation emissions;

(d) use protective equipment provided, as necessary;

(e) be willing to undergo reasonable prescribed medical surveillance.

8.6 Responsibilities of manufacturers

Laser equipment manufacturers are responsible for making equipment that conforms to the appropriate standards within the country and for providing information on the hazards of operating and servicing laser equipment, sufficient to alert the owner or employer of the magnitude of the risk and the appropriate precautions that need to be taken. Such information should include classification of the laser product.

8.7 Cooperation

The following principles should be taken into consideration with regard to cooperation between employers, workers, safety and health committees, manufacturers and so on:

(a) the employer should secure the workers' cooperation in order to protect their health and to reduce laser exposure, and should establish, by joint agreement, instructions and recommendations for the prevention of such exposure;

(b) employers and workers should cooperate in devising and implementing programmes for the prevention and control of laser radiation exposure, particularly in conjunction with any safety committees for monitoring the working environment;

(c) cooperation should be established between manufacturers and purchasers of equipment with a view to reducing unintended laser radiation emissions of such equipment; and

(d) cooperation in the development of both voluntary and regulatory laser equipment standards should be encouraged.

Appendix A – Radiometric terminology and physical characteristics of lasers

1 Radiometric quantities and units

1.1 Irradiance, radiant exposure and radiance

Irradiance is used to describe the concepts of flux density in units of watts per square metre ($W.m^{-2}$) incident upon a surface such as the skin, cornea or retina. The photobiological term for exposure dose is *radiant exposure* which refers to the surface exposure in units of joule per square metre ($J.m^{-2}$). Here the surface area being irradiated is the defining area and it differs from the orthogonal cross-sectional area of the incident radiation by the cosine of the angle of incidence. The volumetric dose concepts are not generally used in the optical spectrum since the radiation penetration is normally only superficial, and if it penetrates, as in the case of light, it may still be absorbed at the surface, such as the retina in the case of visible light penetrating the ocular media of the eye. *Radiance* is a physical concept for brightness, i.e. the radiation emitted from an object per unit area and per unit solid angle. The unit area here is taken normal to the axis of propagation of radiation. This concept is widely used for specifying exposure limits for extended sources (large areas). The units or radiance are watt per square metre per steradian ($W\ m^{-2}$, sr^{-1}), where the steradian is the unit of solid angle. The CIE standard symbols for irradiance, radiant exposure, and radiance are: E_e, H_e, and L_e respectively. These and related quantities and units are presented in table Al.

1.2 Photometric quantities and units

If the above radiometric quantities are mathematically weighted against a spectral sensitivity function, such as V (λ), the photopic (daylight) sensitivity function of the eye, new quantities are formed: in this case photometric quantities. Normally, the photometric quantities, such as luminance L_v, illuminance E_v, and luminous exposure H_v, are not used extensively in considering the health effects of optical radiation, except in the special case of evaluating the potential for flashblindness, or the production of after images by laser light.

1.3 Spectral definitions

Optical radiation is located in the electromagnetic spectrum between the softest ionizing radiations on one side and microwave radiation on the other. According to this definition, the short wavelength boundary is not very precise, but is generally accepted to lie between 10 and 100 nm. The value of 100 nm corresponds to a photon energy of approximately 12 eV, and is generally accepted as the limit of production of single-photon ionization in biological systems.

The optical spectrum is divided into spectral bands based upon different physical and biological effects. The various bands will differ according to the criteria used. For example, the band below 180 nm is the region of vacuum ultraviolet radiation (UVR) which is absorbed by air to such an extent that no biological effects can be realized. The remaining UVR spectrum is then frequently divided by optical engineers into the far-UVR region between 180 nm and 300 nm and the near-UVR region between 300 nm and 380 nm. A somewhat different scheme used by the CIE takes some of the biological effects into account and divides the UVR spectrum into three bands: UV-A, UV-B and UV-C (CIE, 1987). These CIE divisions are used throughout this overview.

Table A.1. Useful CIE radiometric units[1,2]

Term	Symbol	Defining equation	SI unit and abbreviation
Radiant energy	Q_e	$Q_e = \int \Phi_e \, dt$	Joule (J)
Radiant energy density	W_e	$W_e = \frac{dQ_e}{dV}$	Joule per cubic meter ($J \cdot m^{-3}$)
Radiant flux (radiant power)	Φ_e, P	$\Phi_e = \frac{dQ_e}{dt}$	Watt (W)
Radiant exitance	M_e	$M_e = \frac{d\Phi_e}{dA}$ $= \int L_e \cos\theta \cdot d\Omega$	Watt per square meter ($W \cdot m^{-2}$)
Irradiance or radiant flux density (dose rate in photobiology)	E_e	$E_e = \frac{d\Phi_e}{dA}$	Watt per square meter ($W \cdot m^{-2}$)
Radiant intensity	I_e	$I_e = \frac{d\Phi_e}{d\Omega}$	Watt per steradian ($W \cdot sr^{-1}$)
Radiance[3]	L_e	$L_e = \frac{d^2\Phi_e}{d\Omega \cdot dA \cdot \cos\theta}$	Watt per steradian per square meter ($W \cdot sr^{-1} \cdot m^{-2}$)
Radiant exposure (dose in photobiology)	H_e	$H_e = \frac{dQ_e}{dA} = \int E_e$	Joule per square meter ($J \cdot m^{-2}$)
Radiant efficiency[4] (of a source)	n_e	$n_e = \frac{P}{P_i}$	Unitless
Optical density[5]	D_e	$D_e = -\log_{10}(\tau_e)$	Unitless

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[1] The units may be altered to refer to narrow spectral bands in which the term is preceded by the word *spectral* and the unit is then per wavelength interval and the symbol has a subscript λ. For example, spectral irradiance E_λ has units of $W \cdot m^{-2} \cdot m^{-1}$ or more often, $W \cdot cm^{-2} \cdot nm^{-1}$.

[2] 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.

[3] At the source $L = dI / (dA \cdot \cos\theta)$ and at a receptor $L = dE / (d\Omega \cdot \cos\theta)$.

[4] P_i is electrical input power in watts.

[5] τ is the transmission.

The CIE defines the UV-A band from 315 to 380 or 400 nm; and this band (the "black-light" region) is most often used in industry to induce fluorescence. UV-B (280 nm - 315 nm) is the "erythemal" region. The most biologically active and potentially noxious radiation from the sun that reaches the earth is in this spectral region. The UV-C extends from 100 nm to 280 nm. The photobiological spectral bands include the visible (light) band (380 or 400 to 760 or 780 rim) and continue into the infrared, IR-A, IR-B, and IR-C. The IR-A band includes the most penetrating optical radiation and extends from 760/780 nm to 1,400 nm. IR-B radiation (1.4 to 3.0 µm) penetrates only slightly into biological tissue because it is heavily absorbed by water. IR-C radiation is absorbed very superficially and does not penetrate the cornea of the eye or skin. This band extends from 3.0 µm to 1,000 µm. A wavelength of 1 mm corresponds to a frequency of 300 GHz.

2 Physical properties of laser radiation

Laser radiation differs from other forms of optical radiation by its high coherence. Nevertheless, the same radiometric quantities and units apply to laser radiation. Some of the special characteristics of laser radiation require special attention in assessing health risks.

2.1 Stimulated emission

The laser is a device which produces and amplifies optical radiation. The term "LASER" is an acronym. It stands for "Light Amplification by Stimulated Emission of Radiation." All lasers operate by stimulated emission, which requires that they all have at least three basic components: an *active medium* of the excitable atoms or molecules which will emit the laser radiation; *a resonant cavity* which is formed normally by two mirrors, one of which is partially transmitting; and an energy source to excite the atoms or molecules, termed the *pumping mechanism*.

2.2 High radiance

Lasers typically emit at very high levels of spectral radiance (spectral brightness). The sun emits about 7×10^7 $W.m^{-2}.sr^{-1}. nm^{-1}$ at its surface. Lasers are presently capable of producing more than 10^{16} $W. m^{-2}.sr^{-1}. nm^{-1}$. A source of light that exceeds the sun's radiance can certainly be hazardous to vision. A small helium-neon (He-Ne) laser used for alignment exceeds the sun's radiance by a factor of about ten.

2.3 Divergence

When the optical beam emerges from most types of lasers, it diverges (spreads) very little. Source radiance is not greatly reduced as the beam propagates. Laser beam divergence is measured in milliradians (2π radians = 360° or 1 milliradian = 3 minutes of arc). A typical He-Ne laser has a divergence of 0.5 to 1.5 milliradians. Divergence may be defined by the length of the arc subtended by a beam at great distance, e.g. a 1 m diameter beam from a point source at one km denotes a divergence of 1 milliradian.

2.4 Monochromaticity

The optical radiation emitted by most lasers has a very narrow spectral bandwidth, and is very close to being monochromatic, i.e. of one colour or one wavelength. Actually, very few lasers emit at only one wavelength. A typical He-Ne laser emits red light at 632.8 nm and IR-A at 1.15 µm and IR-B at 3.39 µm, and even more wavelengths can be emitted with special design. Like most lasers, the He-Ne laser is usually designed to emit only one of the several possible wavelengths by suitable design.

2.5 Coherence

Coherence is a term used to describe particular relationships between two waveforms. Two waves with the same frequency, phase, amplitude and direction are termed "spatially coherent" (WHO, 1982). Temporal coherence indicates the degree of phase coherence of two adjacent waves and indicates over what duration ("coherence time") the phase relationships remain. Laser light is effectively coherent. Coherence *per se* normally is considered not to affect the relative biological risk of laser radiation exposure.

Appendix B – Biological and health effects of laser radiation

1 Optical properties of tissues

Laser radiation may be either absorbed, scattered or reflected from biological tissues. In most cases, a combination of all of these effects occurs. However, the biological effect is caused only by absorption. From approximately 280 nm to 3.0 µm in the infrared, reflection may exceed 10 per cent, and significant penetration will also occur, such that scattering may play an important role in determining the final exposure to the target tissue.

1.1 Ultraviolet radiation

It is generally accepted that the absorption of ultraviolet radiation (UVR) takes place in organic molecules. The inorganic components of tissue do not absorb at wavelengths longer than 200 nm. The absorbed energy may give rise to photochemical reactions.

Protein molecules and uracanic acid are highly absorbing in the UVC and dominate all absorption up to wavelengths of approximately 300 nm. At wavelengths longer than approximately 300 nm, melanin pigment granules play an important role in the scattering and absorption of UVR in the skin. The granules are concentrated as a shield above the cell nuclei and protect them by the absorption of UVR and partly by radiation scattering. Scattering is probably of greatest significance at longer wavelengths. Furthermore, there is evidence suggesting that melanin may serve another protective role: as a free-radical scavenger.

The depth of penetration of UVR into the human body is very limited. Penetration is somewhat greater at longer wavelengths and some penetration can take place into the dermis at wavelengths above 300 nm in Caucasians. The thickness of the outermost, dead, horny skin layer (stratum corneum) increases following UVR exposure, thus further attenuating later UVR exposures (Health Council of the Netherlands, 1979).

The same general considerations hold for exposure of the eye. At wavelengths less than 290 nm, the cornea will be able to absorb incident UVR completely. However, the lens and tissues of the anterior part of the eye may be exposed to UVR if the wavelengths are greater than about 290 nm. The retina is normally protected by UVR absorption by the cornea and lens, but in aphakes (individuals who have had their lens removed by cataract surgery) and in young children, significant amounts of UVR at wavelengths above about 290 nm may reach the retina. Because of the biological effectiveness of UVR, even smaller amounts of UVR reaching the retina may be of concern when considering a lifetime of exposure.

1.2 Visible and infrared radiation

Light and infrared radiation of wavelengths less than 1,400 nm penetrate skin and ocular tissues since water is relatively transparent at these wavelengths. Melanin is the principal absorber at wavelengths less than 1 µm. The absorption by melanin and its subsequent temperature elevation can lead to thermal injury of the iris and the retina in the eye and of the epidermis of the skin. Since water becomes more highly absorbing with increasing wavelengths greater than 1,400 nm (IRB and IRC), depths of penetration for infrared radiation are very superficial (WHO, 1982).

2 Injury mechanisms

The physical destruction of biological tissue caused by laser radiation may be attributed to thermal, thermoacoustic or photochemical phenomena. For ultrashort pulses, shorter than about 1 ns, there is evidence that non-linear mechanisms may occur. These mechanisms are not yet fully understood (Sliney and Wolbarsht, 1980). Pulses of visible laser radiation damage tissue by heating, whereas ocular and skin tissue may be damaged from lengthy exposures to UVR and blue laser light because of photochemical phenomena. The thresholds of biological damage appear to be lowest for exposure to blue visible radiation and to UVR. Damage mechanisms have been carefully studied for acute exposures only; the effects of long-term chronic exposure to laser radiation can be predicted only from the experience from human exposure to the sun and conventional light sources (Sliney and Wolbarsht, 1980; Ham et al., 1980).

3 Ocular effects

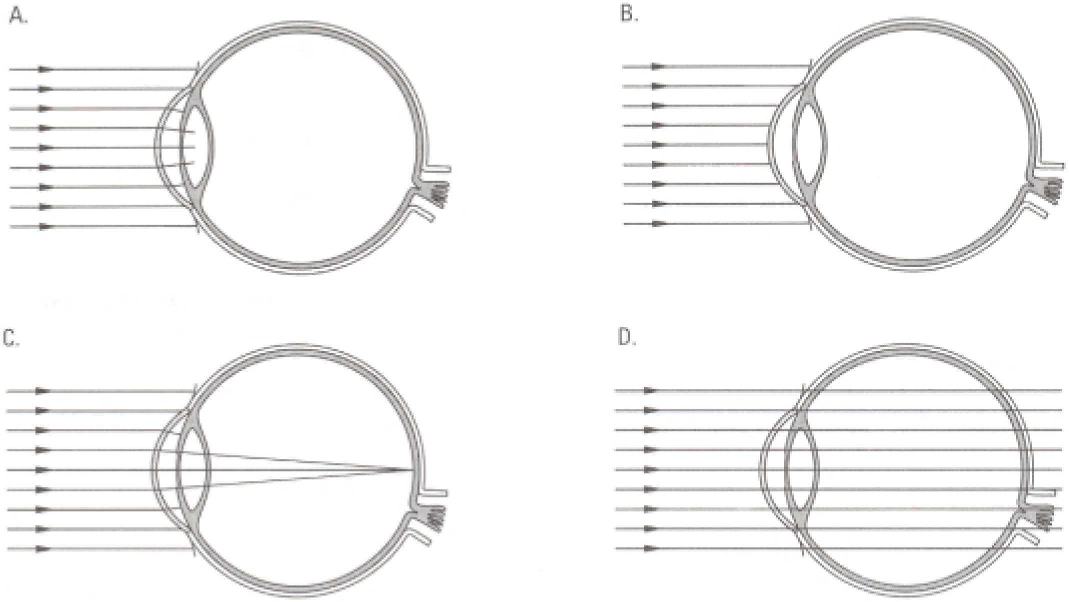
The effects differ with the spectral region as shown in figure B.1. The nature of the effect also varies with the character of the source and the effects are different for direct ocular exposure (intrabeam viewing) and for viewing diffuse reflections of a laser beam on a target and for direct viewing of an extended source laser.

For the wavelength range 400-1,400 nm, the intraocular energy is limited by the pupil area (diameter assumed to be 7 mm) and for the visible band the natural aversion to bright light limits exposure duration to 0.25 s.

For visible and IR-A radiation, the eye is generally the most critical organ in terms of vulnerability to laser radiation. This is because of the refractive power of the cornea and lens which result in an increase in irradiance between the cornea and retina of the order of 2×10^5 (Sliney and Wolbarsht, 1980). Thus for any given exposure of the eye to radiation in the visible and IR-A regions of the spectrum, the retinal irradiance is always significantly higher than that of the cornea or skin. The cornea, lens and other eye media are largely transparent in the visible region. The greater part of visible radiation is absorbed in the melanin granules of the retinal pigment epithelium (RPE) and choroid which underlie the rods and cones (Sliney and Wolbarsht, 1980; Ham et al., 1980).

Most biological studies suggest that several types of damage mechanisms exist. Exposure of the photoreceptors to levels only slightly higher than those presented to the eye under normal ambient conditions, may be sufficient to stress visual cellular activity to the point of failure. This is especially the case if retinal irradiance lasts for an extended period of time, or if relatively shorter more intense exposure is repeated on a daily basis. A remaining problem in determining the two ocular injury thresholds is the lack of complete knowledge concerning the effect of such chronic exposure. Present exposure limits for chronic exposure are based upon humans' extensive experience with exposure to sunlight and commercial artificial light sources. Recommended chronic exposure levels are approximately equivalent to outdoor light levels. There is also lack of knowledge concerning the effects of pulse repetition frequencies (PRF) during repetitive exposure regimens.

Figure B.1. The absorption properties of the eye vary with wavelength.



Note: Biological effects are determined by whether energy reaches the critical tissue and by the interaction mechanism: A: Near-ultraviolet radiant energy; B: Far-infrared (IR-B, IR-C) and far ultraviolet (less than 300 nm) radiant energy; C: Visible and IR-A radiant energy; and D: RF and gamma radiation.

The thermal effects caused by laser radiation usually involve the denaturation of proteins. Thermal injury is generally considered a rate-process; therefore, no single critical temperature exists at which injury will take place independent of exposure time. Also, since the molecules of the melanin granules of the pigment epithelium of the retina are relatively large in size, a broad spectral absorption will be expected to occur. The monochromatic nature of laser radiation, therefore, would not be expected to produce biological effects which are significantly different from those produced by radiation exposure to more conventional light sources. The coherence of the laser beam is not considered to be a significant factor in producing chorioretinal injury or other biological injury.

Recent evidence confirms the fact that short-wavelength light, at the 441.6 nm line of the helium-cadmium laser, produces retinal burns in primates by means of photochemical rather than thermal mechanisms (Ham et al., 1980). For example, the threshold for retinal burns was found to be considerably lower for 441.6-nm laser radiation than for radiation at 1,064 nm. The retinal irradiance of 2.4 10^5 W m^{-2} resulted in a temperature rise of 23 degrees Celsius, and a threshold lesion for a 10^3 s exposure using a wavelength of 1,064 nm (Nd-YAG laser). A wavelength of 441.6 nm (He-Cd laser), however, required only 300 W m^{-2} with a negligible temperature rise to produce a retinal lesion after an exposure of 10^3 s. The 441.6-nm blue light produced a light-yellowish lesion on the fundus; whereas, the lesion induced by the 1,064 nm radiation had a central core thermal burn characteristic (Ham et al., 1980). Exposure in the blue and violet spectral regions are more hazardous to all structures. Recent studies of the effects of ultra-short laser pulses on rhesus monkey eyes have shown that the melanin granules of the retinal pigment epithelium were much more severely damaged by the visible radiation than by the 1,064-nm laser radiation, but the threshold of injury was higher for the visible wavelengths.

Functional as well as histological changes in eye tissues are important and studies have been performed using trained rhesus monkeys. These studies indicate for the most part that visible lesions appear at irradiance levels within a factor near those required to produce permanent adverse functional changes in vision (Beatrice et al., 1977; WHO, 1982; Zwick et al., 1988; Zwick, 1989).

A retinal injury which occurs in the macula, the most central sensitive area of the retina, is serious and will be immediately apparent to the victim. Injury to the paramacula, or peripheral retinal region, may have only a minimal effect upon vision, and in many cases go undetected by the victim (Sliney and Wolbarsht, 1980). This may be particularly true of invisible IR-A radiation which causes retinal injury. In some instances limited visual recovery can be observed after limited macular injury, but such recovery may not occur for many months following exposure.

Infrared radiation of wavelengths greater than 1.4 µm can cause thermal injury to the cornea and conjunctiva. Here the penetration depth greatly influences the damage threshold (Lund, 1989; Sliney and Wolbarsht, 1980).

Although there are relatively few lasers operating in the UVR spectral region, exposures to such devices can be a matter of concern. Recently, the growing use of exciteddimer (excimer) lasers has increased the potential for human exposure to UVR laser radiation. The biological response to UVR laser radiation is similar to that produced by non-coherent UVR sources. Photophobia, tearing, conjunctival discharge, surface exfoliation, and stromal haze are the expected consequences of exposure to these lasers. Damage to the corneal epithelium probably results from the photochemical denaturation of proteins. In the UVC (100 run to 280 nm) and UVB (280 nm to 315 nm) regions, photokeratitis may be produced. Photokeratitis usually has a latency period varying from 80 minutes to as long as 20 hours depending inversely upon the severity of the exposure. A sensation of sand in the eyes accompanied by various degrees of photophobia, lacrimation and blepharospasm is the usual result. In the UVA region (315 nm to 400 nm) photokeratitis may be produced only by chronic, high-level exposure. UVR induced cataract production is probably of importance.

The additivity of UVR exposure within a period of 24 hours is well understood as arising from the photochemical nature of the injury mechanism. However, the additive nature of repetitive pulses of thermal injury of the retina is less well understood. Some empirical relations have been noted (Sliney and Marshall, 1991).

4 Skin effects

The biological consequences of irradiating the skin with laser radiation are considered to be less than those to the eye, since skin damage is often repairable or reversible. On the other hand, exposure of the skin to high levels of optical radiation can cause depigmentation, severe burns and possible damage to underlying organs (WHO, 1982). The aperture assumed for skin exposure measurements is 1 mm with the purpose of limiting the exposed area.

The effects of UVR laser radiation upon the skin are the same as for UVR from conventional sources: erythema from acute exposure and accelerated skin ageing and skin cancer from chronic exposure. Our knowledge of UVR dose effect relationships in man is insufficient and further studies are necessary, especially epidemiological studies of UVR carcinogenesis.

Appendix C – Glossary

Active medium. The atomic or molecular species which can provide gain for laser oscillation. Also called laser medium, lasing medium or active material.

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.

Calorimeter. A type of detector that measures heat produced by absorption of radiation.

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

Continuous wave (CW) laser operation. Laser operation in which radiation is emitted continuously.

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. Any device which detects light, generally producting an electronic signal with intensity proportional to that of the incident light.

Diode laser. See Semiconductor laser.

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.

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.

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.

Infrared. Electromagnetic radiation with wavelength between 0.76 micrometre and about 1 millimetre.

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 metre.

Laser. (acronym for "light amplification by stimulated emission of radiation") is a device which generates or amplifies electromagnetic oscillations at wavelengths between the far infrared (submillimetre) and ultraviolet. 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

Multimode. Emission at several frequencies simultaneously, generally closely spaced, each frequency representing a different mode of laser oscillation in the resonant cavity.

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 the external electric field. Nonlinear optical effects include harmonic generation and the electro-optic effect.

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.

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.

Pulse duration. 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 pulse width or pulse length.

Pulsed laser. A laser that emits light in pulses rather than continuously. With the exception of a switched or mode-locked laser, the duration of a laser pulse is determined by the energy source and pumping machine.

Pumping mechanism. 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 detector. A type of detector incorporating a 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 radiant power, or 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.

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 intrinsic, as chromium is in ruby. This term is generally not applied to semiconductor lasers.

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 volume because of a greater density of lasing molecules.

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 ($YA10_3$), 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.

Appendix D – Background of the INIRC

IRPA began its activities relating to the entire subject of NIR in 1973 with a session devoted to this topic at its Third International Congress in Washington, DC. The International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) was established in 1977. The primary objectives of INIRC were to present the general principles of non-ionizing radiation protection, to determine the most appropriate exposure limits for each type of non-ionising radiation (NIR) and to explore with other international organizations ways of furthering protection in this field.

Over the last decade the Division of Environmental Health of the World Health Organization and IRPA/INIRC have cooperated in the preparation of environmental health criteria documents relating to NIR with the financial support of the United Nations Environment Programme (UNEP). These criteria then become the scientific data base for the development of exposure limits and codes of practice. From the criteria documents, the INIRC has then developed guidelines on exposure limits for the different NIR, including laser radiation (IRPA, 1991). Each of the guidelines for exposure limits have been published in *Health Physics*, before being collected in a single volume as quoted above.

Each set of guidelines must, of course, be subjected to periodic revision to be kept in line with advances in knowledge of the relevant biological effects. The purpose of the guidelines is to provide guidance to international and national bodies or individual experts who are responsible for the drafting of regulations, recommendations or technical advice to protect the workers and the general public from the potentially adverse effects of any non-ionizing radiation.

The laser criteria document (WHO, 1982), like all criteria documents, was published under the joint sponsorship of UNEP, WHO and IRPA, includes a description of the physical characteristics of the radiation concerned, an overview of the sources, applications and exposure levels, measurement methods and instrumentation, a review of the data on biological effects gained from animal experimentation and observations in humans, an evaluation of the health risk of human exposure and a survey of the existing protection standards.

The IRPA/INIRC has collaborated with the International Labour Office by drafting practical guides concerning the protection of workers against occupational hazards due to non-ionizing radiations. They provide information on the hazards involved and on practices which are intended to inform workers of the hazards and the appropriate precautions that need to be taken to minimize NIR exposure.

Since May 1992 the IRPA/INIRC has become an independent scientific body called the *International Commission on Non-Ionizing Radiation Protection (ICNIRP)* and has responsibility for NIR protection in the same way as the International Commission on Radiological Protection (ICRP) has for ionizing radiation.

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