AERB SAFETY GUIDELINES NO. AERB/SG/IS-7

SAFETY IN DESIGN AND APPLICATION OF LASER

Atomic Energy Regulatory Board
Mumbai – 400 094
India

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Price

Orders for this 'Safety Guidelines' should be addressed to:

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FOREWORD

Activities concerning establishment and utilization of nuclear facilities and use of radioactive sources are to be carried out in India in accordance with the provisions of the Atomic Energy Act, 1962. In pursuance of the objective of ensuring safety of occupational workers, members of the public and protection of the environment, the Atomic Energy Regulatory Board (AERB) has been entrusted with the responsibility of laying down safety standards and enforcing rules and regulations for such activities. The Board has, therefore, undertaken a programme of developing safety standards, safety codes, and related guides and manuals for the purpose. While some of these documents cover aspects such as siting, design, construction, operation, quality assurance and decommissioning of nuclear and radiation facilities, other documents cover regulatory aspects of these facilities.

Safety codes and safety standards are formulated on the basis of internationally accepted safety criteria for design, construction and operation of specific equipment, structures, systems and components of nuclear and radiation facilities. Safety codes establish the objectives and set requirements that should be fulfilled to provide adequate assurance for safety in nuclear and radiation facilities. Safety guides elaborate various requirements and furnish approaches for their implementation. Safety manuals deal with specific topics and contain detailed scientific and technical information on the subject. These documents are prepared by experts in the relevant fields and are extensively reviewed by advisory committees of the Board before they are published. These documents are revised, when necessary, in the light of experience and feedback from users as well as new developments in the field.

This 'safety guidelines' will promote safe use of LASER, assist in taking effective measures to control LASER hazards, and facilitate development of safe operating procedures for the use of LASER. Though this document is prepared primarily for use in the units of the DAE, other organisations involved in application of high power LASER may use this document to ensure safe use of LASER.

Consistent with the accepted practice, 'shall' and 'should' are used in the 'safety guidelines' to distinguish between a recommendation and a desirable option respectively. Annexures and references are included to provide further information on the subject that might be helpful to the user(s).

Specialists in the field drawn from Atomic Energy Regulatory Board, Bhabha Atomic Research Centre and Raja Ramanna Centre for Advanced Technologies and other consultants have prepared this document.

AERB wishes to thank all individuals and organisations who have prepared and reviewed the draft document and helped in its finalisation. The list of experts, who have participated in this task, along with their affiliation, is included for information.

(S.S.Bajaj)
Chairman, AERB

DEFINITIONS

Accident

An unplanned event resulting in (or having the potential to result in) personal injury or damage to equipment which may or may not cause release of unacceptable quantities of radioactive material or toxic/hazardous chemicals.

Assessment

Systematic evaluation of the arrangements, processes, activities and related results, for their adequacy and effectiveness in comparison with the set criteria.

Atomic Energy Regulatory Board (AERB)

A national authority designated by the Government of India having the legal authority for issuing regulatory consent for various activities related to the nuclear and the radiation facilities and to perform safety and regulatory functions, including their enforcement for the protection of site personnel, the public and the environment against undue radiation hazards.

Audit

A documented activity performed, to determine by investigation, examination and evaluation of objective evidence, the adequacy of, and adherence to the applicable codes, standards, specifications, established procedures, instructions, administrative or operational programmes, and other applicable documents, and the effectiveness of their implementation.

Event

Occurrence of an unplanned activity, or deviations from normalcy. It may be an occurrence, or a sequence of related occurrences. Depending on the severity in deviations and consequences, the event may be classified as an anomaly, incident, or accident in ascending order.

Fail-safe Design

A concept in which, if a component or a system fails then the component / system / plant will pass into a safe state, without the requirement to initiate any operator action.

Hazard

Situation or source, which is potentially dangerous for human being, the society and/or the environment.

Incident

Events that are distinguished from accidents in terms of being less severe. The incident, although not directly or immediately affecting plant safety, has the potential of leading to accident conditions, with further failure of safety system(s).

Maintenance

Organisational activities covering all preventive and remedial measures, both administrative and technical, to ensure that all structures, systems and components are capable of performing as intended for safe operation of the plant.

Occupier

One who has been given the ultimate control over the affairs of the installation.

Radiation

Gamma rays, X-rays, or rays consisting of alpha particles, beta particles, neutrons, protons and other nuclear, sub-atomic particles, but not sound or radio waves, or visible, infrared, ultra-violet light.

Risk

A multi-attribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with an actual or potential event under consideration. It relates to quantities such as the probability that the specific event may occur and the magnitude and character of the consequences.

Significant Event

Any event, which degrades system performance function(s) without appreciable damage to either the system or life or limb.

SPECIAL DEFINNITIONS

(Specific for the Present 'Safety Guidelines')

Accessible Emission Limit (AEL)

The maximum accessible emission level permitted within a particular LASER hazard class[1].

Angular Subtense (α)

The plane angle (usually specified in milli-radian) subtended by apparent source at a defined distance from the source.

Alpha max (α_{max})

The angular subtense of an extended source beyond which additional subtense does not contribute to the hazard and need not be considered. This value is 100 milli-radian (mrad) for retinal thermal effects and 110 mill-radian (mrad) for the retinal photochemical effects.

Alpha min (α_{min})

The angular subtense of a source below which the source can be effectively considered as a point source. The value of α_{min} is 1.5 milli-radian (mrad).

Aperture

A hole or slit used to restrict the cross-sectional area of a beam of optical radiation.

Authorised Personnel

Individuals granted written permission by management, to perform specific activities, such as operation , maintenance, servicing or installation LASER

Aversion Response (also refer blink reflex)

Closure of the eyelid, or movement of the head, to avoid an exposure to a noxious stimulant or bright light. The aversion response to an exposure from a bright LASER source is assumed to occur within 0.25 s, including the blink reflex time.

Foot Note

[1] LASER Hazard Class:
LASER are classified according to their potential to cause biological damage. The pertinent parameters are: LASER output energy or power, radiation wavelengths, exposure duration and cross-sectional area of the LASER beam at the point of interest. In addition to these general parameters, LASER are classified in accordance with the *accessible emission limit* (AEL), which is the maximum accessible level of LASER radiation permitted within a particular LASER class. These range from Class 1 LASER (which are inherently safe for direct beam viewing under most conditions) to Class 4 LASER (which require the most stringent controls). The LASER classifications are described in the Sections 4&5 of this document.

Beam (LASER)

A collection of light rays/ electromagnetic waves characterized by direction, diameter (or dimensions) and divergence (or convergence).

Beam diameter

The distance between diametrically opposed points in the cross-section of a beam where the power per unit area is typically 1/e (0.368) or $1/e^2$ (0.135) times that of the peak power per unit area depending on cut-off values chosen based on application.

Blink Reflex (also refer Aversion Response)

The blink reflex is the involuntary closure of the eyes as a result of stimulation by an external event such as an irritation of the cornea or conjunctiva, a bright flash, the rapid approach of an object, an auditory stimulus or with facial movements. In this standard the ocular aversion response for a bright flash-light is assumed to limit the exposure of a specific retinal area to 0.25 s, or less.

Coherent Light

A beam of light characterized by a fixed phase relationship across its cross-section (spatial coherence) and/or single wavelength i.e. mono-chromaticity (temporal coherence).

Collateral Radiation

Any electromagnetic radiation, except LASER radiation, emitted by a LASER / LASER system which is physically necessary for its operation.

Continuous Wave (CW) LASER

A LASER operating with a continuous output for a period that is greater than or equal to 0.25 s.

Diffuse Reflection

Change of the spatial distribution of a beam of radiation when it is reflected in many directions by a surface or a medium.

Divergence (ϕ)[2]

The plane angle projection of the cone that includes (1- 1/e) (i.e., 63.2%) of the total radiant energy or power. The value of the divergence is expressed in radians, or milli-radians.

Foot Note

[2] Many LASER have astigmatic divergence, i.e., have different divergences in two orthogonal axes. In such cases, the divergences may be considered separately, or averaged.

Electromagnetic Radiation

The flow of energy consisting of orthogonally vibrating electric and magnetic field lying transverse to the direction of propagation. Gamma rays, X-ray, ultraviolet, visible, infra-red, micro and radio waves occupy various portions of the electromagnetic spectrum, and differ only in frequency, wavelength and photon energy.

Embedded LASER

An enclosed LASER with an assigned classification higher than the classification of the LASER system in which it is incorporated, where system's lower classification is appropriate, because engineered features limit accessible emission.

Enclosed LASER

A LASER that is contained within a protective housing of itself, or that of the LASER/ LASER system in which it is incorporated. Opening or removal of the protective housing provides additional access to LASER radiation above the applicable MPE than possible with the protective housing in-place. An embedded LASER is an example of one type of enclosed LASER.

Emission

Act of giving off radiant energy by an atom or a molecule.

Energy (Q)

The capacity for doing work. Energy content is commonly used to characterize the output from pulsed LASER, and is generally expressed in joules (J). One watt second = one joule.

Excited State

Atom, or molecule, in a higher energy level than it normally occupies.

Extended source

A source of optical radiation, with an angular subtense at the cornea larger than α_{min}.

Fluorescence

The emission of light at a set of wavelengths from atoms and molecules, excited by absorption of light at shorter wavelength(s).

Flux (Φ)

The radiant, or luminous, power of a light beam, the time rate of the flow of radiant energy across a unit area of a given surface.

Frequency (υ)

The number of light waves passing a fixed point in a given unit of time, or the number of complete vibrations in that period.

Ground State

Lowest energy level of an atom, a molecule or an ion.

Infrared Radiation (IR)

Invisible electromagnetic radiation with wavelengths, in the range of 0.7 - 1000 µm. These wavelengths are often divided into regions: IR-A (0.7- 1.4 µm), IR-B (1.4- 3.0 µm) and IR-C (3.0 – 1000 µm). (µm – micrometer)

Integrated Radiance (L_P)

The integral of the radiance over the exposure duration (expressed in joule/ centimeter^2/ steradian).

Intra-beam Viewing

All viewing conditions whereby the eye is exposed to LASER radiation, other than the extended source viewing, in particular, on-axis viewing of LASER source, or specular reflection.

Irradiance (E) (at a point of a surface)

The radiant power incident per unit area on a surface (expressed in watts /centimeter^2).

LASER

An acronym for light amplification by stimulated emission of radiation. LASER is a device which produces an intense beam, of light with the unique properties of coherence, collimation and mono-chromaticity.

LASER Area

Any area having installation/ equipment generating LASER, or a practice involving the use of LASER, and may encompass nominal hazard zone (NHZ) and LASER control area.

LASER Control Area

An area where the occupancy and activity of those within are subject to control and supervision for the purpose of protection from LASER radiation hazards. It is defined for Class 3B and Class 4 LASER and will encompass the NHZ.

Limiting Aperture Diameter (D_f)

The diameter of a circle over which irradiance or radiant exposure is averaged for the purpose of hazard evaluation and classification.

Limiting Cone Angle (γ)

Angle of acceptance for measurement of photochemical hazard for extended sources with radiance and integrated radiance.

Maximum Permissible Exposure (MPE)

The level of LASER radiation to which an unprotected person may be exposed, without hazardous effect, or adverse biological changes, in the eye, or skin.

Meta-stable State

Long lived excited energy state of an atom, a molecule or an ion that often facilitates LASER action by virtue of its long lifetime.

Nominal Hazard Zone (NHZ)

The nominal hazard zone describes the space within which the level of the direct, reflected, or scattered radiation during normal operation exceeds the applicable MPE. Exposure levels beyond the boundary of the NHZ are below the appropriate MPE.

Nominal Ocular Hazard Distance (NOHD)

The distance along the axis of the unobstructed beam from a LASER, fiber end, or connector, to the human eye, beyond which the irradiance or radiant exposure, during installation or service, is not expected to exceed the appropriate MPE.

Non-ionizing Electromagnetic Radiation

Electromagnetic waves of low frequency and moderate intensity unable to cause ionization, (i.e., to remove an electron from an atom, or a molecule) in air or matter.

Optical Cavity (Resonator)

The space between the LASER mirrors where lasing action occurs.

Optical Density (OD)

A logarithmic expression for the attenuation produced by an attenuating medium, such as an eye protection filter.

Optical Pumping

The excitation of the lasing medium by the application of light, rather than electrical or chemical energy.

Photon

In quantum theory, the elemental unit of light, having both wave and particle behaviour. It has motion, but no mass or charge. The photon energy (E) is proportional to the electromagnetic wave frequency (υ) by the relationship: $E= h\upsilon$, where h is Planck's constant ($6.63x\ 10^{-34}$ joule-second).

Point Source

A source with an angular subtense at the cornea equal to, or less than alpha-min (α_{min}) i.e. equal to, or less than 1.5 mill-radian.

Point source viewing

The viewing condition whereby the angular subtense of the source, α, is equal to, or less than the limiting angular subtense, α_{min}

Population Inversion

A condition of matter in which more atoms, molecules or ions are present in a higher energy state than in a lower energy state, as is required for the operation of a LASER.

Power (Φ)

The rate at which energy is emitted, transferred, or received. The unit of measurement used is watts or joules per seconds.

Pulsed LASER

A LASER that delivers its energy in the form of a single pulse or a train of pulses, with pulse duration of less than 0.25 s

Pulse Duration (t)

The "on" time of a pulsed LASER, generally defined by the time difference between the half-peak-power points on the leading and trailing edges of the pulse.

Radian (rad)

A unit of angular measure equal to the angle subtended at the centre of a circle by an arc whose length is equal to the radius of the circle. (1 radian ~ 57.3° and $2\pi = 360°$)

Radiance (L)

The radiant power per unit area of a radiating surface per unit solid angle of emission (watts/ centimeter^2/steradian).

Radiant Energy (Q)

Energy in the form of electromagnetic waves, usually expressed in units of joules (watts-seconds).

Radiant Exposure (H)

The total energy per unit area incident on a given surface. It is used to express exposure to pulsed LASER radiation, in units of joules/centimetere^2.

Radiant Flux (Φ) / Radiant Power

The time rate of flow of radiant energy. Units – watts

Radiant Intensity (I)

The radiant power expressed per unit solid angle about the direction of the light.

Reflection

The return of radiant energy (incident light) by a surface, with no change in wavelength.

Standard Operating Procedure (SOP)

Formal written description of the safety and the administrative procedures to be followed in performing a specific task.

Steradian (sr)

The unit of measure for a solid angle. There are 4π steradians about any point in space.

Stimulated Absorption

Transformation of Radiant Energy to a different form of energy, namely, excitation energy by interaction with matter.

Threshold Limit Value

The threshold limit value (TLV) of a chemical substance is a level to which it is believed a worker can be exposed day after day for a working lifetime without adverse health effects.

Transmittance

The ratio of the transmitted power (energy) to the incident power (energy).

Ultraviolet (UV) Radiation

Electromagnetic radiation, with wavelengths between soft X-rays and visible violet light, often broken down in to UV-A (315- 400 nm), UV-B (280- 315 nm) and UV-C (100- 280 nm).

Visible Radiation (Light)

Electromagnetic radiation which can be detected by the human eye. It is commonly used to describe wavelengths which lie in the range 400 - 700 nm.

Wavelength (λ)

The distance in the line of advance of a sinusoidal wave from any one point to the next nearest point of corresponding phase.

SYMBOLS

(Common meaning, unless specified otherwise in associated text)

a	Diameter of emergent LASER beam (cm)
α	Apparent angle subtended by a source at the location of the viewer (rad)
α_{max}	Apparent angle subtended by a source, above which the thermal hazard is proportional to the radiance of the source [100 milli-radian (mrad)]
α_{min}	Apparent angle subtended by a source above which extended source MPE apply [1.5 milli-radian (mrad)]
C_A	Wavelength correction factor (0.7µm < λ < 1.05 µm)
C_B	Wavelength correction factor (0.4µm < λ < 0.6 µm)
Cc	Wavelength correction factor (1.150 µm < λ < 1.4 µm)
C_E	Extended source correction factor
C_P	Repetitive pulse correction factor (= $n^{-0.25}$)
D	Barrier separation distance from the focal point of the final focusing lens (cm)
D_C/ D_0	Diameter of the collecting aperture of optical system (cm)
De	Diameter of the exit aperture of optical system (cm)
D_f	Limiting Aperture Diameter from Table AN-1.4 of Annexure I
D_L	Diameter of LASER beam at range r (cm)
D_m	Measurement Aperture Diameter from Table AN-2.1 of Annexure II
D_ρ	Diameter of a reflected LASER beam at the reflecting surface (cm)
E	Beam Irradiance, measured in W/cm^2, for CW LASER
e	Base of natural logarithms (2.71828)
F	Pulse –repetition frequency, PRF (s^{-1})
fs	Femtoseconds
γ	Limiting cone angle (field of view) for MPEs based on photochemical hazards
G	Ratio of corneal irradiance or radiant exposure through magnifying optics to that received by the unaided eye
G_{eff}	Ratio of ocular hazard from optically viewing to that for unaided viewing
H	Radiant exposure (H), measured in J/cm^2, for pulsed LASER
λ	Wavelength of source (µm)
υ	Frequency (Hz)
ks	Kilo-seconds
L_e	Radiance of an extended source (W/cm^2/sr)
L_P	Integrated radiance of an extended source (J/cm^2/sr)
MPE	Maximum Permissible Exposure
MPE:E	MPE expressed as irradiance. For exposure to single pulse, the MPE is for peak power and for a group of pulses, MPE is for the average power (W/cm^2)
MPE:H	MPE expressed as radiant exposure for the summation of all the energy in a group of pulses (J/cm^2)
MPE:L_e	MPE expressed as radiance (W/cm^2/sr)
MPE:L_P	MPE expressed as integrated radiance (J/cm^2/sr)
MPE_{skin}	MPE for skin exposure
µs	Microseconds
n	Number of pulses within total exposure duration T
ns	Nanoseconds
P	Magnifying power of an optical instrument
ps	picoseconds
ϕ	Emergent beam divergence measured at the 1/e peak of irradiance point (rad)
Φ	Radiant power (W)

$\boldsymbol{\Phi}_0$	Total radiant power output of a CW LASER, or average radiant power of a repetitive pulse LASER
Q_m:H	Measured/estimated effective exposure level as radiant energy in joules
$\boldsymbol{\Phi}_m$:E	Measured/estimated effective exposure level as radiant power in watts
$\boldsymbol{\Phi}_m(A)$	Measured/ Estimated effective exposure level under optically-aided viewing conditions
Q	Radiant energy (J)
Q_0	Total radiant energy output of a pulsed LASER (J)
r	Distance from the viewer to the LASER (cm)
r_1	Distance from the point of reflection to the point of observation.
$\boldsymbol{\rho}(\boldsymbol{\lambda})$	Spectral reflectance of object at wavelength $\boldsymbol{\lambda}$
$\mathbf{r}_{NHZ}$	Nominal hazard zone
r_{NOHD}	The distance along the axis of the unobstructed beam from the LASER beyond which the irradiance or radiant exposure is not expected to exceed the appropriate ocular MPE (cm)
S_z	Source size of a LASER beam
t	Duration of a single pulse or exposure (s)
t_{min}	Maximum duration for which the MPE is the same as for 1 ns.
T	Total exposure duration (in seconds) of a train of pulses
T_1	Exposure duration depending on wavelength, beyond which the MPE for a point source is based on photochemical effects rather than thermal effects
T_2	Exposure duration, beyond which the thermal MPE for an extended source is constant in terms of irradiance
T_{max}	Limiting exposure duration which is specifically limited by design, or intended use(s)
$\boldsymbol{\theta}$	Viewing angle from normal to a reflecting surface
$\boldsymbol{\tau}(\boldsymbol{\lambda})$	Spectral transmission of object at wavelength $\boldsymbol{\lambda}$

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 General

Light Amplification by Stimulated Emission of Radiation (LASER) is utilised in units of DAE for industrial and R&D purposes and has unique applications in the nuclear fuel cycle. The hazards posed by LASER beams arise from their use in various modes of operation, producing continuous or pulsed beams in the ultraviolet to far infrared regions of the electromagnetic spectrum, and even extending to the X-ray region. LASER can produce damage to the eye and skin. It can cause irreparable damage to vital parts of the eye, such as retina, cornea and eye lens. There are also associated hazards such as electrical, fire, chemical, and production of ionizing radiations during interaction of intense LASER beam with matter.

Atomic Energy Regulatory Board (AERB) is responsible for ensuring safe procedures and practices in the units of Department of Atomic Energy (DAE) under purview of AERB, apart from enforcing safety regulations and norms in all operations involving ionizing radiation in this country. The use of LASER can expose an individual to varying degrees of hazards. The primary hazard from LASER radiation is exposure to eyes and, to a lesser extent to the skin. Most of the LASER can cause eye injury to anyone who looks directly into the beam or, its specular reflection. High power LASER beams can also cause permanent eye damage from the scattered or the diffuse reflection, burn exposed skin, ignite flammable materials and heat materials to high temperatures. The unique nature of the hazards posed by LASER beams arises from the fact that the high degree of collimation or low divergence of a LASER beam, along with its high mono-chromaticity, enables the beam to be focused to a very small spot producing an extremely high intensity, than what is possible with other sources of radiation. Thus, even a low power LASER can deliver a spectral power density at the retina of the eye, well exceeding that produced by directly looking at the Sun. Unlike other sources of hazardous radiation, highly collimated LASER beams retain this hazard potential even at large distances from the source.

Apart from the direct beam hazards, there are several non-beam hazards associated with the production and the use of LASER, which are acquiring growing safety implications. Powerful LASER in common use today in several laboratories in India produce high power densities, which can evaporate, dissociate and ionise matter, releasing hazardous particulates, fumes and gases. However, the mechanism of ionization of the matter is substantially different from that produced by radioactive sources. High power LASER beams incident on solid targets can produce unsafe ultraviolet light emission; while intense ultra-short duration pulsed LASER can indirectly produce high energy X-rays and particulate radiation (electrons, ions, protons & neutrons).

Presently, the use and applications of LASER in R&D units of DAE are mainly carried out in Raja Ramanna Centre for Advanced Technology, Indore, and Bhabha Atomic Research Centre, Mumbai. These R&D organisations have developed various LASER and their applications in different fields of science, which are being used by DAE units as well as by other industries. LASER are also used in other DAE units, such as Indira Gandhi Centre for Atomic Research, Kalpakkam, as well as in DAE supported Institutes, such as Tata Institute of Fundamental Research, Mumbai. LASER are increasingly being used in the nuclear power plants, for remote cutting and welding of components in high radiation area. Currently, LASER are also being exploited by many research laboratories in academic and research institutions.

1.2 Objectives

The objectives of the 'safety guidelines' are as follows:

(a) To identify hazards associated with LASER, and provide guidelines to ensure safety of the operating and the non-operating personnel likely to be exposed to LASER radiation and associated hazards.

(b) To specify guidelines for hazard evaluation and for introducing control measures for development, manufacturing and use of LASER systems.

(c) To specify administrative measures for safe management by providing adequate warning through signs, labels and instructions and documentation.

1.3 Scope

The 'safety guidelines' are intended for the units of Department of Atomic Energy (DAE) (and which are under purview of AERB) where LASER are being developed, manufactured and used by R&D units. It can also be used by general users of LASER as well as those involved in the development of LASER, LASER prototypes and products and LASER based applications.

It seeks to provide guidance on the organisation's policy and requirement of control measures appropriate to the hazard potential of all types of LASER in order to prevent any harm occurring, or any person from being exposed to an unacceptable level of risk. For this purpose, a quantitative measure of safe exposure limit, namely, the maximum permissible exposure (MPE) and its evaluation procedures are taken from ICNIRP Guidelines and ANSI-Z-136.1-2007. These MPE values, however, provide only the guidelines to determine the safe exposure limits for personnel, which may vary, depending on personal susceptibility.

The specific nature of hazards and related control measures associated with the use of LASER in the entertainment industry, in defence, in communication industry and by medical practitioners, as well as, those associated with XUV (extreme ultra-violet) or X-Ray LASER, with wavelengths less than 180 nm, are out of scope of this document.

LASER hazard evaluation, classification and the applicable control measures given in this document are based on the established scientific knowledge on biological effects of LASER exposure. Although an account of the extensive and ongoing research work in this field is not within the scope of this document, it would be necessary to update the knowledge in this area, from time to time, and revise the 'safety guidelines' as and when considered necessary.

1.4 Structure of the Document

The contents of the document are divided into eight Sections, eight Appendices and five Annexures. Section 2 provides a brief introduction to LASER and enumerates the various types of LASER, their characteristics and the parameters used to specify the LASER characteristics. Section 3 describes the diverse nature of the hazards posed by the LASER beams, as well as the associated hazards arising out of the process of production of the LASER beams and their use in a variety of applications. The conceptual approach for LASER hazard assessment and detailed quantitative procedure for evaluation and classification of LASER hazards, are provided in Sections 4 and 5 respectively. Section 4 is meant for the general users of LASER, whereas Section 5 is meant for use by the LASER safety professionals. The organisation's responsibilities and requirements for facilitating safe, sustained and gainful activities, involving LASER through an effective 'LASER safety management' program, is provided in detail in Section 6. Section 7 provides a detailed account of the hazard control measures, and includes a stepwise procedure for carrying out risk assessment. Finally, Section 8 provides the requirements for regulatory clearance of LASER used in DAE facilities.

The Appendices provide sample formats for documents required for procedural and administrative implementation of control measures and risk assessment, as well as, supplementary information to help in choosing the appropriate control measures. The ICNIRP exposure limits, definitions for LASER hazard classes, and standard formats for labels and warning signs are Annexed thereafter for immediate reference. Examples of LASER accidents emphasizing the need for appropriate controls, and a set of solved problems, to facilitate hazard evaluation, are also Annexed at the end.

2. PRINCIPLE OF LASER

2.1 Introduction

The word 'LASER' is essentially an acronym used to describe a device which produces and amplifies light generating an intense and bright beam of radiation, with unique characteristics that are not found in light produced by ordinary or natural sources. Unlike the light from an incandescent lamp, fluorescent tube, sodium vapour lamp, or the sun, the light from a LASER is highly monochromatic, directional and coherent, producing a highly collimated beam in the extreme ultraviolet (XUV), ultraviolet, visible, infrared region or far infrared of the spectrum of electromagnetic waves. The mechanism, by which LASER light is produced, stimulated emission, was first postulated by Albert Einstein in 1917. The light from a LASER has very low divergence. It can travel over a large distance with very little spreading, and can be focused to a very small spot with a brightness which exceeds that of the sun. The special nature of LASER light has made LASER technology a vital tool in nearly each aspect of everyday life, including communications, entertainment, manufacturing, medicine and most importantly in fundamental research and development of new technologies.

2.2 Basic LASER Operation

To understand stimulated emission, consider an atomic process in which an atom is excited to an electronic energy level with energy E_2, above the ground electronic level with energy E_1 (see Fig. 2.1). When an electromagnetic radiation consisting of photons of frequency 'υ', satisfying the condition $h\upsilon = (E_2 - E_1)$, (where h = Planck's constant), is incident on this excited atom, it can force or stimulate the atom to de-excite to the lower energy level E_1, generating an additional photon of frequency 'υ'. This process is known as stimulated emission. The reverse process of stimulated emission is absorption, or 'stimulated absorption', in which a photon of appropriate frequency, or energy, is absorbed by an atom or molecule exciting it from a lower energy level to a higher one. The excited atom or molecule, left to itself, de-excites 'spontaneously' to the lower energy level by emitting a photon which may also have the same frequency. However, spontaneously emitted photons may have a spread of frequencies, depending on the width of the energy levels, and will be emitted, on average, uniformly in all directions. The electromagnetic wave describing the spontaneous emission process will, on average, have arbitrary state of polarization, as well as abrupt and rapid variation of phase of oscillation of the wave with time and across the wave-front.

The salient feature of stimulated emission that makes it possible to produce LASER action is that the emitted photon is identical to the incident photon as regards to frequency, direction of travel, phase and state of polarization. When these photons are incident on more number of excited atoms in energy level E_2, it results in amplification of the incident radiation. However, since the photons are also absorbed by atoms in the lower energy level, amplification of light is possible, generally, if a larger number of atoms are available in energy level E_2 than in energy level E_1, a condition referred to as population inversion.

Population inversion does not occur in nature under equilibrium conditions. In nature, the number of atoms N(E) having energy E is found to vary according to the distribution function:

$$N(E) \propto e^{-E/kT} \qquad \text{............ (eqn. 2.1)}$$

where k is Boltzman constant and T is the temperature (°K) of the collection of atoms. As energy 'E' increases, N(E) decreases. Thus, in order to produce population inversion, it is necessary to supply energy to the material or to the medium so that atoms, molecules, or ions in the ground level are excited, and increasingly accumulated in the higher energy level, often utilizing an additional energy level. This process of non-equilibrium excitation to the higher energy level is called 'pumping'.

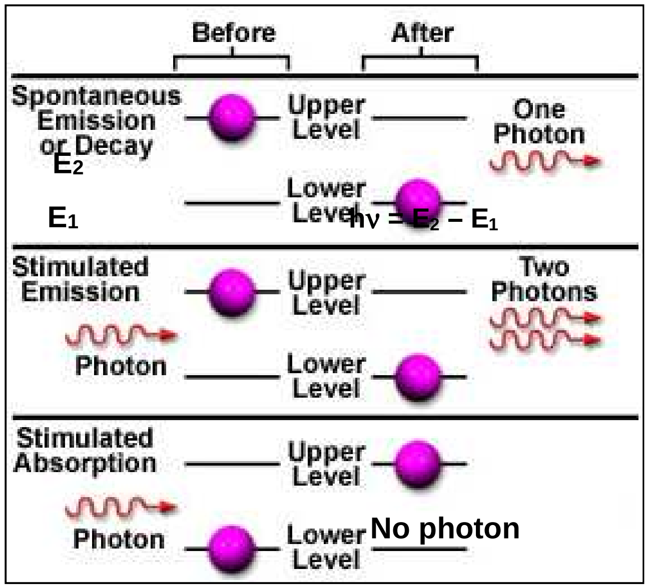


Figure 2.1

SCHEMATIC DESCRIPTION OF THE SPONTANEOUS AND STIMULATED EMISSION

(The processes in the interaction of photons of light (depicted as wavelets), with an atom (depicted by spheres). The horizontal lines indicate energy levels, with energy increasing upwards in the Figure.)

Once the population inversion is achieved, the spontaneously emitted photons can initiate the process of stimulated emission, resulting in amplification, because a larger number of atoms in the required higher energy level are available. The material or medium, which is prepared by this process in a LASER, is called active or gain medium, and its atoms, molecules, or ions are called active centres. The active centres in any LASER material must have an excited energy level having sufficiently long life-time, in comparison to the lower energy level, for achieving population inversion.

The next step is to bring about a large number of collisions between the photons present and the active centres in their excited state. The simplest way to do this is to place the active medium between two mirrors (LASER cavity). Those photons that travel parallel to the axis of the arrangement (perpendicular to mirrors) will travel to and fro between the mirrors because of repeated reflections. Every time they pass through the active medium, some will collide with the excited active centres, and their number will increase due to stimulated emission. If one mirror is made partially transparent and amplifier gain in one round-trip is more than the loss of the cavity, then a collimated beam of photons will come out of it.

2.3 LASER Components

A generalized LASER consists of a lasing medium, a 'pumping' system and an optical cavity. Schematic diagram of a basic LASER is given in Figure 2.2 and each of these LASER components are discussed below:

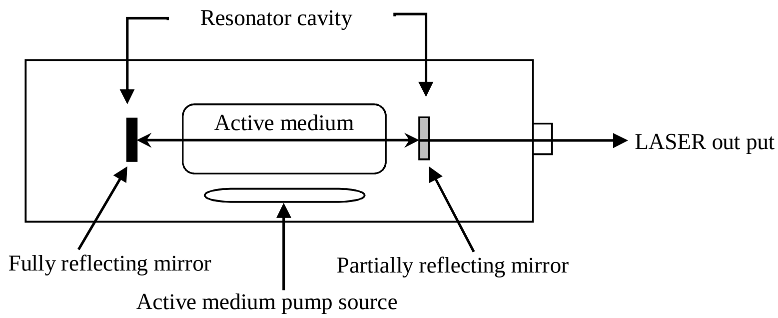


Figure 2.2
SCHEMATIC OF LASER

2.3.1 Lasing Media

Since the first demonstration of LASER action in Ruby, a large number of media in solid, liquid and gaseous states have been exploited for making a variety of LASER. Some of the LASER, which are widely used now-a-days, are listed in Table 2.1.

2.3.2 Pumping System

Pumping, as explained above, can be achieved by a number of processes. Optical pumping uses photons provided by a light source, such as flash, or arc lamp or another LASER, to transfer energy to the lasing material. Pumping is also achieved from energetic electrons in discharge, or electron beam source, by collision with active species of the lasing medium. Chemical pumping systems use the binding energy released in a chemical reaction, to excite one or more of the product species. Injection diode LASER is a forward biased heavily doped pn junction fabricated from suitably designed semiconductor materials, and the injected current is sufficiently large to provide optical gain.

2.3.3 Optical Cavity

An optical cavity is required to provide a positive feedback to the amplifying medium, for the photons traveling in a desired direction, generally along the direction in which maximum amplification or LASER gain exists. This is usually achieved, as stated above, by using two or more mirrors or other reflective optical components, suitably and precisely aligned, to provide the desired feedback. Small misalignment of the mirrors may drastically reduce the LASER output power, or disrupt LASER action altogether. In some monolithic designs such as in LASER made with active ion-doped optical fibers or semiconductor diode LASER, feedback is often provided by using Bragg (resonant) reflection from a spatially distributed periodic modulation of the refractive index induced in the medium, using established optical techniques.

Apart from inducing the LASER to emit a well-directed and collimated beam, optical cavities also favour LASER action at some well-defined frequencies/ wavelengths, which are resonant in the cavity, and are referred to as the 'axial modes', or 'longitudinal modes', or simply the 'modes' of the cavity. At the same time, the use of the cavity mirrors may cause the transverse intensity distribution in the output beam to acquire one or more of some specific forms, which are referred to as the 'transverse modes' of the cavity.

In some LASER, with sufficiently high available amplification (Nitrogen LASER), optical cavities are not used at all, and a single pass amplification of the spontaneously emitted photons (Amplified Spontaneous Emission or ASE) in a suitably designed long amplifying medium is adequate to produce a well-directed powerful beam. ASE is also the currently used process for producing LASER in the deep UV and X-ray region.

2.4 Characteristics of LASER Light

2.4.1 Coherent

Coherence is one of the unique properties of LASER light. It arises from the stimulated emission process which provides the amplification. Since a common stimulus triggers the emission events which provide the amplified light, the emitted photons are 'in step', and have a definite phase relation to each other. This coherence is described in terms of temporal coherence and spatial coherence, both of which are important in producing the interference, which is used to produce holograms.

Ordinary light is not coherent because it comes from independent atoms. The comparison of incoherent light and coherent LASER beam, with regard to the direction of the output light is shown in Figure 2.3.

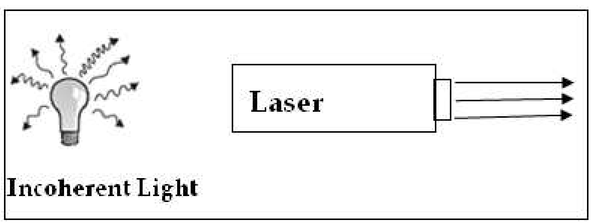


Figure 2.3
COMPARISON OF INCOHERENT LIGHT AND COHERENT LASER BEAM

Incoherent light from a light bulb consists of light wave or photons of various wavelengths emitted in different directions. LASER light has significantly the same wavelength and direction of propagation.

2.4.2 Monochromatic

LASER light consists substantially of one wavelength, with a very small spread in spectrum, having its origin in stimulated emission from one set of atomic, molecular, or ionic energy levels. The spread in spectrum is determined by the width of the energy levels as well as by the characteristics of the optical cavity, and, of course by the extent of stimulated emission over and above the spontaneous emission that may appear as a background. These contributions are usually such that the light from a LASER has typically a narrow spectral width. A schematic depiction comparing light waves from a white light source (e.g. a compact fluorescent lamp), a monochromatic incoherent non-LASER light source (e.g. a sodium vapour lamp), and coherent LASER is shown in Figure 2.4. The stimulated emission and optical cavity together enforce the coherence, or continued 'in step' oscillation of the light waves in a LASER source.

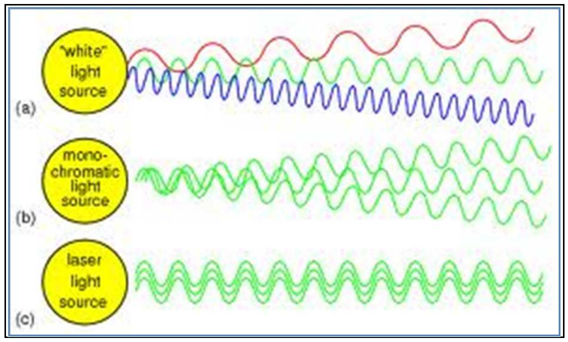


Figure 2.4
COMPARISON OF WHITE-LIGHT, MONOCHROMATIC INCOHERENT NON-LASER LIGHT AND COHERENT LASER LIGHT.

2.4.3 Collimated

Because of bouncing back and forth between the end mirrors of a LASER cavity, those paths which sustain amplification must pass between the mirrors many times and be very nearly perpendicular to the mirrors. As a result, LASER beams do not spread very much. Another way of saying this is that the beam is highly collimated. The degree of collimation is defined by a parameter called divergence. The difference between divergence of conventional light and LASER beam is shown in Figure 2.5.

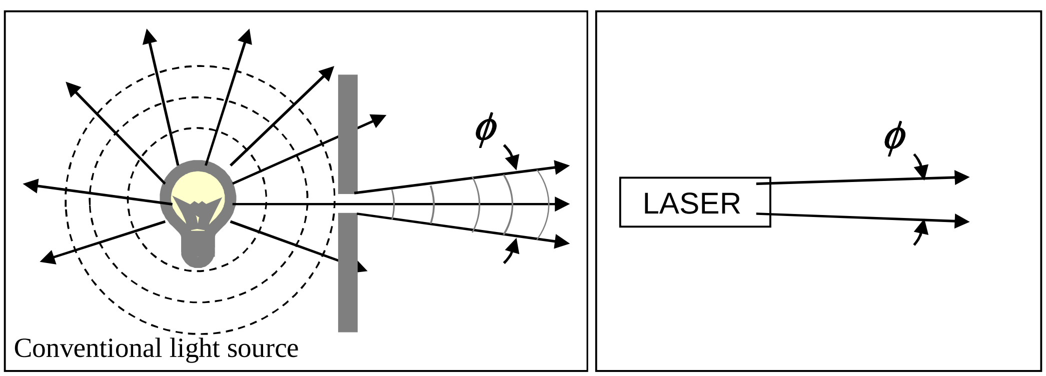


Figure 2.5
DIVERGENCE (ϕ) OF CONVENTIONAL LIGHT SOURCE WHICH CAN BE REDUCED BY PLACING A SMALL APERTURE VS. LOWER DIVERGENCE (ϕ) OF LASER SOURCE OF LARGE APERTURE

2.5 Types of LASER

LASER can be classified based on wavelength, pulse characteristics, active media, or pumping process. In the following, different kinds of LASER are discussed in terms of active media and temporal characteristics.

2.5.1 Based on Active Media

The salient features of some commonly used LASER are described below:

(a) Solid State LASER employ a lasing material dispersed in a solid matrix, e.g., Neodymium:YAG LASER (Nd:YAG). The term ‘YAG’ is an abbreviation for the crystal: Yttrium Aluminum Garnet, which serves as the host for the Neodymium ions. It emits an infrared beam generally at the wavelength of 1064 nm. A large variety of high CW/average power (several kilowatts) and high pulse energy (up to kilojoules) solid state LASER are in use today.

(b) Gas LASER use a gas or mixture of gases, in a discharge tube. The most common gas LASER uses a mixture of helium and neon (He:Ne), with a primary output at 632.8 nm, which is visible in red colour. Carbon dioxide LASER is a powerful gas LASER, producing up to several kilowatts of average power in the infrared (~10.6 micron).

(c) Dye LASER use a LASER medium that is usually a complex organic dye in liquid solution, or suspension. The most striking feature of these LASER is their wavelength ‘tunability’. Proper choice of the dye and its concentration allows the production of LASER light over a broad range of wavelengths in, or near the visible spectrum, e.g. Rhodammine class of dyes, each of which provide tunability over 40 nm bandwidth in yellow-orange-red portion (560 – 700 nm) of the spectrum.

(d) Semiconductor LASER, also known as diode LASER, make use of specially-designed arrangement of suitably-doped semiconductor materials sandwiched together. These LASER are generally very small, and individually, give only modest power. However, these are arranged in larger arrays and stacks, for achieving high output power. Today, diode LASER are available at wavelengths spanning from UV to infra-red.

(e) Fiber LASER is the another type of solid state LASER in which the active gain medium is an optical fiber doped with rare earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, and thulium. These are related to doped fiber amplifiers, which provide light amplification without lasing. Fiber non-linearity, such as stimulated Raman scattering, or four wave mixing, can also provide gain in a fiber LASER.

In addition to these commonly used types, Free Electron LASER (FEL), which extract energy from high energy electrons traveling in specially-designed magnetic fields, have emerged as a powerful source of LASER radiation covering a wide range of wavelengths from X-rays to far Infra-red. Table-2.1 provides the wavelengths of the most commonly used LASER.

2.5.2 Based on Temporal Behavior

Another classification of LASER is based on the temporal behavior of the output beam. The different temporal modes of operation of a LASER are distinguished by the rate at which energy is delivered. LASER can be operated in continuous wave (CW) or pulsed mode.

(a) Continuous wave (CW) LASER produce beams continuous in time with relatively stable average beam power. However, since the blink response of the eye is around 0.25 s, even pulsed LASER output in the visible wavelength region for a duration equal to or greater than 0.25 s is considered as CW as far as eye safety is concerned. The rate of energy production is expressed in units of power, or watts. The power output per unit area is referred to as the power density, irradiance, or optical intensity, expressed in watts/cm^2.

TABLE 2.1: WAVELENGTHS OF SOME COMMONLY USED LASER

Type/Name	Wavelength (nm)	Type /Name	Wavelength (nm)
Solid State LASER			
Titanium sapphire	660-1060 (Tunable)	Ruby	694
Optical parametric oscillatiors	UV - IR	Neodymium: YAG Neodymium: Glass Neodymium: YVO_4	1064/ 1054 (532/ 527, frequency doubled)
Holmium	2060	Fiber LASER	1000 -3000 nm
Alexandrite	700-830 (tunable)		
Gas/ Vapour LASER			
Copper vapour	510, 578	Gold vapour	628
Argon fluoride	193	Nitrogen	337
Krypton-fluoride excimer	248	Xenon-chloride excimer	308
Krypton ion	335-800	Hydrogen fluoride	2600- 3000
Argon ion	450-530 (488 & 515 strongest)	Helium-neon	543, 633, 1150
Carbon monoxide	5000- 6000	Carbon dioxide	9000 – 11000 (mainline 10600)
Chemical Oxygen Iodine LASER (COIL)	1315	Helium-cadmium	325, 442
Dye LASER			
Organic dye (in solution)	300 –1000 (tunable)		
Semiconductor LASER			
Semiconductor (GaAlAs family)	750-900	Semiconductor (GaInP family)	670- 680
Semiconductor (InGaAsP family)	1300- 1600	Semiconductor (lead salts)	2700- 30000
Free-electron LASER	X-rays – IR		

(b) Pulsed LASER produce time varying output beams in the form of a single pulse on operator action, or a train of pulses. Generally, these LASER are designed to produce a specified pulse duration, ranging from ms (10^{-3} s) to fs (10^{-15} s). LASER which emit periodically spaced train of pulses are referred to as repetitively pulsed LASER with a pulse repetition frequency (PRF) or repetition rate, which may range from a few hertz to several tens of mega-hertz. Because the output is a series of energy pulses, it is more conveniently expressed in terms of pulse energy in joules (the average power can be calculated by multiplying the pulse energy by the repetition rate). The energy output per unit area is referred to as the energy density, or more commonly, the fluence, or flow of energy, expressed in joules/cm^2**.**

In general, pulses of the order of nanoseconds are produced by a mechanism known as Q-switching. Q-switching can be used to increase the power (not the energy!) of a LASER pulse. In this mechanism, lasing action is allowed to start by rapidly reducing the cavity loss (increasing the 'Q' value), only after the population inversion reaches its maximum value. As a result, high peak power pulses, with pulse duration of typically 5 to 250 ns, are produced. Power is energy per unit time, so although the pulses are powerful, the average energy output of a Q-switched LASER is actually lower than that of a 'free running' pulsed LASER. A typical example of such LASER is nanoseconds Q-switched Nd-YAG LASER which is commonly used in many laboratories. In some nanoseconds LASER, the nature of the active medium itself restricts operation to short duration pulses, such as in copper vapour, nitrogen, or excimer LASER.

Pulses of duration of a few femtoseconds (10^{-15} seconds) to few hundred picoseconds (10^{-12} seconds) are produced by using a technique known as mode locking. In mode locking, phase coherent waves of different mode frequencies interfere with one another to generate a stable beat effect, producing ultra-short duration pulses. Here, the LASER media with large spectral bandwidth are necessary in order to produce ultra-short pulses, as the minimum pulse duration is inversely proportional to the spectral bandwidth. While some mode-locked LASER continuously produce low-energy pulses, with a PRF of several tens of MHz, others involve simultaneous Q-switching producing higher energy bursts of ultra-short with burst duration several tens to a few hundred ns. In recent advancements, ultra-short LASER pulses at lower PRF are further amplified, producing extremely high peak powers exceeding terra-watts (10^{12} W) in the commercially available table-top systems, to peta-watts (10^{15} W) in the systems built in a few laboratories in the world.

2.6 Quantities and Units

All LASER safety assessments are based on absolute quantities of radiant power / radiant energy (radiometric quantities). The main radiometric quantities are given in Table 2.2.

The fundamental quantity of LASER radiation is radiant energy. This quantity is denoted as the symbol Q, and is normally measured in units of joules (J). The radiant power of LASER radiation (symbol $\mathbf{\Phi}$), sometimes called the flux, is the rate at which energy is generated, or transferred. It is normally measured in units of watts (W). A power of 1 W is equivalent to an energy production, or delivery rate, of one joule per second (1 J/second).

The output of CW LASER which provide a constant, continuous emission, is usually expressed in terms of radiant power $\mathbf{\Phi}$, i.e. the rate at which radiant energy is being produced and therefore specified in units of watts. Pulsed LASER are generally quantified in terms of the energy per pulse Q_{pulse} (in joules) and pulse repetition frequency, F (in hertz).

Then, the power of an individual pulse is given by,

$$\mathbf{\Phi}_{pk} = Q_{pulse}/t, \qquad \text{……… (eqn. 2.2)}$$

where t is duration of the pulse in time, expressed as Full Width at Half Maximum (FWHM).

The average power of a pulse LASER emission can be expressed as

$$\mathbf{\Phi}_{av} = Q_{pulse} . F \qquad …….. \text{(eqn. 2.3)}$$

The exposure that is produced by a LASER beam at a surface some distance from the LASER is expressed in terms of either its power density or energy density. The power density is more correctly termed as irradiance, symbol E (W/cm^2), and the energy density is termed as the radiant exposure, symbol H (usually specified in J/cm^2). In LASER medicine, the term 'dose' is sometimes used for radiant exposure H, and 'dose rate' for the irradiance E.

TABLE 2.2
SUMMARY OF RADIOMETRIC QUANTITIES AND UNITS

Quantity	Symbol	Units
Radiant Energy	Q	joules (J)
Radiant Power (flux)	**Φ**	watts (W)
Radiant Exposure	H	joules per square centimetre (J/cm^2)
Irradiance	E	watts per square centimetre (W/cm^2)
Radiant Intensity	I	watts per steradian (W/ sr)
Radiance	L	watts per square centimetre per steradian (W/cm^2 / sr)

3. HAZARDS OF LASER

3.1 Introduction

The intensity of LASER radiation is often such that exposure can result in serious and permanent injury to the eyes and skin. There are also a number of non-beam hazards associated with LASER systems. They include electrical shock, exposure to dyes and chemicals, and production of potentially hazardous gases or vapour plumes. For beam hazards to the eye, the site of injury following LASER exposure depends on the wavelength, as beam of different wavelengths are absorbed to a varying extent in different parts of the eye such as cornea, retina, etc. Acute exposure of the cornea can cause corneal burns, or photo-keratitis (welder's flash). Lens opacities (cataracts) are associated with chronic exposure of the lens. Chronic exposure of the retina may also result in retinal injury. Exposure of the retina can be particularly hazardous because of the focusing effect of the lens. Objects in the center of the field of vision are focused on an area of the retina called the fovea. This area of the retina is the most sensitive and is responsible for most of our visual acuity. Injury of the fovea may result in permanent blindness in the injured eye. If the peripheral areas of the fovea are injured, the effect on vision is less serious. Skin burns are caused by radiation from high power LASER, particularly in the infrared region. Exposure to the skin at different wavelengths may result in erythema, skin cancer, skin aging, dry skin effects, and photosensitive reactions in the skin.

LASER hazards are of great concern for its user because of the several known biological effects under the irradiation of intense LASER light. The biological damage caused by LASER is produced through thermal, acoustical and photo-chemical processes. Thermal effects are caused by a rise in temperature, following absorption of LASER energy. Tissue reaction to thermal effect is related to temperature, and at different temperatures different reactions can occur. These reactions are hyperthermia, coagulation and ablation. Hyperthermia occurs when temperature increases to 41°C resulting in tissue death during exposure of a few tens of minutes. Coagulation occurs at temperatures between 50 and 100°C, which results in desiccation, whitening and retraction of tissues due to protein and collagen denaturation. Ablation corresponds to matter loss, and occurs at temperatures greater than 100°C. The severity of the damage is dependent upon several factors such as exposure duration, wavelength, energy of the beam, area and type of tissue exposed. Acoustical effects result from a mechanical shockwave, propagated through a tissue which can cause localised vaporization of the tissue. Photo-chemical effects results from change in cell chemistry and depend greatly on wavelength.

In the following sub-sections, the hazards originating from exposure of the eye and skin to a LASER beam are discussed. Collateral and non-beam hazards, arising during LASER operations are discussed separately.

3.2 Beam Hazards

High intensity of LASER radiation and long duration of LASER exposure can cause irreversible damage to the eye and skin of human beings. The most common causes of LASER-induced tissue damage are thermal in nature. These hazards depend on power/pulse energy, temporal characteristics, wavelength, size of the LASER beam at the source, beam divergence and exposure duration of LASER. In addition, environmental conditions and individual susceptibility are also important factors in assessment of these hazards.

Hazard from LASER beam exposure is not limited to only direct beam exposure but can also occur from reflections. Intra-beam exposure means that the eye, or skin, is exposed directly to all or parts of the LASER beam. Specular reflections from mirror-like surfaces can be nearly as harmful as exposure to direct beam, particularly, when the surface is flat. Convex curved mirror-like surfaces will widen the beam such that exposed eye or skin is not exposed to the full impact of the beam. A diffuse surface is a surface that will scatter the LASER beam in many directions. These scattered or diffuse reflections do not carry the irradiance or radiant exposure of the primary beam, but may still be harmful, particularly, in the case of high power LASER. Whether a surface is a diffuse reflector, or a specular reflector will depend on the wavelength of the beam as compared to the surface irregularities. A surface that would be the diffuse reflector for a visible LASER may be a specular reflector for an infrared LASER beam. The difference of diffuse and specular reflection is shown in Figure 3.1.

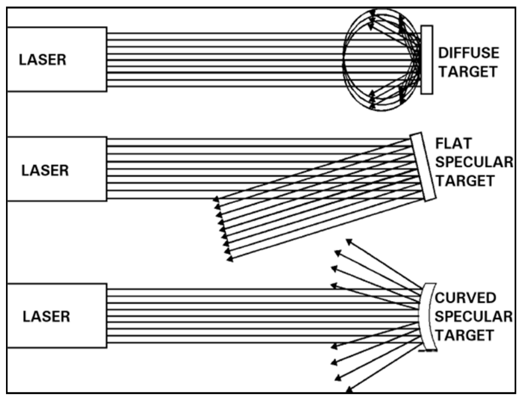


Figure 3.1
DIFFUSE AND SPECULAR REFLECTIONS OF LASER

A LASER beam, with low divergence entering the eye can be focused down to an area of 10 to 20 microns in diameter. A 30 mW LASER is capable of producing enough irradiance to instantly burn through paper.

3.2.1 The Eye Injury

LASER of all wavelengths can cause ocular injury, although the particular part of the eye at risk will depend on the optical wavelength. A cross-section of the human eye is shown in the Figure 3.2. Because of the high degree of focusing that occurs within the eye, exposure to a relatively weak coherent LASER beam can cause permanent, instantaneous damage to the retina. A retinal injury which occurs in the macula, the most sensitive area of the retina, is serious, and will be immediately apparent to the victim. Injury to the para-macula, or peripheral retinal region, may have only a minimal effect on vision, and can go undetected by the victim. Absorption in the other eye components, primarily, the cornea and lens is responsible for limiting exposure of the retina. In the absorption process, the absorbing structures become subject to damage themselves. The cornea behaves similar to the skin, in that, it is constantly undergoing replenishment, and only rather severe damage results in scarring that may have some effect on the vision. LASER beam reflection from a rough surface (diffuse reflection) enters the eye, with large divergence, and produces a large image on the retina compared to coherent light source. Hence, diffused scattering of the beam reduces the likelihood of eye damage.

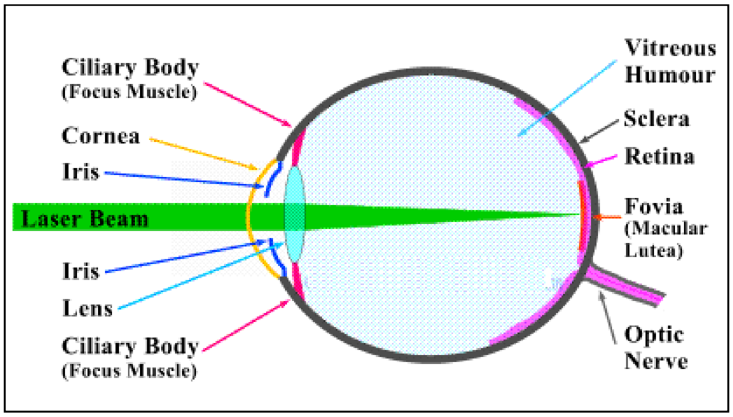


Figure 3.2
THE CROSS-SECTION OF HUMAN EYE

The light between 400 and 1400 nm is focused by the curved cornea and lens on the retina, the increase in irradiance is about 100,000- 200,000 times. Viewing a coherent LASER beam also called point source, will focus all the light on a very small area of the retina, resulting in a greatly increased power density and an increased chance of damage. A large source of light from a diffuse reflection of LASER light that enters the eye at a large angle is called extended source, which produces a relatively large image on the retina, and the energy is not concentrated on a small area of the retina as in the case of a point source. This difference of viewing of the point source and extended source can be understood with the help of Figure 3.3.

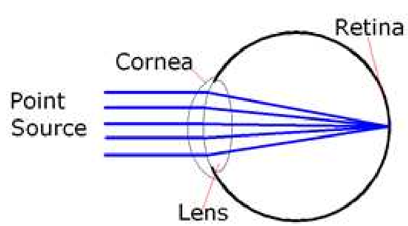
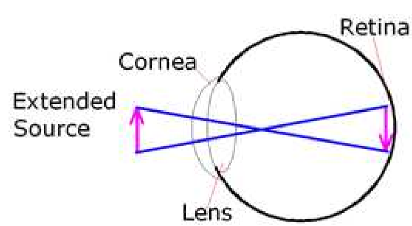
Point Source Viewing	Extended Source Viewing
	

Figure 3.3
POINT SOURCE VIEWING VS. EXTENDED SOURCE VIEWING

Symptoms of a LASER burn in the eye may include a headache shortly after exposure, excessive watering of the eyes and sudden appearance of floaters in the vision. Floaters are those swirling distortions that occur randomly in normal vision most often after a blink or when eyes have been closed for a couple of seconds. Floaters are caused by the dead cell tissues that detach from the retina and choroid, and float in the vitreous humor. Minor corneal burns may cause a gritty feeling, like sand in the eye.

The physical response of the human eye differs for light of different wavelengths, and this has a bearing on the potential damage that may occur for several reasons. At the high intensity exposure which is possible with LASER, damage to the eye can occur in any of its components that absorbs the maximum radiant energy per unit volume of the tissue. The absorption characteristics of human eye for different wavelengths along with biological effects, are illustrated in Figure 3.4. The hazard to eye is particularly important in the visible and near-infra red spectral regions (400 – 1400 nm), also called retinal hazard region. Intra-ocular energy in this retinal hazard region is limited by the pupil area (diameter assumed to be 7 mm), for the visible band (400 – 700 nm), the natural aversion to bright light limits the exposure duration to 0.25 s. Infrared LASER in the wavelength range 700 – 1400 nm are particularly hazardous, since those penetrate to a varying extent to the retina, while the body's protective aversion response, including blink reflex, is triggered only by visible light.

Based on current understanding, the harmful effects of light, at different wavelengths, on human eye, can be briefly described as follows:

(a) Exposure to Ultra-violet Wavelengths (200- 400 nm)

Ultraviolet spectrum is divided into three regions namely UV-C (100-280 nm), UV-B (280-315 nm) and UV-A (315-400 nm), which are related to the different biological effects depending on the wavelength as shown in Figure 3.4. Excessive ultra-violet exposure of the eye can produce photo-phobia, accompanied by redness, tear formation and discharge from the mucous membrane that lines the inner surface of the eye-lid (conjunctiva), corneal surface cell layer splitting (exfoliation) and stromal haze. This leads to the syndrome of photo-keratitis, which is radiant energy induced damage to the outer epidermal cell layer of the cornea. Photo-keratitis is the primary result of excessive acute (short term) exposures in 200 to 315 nm wavelength region (UV-C and UV-B). In the UV-A region, cataract may result from chronic high level exposures due to photochemical denaturation of proteins in the lens.

(b) Exposure to Visible and Near Infrared Wavelength (400 – 1400 nm)

Retinal damages are possible when the LASER wavelength is in the visible, or near infrared spectral region. LASER radiation at these wavelengths, directly from the LASER, or from a specular reflection, entering the eye, is transmitted, without significant absorption as shown in Figure 3.4. The eye lens focuses the coherent LASER radiation to an extremely small image spot (10-20 micrometer diameter) on the retina, producing a high irradiance (W/cm^2) or radiant exposure (J/cm^2), sufficient to cause damage even for modest corneal exposure levels.

In the visible portion of the spectrum (400 -700 nm), the cornea, lens and ocular media are largely transparent. Damage to the retina is possible either through thermal or photochemical processes. Only about 5% of the incident radiation is actually used for creating vision, the remainder is absorbed in the pigment granules in the epithelium layer of the retina and the choroid layer, which lies under the rods and cones (photo-receptors). This absorbed energy is converted into heat, and if the incident LASER energy or power is higher than a threshold, can cause an irreversible retinal burn. Photochemical damage to photoreceptor cells of the retina can degrade overall light or colour sensitivity. Infrared radiation may cause cataract formation in the lens. A transition zone between the retinal effects and the effects on the front segments of the eye (cornea, lens, aqueous media) begins at the far end of the visible spectrum and extends into the infrared 'A' region (0.7- 1.4 μm).

LASER operating in pulsed mode present an additional hazard from the possibility of acoustic shock wave generation in the retinal tissue. LASER pulses with duration less than 10 µs, induce shock waves that cause tissue rupture. This type of injury is permanent and potentially more severe than the thermal burns, because acoustic damage usually affects a larger area of the retina, and the required energy to produce the effect is lower. Hence, the limits for exposure to short duration pulses are lower.

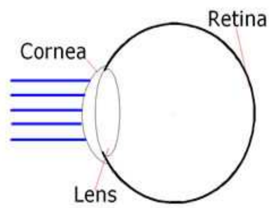
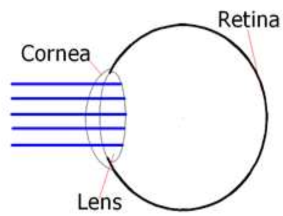
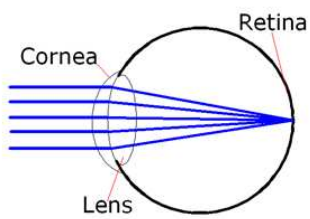
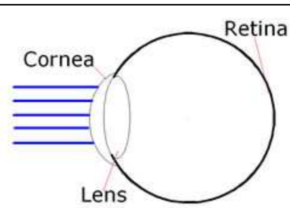
<table>
<tr><th colspan="2">Wavelength</th><th>Pictorial View</th><th>Effect</th></tr>
<tr><td rowspan="3">Ultraviolet Light</td><td>UV-C
(200- 280 nm)</td><td rowspan="2">
</td><td rowspan="2">Photo-keratitis due to high level acute exposure</td></tr>
<tr><td>UV-B
(280- 315 nm)</td></tr>
<tr><td>UV-A
(315- 400 nm)</td><td>
</td><td>Cataract may result from chronic high level exposures</td></tr>
<tr><td>Visible Light</td><td>(400-780 nm)</td><td rowspan="2">
</td><td>Photochemical and thermal retinal injury</td></tr>
<tr><td rowspan="3">Infra-red Light</td><td>IR-A
(780-1400 nm)</td><td>A transition zone between retinal effects and front segment of the eye. Retinal burns and cataract</td></tr>
<tr><td>IR-B
(1400- 3000 nm)</td><td rowspan="2">
</td><td>High exposure can damage lens and cornea</td></tr>
<tr><td>IR-C
(3000 nm –
1mm)</td><td>Ocular media becomes opaque</td></tr>
</table>

Figure 3.4
ABSORPTION CHARACTERISTICS AND BIOLOGICAL EFFECTS OF LASER ON HUMAN EYE

(c) Exposure to Mid and Far Infrared Wavelengths (1400 nm – 1 mm)

In the infrared 'B' region (1.4 - 3.0 µm) damage to both the lens and cornea is observed. The ocular media becomes opaque to radiation in the infrared 'C'region (3.0 µm – 1mm), as the absorption by water, a major portion of all body cells, is high in this region.

Thus, the minimum power or pulse energy of the LASER radiation incident on the eye which is likely to damage different parts of the eye, i.e. the damage threshold, depends on the wavelength.

3.2.2 Skin Injury

LASER radiation injury to skin is normally considered less serious than the injury to the eye, since the latter involves functional loss of vision. Except in the retinal hazard region (400- 1400 nm), injury threshold for both skin and eyes are comparable. The probability of exposure of the skin is, of course, greater than that for the eye because of the skin's greater surface area, and because of the common practice of carrying out alignment, with parts of the hand being in close proximity to a high power beam. The layers of the skin, which are of concern, are the epidermis and dermis. The epidermis layer lies beneath the stratum corneum and is outermost living layer of the dermis. LASER can harm the skin via photochemical, or thermal burns. A sun-burn (reddening and blistering) may result from short term exposure to the beam.

UV exposure is also associated with an increased risk of developing skin cancer and pre-mature aging of the skin. Ultraviolet radiation, UV-A (315-400 nm), induces photochemical reaction, leading to erythema (abnormal reddening of skin) and hyper-pigmentation. With prolonged exposures it may initiate long-term degenerative processes, like accelerated skin ageing and increased risk of certain types of skin cancer. There is also the possibility of radiation carcinogenesis from UV-B (280-315 nm) either directly on DNA or from the effects on the potential carcinogenic intra-cellular viruses. Exposure in the UV-B range is the most injurious to skin, while that in the shorter UV-C (200- 280 nm) and the longer UV-A ranges seems less harmful to human skin, as these are mostly absorbed in the outer layers of the epidermis.

The skin reflectivity is high in the visible and near infrared spectral regions and low elsewhere. Further, the red portion of the visible region and near infrared region is able to penetrate deeper into the skin. The greater the penetration depth, the greater is the volume of the tissue available to deposit the absorbed energy. Because of these two factors the damage threshold for visible and near infrared radiation are higher compared to the other spectral regions. The injury in this range is believed to be thermal.

The biological effects of LASER on eye and human skin in the different wavelength region are summarised in Table 3.1.

TABLE 3.1: SUMMARY OF BIOLOGICAL EFFECTS OF LASER LIGHT

Spectral Range	Eye Effects	Skin Effects
Ultraviolet C (0.200-0.280 µm)	Photokeratitis	Erythema (sunburn), skin cancer
Ultraviolet B (0.280-315 µm)	Photokeratitis	Accelerated skin aging increased pigmentation
Ultraviolet A (0.315-0.400 µm)	Photochemical UV cataract	Pigment darkening, skin burn
Visible (0.400-0.780 µm)	Photochemical and thermal retinal injury	Photosensitive reactions, skin burn
Infrared A (0.780-1.400 µm)	Cataract, retinal burns	Skin burn
Infrared B (1.400-3.00 µm)	Corneal burn, aqueous flare, IR cataract	Skin burn
Infrared C (3.00-1000 µm)	Corneal burn	Skin burn

3.3 Non-beam Hazards

Non-beam hazards, although not related with direct exposure of the eye or skin to LASER radiation, can arise during normal operation, maintenance, or servicing of LASER. Unlike the beam hazards, non-beam hazards are not confined to the ‘nominal hazard zone’ (NHZ), which is the space within which the level of LASER radiation can cause hazardous effects, or adverse biological changes, in the eye or skin. A description of the common non-beam hazards is given below:

3.3.1 Electrical Hazards

The high voltage power supplies, large capacitor banks and trigger transformers used in many LASER systems are potentially lethal, and are required to be handled with appropriate caution. The sources of electrical hazards in power supplies are high voltage DC or RF electrical power circuits, the capacitor banks used in pulsed LASER which can be source for electrical shock, even after the equipment is switched off because of its charge storage capacity for a long time. Many LASER systems incorporate water-cooling arrangement, and the presence of water circulating at high pressure in proximity of high voltage electrical components can enhance the risk. In dye LASER, static electricity can build up in less polar solvents, such as alcohol and dioxane, during circulation of liquid dye solutions through non-conducting tubes, leading to additional electrical hazards.

3.3.2 Heat, Fire and Explosion Hazards

High average power (>0.5 W) CW and high pulse repetition frequency LASER represent significant fire hazard from the direct beam and unexpected specular reflections, in presence of flammable materials in the vicinity of the beam. The fire hazard is enhanced when the beam is focused tightly, or when emerging from optical fibers. Apart from inflammable solvent vapour and gases, even high concentration of airborne dust may get ignited and cause explosions.

High average power LASER beams when incident on metals and beam dumps may raise the temperature sufficiently high to cause skin burn when touched inadvertently. Mirrors which may absorb a minute fraction of the incident beam may shatter, if the beam power is high and the absorbed energy is not dissipated rapidly.

Several solvents used in dye LASER are highly inflammable and there are a few reports of them getting ignited, when used in unsafe conditions, such as with improper grounding or overheating during circulation with pumps.

Explosions may occur as a result of concentrated amounts of flammable or combustible materials, which come in contact with an ignition source. Apart from these, a large variety of LASER use various gases, which lead to additional hazards resulting from improper handling of pressurised cylinders. For example, an improperly secured cylinder can fall over, shearing off its valve stem, and get propelled into the air like a missile.

High pressure discharge lamps used for excitation of many LASER and capacitors used in electrical power supplies may explode during operation. Such components should be enclosed in a housing which will withstand the explosive forces that may be produced.

3.3.3 Chemical and Associated Hazards

Chemical hazards may arise due to the use of hazardous chemicals in LASER operation, and also during LASER processing of materials. Most notable among the chemical agents representing hazard are dyes, solvents, toxic gases and LASER generated air contaminants (LGAC).

LGAC is a term used for hazardous particulate, aerosol, and gaseous contaminants produced when there is an interaction between the LASER beam and the target matter. Generation of airborne contaminants which may be carcinogenic, toxic or noxious, are mainly associated with the use of high power LASER in material processing and LASER surgery. Some optical materials used in the far IR region may also release toxic contaminants, when the incident irradiance exceeds the safe use limits. Another common air contaminant is ozone, generated by UV LASER, flash lamps and electrical discharges.

Many molecular, atomic vapour/ gas LASER use, or produce during operation, toxic, flammable, or explosive gases, such as hydrogen, chlorine, fluorine, carbon monoxide, hydrogen fluoride, hydrogen bromide, hydrogen chloride, etc. Potential hazards include leakage from the cylinders not connected to a regulator, absence of purging gas system for empty cylinder shut off and change out, incorrect labeling of the gas cylinders and gas lines, and improper storage of the gas cylinders. Other adverse outcomes of gas cylinder mishandling include asphyxiation, toxic, flammable, and corrosive gas spills/ releases; or explosion.

Many LASER dye molecules are polycyclic aromatic hydrocarbons (PAH), which are toxic and /or carcinogenic materials. Dye powder can easily become airborne and possibly get inhaled and/ or ingested. Solvents used for dissolving LASER dyes, such as ethyl and methyl alcohol, dimethyl sulfoxide, etc., apart from being flammable, may also be skin irritant, narcotics, or toxic.

3.3.4 Cryogenic Hazards

Cryogenic fluids are used in cooling system of certain LASER, and can cause hazardous situations. As these materials evaporate, these can create oxygen deficient atmosphere and an asphyxiation hazard. Cryogenic fluid containers may pose explosion hazards when ice collects in the outlet neck, valves, or connectors that are not specifically designed for use with cryogenic fluids. Condensation of oxygen in liquid nitrogen presents a serious explosion hazard, if the liquid oxygen comes in contact with any organic material.

3.3.5 Noise

High power repetitive pulsed LASER, ablation of material, when such LASER are focused on the target, and fast HV discharges generate high intensity of noise.

3.4 Non-beam Radiation Hazards

Non-beam radiation is incoherent electromagnetic radiation, usually at wavelength(s) different from that of the LASER beam, that is generated by LASER components (collateral radiation), or is from the plasma generated during the interaction of LASER with materials in various forms (plasma radiation).

3.4.1 Collateral Radiation

Collateral radiation usually refers to X-rays, UV, radio frequency emissions, or even the bright fluorescence generated during LASER operation from discharges in plasma tubes, flash lamps, optically excited fluorescence, etc. Collateral radiation is also generated as a result of the operation of any high voltage electronic switching components necessary for the operation of LASER. For example, X-rays may be generated when electrons are accelerated, under the influence of a difference in potential, and then rapidly decelerated in a material. One such source of collateral X-rays is the thyratron switch used in the electrical circuit of pulsed gas discharge LASER. Generally, the protective housing of the LASER, or such accelerated electron devices, attenuates X-rays so that accessible exposures are within natural background of ionizing radiation. However, if the protective housing is removed, then it is necessary to evaluate X-ray exposure with a radiation survey meter.

Personnel may get exposed to high frequency electromagnetic radiation produced in RF-excited LASER, or generated from HV Q-switches, or thyratrons which rapidly switch high currents. This can be particularly hazardous for persons, using body-worn or implanted medical electronic equipment.

3.4.2 Plasma Radiation

Plasma radiation, also called plume radiation, is generated when the beam from a powerful LASER interacts with matter. Typically, this involves CW or pulsed emissions from Class 4 LASER, such as CO_2, Nd:YAG, Nd:glass, Excimer, or COIL (Chemical oxygen iodine LASER). Generally, plasma is a source of broadband optical radiation. Plasma emissions from LASER welding and cutting operations have sufficient UV to be of concern for long-term eye and skin exposure.

With the rapidly growing use of extremely high peak power LASER, with output powers in the terawatt to peta-watt range, it has become necessary to take cognizance of the secondary radiation that may be emitted when these LASER are tightly focused on materials. These may range from emission of energetic X-rays to production of high energy particles, including electrons, ions, protons and neutrons.

3.5 Hazard Enhancement by Human Factors

Human factors, well recognized as a cause of work related accidents, may enhance LASER beam or non-beam hazards. These factors include:

(a) Neglect of ergonomic principles in setting up LASER systems – such as poor layout design and lack of space, resulting in a congested environment, making operating procedures difficult to perform.

(b) Personal aspects, such as job capability, alertness and attitude to safety, all of which can be affected by high levels of prolonged stress.

(c) Lack of adequate appreciation of the relatively new LASER safety requirements, and organisational approach towards safety vis-à-vis achievement pressures.

4. BASIC APPROACH FOR LASER HAZARD EVALUATION AND RISK ASSESSMENT

4.1 Introduction

In general, one perceives the hazards of a LASER to be related to its output power. However, the LASER induced injury depends not only on the output power, but also on several other factors, such as wavelength, temporal characteristics (continuous or pulsed), duration of exposure, source size, etc. The damage mechanisms, such as photochemical and photo-thermal, depend on the wavelength of LASER. Thus, the hazard classification should be based on the risk potential to the eye or skin under the LASER exposure assessed in realistic conditions. Due to the large variety of LASER, and the complexities of LASER hazard evaluation, a scheme of LASER classification has been conceived to grade the risk. The purpose of the LASER hazard classification discussed in this document is to familiarize the users, developers and manufacturers with the methodology of hazard classification, enabling them to assess the risk, and take appropriate safety measures, given in this document.

The objective of hazard evaluation is to classify the potential risk into a few broad categories so that minimum pre-defined control measures for each category, when applied, will provide adequate safety. It is important to introduce two types of safety limits which are commonly used for LASER hazard evaluation: Maximum Permissible Exposure (MPE) to assess the risk of exposure to human being based on injury threshold evaluation, and Accessible Emission Limits (AEL), to grade the hazard potential of the emissions from a LASER/ LASER system to cause injury. Based on these concepts of LASER safety limits, LASER are classified into four fundamental risk groups and a few sub classes in accordance with the internationally accepted standards, such as ANSI-Z-136.1-2007and IEC-60825-1:2007.

The procedure for hazard classification of a LASER/ LASER system requires application of a complex set of rules and specifications, to compute the appropriate MPE, as well as various measurement conditions to evaluate the accessible output from the LASER / LASER system. A complete LASER hazard evaluation requires additional aspects to be considered, e.g. the environment in which the LASER is used, and the personnel who may use, or be exposed to, the LASER radiation. The entire procedure can be demanding, putting off even regular users from correctly evaluating the hazard, and taking appropriate control measures. Table 4.1 provides the list of the various LASER hazard classes.

As a first step, therefore, this Section introduces the basic concepts and terminologies used in hazard classification of LASER, hazard evaluation and risk assessment for the general LASER user. Tables 4.2 and 4.3, at the end of this Section provide a ready reference to guide the classification of the commonly used LASER. The detailed procedures for determining MPE, hazard classification and total hazard evaluation are addressed in the subsequent Sections, for the LASER safety experts, or the designated LASER Safety Officer (LSO). The requirements and responsibilities of the LSO are addressed, in detail, in Section 6. However, the rationale underlying the development of the complex set of rules and specifications are diverse and extensive, and will not be addressed in this document.

4.2 Maximum Permissible Exposure (MPE)

Central to the concept of LASER hazard evaluation is the safe exposure limit, or MPE. Exposure limits for LASER radiation for the eye and skin are developed by International

Commission on Non-Ionizing Radiation Protection (ICNIRP), based on the extensive reviews of available injury threshold data and application of appropriate ‘reduction’ or ‘safety’ factors, to insure that there is no realistic chance of injury at the exposure limit, which, however, is not unnecessarily restrictive to deter safe use of the LASER. The safety factor is based upon a thorough review of uncertainties, experimental details including delay between the exposure and the examination, potential error sources, the differences between the experimental models and human beings, the state of knowledge of injury mechanism and biological sequelae. In the USA, LASER exposure limits are developed independently through a similar procedure. These exposure limits are almost identical, and are adopted for developing guidelines and standards by various organisations, using different terminologies and modes of presentation. While ICNIRP uses the term ‘exposure limit’, IEC and ANSI documents refer to MPE, some European documents refer to ‘exposure limit values’, or simply ‘limit values’, and the other US documents use ‘threshold limit value’ (TLV).

The term MPE, specified separately for ocular or skin injury and adopted in this document, is thus an upper limit of the LASER radiation level, which an unprotected person of normal health may be exposed to, with no realistic probability of adverse biological changes to the eye or skin, immediately, or at a later time. As explained above, the MPE values are based on the best available information and assessment, and should be considered as guidance for applying exposure control. Exposure at MPE levels, although not dangerous, may cause discomfort to the eye, or skin. Therefore, as a general practice, it is always recommended to maintain exposure levels sufficiently below the MPE.

MPE may be expressed in terms of irradiance (W/cm^2) or radiant exposure (J/cm^2), sometimes represented by MPE:E and MPE:H, respectively. These are equivalent descriptions, with the ‘applicable’ exposure duration relating the two quantities (Energy = Power × Time), consistently, with due consideration to the temporal variation of the radiation power during the exposure ‘time’. For hazard evaluation, the power quantities are usually used for quantification of the exposure to continuous sources. However, it may be used for maximum power levels in a pulse (peak power), particularly, for short duration pulses with relatively long intervals. The ‘energy quantities’ are usually used for quantification of exposure to pulsed sources. However, energy quantities are also used for continuous exposure to CW or repetitive pulsed sources, when photochemical damage of the skin or the eye is possible, since the effect of photochemical damage is additive over time. For the continuous exposure, with varying irradiance or radiance level, the corresponding energy quantity of the exposure is determined by temporal integration over the specified exposure duration.

The biological hazards, and as a consequence, the MPE values for the eye or skin are dependent upon various factors: wavelength or wavelength(s) of radiation, exposure duration, the temporal and spatial characteristics of radiation source, nature of the tissue exposed, and for visible and near-infrared radiation in the range 400 to 1400 nm, on the size of the retinal image, the last parameter, in turn, depends on angular subtend of the source at the eye. Many of these factors are interdependent. In order to prescribe a rule-based approach to determine MPE, these parametric dependencies are accounted for, by applying various multiplicative correction factors to a basic set of MPE values, or formulae, available in tabular form in ICNIRP guidelines (vide Annexure I), for various ranges of the parameters and applicable conditions. Because of significant differences between the nature of photochemical and thermal damage, dual MPE are prescribed, depending on the wavelength of the radiation and applicable exposure duration. The applicable exposure duration itself is dependent on the wavelength and the nature of the exposure [intended or unintended (accidental) exposure, intra-beam exposure, or exposure to diffuse radiation]. For example, for accidental intra-beam viewing of CW visible LASER radiation (400– 700 nm) by a person in normal health, and where purposeful staring is not intended or anticipated, the exposure time is limited to the aversion response time of 0.25 s.

4.3 LASER Hazard Classification

The hazard classification system uses the concept of AEL. AEL for a hazard class is the maximum total power, or energy of the radiation over a specified duration that can be emitted from a LASER of a particular class. The capability to cause injury is thus determined through a comparison of the measured or estimated 'accessible emission' or 'accessible radiation', from the LASER with the AEL for each class in equivalent units. A LASER is assigned to a particular class when the measured emission level exceeds the AEL for all the lower LASER classes, but does not exceed the AEL for the Class assigned. This is a critical step in hazard assessment, as the class determines the administrative and engineering control measures required to ensure safe operation. In turn, this has an impact on the ability to utilise the LASER for the intended task, and also a financial impact on manufacturing, installation, and field use of the LASER.

The first step in evaluating the hazard of a specific LASER / LASER system is to determine the MPE and calculate the AEL for the least hazardous class, defined as Class-1, according to the expression:

Class 1 AEL = MPE x (area of limiting aperture) …….(eqn. 4.1)

$$\text{Class 1 AEL} = \text{MPE}\,\frac{\pi D_f^2}{4}\,\text{watts} \qquad \text{…….(eqn. 4.2)}$$

Where D_f, the diameter of a specified 'Limiting Aperture', is dependent on factors, such as LASER wavelength and exposure duration, and are based on physical factors such as the fully dilated pupil size (7mm), involuntary movement of the eye and body parts, heat conduction and scattering of radiation in tissue, which tends to increase the affected area and reduce the probability of injury. AEL are expressed as a radiant power (W), for CW LASER, or radiant energy (J), for pulsed LASER. The notations use to represent these limits are AEL:Q and AEL:**Φ** in terms of energy and power respectively.

Next, one measures or uses the specifications of the system, and calculates the 'worst case' maximum exposure that an unprotected person might experience while the system is being operated, and check whether it is less than the Class-1 AEL. This procedure again requires the use of specified measurement apertures and exposure conditions. A systematic procedure (vide Section 5) is then applied to determine the class of the LASER.

4.4 Considerations for LASER Hazard Classification

Table 4.1 provides an outline of the different classes that illustrates the hazard potential of LASER belonging to various classes, whereas the definition of the class limits, and the detailed procedure for classification are provided in Section 5. At all stages of LASER hazard classification, it is necessary to note that any LASER system, if operated and used inside a protective housing, may suitably be downgraded. The converse situation, enabling access to an embedded LASER in an otherwise lower class LASER system, would require reassessment of its hazard classification.

This outline does not provide a prescription for classification of LASER which is given in Section 5. Tables 4.2 and 4.3 provide the accessible power / energy levels computed in accordance with such prescription, at which the crossover from a lower class to a higher class occurs for many of the commonly used LASER. These Tables assist the general user in taking the first step in assessing the hazard of LASER.

TABLE 4.1: OUTLINE OF LASER HAZARD CLASSES

Class	Description
Class 1 LASER System	• Very low power LASER, enclosed, encapsulated or embedded LASER of higher Class with adequate engineering control measures, to ensure that access to the higher Class LASER beam is not reasonably likely. • Safe under reasonably foreseeable conditions of operation and use, including intra-beam viewing, with or without optical aids. • The LASER systems in this class are not capable of causing damage to the eye or skin, and, therefore, exempted from any control or surveillance.
Class 1M LASER System	Low power, large size collimated beam, or highly divergent LASER • Safe under reasonably foreseeable conditions of operation and use, excluding optically-aided intra-beam viewing. • Compared to Class 1 sources, Class 1M sources may carry higher powers, but low intensities, as they are either diverging or collimated with a large diameter, so that the energy carried through the area of a pupil is lower than Class 1 limits. • Like any Class 1 source, these are harmless in standard conditions of use, but can present a danger when an optical instrument is used in the beam trajectory which may collimate a diverging beam, or focus a collimated source, so that the intensity at the eye increases. • This classification would be applicable for emission wavelengths between 302.5 and 4000 nm, outside which the commonly used optical components have negligible transmission.
Class 2 LASER System	Visible region (0.4 to 0.7 µm), low power LASER • Eye protection is generally provided by aversion response including blink reflex, even with optical instruments in the beam trajectory. • The exposure is considered to be hazardous, if viewed for more than 0.25 s, or repeatedly.
Class 2M LASER System	• Visible region (0.4 to 0.7 µm), low power LASER, with larger collimated beam, or divergent beam, as compared to Class-2 LASER. • Eye protection is generally provided by the aversion response, including blink reflex, only for unaided viewing. • Unsafe if viewed using optical aids, or if optical instruments are inserted in the beam trajectory.
Class 3 LASER System	Medium power LASER potentially hazardous when viewed directly or after specular reflection (intra-beam viewing). • The Class 3 systems are further divided into two sub classes as given below.

Class	Description
Class 3R	Potentially hazardous for intra-beam viewing either directly or after specular reflection, particularly when the eye is sufficiently focused and stable. However, the probability of injury upon exposure as defined above, is small. • The LASER beam does not pose any fire hazard, or hazard due to diffuse reflection. • The LASER beam is not hazardous to skin.
Class 3B	• Normally hazardous for intra-beam viewing either directly or after specular reflection. (Power is greater than the Class 3R LASER), but is not a diffuse reflection hazard or fire hazard. • For Class 3B visible LASER viewing of diffuse reflections is considered safe for a minimum viewing distance of 13 cm between the screen and the cornea and a maximum viewing time of 10 s, else the diffuse reflection exposure needs to be compared with the applicable MPE. • It is also not a hazard to skin, except at the focus.
Class 4 LASER System	High Power LASER hazardous for direct, specular and diffuse reflection, and pose Fire Hazard • The direct and specularly reflected beam is hazardous to the eye and skin, and constitute fire hazard. • The diffuse reflection is also potentially hazardous to the eye and skin, and may also initiate fire in certain conditions. • Additionally, the beam may produce LASER-generated air contaminants (LGAC) and dangerous plasma radiation

4.5 Nominal Hazard Zone (NHZ)

It is often necessary in some applications where open beams are required, (e.g., industrial processing, field applications, various R&D laboratory applications) to define the area where the possibility exists for potentially hazardous exposure. This is done by determining the Nominal Hazard Zone (NHZ). The NHZ describes the boundaries of the minimal space around and encompassing the LASER/ LASER system, outside which the level of direct, reflected, or scattered radiation during normal operation does not exceed the appropriate MPE [see Fig.4.1].

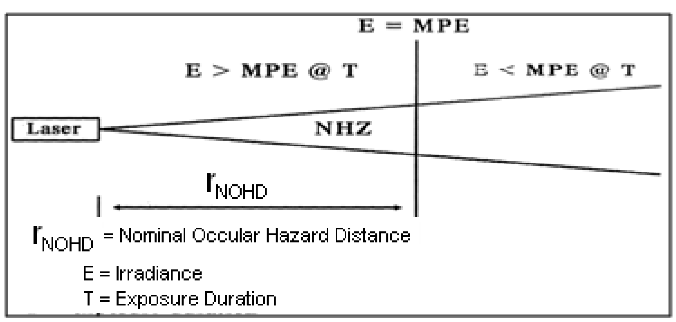


Figure 4.1
NOMINAL HAZARD ZONE FOR VIEWING LASER BEAM

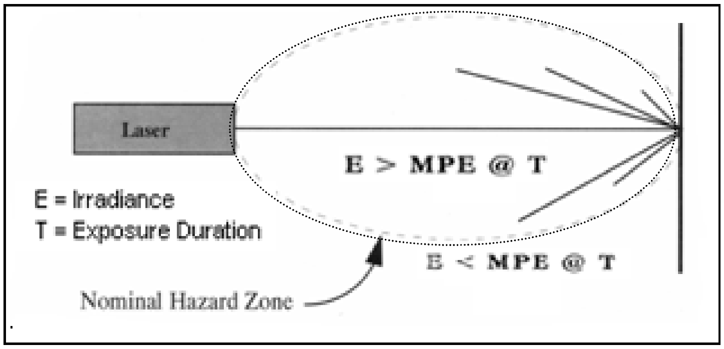


Figure 4.2
NOMINAL HAZARD ZONE FOR VIEWING DIFFUSE REFLECTION

The nominal ocular hazard distance (NOHD), or r_{NOHD}, is the distance beyond which an unprotected individual may be exposed to intra-beam viewing, without injury, provided optical devices are not used. The basic method for evaluating the NOHD is to calculate the maximum irradiance that an unprotected eye might experience while the system is operating, and check whether it is less than MPE. For this, different exposure conditions, such as accidental viewing, operations during alignment, reflections from tools, or safety goggles, etc., are to be considered. The NHZ may be determined by the information supplied by the LASER/ LASER system manufacturer, by measurement, or by using the appropriate LASER range equation, or other equivalent assessment, as discussed, in detail, in Section 5. While determining the hazard distances and hazard zones, it is necessary to take into account the presence of opaque obstacles that may terminate the LASER beam.

The purpose of an NHZ / NOHD evaluation is to define that region where control measures are required. Thus, as the scope of LASER uses has expanded, the classic method of controlling LASER by enclosing them in an interlocked room has become limiting, and, in many instances, can be an expensive over–reaction to the real hazards present.

It is generally necessary to determine the NHZ for Class-3B and Class-4 LASER. The LASER Safety Officer (LSO) shall ensure that consideration is given to direct, reflected and scattered radiation in the establishment of boundaries for the LASER control area. The LSO may declare the LASER use area as the NHZ in lieu of calculating all the possible NHZ distances, such as in the case of a dedicated LASER use room. Control measures are required within the NHZ.

The NOHD can be short for divergent beam LASER and the NHZ is, therefore, limited close to the emitting aperture. However, for collimated beam LASER, the NOHD may be very large. Particularly, for Class 1M or 2M LASER products used in situations where the use of magnifying aids, such as binoculars, cannot be precluded, it is necessary to determine an extended nominal ocular hazard distance (ENOHD) and extended hazard zone.

4.6 Hazard Evaluation and Risk Assessment

A comprehensive analysis of LASER hazards involves an assessment of the environmental and the personnel factors, which are closely related with an assessment of the risk. A hazard is any condition with the potential for causing harm. While the harm that could be caused by a hazard is normally taken to mean personal injury, it can also cover financial loss. In the context of LASER safety, hazard evaluation includes LASER radiation hazard, associated non-beam hazards (see Section 3) and any other additional hazards, arising from the reasonably foreseeable use, misuse, or failure, of the LASER, its support equipment, and its application process. Assessment of risk is based upon probabilistic analysis, and involves two factors - the likelihood of occurrence of harm and the severity of the harm, if caused. Nearly all the activities involve some amount of risk. It is not always possible to remove all risks, and the approach is to reduce the risk to acceptable levels, using hazard control measures. Thus, risk assessment involves application of judgment, and needs to be carried out with due care, so that its conclusions stand up to scrutiny. Recent literature vide S. No. 16 in Bibliography has dealt with quantification of the probabilistic aspects of risk assessment in detail, which is likely to be included in the forthcoming revision of IEC 60825-1.

The objective of LASER hazard evaluation and risk assessment is to enable the informed user or the LSO, to select an appropriate mix of control measures that is effective and sufficient, but not unreasonably restrictive. The process of hazard evaluation and risk assessment, selection and application of control measures, to reduce the risk to acceptable levels, is an iterative and integrated process. At present, a structured approach for comprehensive hazard evaluation and risk assessment for hazard control of LASER and LASER systems is based upon documented procedures that use forms and checklists, to record and audit various aspects of the system, its application, the hazards, and the controls. The overall procedure can be complex owing to the unique characteristics that the beam-hazard can persist at long distances from the source. In addition, there are a variety of non-beam hazards associated with LASER, which can be more frequent causes of accidents. A step by step procedure for implementation of the structured approach is provided in sub section 7.4, Section 7.

The metrics for quantitative LASER hazard evaluation and the concepts of comprehensive hazard identification have been introduced in this Section. The detailed procedures and conditions for assessment of the metrics, and subsequent hazard classification, are addressed in Section 5.

TABLE 4.2
TYPICAL LASER CLASSIFICATION FOR CONTINUOUS WAVE (CW) POINT SOURCE LASER

Wavelength Range (µm)	LASER Type	Wavelength (µm)	Class 1* (W)	Class 2 (W)	Class 3R (W)	Class 4 (W)
Ultraviolet 0.180 to 0.280	Neodymium: YAG (Quadruple)	0.266	≤ 9.6 x 10^{-9} for 8 hours	None	> Class 1 but ≤ 0.5	> 0.5
	Argon	0.275				
Ultraviolet 0.315 to 0.400	Helium-Cadmium	0.325				
	Argon	0.351, 0.363	≤ 3.2 x 10^{-6}	None	> Class 1 but ≤ 0.5	> 0.5
	Krypton	0.3507, 0.3564				
Visible 0.400 to 0.700	Helium-Cadmium	0.4416 only	≤ 4 x 10^{-5}			
	Argon (Visible)	0.457	≤ 5 x 10^{-5}			
		0.476	≤ 1 x 10^{-4}			
		0.488	≤ 2 x 10^{-4}			
		0.514				
	Krypton	0.530				
	Neodymium:YAG (Doubled)	0.532	≤ 4 x 10^{-4}			
	Helium-Neon	0.543		> Class 1	> Class 2	
				but	but	>0.5
	Dye	0.400- 0.500	≤ 0.4C_B x 10^{-4}	≤ 1 x10^{-3}	≤ 0.5	
	Helium-Selenium	0.460 - 0.500				
	Dye	0.550 – 0.700				
	Helium-Neon	0.632				
	InGaAlP	0.670	≤ 4 x 10^{-4}			
	Ti:Sapphire	0.350 – 0.5				
	Krypton	0.6471, 0.6764				
Near Infrared 0.700 to 1.40	GaAlAs	0.780	≤ 5.6 x 10^{-4}			
	GaAlAs	0.850	≤ 7.7 x 10^{-4}			
	GaAs	0.905	≤ 9.9 x 10^{-4}			
	Neodymium:YAG	1.064	≤ 1.9 x 10^{-3}			
	Helium-Neon	1.080	≤ 1.9 x 10^{-3}			
		1.152	≤ 2.1 x 10^{-3}			
	InGaAsP	1.310	≤ 1.5 x 10^{-2}			
Far Infrared 1.40 to 10^3	InGaAsP	1.550			> Class 1	
	Holmium	2.100		None	but	> 0.5
	Erbium	2.940			≤ 0.5	
	Hydrogen Fluoride	2.600- 3.00	≤ 9.6 x 10^{-3}			
	Helium-Neon	3.390 only				
	Carbon Monoxide	5.00 – 5.50				
	Carbon Dioxide	10.6				
	Water Vapour	118	≤ 9.5 x 10^{-2}			
	Hydrogen Cyanide	337				

* Assumes no mechanical or electrical design incorporated into LASER system to prevent exposures from lasting up to T_{max} = 8 hours (one workday); otherwise the Class 1 AEL could be larger than tabulated (Reproduced from ANSI-Z13.1-2007).

TABLE 4.3
TYPICAL LASER CLASSIFICATION FOR SINGLE PULSE POINT SOURCE LASER

Wavelength Range (µm)	LASER Type	Wavelength (µm)	Pulse Duration (s)	Class 1 (J)	Class 3B (J)	Class 4 (J)
Ultraviolet 0.180 to 0.400	Excimer (ArF)	0.193	20 x 10^{-9}	≤ 2.4 x 10^{-5}		
	Excimer (KrF)	0.248	20 x 10^{-9}	≤ 2.4 x 10^{-5}		
	Neodymium:YAG Q-Switched (Quadrupled)	0.266	20 x 10^{-9}	≤ 2.4 x 10^{-5}	> Class 1 but	>0.125
	Excimer (XeCl)	0.308	20x 10^{-9}	≤ 5.3 x 10^{-5}	≤0.125	
	Nitrogen	0.337	20 x 10^{-9}	≤ 5.3 x 10^{-5}		
	Excimer (XeF)	0.351	20 x 10^{-9}	≤ 5.3 x 10^{-5}		
Visible 0.400 to 0.700	Rhodamine 6G (Dye LASER)	0.450 – 0650	1 x10^{-6}			
	Copper Vapour	0.510, 0.578	2.5 x10^{-9}	≤ 1.9 x 10^{-7}		
	Neodymium:YAG (Doubled) (Q-switched)	0.532	20 x 10^{-9}		> Class 1 but	> 0.03
	Ruby (Q-switched)	0.6943	20x 10^{-9}		≤ 0.03	
	Ruby (Long Pulse)	0.6943	1 x10^{-3}	≤ 3.9 x 10^{-6}		
Near Infrared 0.700 to 1.4	Ti:Saphire	0.700 – 1.00	6 x 10^{-6}	≤ 1.9 x 10^{-7}		
	Alexandrite	0.720 – 0.80	1 x 10^{-4}	≤ 7.6 x 10^{-7}	>Class 1 but ≤ 0.033*	> 0.033**
	Neodymium:YAG (Q-switched)	1.064	20 x 10^{-9}	≤ 1.9 x 10^{-6}	>Class 1 but ≤ 0.125	> 0.125
Far Infrared 1.400 to 10^3	Erbium:Glass	1.540	10 x 10^{-9}	≤ 7.9x 10^{-3}		
	Co:Magnesium Fluoride	1.8- 2.5	80 x 10-6	≤ 7.9x 10^{-4}		
	Holomium	2.10	250 x 10^{-6}	≤ 7.9x 10^{-4}	> Class 1	> 0.125
	Hydrogen Fluoride	2.60- 3.00	0.4 x 10^{-6}	≤ 1.1 x 10^{-4}	but	
	Erbium	2.940	250 x 10^{-6}	≤ 5.6 x 10^{-4}	≤ 0.125	
	Carbon Dioxide	10.6	100 x 10^{-9}	≤ 7.9 x 10^{-5}		
	Carbon Dioxide	10.6	1 x 10^{-3}	≤ 7.9 x10^{-4}		

* Assuming that both eye and skin may be exposed i.e., 1.0 mm beam (area of limiting aperture = 7.9 x 10^{-3})

** Class 3B AEL varies from 0.033 to 0.480 J corresponding to wavelengths that may vary from 0.720 to 0.8 µm

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5. PROCEDURE FOR EVALUATION AND CLASSIFICATION OF LASER HAZARD

5.1 Introduction

The basic concepts of LASER hazard evaluation, including some of the important parameters, such as MPE, AEL & NHZ, used for classification and total evaluation of the hazards, are discussed in Section 4. This Section covers the technical details and procedures for determining the hazard evaluation parameters, LASER exposure parameters, the Hazard Class for different types of LASER, and for total hazard evaluation. These procedures are illustrated through solved examples in Annexure IV.

The hazard classification and evaluation procedure requires the level of human being exposure to the radiation emitted by a LASER to be compared with the safety limits, viz. the AEL or MPE. This requires an assessment of the output beam from the LASER, using its characteristics, and applying appropriate estimates, such that an ‘effective exposure level’ is obtained, which would represent its realistic hazard potential. The ‘effective exposure levels’ are also referred to as ‘accessible emission levels’ or ‘accessible exposure levels’.

For example, the accessible emission level should be determined by measurement, or computation using output beam specifications, at the positions at which human being presence might be anticipated under reasonably foreseeable conditions, and next, where the highest level of exposure might occur. This maximum level of exposure may not occur immediately adjacent to the emission aperture of the equipment. Also, careful attention is necessary to determine a ‘limiting aperture’ that should be used to assess the amount of the LASER beam radiant power / energy passing through the aperture as a measure of the realistic hazard potential. Similarly, while dealing with large visible LASER sources, the angle subtended by the source at the eye would modify the assessment to account for a larger image size on the retina than that with highly collimated sources. The exposure levels, e.g., the radiant exposure or average power measurements (or estimates), taken at specified distances from the LASER exit aperture through a ‘measurement aperture’, after accounting for source size, in accordance with the international guideline prescriptions, is called effective power or effective energy.

Classification is determined by comparing these effective power / energy measurements/ estimates, and not the total emitted power or energy of the LASER, with the AEL. Viewing a LASER beam with optical aids (other than ordinary eye-glasses or contact lenses) may increase the risk, and therefore, the hazard classification must consider the potential use of optical aids, which would require different measurement aperture to assess the realistic hazard. Thus, a complete hazard evaluation of a LASER / LASER system requires the evaluation of many parameters and classification. The first step in such assessment is the determination of MPE.

5.2 Determination of Maximum Permissible Exposure (MPE)

5.2.1 Ocular MPE:

Table AN-I.1 of Annexure-I gives the MPE for the eye under the condition of direct exposure to ‘single point source’ LASER beams. The MPE are categorised as per broad wavelength regions and exposure durations, as well as for types of injuries – photochemical and thermal in certain wavelength regions. Wherever the applicable conditions give rise to more than one MPE, e.g. photochemical and thermal, the lower value is to be used for hazard classification.

Table ANI.1 and the accompanying notes also specify various multiplicative correction factors that represent biological effectiveness of various source parameters.

5.2.1.1 Evaluation Parameters

The various evaluation parameters, applicable conditions, rules and restrictions required to compute the ocular MPE for a given LASER / LASER system, are discussed below in items (a) to (d). It is emphasised that the parameters play interdependent roles in determination of MPE and subsequent evaluation of the hazard. Thus, the criteria discussed below should not be applied in isolation, but in conjunction wherever applicable.

(a) Wavelength (λ)

For single-wavelength LASER, the procedure is relatively straightforward, and the MPE values can be obtained from Table AN-I.1, along with the applicable correction factors. Both photochemical and thermal MPE is determined depending on the wavelength and 'applicable exposure duration' (see below), which may be further modified by source size considerations. For multiple-wavelength emission the hazard should be considered to be additive on a proportional basis of spectral effectiveness, provided that:

(i) For pulsed sources, the emissions at different wavelengths are simultaneous.
(ii) For CW sources, the applicable exposure durations are within one order of magnitude.
(iii) The wavelengths belong to the spectral regions for additive effects shown in Table AN-I.7.

In other situations the hazards should be assessed separately with caution, applying additional considerations stated below.

(b) Exposure duration (t)

The length of time of exposure and the guidelines for determining the corresponding MPE are specified as follows, for different exposure conditions:

(i) Single-Pulse Exposure: Pulse duration at half power points, or commonly known as Full Width at Half Maximum (FWHM), for hazard assessment of exposure to a single pulse from a repetitive pulse LASER (Pulse Repetition Frequency, PRF $\leq$ 1 Hz), or, a single-pulse LASER. The corresponding MPE is the Single-Pulse MPE.
(ii) [400 nm $\leq \boldsymbol{\lambda} \leq$ 1400 nm], < 100 fs exposure: Single Pulse MPE for pulse duration of less than 100 fs in this region, not available because of lack of biological data, should not exceed the irradiance MPE for 100 fs duration, which should be assigned to the peak of the pulse.
(iii) [$\boldsymbol{\lambda}$ < 400 nm, > 1400 nm], < 1 ns exposure: In this wavelength region, the single-pulse MPE for pulse duration < 1 ns, also not available, should not exceed the irradiance MPE for 1 ns duration, which should be assigned to the peak of the pulse.
(iv) Limiting Exposure Duration (T_{max}) given in Table AN-I.3, for CW or repetitive pulse LASER, is the applicable maximum time of direct exposure under

reasonably foreseeable conditions, to be used, if not specified by the design or intended use of the LASER, or if indeterminate from the given conditions. As seen, T_{max} can take various values, such as the aversion response time of 0.25 s for CW visible LASER when purposeful staring into the beam is not intended or anticipated. On the other hand, for exposure in the near infrared (700-1400 nm) region a T_{max} of 10 s provides adequate assessment of the hazard.

(v) [400 nm ≤ $\boldsymbol{\lambda}$ ≤ 600 nm], Point Source Exposure, Dual MPE: The Table provides dual MPE for photochemical and thermal effects on the retina. Thermal MPE apply for exposure duration t, 10 s < t < T_1, where T_1 is computed in accordance with definition in Table AN-I.1, while Photochemical MPE apply for $t \geq T_1$. T_1 is thus a wavelength-dependent exposure duration breakpoint beyond which thermal MPE are replaced by photochemical MPE.

(vi) [400 nm ≤ $\boldsymbol{\lambda}$ ≤ 600 nm], Extended Source Exposure, Dual MPE: Both photochemical and thermal MPE are to be determined, and the lower MPE used for hazard evaluation. For determining the thermal MPE, the extended source correction factor C_E is to be used, where necessary, to modify the point source MPE for t ≤ 10 s.

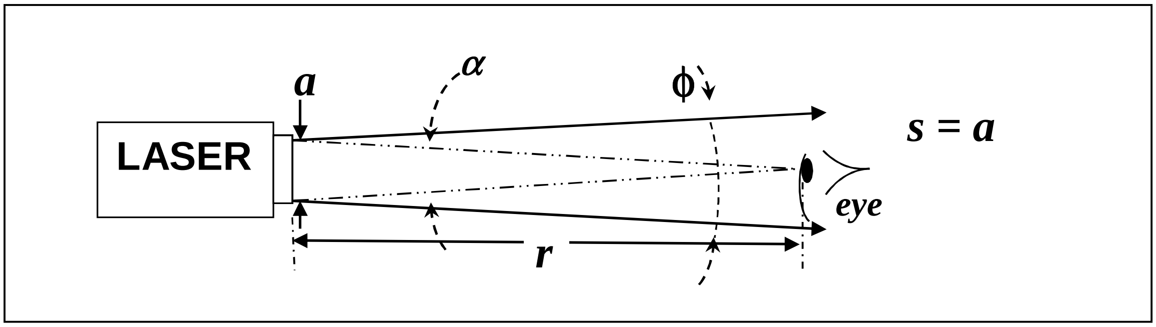
(vii) [400 nm ≤ $\boldsymbol{\lambda}$ ≤ 1400 nm], Extended Source Exposure, Thermal MPE: In this wavelength region, a second exposure duration breakpoint, T_2, is prescribed to characterise thermal injuries from extended source exposures. For exposure durations $t > T_2$, the corresponding MPE has a constant value that depends on T_2 but not on the exposure duration't'. T_2 itself changes with the source size from 10 s ($\boldsymbol{\alpha} < \boldsymbol{\alpha}_{min}$) to 100 s ($\boldsymbol{\alpha} > \boldsymbol{\alpha}_{max}$, see sub section 5.2.1.2) and is computed in accordance with its definition in Table AN-I.1.

Note: For classification evaluation, T_{max} is 30,000 s for $\lambda \leq 700$ nm, and 100 s for $\lambda > 700$ nm.[Reference: S.No.10 of Bibliography]

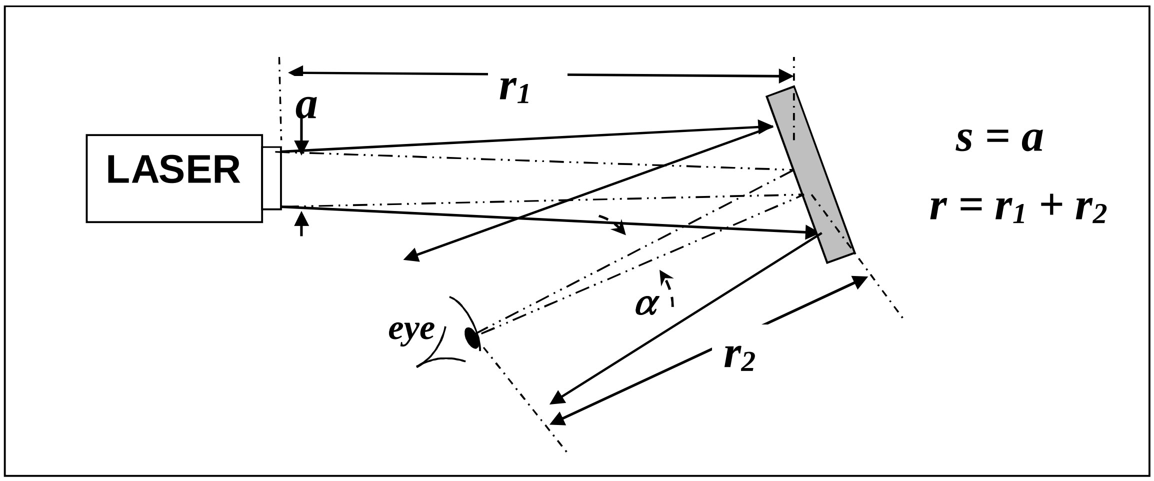
(c) Apparent Source Size – Point Source vs Extended Source (400 – 1400 nm)

For MPE calculations within the retinal hazard region (400– 1400 nm), sources are categorised as point (or small) sources, and extended sources. A source of size, S_z, measured in a direction perpendicular to the line of sight from the eye placed at a distance r from the source, subtends a plane angle $\boldsymbol{\alpha} = 2\tan^{-1}(S_z/2r)$ at the eye, referred to as the angular subtense. Figure 5.1 illustrates the angular subtense parameter under different viewing conditions. The angular subtense α should not be confused with the beam divergence ϕ. For example, the angular subtense of the sun at the earth is ~0.5^o, but the emission divergence is 360^o.

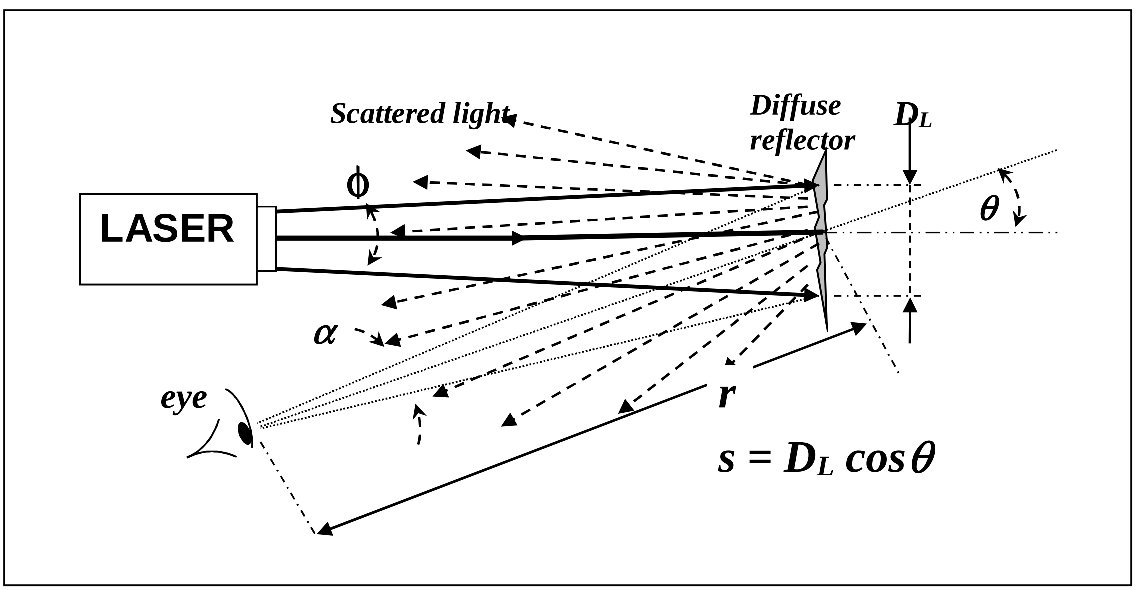
A point source is defined as the one for which, $\alpha \leq \alpha_{min}$, specified for LASER hazard evaluation as 1.5 milli-radian (mrad). Light from the 'point source' entering the pupil produces a nearly diffraction-limited retinal image of diameter less than 30 µm. An extended source is defined as the one for which $\alpha > \alpha_{min}$. As seen in Table AN-I.1, an extended source correction factor, C_E, is used to determine the thermal MPE in this wavelength region. The variation of C_E with α, increasing linearly up to a α_{max} [≈ 100 milli-radian (mrad)], for retinal LASER hazard evaluation in this wavelength range), and then as α^2, reflects the corresponding increase in retinal image size and decrease in temperature rise of the tissue. The following conditions apply for computation of α and C_E:



(a) Direct intra-beam viewing



(b) Intra-beam viewing, after specular reflection by a mirror



c) Diffuse reflection viewing

Figure 5.1
SCHEMATIC OF ANGULAR SUBTENSE UNDER DIFFERENT VIEWING CONDITIONS

(i) The angular subtense is calculated at the ‘evaluation distance’ which is the minimum accessible distance that creates the maximum hazard, but no closer than 10 cm from the LASER exit port. This condition is applicable when no optical aids are used for viewing.

(ii) When the use of viewing optics, such as binoculars, is required to be taken into account, the angle subtended by the source through the optics at the evaluation distance is to be used. The angular subtense is then increased by a factor equal to the power of the optics. For example, the angular subtense of an extended source, viewed through a binocular of magnification M, is increased by the factor M. The standard is 7 power optics, or magnification of 7, and the evaluation distance is that which creates the maximum hazard, but no closer than 200 cm.

Conditions (i) and (ii) also apply when measuring or evaluating the effective output, or accessible emission level.

(iii) For photochemical effects, extended source correction is not required. However, for retinal photochemical hazard in the 400-600 nm wavelength region, for exposure duration > 0.7 s, and for α > 11 milli-radian (mrad), the MPE is expressed in radiance and integrated radiance, averaged over a limiting cone angle, γ, specified separately in Table AN-I.1, and indicating the measurement acceptance angle (see sub section 5.3).

(iv) For non-uniform and non-symmetric extended sources, such as LASER arrays, diffuse reflections, rectangular beams, special considerations apply as follows:

(1) The sources should be considered as separate sources if the angular separation at the applicable evaluation distance is > α_{max} [100 milli-radian (mrad)]. Else, treat it as a single source.
(2) For noncircular sources, or a circular source not oriented orthogonal to the line of sight and thus subtending an apparent elliptic source, the effective diameter for angular subtense calculation is the arithmetic mean of the maximum and minimum dimensions of the apparent source. If the angular subtenses thus calculated are < α_{min}, or > α_{max}, these are replaced by the corresponding limiting values.
(3) For circular non-uniform sources, the angular subtense is determined using the separation between the 1/e of peak irradiance points.

(d) Limiting Aperture Diameter (D_f)

Table AN-I.1 refers to ‘aperture sizes’ and ‘limiting apertures’ in the column titled ‘Restrictions’, in accordance with the format of ICNIRP guidelines. The limiting aperture diameter is the maximum diameter of a circle over which the irradiance and radiant exposure are averaged for the purposes of hazard evaluation and classification. The ‘averaged’ MPE thus obtained with effectively uniform or homogeneous profile, when multiplied by the area of the applicable limiting aperture, provides the Class-1 AEL. ICNIRP uses the term ‘averaging apertures’, while IEC and ANSI use the term limiting aperture. The aperture sizes, varying with the exposure duration and wavelength, are related to the biological parameters, such as pupil size and eye movement. Apart from the specifications for limiting apertures in Table AN-I.1, an updated list applicable under different conditions is provided in Table AN-I.4.

5.2.1.2 Repetitive exposure to Pulsed, or Modulated LASER

Several commonly used LASER produce repetitive pulsed outputs. The hazard evaluation of these LASER requires assessment of three potential sources of injury: thermal injury from individual pulses, heat build-up or cumulative photochemical effect produced by the time averaged exposure of all pulses during the applicable exposure duration, and lastly, the pulse-cumulative thermal effects of otherwise sub-threshold pulses. Accordingly, three rules are applied that define three separate MPE as discussed below:

Rule 1: Single-pulse MPE

The exposure from ***any*** single pulse in a train of pulses shall not exceed the MPE for a single pulse of that pulse duration.

Rule 2: Average power MPE for thermal and photochemical hazards

The average exposure from any group of pulses delivered in time T shall not exceed the MPE for a single pulse of exposure duration T. This rule tests whether a CW equivalent exposure of duration T, with a constant radiant power equal to the average power of the train, is below the exposure limit. Both thermal and photochemical limits are tested separately, and the most conservative limit is taken for comparison with the MPE computed by the other rules. Application of this rule requires careful analysis, to determine the worst case average power over a variety of intervals in the case of pulsed LASER that produce groups or 'bursts' of LASER pulses at regular or erratic intervals. The Q-switched, mode-locked Nd:YAG LASER is a typical example where the output may consist of groups of a few numbers of 100 ps pulses, separated by about 10 ns, under an envelope of about 100 ns, with the group PRF of 10 Hz (see Figure 5.2).

Rule 3: Multiple-pulse MPE for thermal hazards

The exposure from any single pulse, within a group of pulses (each separated by at least t_{min}), shall not exceed the single-pulse MPE (for pulse duration $t \geq t_{min}$) multiplied by a multiple-pulse correction factor C_p (= $n^{-0.25}$, where n is the number of pulses delivered in the exposure duration T). Rule 3 applies only to MPE for thermal injury.

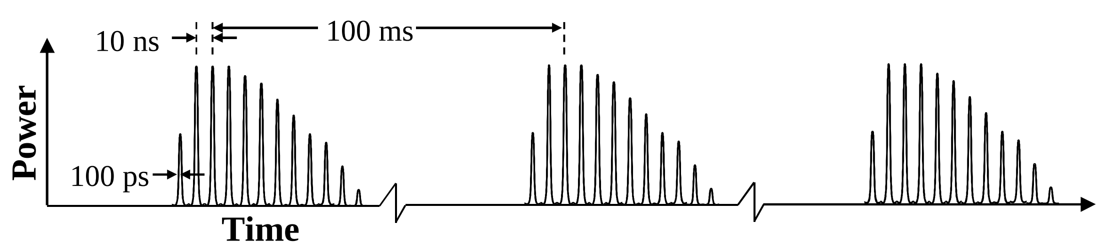


Figure 5.2

SCHEMATIC OF COMPLEX REPETITIVE PULSE TRAIN PRODUCED BY A REPETITIVE Q-SWITCHED MODE-LOCKED LASER, SHOWING GROUPS OF PULSES.

5.2.1.3 Criteria for Assessment of Repetitive Pulse MPE

The following conditions apply for repetitive pulse MPE calculations:

(a) Rule 3 is applicable to individual pulses, or a group of pulses of duration shorter than 0.25 s.

(b) For application of Rule 3, special conditions are prescribed based on the 'thermal confinement' duration, t_{min}, during which heat flow away from the exposed site is small. Exposure to individual pulses or a group of pulses within a duration $T < t_{min}$, (or, if the separation between the pulse structures $< t_{min}$) may be treated as exposure to a single pulse of duration T. t_{min} itself varies significantly by the wavelength range (see Annexure I, Table AN-I.6).

(c) Repeated UV exposure (180 – 400 nm): While all the three rules apply for determining thermal MPE, for determining photochemical MPE, only Rules 1 and 2 are applied with the condition that repetitive exposures are to be added (for determining photochemical MPE) over a 24 hour duration, irrespective of the repetition rate.

(d) Repeated UV exposure (280 – 400 nm): In addition to (c), the MPE for any 24 hour period is reduced by a factor of 2.5, if the exposure in succeeding days is expected to approach that MPE.

(e) In the retinal hazard region (400 -1400 nm) the maximum duration of the pulse train to be used for determining 'n' is T_2. (see Annexure I, Table AN-I.1, Note 3)

(f) As applicable in general, the exposure dose for determining the photochemical MPE in the range 400-600 nm, and for T>0.7 s, is linearly additive up to Tmax. This MPE is also limited by the radiance of the source, and may be expressed as 100 C_B J/(cm^2 sr).

(g) All the rules need not be applied for computation of MPE in all the cases. The following flow chart (Figure 5.3) is an adaptation of the results from the S. No. 12 of Bibliography, provided to facilitate application of the three rules when a unique pulse repetition frequency, F, can be defined; e.g., an equi-spaced pulse train of individual pulses of duration t_1. Here F_{cr} (= $1/t_{min}$) signifies that, for $F > F_{cr}$, the MPE per pulse for Rule 3 will be same as the thermal limit derived in Rule-2, and need not be tested.

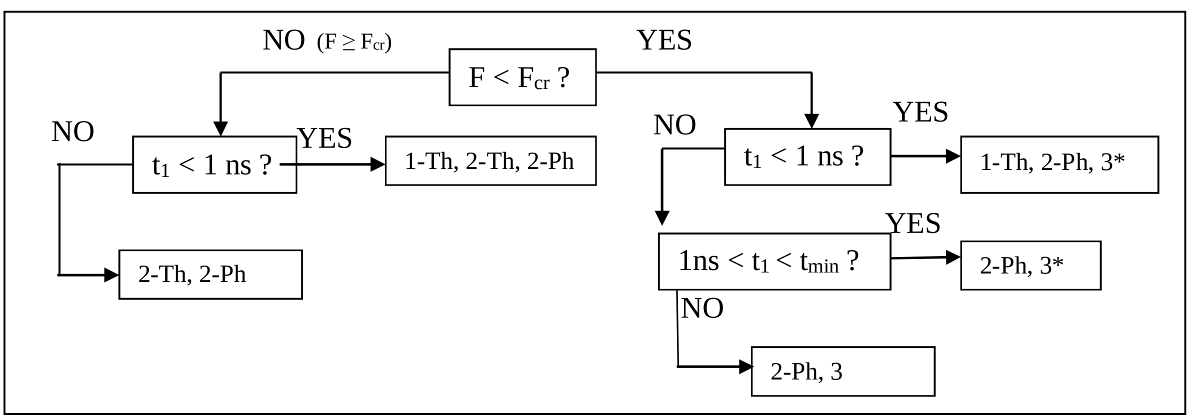


Figure 5.3
FLOW CHART FOR APPLICABILITY OF THE THREE RULES UNDER VARIOUS CONDITIONS

Note: 1-Th, 2-Th, 2-Ph indicate that MPE values may need to be determined by application of Rule-1 (thermal), Rule 2 (thermal) and Rule 2 (photochemical), respectively. 3 and 3* indicate applicability of Rule-3, with restrictions, * $t_1 = t_{min}$ and duty cycle = F. t_{min}.

However, this flow chart should not be applied for wavelength below 315 nm in UV-B and UV-C regions. In this region, the exposure is additive for 24 hours duration, and the principle of thermal confinement for biological effects based on t_{min} cannot be applied. Hence, all the three rules should be applied below 315 nm.

It might be expected, prima facie, that one of these three rules will establish the smallest MPE that should be used for hazard classification. However, this approach is not valid in situations where, because the applicable exposure duration may take different values while applying the three rules, the size of the limiting aperture over which the MPE is averaged also takes different values. In such cases, the comparison is no longer on equivalent basis. The first prescribed step to resolve this issue is to express all MPE in same units, and multiply by the area of the corresponding limiting apertures, to determine the maximum permissible radiant flux (radiant power) ($\boldsymbol{\Phi}_{MPE}$) or radiant energy (Q_{MPE}) transmitted through the applicable apertures. This step converts the 'MPE' to an equivalent basis, but may not still allow a comparison for hazard classification, or analysis, because the effective exposure level, or accessible emission level, of the LASER that needs to be compared with the 'MPE' for such analysis may itself take different values under the different conditions of the three rules, again, because of different exposure durations and limiting aperture values. Hence, the second prescribed step is to determine the effective exposure levels under conditions applicable for each rule, divide by the corresponding 'MPE', and compare the ratios.

In other words, application of the three rules is similar to making an assessment, as if there are three different LASER, and determining, at the end of the exercise, which among the three is the most hazardous. The lowest MPE value does not always indicate the most hazardous condition since, as discussed above, the limiting aperture diameter varies as a function of exposure time for some wavelengths. Since this procedure requires knowledge about evaluating effective exposure levels and measurement conditions, it will be treated, in detail, later in the Section, after these evaluation procedures are discussed.

5.2.1.4 Special Exposure Conditions

The procedures for ocular MPE determination discussed above are applicable for healthy alert individuals, and under normal exposure conditions. Under special exposure conditions, when the eye may be immobilized, or has a dilated pupil, or if the normal protective functions are inhibited by drugs or other means, lower values of MPE are required in the visible wavelength range (400-700 nm). For exposure durations greater than one second, the reduction of ocular MPE are prescribed as follows:

(a) Photochemical MPE for the retinal exposure: Integrated radiance of the source = 20 C_B J/(cm^2steradian) averaged over a cone angle γ, specified in Table AN-I.1. This corresponds to a retinal radiant exposure limit of 2.7 C_B J/cm^2.
(b) Thermal MPE for retinal exposure, both point source and extended source: The reduction factor is as specified in Table AN-I.8.

5.2.2 MPE for Skin Exposure

a) Table AN-I.2 provides the MPE for skin exposure to a LASER beam. These MPE are to be used more as a guideline based on limited studies.
b) For repetitive pulsed LASER exposures of the skin, Rule 1 and Rule 2 are applicable (but not Rule-3), such that the MPE do not exceed the single pulse MPE or the CW MPE.

c) Large area exposures and exposure durations > 10 s

i. MPE for beam cross-sectional areas between 100 cm^2 and 1000 cm^2 = 10,000/A_s mW/cm^2, where A_s is the area of the exposed skin in cm^2.

ii. MPE for exposed skin area > 1000 cm^2 = 10 mW/ cm^2.

d) The MPE for skin exposure should not be used for LASER classification unless the product design or the additional control measures totally prevents ocular exposure, and only skin exposure is possible.

5.3 Measurement and Computation of Source Parameters

Apart from the MPE parameters discussed above, there are several parameters that must be determined in order to establish the hazard classification of a LASER system, and to carry out a complete hazard evaluation. This group of parameters consists of a set of primary source parameters and hazard evaluation parameters, which should be measured and computed in accordance with specified rules and conditions. Often, the manufacturer's specifications of the LASER are directly used to compute the parameters using analytical expressions derived from radiation propagation models. Caution should be applied when physical measurements are substituted by numerical estimates based upon a few primary source parameters. The source parameters and the related evaluation parameters that may be required for hazard evaluation are discussed below:

5.3.1 Emission Wavelength (λ)

For most of the LASER, the emission wavelength will be known with adequate accuracy at one or a few relatively discrete values. Exceptions are LASER with spectrally wide emissions (broadband LASER), such as dye LASER, optical parametric oscillators and amplifiers, free electron LASER, and several solid state LASER, such as Ti:Sapphire, Cr:Forsterite, etc. These LASER are configured for producing narrow line width widely tunable LASER beams, or for producing and amplifying ultra-short pulsed radiation. The multi-wavelength criterion stated in sub section 5.2.1.1(a) and associated hazard evaluation will be elaborated further in sub section 5.4.2.

5.3.2 Beam Diameter (D_L)

Beam diameter of the smallest circle which contains 86% of the total LASER power / energy. For a Gaussian beam (see Figure 5.4), D_L corresponds to the points at which the irradiance or radiant exposure falls to $1/e^2$ of its central peak value.

The beam diameter varies with range or distance of propagation from the exit port of the LASER (refer Figure 5.5**)**. When the beam waist $2W_o$ (the smallest beam diameter) occurs deep within the cavity of the LASER, a good approximation of the beam diameter with range, r, is given by the equation

$$D_L = a + r\phi. \qquad \text{…..(eqn. 5.1)}$$

Where 'a' is the beam diameter at the exit port of the LASER, and ϕ is the far field divergence of the beam.

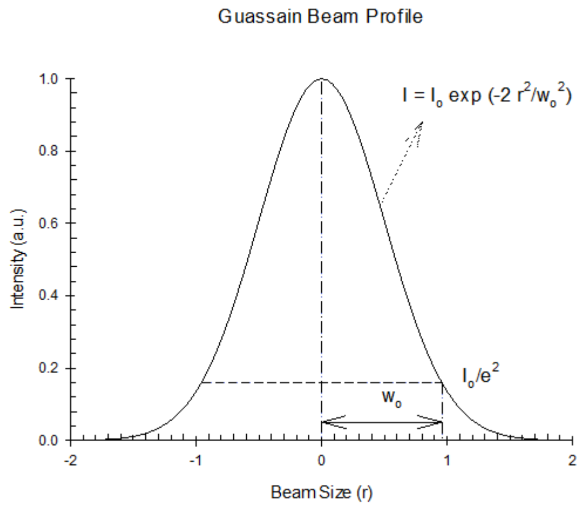


Figure 5.4
INTENSITY PROFILE OF A GAUSSIAN BEAM

If the beam waist for the LASER occurs at or very near to the exit port, a better approximation of the beam diameter change with distance is given by the equation

$$D_L = \sqrt{a^2 + r^2\phi^2} \qquad \text{.....(eqn. 5.2)}$$

Beam waist is the location where the beam diameter exhibits a minimum, increasing away from the waist in both the upstream and downstream directions.

There are instances where the beam waist occurs at a distance in front of the LASER exit port. In this case, the beam diameter gets smaller from the exit port until the beam waist is reached, and then begins to expand. For Guassian beam of this nature, the beam expansion equation becomes

$$D_L = \sqrt{D_w^2 + (r - r_0)^2 . \phi^2} \qquad \text{.....(eqn. 5.3)}$$

The apparent source diameter (e.g., the diffuse reflecting source diameter shown in Figure 5.1 is used for computing the angular subtense, α.

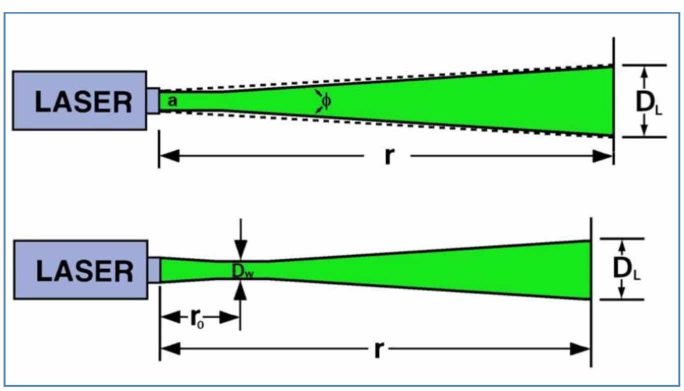


Figure 5.5
BEAM EXPANSION WITH DISTANCE FROM LASER

5.3.3 Divergence (ϕ)

Beam divergence is the rate of change of beam diameter with distance measured in radians, taken as the plane angle projection of the cone measured at the points where the local irradiance is 1/e times the central peak. Simply put, the divergence is the measure of beam spread as it propagates. The divergence also changes with distance of propagation close to the beam waist, or just after an aperture obstructing part of the beam. For hazard evaluation the far-field divergence is required, which is the value at a distance large compared with a^2/λ or $\pi D_w^2/\lambda$, depending on the two situations discussed above. A simple measure of the far field divergence is obtained by focusing the beam with a long focal length lens with minimal aberrations, and dividing the beam diameter at the focal plane of the lens by its focal length.

5.3.4 Measurement Aperture Diameter (D_m)

This defines the aperture diameter that should be used to measure or compute the amount of radiant power / energy that is compared to the AEL for the various LASER classes, and are same as the limiting apertures D_f given in Table AN-I.4 under viewing conditions that precludes the use of binoculars, or other optical viewing aids. Table AN-I.5 gives the values of D_m that should be used for various wavelength and exposure durations, when the potential use of binoculars, or other viewing aids, need to be taken into consideration and the light gathering capability of the instrument accounted for. Hazard evaluation is based on standard binoculars of magnification 7 (50 mm diameter objective), which acts as a scaling factor in increasing the hazard potential. Table AN-I.5 also provides the transmission factors that should be used for a realistic assessment by taking into account the reduced transmission of standard optical components in various wavelength regions.

Note: The measurement aperture diameter would also determine the acceptance angle of the detection system when radiance measurements are required (see sub section 5.3.12).

5.3.5 Output Power ($\boldsymbol{\Phi}_0$)

The maximum output radiant power of a CW LASER measured in watts.

5.3.6 Average Output Power $\boldsymbol{\Phi}_{0(avg)}$

The output radiant power of repetitive pulsed LASER averaged over the pulse separation time period, measured in watts and related to the energy per pulse Q_0 and pulse repetition frequency F through the relation: $\Phi_{0(avg)} = Q_0.F$.

5.3.7 Accessible Power or Effective Power ($\boldsymbol{\Phi}_m$)

The measured amount of radiant power transmitted through a measurement aperture, with diameter D_m (refer Tables AN-I.4 and AN-I.5). For LASER beam profiles (irradiance or radiant exposure profiles) which can be approximated as Gaussian, the effective power may be computed using the equation:

$$\Phi_m = \Phi_0 \, \tau(\lambda) \left[1 - e^{-\left(\frac{D_m}{D_L}\right)^2}\right] \text{ watts} \quad \text{.....(eqn. 5.4)}$$

Here, the transmittance value, $\tau(\lambda)$, is applicable for optically aided viewing. It refers to the transmission of the optics used in optical aids and is taken from Table AN-I.5 unless otherwise specified or known.

5.3.8 Output Energy (Q)

The maximum output radiant energy of an emitted pulse of a pulsed LASER, or the total radiant energy of a CW, or group of repetitive pulsed LASER radiation emitted in a time T, measured in joules. The last parameter is often designated by $Q_{0(group)}$, and equals the product Q_0.n, where 'n' is the number of pulses in the group. For a pulse train consisting of evenly spaced pulses, with a pulse repetition frequency (PRF), F, the number of pulses, n, is the product 'F.T', rounded up to the nearest higher integer.

5.3.9 Accessible Energy or Effective Energy (Q_m)

The measured amount of radiant energy transmitted through a measurement aperture with diameter D_m (refer Tables AN-I.4 and I.5). For LASER beam profiles (irradiance or radiant exposure profiles) which can be approximated as Gaussian, the effective power may be computed using the equation:

$$Q_m = Q_0 \, \tau(\lambda) \left[1 - e^{-\left(\frac{D_m}{D_L}\right)^2}\right] \text{ joules} \quad \text{.....(eqn. 5.5)}$$

Where $\tau(\lambda)$ is the transmission of the optics

5.3.10 Irradiance (E)

The irradiance at any location in the path of the LASER beam is obtained by dividing the radiant power of the beam divided by the area of the beam, both measured at that location, and is given by

$$E = \frac{4\Phi}{\pi D_L^2} \quad \text{.....(eqn. 5.6)}$$

This formula is applicable when the beam has a circular cross-section and exhibits an irradiance profile which is uniform as in a top hat profile often seen in beams of LASER which operate in large number of transverse modes (multimode), or is transmitted through large core fibers, or through special beam shaping optics.

For comparison with the MPE, the irradiance is averaged over an appropriate aperture area. For example, for the retinal hazard assessment, the irradiance of a beam with a diameter smaller than the limiting aperture should be averaged over the area of the limiting aperture for comparison with the MPE. A prescribed approach is to calculate E by the following formula:

$$E = \frac{4\Phi}{\pi[\max(D_f, D_L)]^2} \quad \text{.....(eqn. 5.7)}$$

Where max (D_f, D_L) represents the greater of the two parameters. Similar considerations apply for elliptical or rectangular beams.

For large inhomogeneous beams, the measurements should be made with the applicable measurement aperture in the area of the beam where the measured radiant power / energy is the largest.

a) Diffuse reflection viewing

The irradiance for diffuse reflection viewing (see Figure 5.6), for viewing distance r_1 >> source size D_L, can be computed using Lambert's law:

$$E = \frac{\Phi}{\pi r_1^2} \rho(\lambda). \cos\theta \qquad \text{. …..(eqn. 5.8)}$$

where $\rho(\lambda)$_ is the wavelength dependent reflectivity

Although diffuse reflection irradiance decreases rapidly with distance thereby reducing the hazard, it should be stressed that a rough surface would scatter less at longer wavelengths; a diffuse reflector in the visible wavelength range may act as a specular reflector for an infrared LASER. Additionally, it is generally the rule that most rough surfaces will allow a small component of specular reflection. This component would also increase with increase in wavelength.

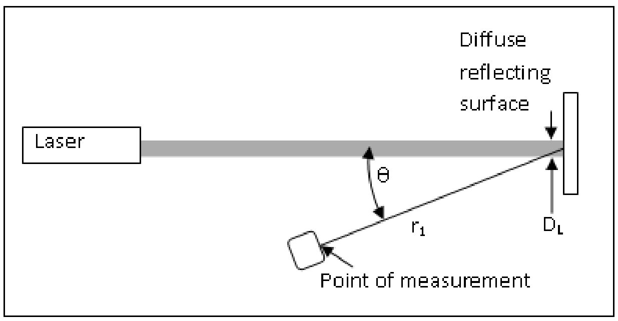


Figure 5.6
DIFFUSE REFLECTION VIEWING

b) Optically aided viewing

The criteria stated in sub section 5.3.4 for measurements under the conditions of optically-aided viewing and the formulation specified in sub sections 5.3.7 & 5.3.9 provide an adequate procedure for measurement or computation of effective radiant power / energy. However, it is useful to express the increase in irradiance at the cornea, when viewing is aided by an optical system, such as binoculars, as an optical gain given by

$$G = \tau(\lambda) \frac{D_0^2}{D_e^2} = \tau(\lambda) \times P^2. \text{ …..(eqn. 5.9)}$$

where, D_0 is the diameter of the entrance aperture of the optical instrument, D_e is the diameter of the exit aperture, P is the magnifying power of the instrument, and $\tau(\lambda)$ has the same significance as mentioned earlier.

After the optics, the aperture diameter for determining the effective exposure level (D_m) is the same as the limiting aperture D_f for hazard evaluation. Therefore, the collecting aperture D_C to be used for effective gain computation (instead of D_0) should be taken as

$$D_C = \min(D_0, P \times D_f) \quad \text{.....(eqn. 5.10)}$$

Similarly, if the beam diameter D_L is less than D_C, or if optics power is higher than the standard value of 7, the beam diameter after the optics would be less than D_f. However, for retinal hazard measurement the irradiance is based on the area of the limiting aperture, rather than the actual beam area. Therefore, the effective optical gain is given by,

$$G_{eff} = \tau(\lambda) \times \frac{\min(D_C^2, D_L^2)}{D_f^2} \quad \text{.....(eqn. 5.11)}$$

5.3.11 Radiant Exposure (H)

The radiant exposure at any location in the path of the LASER beam is obtained by dividing the radiant energy of the beam by the area of the beam, both measured at that location, and is given by

$$H = \frac{4Q}{\pi D_L^2} \quad \text{.....(eqn. 5.12)}$$

The considerations and formulations stated in sub section 5.3.10, for estimating or measuring irradiance under various conditions, are applicable for estimation of radiant exposure under same conditions.

5.3.12 Angle of Acceptance, Limiting Cone Angle ($\boldsymbol{\gamma}_p$)

Table AN-I.1 and its accompanying note refer to certain limiting cone angles, or acceptance angles, $\boldsymbol{\gamma_p}$, in the photochemical retinal hazard wavelength region, 400 – 600 nm. The limiting cone angle defines the solid angle field of view (FOV) of the measurement system used for measuring the radiant power/energy, and converting the same to the effective exposure for the purpose of comparison with the corresponding photochemical AEL.

The importance of the FOV in evaluation of the effective exposure becomes clear on considering an extended source such as a diffuse reflecting source. The eye collects only a part of the radiation emitted from the extended source, while forming an image on the retina. While the size of the retinal image depends on the angular subtense, the amount of light collected within the image depends on the solid angle determined by the angle of acceptance of the eye. In turn, this depends on the geometry of the eye, including the pupil that acts as an aperture stop of the eye imaging system. Further, with increasing exposure duration, movements of the eye increasing from involuntary tremors to larger, task-oriented movements, and even head movements, come into play. This causes movement of the image on the retina and an increase of the effectively irradiated area, thus decreasing the time averaged irradiance. Instead of increasing the MPE in view of the lower hazard, the averaging FOV is increased, so that the effective exposure level, for instance, the effective radiance measurement value, is reduced, before being compared with the radiance MPE. In practice, the MPE is converted to the AEL, using the limiting aperture area and limiting solid angle. The measured or computed exposure level constrained by the applicable measurement aperture, limiting cone angle and measurement distance is then compared with the AEL.

The prescribed guidelines for the measurement are as follows: For $\alpha > \gamma_p$ (specified), γ_p (measurement) $\leq \gamma_p$ (specified). For $\alpha \leq \gamma_p$ (specified), γ_p (measurement) $> \alpha$, and can also be $> \gamma_p$ (specified); in other words, for a relatively small source size, the measurement angle of acceptance should fully encompass the apparent angular subtense of the source, but otherwise need not be restricted to the specified limiting cone angle. The field of view (FOV) control in measuring systems may be achieved by using imaging systems and measurement apertures at suitable locations, and applying the standard formulations of geometrical optics.

5.3.13 Atmospheric Attenuation (μ)

A correction factor, $\exp(-\mu r)$, for atmospheric attenuation is required for a realistic assessment of the level of exposure when long path travel through atmosphere is envisaged. For example, for irradiance, it is given by

$$E(r) = E(0) \exp(-\mu\, r), \quad \text{.....(eqn. 5.13)}$$

when variation in beam diameter or profile shape is disregarded. Here, μ is the atmospheric attenuation coefficient, changing for visible wavelength, from 10^{-4} cm^{-1} in thick fog to 10^{-7} cm^{-1} in clear air with good visibility at the normal eye level along the horizontal. Additional considerations such as reduction of attenuation coefficient with height in atmosphere and dependence on wavelength would apply.

5.3.14 LASER Monitoring Detectors

LASER radiation levels for the purposes of hazard evaluation, apart from those undertaken for classification purposes, are more often determined by calculation than by actual measurement. The physical measurement of exposure levels can be difficult, because the quantities involved, when close to a safety threshold, are usually quite small. Furthermore such measurements must be made under precise geometrical conditions of aperture size and detector alignment, and the elimination of ambient light can be a problem.

At infrared wavelengths, cooled detectors may be needed to reduce thermal background. Other environmental factors can also affect detector performance, such as susceptibility to mechanical vibrations. Detector saturation (operation of the detector at power levels beyond its intended capability) can give rise to false low readings, and therefore, underestimate the hazard. This can be a particular problem with small beams, when the incident power is deposited over a very small area of the detector, and also with pulsed LASER of high peak power, when it may not be recognized that saturation at the peak of each pulse is occurring. Sensitive measurements at very low incident power levels can be influenced by other light sources in the detector's field of view. At the other extreme, the measurement of high LASER powers can cause problems because of the need to attenuate the beam by a precisely known amount to bring it to a level that a detector can handle without damage.

Radiometric measurements can therefore require the use of a range of specialized equipment, together with expertise in its operation that many LASER users could not reasonably be expected to possess. As the manufacturer has the responsibility for classifying the LASER product and for specifying its emission parameters, this information can usually be used as the basis for assessing likely exposure conditions under a variety of operating circumstances. When measurements of LASER radiation are necessary, the measurement equipment needs to be selected with care, and used under carefully controlled conditions.

The principal factors governing the performance of optical detection equipment that may need to be considered when selecting suitable detection systems and radiometric instruments, include the following:

(a) Responsivity, the ratio of the detector output (typically amps or volts) to the incident radiation
(b) Linearity, the range of incident power levels over which the detector responsivity remains constant
(c) Response time, the time taken by the detector output to respond to the radiation input, and the time taken for the output to return to zero once irradiation of the detector ceases – this is an important factor when measuring pulsed LASER radiation
(d) Quantum efficiency, the ratio of the number of photoelectrons produced in a quantum detector for a given number of incident photons
(e) Noise equivalent power (NEP), the level of incident power that produces an output signal equal to the noise level of the detector
(f) Signal to noise ratio (SNR), the ratio of the incident optical power to the NEP
(g) Detectivity (D), this is the reciprocal of NEP, and is a measure of sensitivity of the detector

The distribution of power / energy across a LASER beam can be an important factor in many LASER applications and also in determining beam quality for safety purposes. The beam profile of CW LASER can be assessed by recording the time-varying output of a small area detector moved through the beam, or by using scanned pinholes, slits or knife edges in front of a large area detector. The profile of a pulsed LASER, however, may need to be captured in a single pulse. This can often be done, using detector arrays or electronic cameras. A range of beam analysis equipment are available, some of which are computer linked to provide graphic representations of LASER beam profiles. The equipment required to measure the time varying profile of pulsed LASER, particularly repetitive pulsed LASER, may range from simple photodiodes and conventional oscilloscopes to sophisticated high bandwidth detection and recording systems, for measuring short pulses.

5.3.15 General Measurement Criteria

The following general criteria are applicable while making the measurements, estimates and assessment of the effective exposure level:

(a) Measurements are required when no authenticated classification is available, when the application may need system alterations or use that may be perceived to have altered the hazard, when the data available is not adequate for estimating all the parameters for hazard evaluation, such as defining the nominal hazard zone.
(b) The estimated error in measurement should not exceed ±20%. Larger inaccuracies, if unavoidable, should be analyzed with caution, so that they do not falsely imply a safe condition. Regular and reliable calibration of the measuring instruments to a traceable standard is an important requirement.
(c) The LASER should operate in the mode, in which it would produce the most hazardous exposure conditions.

(d) For determination of the AEL, for LASER classification, all the measurements on the beam should be made at the point of greatest hazard, but no closer than the specified closest distances, as discussed below (Also see sub section 5.2.1.3):

Measurement distance conditions (in accordance with ANSI-Z.136.1-2007)

(i) For naked eye viewing : For the retinal hazard region, the aperture diameter is derived from the maximum dark adapted diameter of human pupil. The viewing distance is used as no closer than 10 cm, which is the closest distance that can be accommodated, i.e. where the source is focused as a sharp image on the retina.

(ii) Condition 1: Viewing through telescope or binocular

The image of large diameter source (e.g., the emitting aperture), when viewed with binoculars or telescopes, allows a larger part of total beam power to be incident on the eye (Figure 5.7). These instruments cannot be used at distances shorter than 2 m, for large diameter sources. The measurement Condition 1 takes this aspect into account and specifies a measurement aperture diameter of 50 mm and a measurement distance no closer than 2 m.

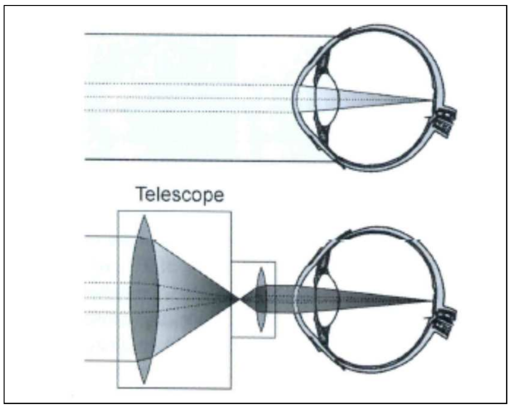


Figure 5.7
VIEWING WITH TELESCOPES AND BINOCULARS

(iv) Condition 2: Viewing through eye loupes (also for unaided viewing)

When viewing highly diverging beam from small sources, such as an optical fiber exit aperture, with an eye loupe or a magnifying glass, the hazard can be enhanced than when viewed with an unaided eye (Figure 5.8). This aspect is taken in to account in Condition 2 which specifies the measurement condition as 7 mm aperture diameter and a viewing distance of no smaller than 10 cm.

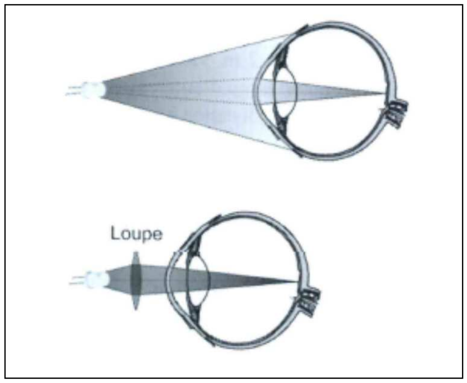


Figure 5.8
VIEWING WITH EYE LOUPES

5.4 Classification of LASER:

The classification of a LASER / LASER system gives an indication of its potential for causing injury. All LASER / LASER systems should be classified, so that the applicable protection and control requirements can be determined. Classification is applicable not only to the manufactured products, but also to the experimental or the prototype systems under development. If a LASER is incorporated in equipment, that equipment should also be classified.

The various hazard classes were introduced in Section 4. As a first step, hazard classification requires determination of effective exposure level and the accessible emission limit for Class-1 LASER / LASER system. The procedures and conditions required for determination of the two parameters are given in sub sections 5.2 and 5.3. The next step involves comparison of the effective exposure level with a set of AEL, starting with the Class-1 AEL, in accordance with standard definitions for increasing hazard classes. This document adapts the definitions and classification procedure as per ANSI-Z-136.1:2007 (see Annexure II), and converts these into a stepwise flow chart given in Figure 5.9, to facilitate application of the complex rule based standard. AEL for the different classes, against which the effective exposure levels are compared, are taken from the ANSI standard. In Figure 5.9, the symbols have the same meaning as stated above, except for the following:

Q_m:H : Measured/estimated effective exposure level as radiant energy in joules. (may be replaced with Q_m:H)

Φ_m:E : Measured/estimated effective exposure level as radiant power in watts.

$\Phi_m(A)$: Measured/estimated effective exposure level under optically aided viewing conditions.

Note: While determining the applicable exposure duration, T, for computing MPE & AEL-1, it should not exceed 30,000 s, for $\lambda \leq 700$ nm, and 100 s for $\lambda > 700$ nm.

5.4.1 Classification of Repetitive Pulsed LASER

The hazard evaluation for repetitive pulsed LASER (or for repetitive exposures) requires a different approach. Sub section 5.2.1.2 provides the criteria for determining the MPE for repetitive pulsed LASER using the three rules (as given in sub section 5.2.1.1), and points out that under certain conditions the lowest value among the MPE obtained using the three rules does not indicate the most hazardous condition. A generalised approach for repetitive pulsed LASER, adapted from S. No.10 of Bibliography is presented here. In addition to the parameters provided earlier in this Section, the following parameters are required:

k – The number of LASER pulses which are produced within the time t_{min}.

n_{eff} – The 'effective' number of groups of LASER pulses which are used in Rule 3 of the multiple-pulse MPE analysis. The value of n_{eff} is smaller than n (the integer number of pulses emitted within the applicable exposure duration, T) if more than one pulse occurs within t_{min}.

MPE_{TSP} – The single pulse MPE determined considering only thermal damage mechanism.

Φ_{MPE} and Q_{MPE} – These are the maximum permissible radiant power / energy transmitted through the applicable limiting aperture, and computed as follows:

$$\Phi_{MPE} = MPE{:}E \times \frac{\pi D_f^2}{4} \quad \text{.....(eqn. 5.13)}$$

$$Q_{MPE} = MPE{:}H \times \frac{\pi D_f^2}{4} \quad \text{......(eqn. 5.14)}$$

The procedures outlined below should be applied separately to all pulse groups with each group considered as a 'single pulse'. Next, a MPE per pulse, for a single pulse within the group, should be computed for each case. For example, for the repetitive group of pulse bursts shown in Figure 5.2, a MPE should be computed for the burst duration as well as the total exposure duration. In the following steps, t_1 is the duration of a single pulse.

5.4.1.1 Determination of Φ_{MPE} / Q_{MPE} for the three rules:

Rule 1: Single pulse MPE-1

(i) Determine MPE for a single pulse of duration t_1. If there are dual limits arising from photochemical and thermal hazards, the lower value should be used as the most conservative MPE. Express the MPE in terms of both irradiance (MPE-1:E) and radiant exposure (MPE-1:H), multiplying, if necessary, the irradiance MPE by the exposure duration, T.
(ii) Determine the limiting aperture (D_f), using the wavelength and pulse duration, t_1.
(iii) Compute Φ_{MPE-1} and Q_{MPE-1}

Rule 2: Average power MPE-2

(i) Determine the applicable total exposure duration, T, from the given situation or design of the LASER, or from the inadvertent exposure durations in Table AN-I.3.
(ii) Compute CW LASER MPE labeled MPE_{CW}, for duration T, applying the same approach as above in case dual limits are applicable.
(iii) Express MPE_{CW} in terms of radiant exposure, multiplying, if necessary, the irradiance MPE by the exposure duration, T, as shown below:

$$MPE_{CW}{:}H \ (J.cm^{-2}) = MPE_{CW}{:}E \ (W.cm^{-2}) \times T \ (s) \quad \text{......(eqn. 5.15)}$$

(iv) Compute n from the expression, n = F x T, rounded to the nearest larger whole number, with

$$n = F \times \min(T, T_2) \text{ for } (400 \text{ nm} \le \lambda < 1400 \text{ nm}). \quad \text{......(eqn. 5.16)}$$

(v) Compute MPE per pulse for Rule 2 from

$$\text{MPE-2:H} = (\text{MPE}_{CW}\text{:H}) / n \qquad \text{......(eqn. 5.17)}$$

(vi) Determine D_f corresponding to exposure duration T.
(vii) Compute Q_{MPE-2}.
(viii) Apply the above procedure for all pulse groupings.

Rule-3: Multiple pulse MPE-3

(i) If $t_1 < t_{min}$, determine MPE_{TSP} as MPE, for exposure duration between 1 ns and t_{min} from Table AN-I.1, even if $t_1 < 1$ ns, and if, $t_1 \geq t_{min}$, determine MPE_{TSP} as MPE for exposure duration t_1.
(ii) If there are dual limits, compute only thermal MPE, and express in terms of radiant exposure.
(iii) Compute the total number of pulses (k) in time t_{min} from $k = F \times \min(t_{min}, T)$. If k is a fraction, convert to next larger whole number only for $T < t_{min}$, or, $k < 1$.
(iv) Compute n_{eff} from $n_{eff} = n$, for $k \leq 1$, and $n_{eff} = n/k$ for $k > 1$, using n computed in Rule 2.
(v) Compute multiple pulse correction factor C_p from $C_p = (n_{eff})^{-0.25}$
(vi) Compute $\text{MPE-3} = \dfrac{C_p \times MPE_{TSP}}{k}$
(vii) Determine D_f, using a newly determined exposure duration, T_{new}, for application of Rule 3, in accordance with Figure 5.10
(viii) Compute Q_{MPE-3}.

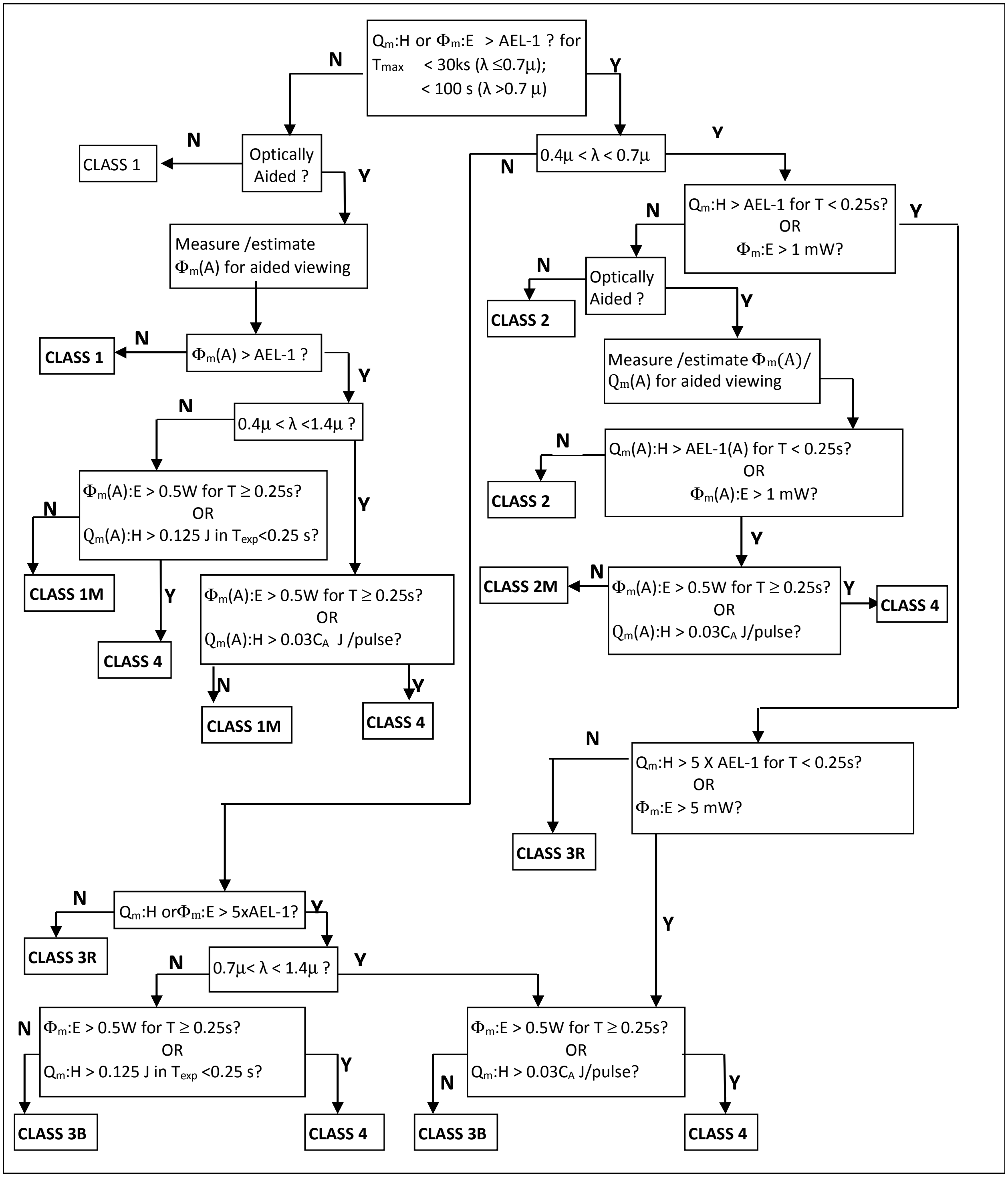


Figure 5.9
FLOW CHART FOR DETERMINATION OF LASER HAZARD CLASS

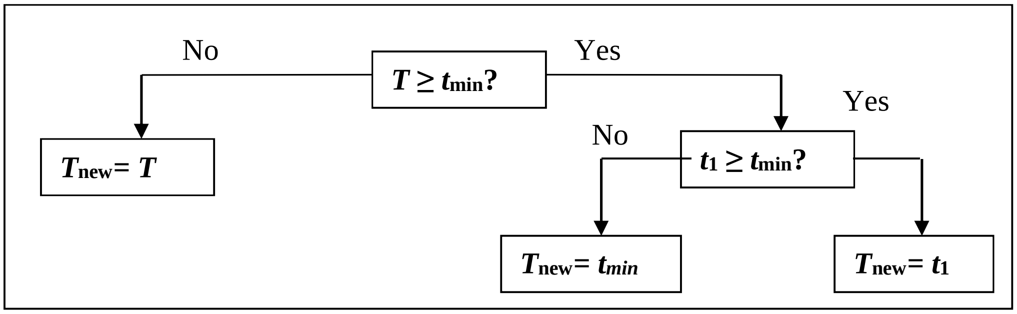


Figure 5.10
DETERMINATION OF EXPOSURE DURATION, T_{new}, FOR COMPUTING APPLICABLE APERTURE DIAMETER, D_f, FOR HAZARD EVALUATION UNDER RULE-3

5.4.1.2 Comparison of hazards under the three rule method

(a) Compute or measure effective exposure values, Q_m, for each applicable value of D_f (see sub section 5.3.9) determined under the three rules. Here, note that D_f is same as D_m, when viewed without optical aids. In case viewing with optical aids is to be included, values of D_m for each of the applicable exposure durations determined under the three-rule-method should be used. In the literature, or other documents, this may be referred to as Q_f.

(b) Compute and compare the corresponding ratios, Q_m / Q_{MPE}.

(c) The largest value of Q_m/Q_{MPE} indicates the most conservative assessment, and determines the MPE for classification for the given exposure conditions.

(d) It is essential to note that the exposure conditions play an important role here, because Q_m depends on the LASER beam diameter, D_L. Hence, the appropriate MPE and classification may change with beam diameter, and, therefore, also with distance from the source.

5.4.2 Classification of multiple LASER and multiple-wavelength LASER

It was stated in sub section 5.2.1.1 that, for determination of MPE, for exposure to multiple wavelength emission, the hazard should be considered to be additive, under certain conditions, on a proportional basis of spectral effectiveness. This sub section provides the procedure for classification of multiple LASER or multiple-wavelength LASER satisfying these conditions. However, this approach must be applied with caution, as the additive effect may not be valid when synergistic effects of retinal biological effects are suspected. Also, the exposure safety for broadband sources would require the use of 'hazard functions' which are not specified here. The description is for irradiance based analysis, but may also be used for analysis, using radiant exposure.

(a) Compute Φ_{MPE} for each independent emission at wavelengths λ_k, and label these as $\Phi_{MPE}[\lambda_k]$.

(b) Compute, or measure the effective exposure levels $\Phi_m[\lambda_k]$.

(c) Assess the hazard by computing the exposure limit as in (Reference: S. No 13 of Bibliography)

$$\sum_k \frac{\Phi_m[\lambda_k]}{\Phi_{MPE}[\lambda_k]} < 1 \qquad \text{……..(eqn. 5.18)}$$

5.5 Determination of Nominal Ocular Hazard Distance (NOHD)

The determination of NOHD consists of computing or measuring the minimum distance at which the effective irradiance and the radiant exposure fall below the appropriate MPE. One may equivalently compare the effective radiant power / energy with the appropriate AEL for Class-1. The distance to be determined is generally the range along the direction of the propagation of the beam, measured from the emitting aperture. However, it is necessary to assess the environment in which the LASER is used, to take into account the potential extension of hazard outside the direct beam by specular or diffuse reflection.

For computational assessment, where the beam parameters, including the output radiant power / energy are known, the procedure involves the following steps:

(a) For intra-beam viewing

(i) Use the formulae for irradiance (E) (see sub section 5.3.10) or radiant exposure (H) (see sub section 5.3.11) expressed, respectively, in terms of the radiant power (Φ) or energy (Q) output from the LASER, and the beam diameter (D_L) at the location of evaluation.
(ii) Use the appropriate formula for the beam diameter (D_L) which is a function of beam parameters, such as the range measured from the exit port (r), beam diameter at the exit port (a), beam divergence (ϕ), beam waist position from exit port (r_0), beam waist diameter (D_w), etc. (see sub section 5.3.2).
(iii) Use the appropriate numerical value of MPE, in place of irradiance (E) or radiant exposure (H), in the formulae, and compute the range (NOHD) at which the effective exposure level equals the MPE. Where applicable, reduce the MPE value by the effective optical gain factor.

(b) For diffuse reflection viewing

(i) Use the appropriate formula for irradiance [see sub section 5.3.10(a)] or radiant exposure.
(ii) Assume for conservative estimate, unless otherwise specified that the entire output radiant power / energy from the LASER is incident on the diffuse reflector. This determines Φ, or Q in the formula.
(iii) Compute the beam diameter at the diffuse reflector, using appropriate formula for D_L (see sub section 5.3.2), and the known distance of the diffuse reflector from the LASER source.
(iv) Compute the angular subtense of the diffuse source at the eye located at a distance (r_1) from the diffuse source at the viewing angle ($\boldsymbol{\theta}$), and determine whether extended or point source conditions apply. Assuming that the source is a small source is conservative, and would overestimate the hazard.
(v) Follow steps in a(ii) and a(iii) above, taking care that the appropriate computed MPE for point source or extended source is used, as applicable.
(vi) Since the extended source correction factor, and hence the extended MPE, depend on both the viewing angle and the distance, an iterative procedure may be required to determine the NOHD.

6. MANAGEMENT OF LASER SAFETY

6.1 Introduction

LASER pose unique hazards which must be identified, analyzed, assessed and controlled. Since the risks involved are not always immediately obvious, the hazards are often deceptive in nature and underrated until avoidable ‘accidents’ occur. On the other hand, over-restrictive controls obstruct effective and beneficial use of the technology. Particularly, where Class 3B/4 LASER are used, it is necessary for the organisation itself to help implement a comprehensive LASER safety management program for safe, sustained and gainful activities involving LASER. The following sub sections address the various components of a standard organisational approach towards developing a ‘LASER Safety Program’ for organisations that have large activities for the use, or development of various types of LASER, particularly assessed as Class 3B, or Class 4.

6.2 LASER Safety Policy

As a first step, it is necessary to declare a ‘LASER Safety Policy’ for establishing clarity of commitment by the organisation, as well as ensuring compliance by the users and those responsible for implementation of LASER safety. It defines the objective of the LASER safety program to ensure that personnel are not exposed to LASER radiation in excess of the MPE for eye and skin, and to mitigate LASER related ‘collateral’ hazards, thus establishing safe working conditions. The policy should require that all the LASER be operated in compliance with the accepted safety guidelines and/or regulations, and also provide guidance to the users in establishing procedures and utilizing proper means and equipment for safe use of LASER.

The applicability of the policy needs to be stated. For example, it may apply to all employees, students and visitors, as well as to authorised usage of products developed and/or supplied by the organisation; but it may not apply to service personnel from other organisations or industry servicing any LASER. Also, it is necessary to formulate a standardised enforcement policy and intervention procedure to facilitate execution of actions against non-compliance.

The policy should also define the organisational structure for management of LASER safety including training at various levels for effective implementation. These aspects are addressed in detail below:

6.3 LASER Safety Organisational Structure

Various approaches are adopted by different international organisations, research institutes and industry, for setting up a LASER safety organisational structure, depending on the diversity and magnitude of the LASER related activities within the organisation. A common aspect of all such approaches is the designation of a LASER Safety Officer (LSO) or ‘LASER Safety Manager’ by the Head or ‘Occupier’ of the organisation. The primary responsibility of the LSO is to carry out knowledgeable evaluation of LASER hazards, assess the related risks, and ensure directly, or through higher authority, compliance with required safety guidelines. The LSO should have adequate training, knowledge and experience in evaluation and control of LASER hazards. For large and diverse activities, the LSO may be assisted by local area safety coordinators, to monitor exposure parameters, undertake hazard evaluation, and advise the users on the implementation of safety control measures. In such cases, organisations often constitute a ‘LASER Safety Committee’ (LSC), with oversight responsibilities.

The LSO, or the Chairperson of the LSC, may also be granted authority by the organisation, on behalf of the occupier, to authorise the use of a LASER/LASER system, and indeed to suspend, restrict, or terminate, its operation, if it is deemed that an adequate level of hazard control has not been implemented. An important aspect here relates to legal responsibility for safety, which is carried by the management within the organisation, and is not transferred by the appointment of a LSO.

It is envisaged that there may be multiple installations of LASER-based activities within the organisation. Some of these may be individual laboratories or workshops, with dedicated applications, while others may be facilities catering to multiple uses and users. Some of the installations may be of industrial plant scale or plant prototypes, incorporating several LASER, with limited familiarity of the operators with LASER hazards. Some of the applications may require outdoor use, resulting in expansion of the nominal hazard zone. For facilitating effective implementation of LASER safety depending on such requirements, the organisation should, therefore, assign additional responsibilities to suitable individuals working directly with the LASER installations, designated as ‘In-charge of LASER Facility’, or ‘Principal LASER User’, and ‘LASER Operator’ or ‘LASER User’. The primary responsibilities envisaged here are providing inputs to the LSO and area safety coordinators, regarding LASER parameters, intended applications, associated hazards and user information, and also assisting in implementation of the LASER safety program.

In order to meet the requirements discussed above, the LASER safety program should address the following aspects:

(a) Establishment of duties and responsibilities at various levels
(b) Development of standard procedures to facilitate implementation of the safety policy and compliance with the safety guidelines, standards or regulations.
(c) Education of authorised personnel (LSO, operators, service personnel, research students and others) in the safe use of LASER and LASER systems and, where applicable, in the assessment and control of LASER hazards.
(d) Implementation of adequate protective measures for the control of LASER hazards.
(e) Preparation of necessary documents, such as standard operating procedures (SOP), safety manual, alignment procedures etc.
(f) Reporting of LASER accidents and safety significant events, their investigation and establishing an emergency response procedure.
(g) Establishment of a suitable medical surveillance program.
(h) Reviewing of the LASER safety program, and maintaining awareness of the new or the revised LASER safety standards.

The roles and responsibilities of the various functionaries and the related safety management procedures are described, in greater detail, below:

6.4 Duties and Responsibilities

6.4.1 In-charge of LASER Facility/Principal LASER User (PLU)/Supervisor

Depending on the nature of the LASER installation and its use, the occupier of the organisation shall appoint an In-charge or PLU for all installations where Class 2, or higher hazard class, LASER are operated, which may include Class-1M or Class-2M LASER.

The duties and responsibilities of the In-charge or PLU with respect to Class-2, or higher hazard class, LASER should include, but may not be limited to, the following:

(a) Supervise the safe use of LASER under his/her responsibility.
(b) Ensure with the help of LSO that all the LASER/ the LASER systems under their responsibility are properly classified and labeled.
(c) Prepare pre-commissioning work plan, indicating location, human occupancy, projected beam path, and alignment procedure, ensuring absence of any optical components or protective components, such as beam dump in the beam path which may change position or orientation beyond acceptable safe range, except under supervised action by authorised users. List potential situations which may cause beam steering outside the planned path.
(d) Ensure availability and the use of appropriate personal protective equipment (PPE) for each person, with access to the LASER system.
(e) Assist LSO, as and when required, for providing data related with LASER and associated hazards, for hazard evaluation and risk assessment, and to determine appropriate hazard control measures.
(f) Implement all applicable hazard control measures and procedures for LASER and associated hazards.
(g) Prior to operation of any LASER / LASER system submit LASER registration form (vide Form-1 of Appendix-A), LASER inspection Form/ Checklist for pre-operational safety assessment (vide Appendix-B), and standard operating procedure (SOP) (vide Appendix-C) and obtain LSO's approval signature on the pre-operational checklist, which may be modified by the LSO.
(h) Obtain LSO's approval for any modification to the LASER / LASER system and its use.
(i) Prepare and update list of the personnel, with access to the LASER and its output, and obtain approval of LSO on personnel authorisation form (vide Form-2 Appendix-A) prior to authorising access. Only authorised persons should operate or service, Class-3B/4 LASER / LASER systems.
(j) Verify that the personnel with access to the LASER / LASER system have received training in LASER safety (vide sub section 6.6), undergone baseline eye examinations prior to beginning work with LASER, and undergo periodic examinations (vide sub section 6.7).
(k) Post a written SOP in a location readily available to all the personnel with access, and ensure compliance with SOP.
(l) Ensure that safety controls are not disabled, or modified, or safety measures are not compromised, without approval from the In-charge/PLU, and notify LSO of any change in status.
(m) Authorise entry of unregistered personnel, such as visitors, or untrained service personnel for peripheral services, after hazards orientation briefing, ensuring availability and the use of PPE, with due consideration to safety, when LASER are in use.
(n) Inform the LSO whenever any LASER / LASER system is to be sent offsite and ensure that all product safety requirements (vide sub section 7.9) are met.
(o) Promptly notify the LSO of any malfunctions, problems, incidents, injuries, or suspected over-exposure, which may have impact on safety. Review, in consultation with LSO, and take necessary action to avoid such problems.

(p) Provide workers with an opportunity to participate in the hazards evaluation and development of controls.

6.4.2 LASER User / Operator

LASER user and operator responsibilities include but may not be limited to, the following:

(a) Attend and complete the applicable LASER safety course followed by on-the-job, training before operating any LASER / LASER system un-supervised.
(b) Ensure that his name is registered as an authorised LASER user for the LASER system he is operating.
(c) Comply with the applicable safe operating procedures and safety plans, procedures, requirements, and controls given in this document, or generated by the LSO. This includes reading, understanding, and following all applicable procedures.
(d) Alert the In-charge or PLU of any unaddressed potential hazard, and suggest control measures to the best of his knowledge.
(e) Inform LSO/In-charge/PLU of the LASER system, in case of
  (i) Exposures that cause a burning sensation or a change in the condition of the skin, visual afterimage, and blurring, obstruction of vision or headaches.
  (ii) Any injury or unsafe incident, caused by exposure to associated equipment, components, or materials.

6.4.3 LASER Safety Officer (LSO)

The LSO's responsibilities include, but may not be limited to, the following:

(a) Administer and maintain the LASER safety program.
(b) Update LASER safety policy and procedures.
(c) Function as a liaison between the In-charge of LASER facilities/ PLUs/LASER operators/ users, and the organisational safety committee, or LASER Safety Committee as applicable.
(d) Accompany safety inspectors/regulators on LASER safety inspections.
(e) Maintain a current inventory of Class-1M, 2M, 3B and 4 LASER.
(f) Carry out hazard classification or verification of hazard class of LASER as applicable, evaluate total hazard, including the application and non-beam hazards, and specify Nominal Hazard Zone (NHZ) or LASER control area, as applicable.
(g) Recommend/specify control measures, provide technical advice for safe LASER operation, approve hazard mitigation plans, including wording on area signs and equipment labels; develop, review and approve alternate or substitute control measures, other than those listed in this document, when the standard means are not feasible or practical.
(h) Coordinate with industrial safety agencies to ensure that non-beam hazards are addressed, or verify valid approvals for the same, in accordance with the safety policy of the organisation.
(i) Ensure that the prescribed control measures are in effect.
(j) Review, approve and maintain copy of standard operating procedures, pre-operation checklist, alignment procedures and other procedures that may be part of the requirements for administrative and procedural controls; coordinate with In-charge/PLU to ensure compliance prior to approval.

(k) Recommend and approve protective equipment, i.e. eye-wear, clothing, barriers, screens, etc. as may be required to ensure personnel safety. The LSO should ensure that protective equipment is audited periodically, to maintain proper working order.

(l) Review the LASER Inspection Form/ Checklist (vide Appendix B), submitted by the principal LASER user, and based on the review and the observation, perform and document LASER-safety audits of LASER installation and equipment, using Class 3B/ Class 4 LASER, while the LASER is operational, to ensure that all the safety deficiencies are addressed.

(m) Perform and document observational survey as per management policy, or on-request visits to LASER use areas.

(n) Wherever necessary, carry out LASER hazard evaluation and risk assessment, along with the In-charge of the facility

(o) Develop appropriate safety orientation, awareness and training courses, and ensure availability of the courses to personnel, as deemed necessary, on a regular basis. Ensure the appropriateness of on-the-job training, where applicable.

(p) Develop and maintain medical surveillance program coordinating with appropriate agencies.

(q) Investigate all instances of accidents, suspected exposures and near-misses; coordinate with health services and industrial safety agencies as required, for performing this task; develop 'Lessons Learned' programs (see below) and organise interactive dissemination.

(r) Report to, and assist LASER Safety Committee, or the organisational safety oversight agency, on arriving at decisions to suspend, restrict, or terminate, the operation of a LASER / LASER system, if it is deemed that the hazard controls are inadequate and that, it presents imminent danger, or excessive hazard.

6.5 Management of LASER Accidents and Significant Events

A LASER incident management plan should be developed, as a part of the LASER Safety Program, and followed in case of an over exposure, suspected LASER injury confirmed LASER inflicted injury, incident. A sample example set of actions is provided below:

6.5.1 Actions for Suspected LASER Exposure/Injury

(a) Keep the individual calm – key initial action.

(b) Seek medical attention. Arrange transport to health services. Provide summary of the LASER beam characteristics, to assist the ophthalmologist.

(c) Shut down the LASER.

(d) Notify all the others in the area, and ensure that set-up is not altered, to enable cause analysis.

(e) Report to the immediate superior, In-charge and LSO, as per the format prescribed in Appendix D.

(f) LSO should carry out an investigation of all the reported suspected incidents, with assistance from the others in a position to provide useful information, with the aim to mitigate the hazard, and prevent recurrence, followed by generation of a 'Lessons Learned' activity and report. Sharing of accident or feedback information, through a regular program, termed 'Lessons Learned', is considered highly effective for enhancing safety awareness and continuous improvement of control measures and safe practices. Due care is advised to focus on professional communication, and avoid criticizing approaches.

6.5.2 Actions for LASER-inflicted Injury

In case of a distinct LASER inflicted injury or incident, in addition to the immediate actions stated above, it would be necessary for the LSO to submit a primary report, describing the extent of injury to the appropriate safety committee and regulatory body. A guideline to categorize the injury is as follows:

(a) No injury : Exposure below the MPE
(b) Minor injury: Ocular exposure up to 10 times the MPE and skin exposures up to 100 times the MPE (Injuries will normally be reversible)
(c) Major injury: Ocular Exposure in excess of 10 times the MPE, and skin exposures in excess of 100 times the MPE (injuries will normally be irreversible).
(d) Injuries due to non-beam hazards of the LASER system, such as high voltages and toxic chemicals.

The safety committee should review, and, if deemed necessary, suspend operation within first few hours. Thereafter, the standard approaches for investigation, further review and action may be planned in accordance with the organisational policies. The report structure, contents, step-wise procedures, and approvals may be drawn up by the organisation, as a part of its LASER safety program, in consultation with the regulatory body.

Annexure III gives some examples as well as detailed case study of the LASER accidents which may occur in a LASER facility. These are by no means exhaustive, and are provided, to indicate the deceptive nature of LASER hazards, and to emphasize the need for a rule-based organisational approach, to implement safe working conditions.

6.6 Training and Qualification

All safety related training applies as much weightage to worker attitudes and perceptions as to imparting core technological knowledge and safe practice methodologies. This is no different in the case of LASER, where the ability to cause harm at a distance from the source is enormous and underrated. Training in LASER safety is normally required for all those whose actions and behavior in working with LASER equipment could put them or other people at risk.

All persons, employees, students or guests, who are authorised to work unsupervised with Class 3B/4 LASER, must receive and complete appropriate LASER safety training courses. Those who may be exposed to lower hazard class LASER 1M, 2, 2M and 3R, may also be trained. Those having the responsibility for safety, such as LSO and In-charge of LASER facility, need special training to enable them to perform their duties satisfactorily.

An on-the-job-training (OJT) on LASER safety is also deemed necessary and beneficial. The In-charge/PLU, or a competent qualified member associated with a specific activity, should provide OJT to other members associated with the activity on the hazards specific and peculiar to the activity. In particular, OJT should bring out the deviations from the standard control measures, on account of practical difficulties, and the substitute measures adapted. OJT would be particularly important for fresh entrants. Some organisations require OJT to be documented and signed by both the trainer and the trainee.

The training program should be designed appropriate to the class of the LASER radiation accessible during the required tasks of the personnel. Thus, whereas, for persons working with Class 1M or 3R LASER, an awareness-training may suffice, comprehensive LASER safety training is required for the LSO.

The LSO shall ensure that all employees assigned to service, maintain, install, adjust and operate LASER equipment be appropriately qualified and trained. In-charge of the LASER system shall maintain the names of all the persons trained and date of training, and inform the LSO of the training completions and requirements.

It would be instructive to refer to the available publications and documents of the organisations which use Class 3B/4 LASER, with an established LASER safety program. Some of the observations are summarised here. Suitable criteria need to be established to reduce the element of subjectivity in audit checklists and findings by the auditor, which may otherwise depend on the experience and foresight of the person. For example, some of the control measures, such as a beam block arrangement, may seem adequate to one, and not to another. Some organisations require the use of a hazard communication poster, and urges the users to check these or other documentation and provide feedback.

In order to make the emergency medical response and medical surveillance programs more effective, a panel of ophthalmologists and physicians may be provided with suitable training in LASER-induced injuries.

6.7 Medical Surveillance

Apart from medical evaluation, following the suspected or the confirmed exposure, a general medical examination program should be developed as a part of the LASER safety program. It should address the following issues, among others:

(a) Drawing up examination protocol in consultation with ophthalmologists and physicians.

(b) Pre-assignment examination to establish baseline data, primarily ocular, to serve as a reference for future examinations that may become necessary after a suspected or confirmed exposure. A second purpose is to identify certain workers who might be at special risk from chronic exposure to selected continuous wave LASER. This would be of importance in long-term epidemiologic studies, which may lead to extension of the hazardous wavelength range for injury from chronic exposure to low level radiation.

(c) Although periodic medical examinations are not required by the standards, such as ANSI, an annual skin examination may be recommended for those who routinely receive UV exposure during experimental work. Another aim will be to screen workers who may not report minor exposures or injuries that do not appear to interfere with regular work. Requirements for periodic ophthalmic examination should be arrived at, in consultation with ophthalmologists, taking into account both potential benefits and adverse side effects of such examinations.

(d) Requirement for medical examinations, prior to leaving the organisation, particularly eye examinations for persons working with Class 3B/4 LASER, needs to be examined by the organisation. Apart from medico-legal importance, such examinations can also provide epidemiological data.

(e) Period for retention of the medical examination reports should be decided by the organisation.

7. CONTROL MEASURES

7.1 Introduction

Protective hazard control measures are devised with the aim of reducing an unacceptable level of risk, arising out of an existing hazard, to an acceptable level. The three-step procedure of hazard evaluation, risk assessment and determination of appropriate control measures are interrelated, and should be repeated in an iterative manner to arrive at the control measures that are necessary to effectively contain the hazard. This Section provides the hazard control measures based on the LASER safety standards and guideline documents referred earlier. It starts with a description of the standard control measures for potential exposure of the eye, or skin, to hazardous levels of LASER radiation, and next, specifies control measures for non-beam hazards associated with LASER and LASER systems during operation, maintenance and application. Guidelines for risk assessment, which require experienced judgment, are provided thereafter in a step-wise mode, as prior awareness of the standard control measures would itself serve as a primer.

There are general considerations as stated in the sub-paragraphs of this sub section, which shall be considered while applying the specific control measures stated in the subsequent sub sections.

7.1.1 Need-based Minimisation of Hazard

As a first step in controlling hazards, the feasibility of using a lower class LASER, with the minimum level of LASER radiation required for the application, should always be examined, and used where acceptable. The need for a higher class LASER, or even a higher power LASER within a given class, should be assessed by Competent Authority, prior to purchase, or development. The LSO may assess whether excessive levels of radiation (power / radiant energy) is accessible during operation, or maintenance of a Class 3R, 3B, or Class 4 LASER, not essential for the envisaged application, and advise reduction of the radiation level.

7.1.2 Modification of Equipment, Application or Exposure Environment

Where a LASER / LASER system, or its application, has undergone a modification subsequent to the initial hazard evaluation, classification, and risk assessment, the Principle Laser User (PLU) should carry out a reassessment of the hazard and control requirement which is approved by LSO. This is important where the LASER is used for special applications, not envisaged during its initial safety assessment. However, access to an embedded or enclosed LASER beam during maintenance or service shall not alter the hazard classification of the LASER system. Rather, control measures appropriate to the class of the embedded or enclosed LASER and specified for such maintenance and service tasks (see sub sections 7.2.1 and 7.2.2) shall be implemented.

7.1.3 Healthcare Related Applications

The applicability of the control measures for the use of LASER in healthcare, such as for diagnostics, therapy or medical research purposes, poses a problem, as many of these applications require intended *in vivo* tissue interactions with patients, or volunteers, in clinical research, which may be invasive in nature. ANSI, for example, has developed separate standards for safe use of LASER in healthcare facilities (ANSI Z-136.3-2005 or latest revision thereof). In absence of a separate guideline document for this purpose, the control measures specified herein shall be applicable for protection of personnel involved in administration of LASER, as well as for the patients if involved, unless otherwise authorised by the occupier of the organisation.

7.1.4 Multi-group Usage

Where more than one group is involved in setting up the LASER / LASER system and its operation, maintenance and usage, the responsibilities for safety should be clearly defined.

7.1.5 Categories of Control Measures

Control measures are categorized, in general, under three groups: engineering controls, administrative controls and personal protective equipment (PPE). Engineering control measures include features incorporated by the manufacturer, the developer or the user in the LASER, LASER system and/or its application environment including the beam path, which prevents human access to hazardous levels of LASER radiation or to non-beam hazards. Administrative or procedural control measures specify rules and/or work practices intended to minimise the hazards when the engineering controls are inappropriate or not adequate. It covers the overall policy, including training, hazard warning, assignment of responsibilities and prohibitions. Personal protective equipment refers to protection worn by the individual. Administrative measures are used to ensure implementation of engineering controls, as well as govern the use of PPE where a combination of engineering and administrative controls stated herein are considered to be inadequate, to provide a reasonable level of protection. In the latter situation, which may arise, for example in R&D efforts, the LSO shall carefully review and institute alternate control measures, on approval of the LSC (LASER Safety Committee) or the authorised agency, and ensure that appropriate LASER safety and operational training is provided.

7.1.6 Supervised / Unsupervised Operation and Application

An important consideration while specifying the control measures is the presence or absence of trained operator(s) supervising the operation and application when a LASER is operating.

(a) Operation of Class 3B, or Class 4 LASER / LASER systems require direct supervision and visual surveillance of the LASER and its entire application or exposure environment by an experienced and trained operator, who shall take appropriate measures, including termination of LASER emission and shutdown of equipment or application, if any condition occurs, which is perceived to be unsafe.

(b) Operation of Class 1 LASER does not require supervision, surveillance, or application of control measures. However, as a general practice to guard against potential hazard classification errors, direct intra-beam viewing should be avoided.

(c) Unsupervised operation of Class 1M, Class 2, Class 2M, and Class 3R LASER requires the posting of clearly visible caution labels on the equipment, and at the entry of beam exposure area where applicable, as specified in Annexure V.

(d) Unsupervised operation of Class 3B or Class 4 LASER requires appropriate control measures preventing exposure of the unprotected potential spectators to hazardous levels of LASER radiation, adequate LASER safety training and protection to those who may be exposed, standard appropriate warning area signs and instructions, and above all, a prior permission by the LSO, confirming implementation of these measures.

7.1.7 Common Causes for Accidents:

Some of the causes of the commonly occurring LASER related accidents, arising from beam and non-beam hazards, are listed below. These may not be mutually exclusive nor arranged in any specific sequence. A few examples of accidental exposure to LASER beam hazards are provided in Annexure III.

(a) Avoiding the use of appropriate eye protection where applicable.
(b) Inadequate hazard evaluation while altering experimental set-up.
(c) Intentional intra-beam viewing, or viewing close to beam direction.
(d) Improper methods of handling high voltage equipment.
(e) Failure of temporary safety arrangements.
(f) Lack of familiarity with LASER equipment and optical components.
(g) Unprotected viewing of LASER irradiated targets, or LASER-generated plasmas.
(h) Unanticipated exposure of the operator, or spectator, to LASER beam during alignment or usage.
(i) Photochemical hazards from incoherent optical sources used in optical pumping.
(j) Equipment malfunction and improper post-service restoration.
(k) Improper introduction of components or materials, in the beam paths.
(l) Stray reflections and upwardly directed beams.
(m) Ignition of materials.
(n) Failure to follow standard operating procedures (SOP).

In view of the interdependence of the different categories of LASER safety control measures, particularly in R&D environments, it is necessary to extend the iterative approach stated earlier in the context of hazard evaluation and risk assessment, to the process of identifying an appropriate mix of various control measures that would contain the hazard. Therefore, the specifications for control measures in the subsequent sections, while specified under different categories in general, do not maintain a strict differentiation between the categories (engineering, administrative and protective equipment) in all the cases. For the same reason, overlap in stating the control measures, or the repetitions, have not been strictly avoided. However, as stated above, the hierarchy of determining the control measures with engineering controls taking preference over administrative controls, and personal protective equipment being the last resort, need to be maintained. Similarly, the control measures should be determined, after an experienced assessment of the applicability is conducted by the LSO. These are not stated here explicitly for each case. Appendix F provides a summary of control measures, engineering as well as administrative and procedural, to assist a preliminary assessment.

7.2 Engineering Controls for LASER Beam Hazards

Engineering controls are based on the approach of enclosing and/or mitigating the hazard by various engineered means built into the LASER equipment, as well as incorporated in the applications and in the environment in which beam hazards may exist, as enumerated below:

7.2.1 Protective Enclosures

Total hazard containment by protective enclosures should be considered as the primary means of preventing human access to the levels of LASER radiation above the applicable MPE at all the times. The beam path from the LASER equipment to the application and the potential scattered or reflected radiation should also be contained inside the enclosure.

The enclosures shall be designed to reduce the level of LASER radiation outside the enclosure, as well as to prevent unintended, or unauthorised, removal of the enclosure or part thereof which would allow access to hazardous levels of LASER radiation above the applicable MPE. In addition, the enclosures need to be constructed with appropriate materials which are stable and resistant to mechanical impact, heat and light. These should be opaque, or of sufficient optical density at wavelengths at which hazardous levels of radiation may exist inside the enclosure. These should also be resistant at all times to penetration by the LASER beam at its maximum emission level that may be incident on the enclosure.

If an enclosure does not meet all these requirements, it shall not be considered as a 'protective enclosure' and may be considered as a 'barrier', and other control measures are required, as stated in subsequent sub sections.

Any LASER, with a completely enclosed protective housing that includes all possible locations at which the beam may be present during its operation, or use, and with all applicable engineering controls, including interlocks as further specified below, will fulfill the requirements of a Class-1 LASER, for operation as an enclosed or embedded LASER.

All classes of LASER sources shall require protective enclosures, with further applicable qualifications under different situations, as provided in this Section. Protective enclosures for beam paths, from the source to the application, and where the radiation levels may exceed the applicable MPE, are specified in sub section 7.2.7.

7.2.2 Removal of Protective Enclosure

If the protective enclosure of a Class 3B, or Class 4 LASER / LASER system, or any part thereof is removed, or breached, to meet the work requirements such as in R&D activities, manufacturing, or servicing of LASER, thereby enabling access to the LASER radiation, the LSO shall carry out a hazard evaluation and ensure that control measures appropriate to the maximum accessible emission level are established. The LSO shall assess that these control measures are available and maintainable. These control measures may include, among others:

(a) Implementation of administrative and procedural controls, along with training
(b) Establishing a LASER control areas with limited access
(c) Reduction of accessible emission level to minimum necessary for the work
(d) Measures for eye protection
(e) Use of appropriate beam attenuators, beam stops, barriers, etc.

While applying these control measures, the LSO may need to distinguish between the enclosures of the LASER source equipment itself, and that of the beam path outside the LASER equipment (see sub section 7.2.7). In many R&D activities and the user-built LASER material processing set-ups, the user may not possess adequate training for safe operation within the equipment enclosure provided by the manufacturer. Such enclosures, containing Class 3B /

Class 4 LASER, intended for removal by authorised and trained service personnel, shall be interlocked, and designed to prevent casual removal.

7.2.3 Walk-in Protective Enclosure

In many circumstances, one or more Class-3B, or Class-4 LASER / LASER systems may be placed inside a large-sized protective enclosure that allows personnel within the enclosure, e.g., a suitable laboratory, custom-made large enclosure, or LASER facility building, with the beam paths completely enclosed, preventing access to hazardous levels of LASER radiation outside the enclosure. Such enclosures shall be provided with appropriate interlocks to be activated upon entry of personnel, or shall be administratively controlled, to preclude operation of the LASER. Only authorised and trained personnel, with appropriate PPE, shall be provided entry and means to override the interlocks where applicable, if LASER operation and beam access is required for alignment and testing. In R & D laboratories where tripping of the LASER by activation of door interlocks may be undesirable, the access to such labs shall be limited to authorised and trained personnel, realized by suitable hardware means, such as RFID/Biometric, etc. In such cases, an appropriate warning (see section 7.2.10) shall be implemented to avoid unauthorised entry.

7.2.4 Protective Enclosure with Viewing Windows

Viewing or observation windows on protective enclosures, particularly the walk-in enclosures, may be necessary, to permit inspection inside the enclosure, both for inspection of the process involving LASER generation or LASER application, as well as to meet additional safety requirements. Such additional safety requirements may also arise from the use of various equipment and instrumentation inside the enclosure. The use of viewing windows should be minimised, and remote viewing with TV systems should be used instead. Viewing windows, when used, shall be designed and located, to ensure that the level of LASER radiation at foreseeable viewing positions from outside the window is below the applicable MPE at all times during the operation of the LASER system, as determined by the LSO.

Flammability and potential release of LASER-generated airborne contaminants (LGAC), produced on exposure to the LASER radiation are additional important considerations in selection of the window materials.

In situations where authorised personnel are required to work inside a walk-in enclosure containing Class-3B or Class-4 LASER / LASER systems, which have been provided with viewing windows and not designed for protecting against direct incidence of the beam, there shall be supplementary protections through the use of interlocks, attenuators, beam blocks, LASER barriers, etc., and a suitable warning (see sub section 7.2.10) provided outside the enclosure. This step is necessary to protect a viewer from an inadvertent steering of a beam on to the viewing window.

The use of ‘collecting optics’ such as lenses/ curved mirrors or combinations thereof, including telescopes/endoscopes should not be allowed for observation through viewing windows, unless approved by the LSO.

7.2.5 Interlock Protection for Removable Enclosures

Protective enclosures containing Class 3B or Class 4 LASER / LASER systems, shall be provided with interlock systems designed to activate beam shutters and/or power supply trips on removal of all or a part of the enclosure, which would permit access to the enclosed LASER by unauthorised personnel. The features of the protection interlock shall consist of, but not be limited to the following:

(a) Fail safe designs which may incorporate redundancy, positive break, etc.
(b) Overriding or defeating the interlock may be allowed only when conditions stated in sub sections 7.2.2 to 7.2.4 are complied with.
(c) There should be a distinct warning (see sub section 7.2.10), when override is in operation.
(d) It shall not be possible to reinstate the enclosure, with the interlock remaining overridden or defeated.
(e) Resetting the interlock and replacing the enclosure shall not allow automatic restart of the LASER, or removal of the beam shutter, but should require manual ‘start’ activation.

7.2.6 Master Switch or Key Control

Class 3B or Class 4 LASER should require a master switch / key for activating start up that under normal operating conditions would result in beam production, and for affecting shutdown or beam termination. The access to the key shall be restricted to the supervisory personnel (principle LASER user/ facility In-charge) entrusted with the responsibility to maintain safe working conditions. Multiple LASER when designed to operate under an integrated control system, may be activated by a single master switch/key. In R&D LASER development facilities where master key/switch has been disabled temporarily, or has not been implemented, access to the LASER system shall be restricted by administrative control.

7.2.7 Beam Path Conditions

The concept of an engineered protective enclosure to completely enclose hazardous levels of LASER radiation is effective only if the entire beam path, including the application, is also enclosed, preventing human being access to all the areas where LASER radiation above the appropriate MPE, or associated hazards above acceptable levels, might exist. It may be necessary, in this context to categorize the beam path of the LASER, and specify special control measures, after the beam emerges from a source that is itself designed to meet all the safety norms, as follows:

7.2.7.1 Completely Enclosed Beam Path

Completely enclosed beam path, satisfying the conditions applicable for Class-1 LASER/ LASER systems require no additional controls. Relaxation of the conditions shall require the LSO to carry out a hazard evaluation and implementation of appropriate controls.

7.2.7.2 Limited Open Beam Path

Limited open beam path**,** for Class 3B or Class 4 LASER / LASER systems shall require hazard analysis by the PLU, and approved by the LSO, to define the space (NHZ) over which LASER radiation is accessible at levels above the applicable MPE, and implementation of appropriate control measures in that space by the user. Such control measures shall confine the beam and its potential reflections, whether specular or diffuse, as well as secondary radiation that may be produced on interaction with matter, by appropriate secure means, so as to significantly and reliably limit potential access to hazardous levels of radiation.

Where the NHZ, after application of suitable engineering controls, is sufficiently limited to allow adequate protection through administrative control, applicability of Class-1 conditions may be assessed by the LSO through analysis and measurements and approved, subject to implementation of appropriate procedural controls, operator training appropriate to the enclosed /embedded LASER, and periodic reviews.

Relaxation of the engineering controls in such cases, for example, during set up and maintenance, shall require the use of protective equipment and application of control measures appropriate for servicing of the embedded LASER.

7.2.7.3 Completely Open Beam Path

Completely open beam path for Class 3B, or Class 4, LASER / LASER systems, where any part of the beam path or its reflections, whether specular or diffuse, is not sufficiently enclosed to prevent access to radiation above the appropriate MPE, shall be subjected to a complete LASER hazard evaluation and NHZ analysis by the PLU, and approved by LSO, and control measures appropriate to the evaluation shall be implemented. The evaluation shall require analysis of the application and the environment in which the LASER is used, as use of optics, and interaction of the LASER beam with materials may increase the direct or associated hazard potential. Appropriate control measures may require a ‘LASER control area’ to be established.

7.2.8 Beam Stop or Attenuator

A beam stop or attenuator, suitably designed to withstand the LASER beam intensity and prevent access to LASER radiation, in excess of the applicable MPE, when the LASER beam is not required, shall be permanently attached to all stand-alone Class 4 LASER / LASER systems. A Class 3B LASER / LASER system should be provided with such beam stop or attenuator. For Class 3R LASER, the requirement of a beam stop or attenuator should be determined on assessment by LSO.

Where multiple Class 3B or Class 4 LASER are used for a single application, for example with all the LASER / LASER systems enclosed within a protective enclosure that is separated from the application area, beam stops or attenuators shall be permanently provided at the beam entry location to the application area.

7.2.9 Remote Interlock Connector

For Class 3B or Class 4 LASER / LASER systems, with limited or completely open beam paths within a LASER control area, or a walk-in protective enclosure, the LSO shall evaluate the requirement for a remote interlock connector that would enable deactivation of the LASER, or reduce the output to level below the applicable MPE of the LASER, from the entryway of the LASER control area, or the walk-in enclosure. The entry access with such provision should be designed to prevent unintended interruption of LASER emission.

7.2.10 LASER Area and Activation Warning System

An audible tone, bell and/or visual warning (such as a flashing light) are recommended at the entry to a walk-in protective enclosure or a LASER control area containing a Class 3B LASER / LASER system. Such a warning system shall be compulsory for Class 4 LASER. The warning devices are to be activated on system start up, should be wired for automated activation, and shall be uniquely identified with LASER operation.

7.2.11 LASER Control Area

Wherever the entire beam path of a Class 3B, or Class 4 LASER, including its reflections, scattering, or secondary radiation, produced on interaction of the LASER with matter, is not sufficiently enclosed, such that a reasonably foreseeable risk or harm arising from the use of the LASER equipment may exist, a 'LASER control area' shall be established, and appropriate control measures instituted, as specified in this and the following sub sections. A LASER control area is recommended for other LASER hazard classes, excluding Class 1, where such risk or harm is perceived. The LASER control area shall encompass the applicable NHZ (see sub sections 4.5 and 5.5). The boundaries of the LASER control area shall be designed to ensure that (a) access to the area is adequately controlled, and (b) no foreseeable risk exists to persons outside the control area. The boundaries may be implemented by placement of suitable LASER barriers, designed to withstand irradiation at all times. Guidelines on the type of LASER control areas and requirement of control measures, adapted from existing safety standards (IEC 60825), are provided in Table 7.1.

Administrative and procedural control measures assume greater importance in LASER control areas, particularly where area or entryway engineered controls cannot be implemented without limiting the intended use of the LASER / LASER system. However, a suitably designed barrier or screen should be used at the entryway to block or attenuate the LASER in any unforeseeable event of being directed towards the entryway, such that the personnel without appropriate protective equipment shall not experience any exposure above the MPE, immediately on entry.

Whenever overriding interlocks become necessary during periods of special training, service, or maintenance, and access to Class-3B/ Calss-4 LASER is required, a temporary LASER control area shall be established following the specific procedures approved by LSO. These procedures shall outline all the safety requirements necessary during such operation within the NHZ. The requirement of NHZ analysis for Class 3R LASER should be based on assessment by LSO.

TABLE 7.1
LASER CONTROL AREA GUIDELINES FOR OPERATING LASER / LASER SYSTEMS
(subject to modifications on hazard evaluation and risk assessment by LSO).

LASER Hazard Class	Description of Area Control Requirement	Outline of General Protective Control Measures
Class 1 or Class 2	No requirement under normal operation.	Compliance with warning signs where applicable.
Divergent beam Class 1M or Class 2M	No requirement subject to procedural control over a short distance from the source (depending on divergence).	Training recommended; Prevent the use of eye-loupes, or other magnifying optics in the vicinity of LASER. Prevent re-focusing or collimation of beam.
Collimated beam Class 1M or Class 2M	Enclosure recommended. Access through procedural control. Where unenclosed, prevent unauthorised access in NHZ.	Training required, LSO recommended. Prevent the use of telescopes and binoculars.
Class 3R	No requirement subject to careful use.	Comprehensive operator training (safety and operation) recommended. Avoid direct eye exposure.
Class 3B	NHZ analysis and boundary enclosure required, with access and activation control by procedural measures.	Requirements: a. Posting of appropriate warning signs. b. Comprehensive operator training and LSO. c. Operation with LASER secured and well defined beam path. d. PPE, if exposure risk is unavoidable. e. Procedural control. Recommendations: i. Maximum enclosure, preventing emission above MPE through windows and entryways. ii. Beam termination in the beam stop of appropriate material. iii. Beam path above, or below the eye level in standing, or seated position, except with appropriate barriers and LSO approval. iv. Warning device.
Class 4	NHZ analysis and boundary enclosure required, with access & activation control by engineering measures, unless approved by LSO for accepting procedural control measures.	Same as those for Class 3B. Additional Requirements: i. Protection against associated hazards. ii. Rapid entry and egress facility. iii. Emergency stop (remote controlled) to deactivate LASER. iv. Beam path vis-à-vis operator eye position, as for Class 3B. v. Warning device

7.2.12 Outdoor Control Measures

All Class 3B and Class 4 LASER / LASER systems used outdoors require both conventional control measures as well as additional measures, to comply with appropriate public health and safety regulations, where applicable. The overall control measures shall be based on a combined hazard analysis and risk assessment by the LSO, the In-charge of the organisation and appropriate authorities. These control measures shall include, but not be limited to, the following:

For Class 1, Class 2, Class 1M, Class 2M and Class 3R: Control measures, as stated in Table 7.1 above, and as stated separately in this Section.

For Classes 3B and Class 4: Establishing the NHZ with appropriate warning signs, demarcation, administrative controls, to effect authorised entry with appropriate personal protective equipment.

Appropriate use of LASER barriers, screens, beam blocks, attenuators, etc., to confine and terminate the beam, wherever possible.

LASER demonstrations, LASER-based entertainment, or artistic systems, involving general public, whether used indoors or outdoors, are outside the scope of this 'safety guidelines'.

7.2.13 LASER Protective Barriers and Screens

LASER protective barriers and screens may be used inside LASER control areas and at entryways, to prevent inadvertently or accidentally steered LASER beams exposing personnel at radiation levels exceeding the appropriate MPE. Generally, such barriers or screens may not provide complete enclosure, requiring an NHZ analysis by the LSO, to assure that adequate safety is provided to personnel, while entering or working within the LASER control area.

While selecting LASER protective barriers or screens, factors, such as beam penetration by LASER-induced damage, flammability, and capability to release toxic fumes, or gases, or support combustion shall be taken into account, with due consideration to the applicable exposure duration which, in turn, should be based on total hazard evaluation.

7.3 Administrative and Procedural Controls

Administrative and procedural controls are implemented through the specified and documented rules and work practices, which may augment engineering controls, and are also required to implement the use of personal protective equipment. Such documented rules and work practices shall require approval by appropriate authority, as specified by the organisation's LASER safety management policy. Requirements of approval by the LSO, as stated in this document shall be deemed to imply approval by the said authority, which may involve recommendation by the LSO, or an authorised and appropriately qualified representative.

Although, as the hazard control measures, administrative and procedural controls need not include policy requirements prescribed by the LASER safety management system (see Section 6), such distinctions are subject to interpretation. Thus, LASER safety management policy requirements which are necessary for effective hazard control, are specified in this Section.

Administrative and procedural controls are generally applicable for Class 3B and Class 4 LASER. These may be prepared for a specific equipment, system, or organisation, and shall include the following:

7.3.1 Registration of LASER and LASER Users

Depending on the policy of the organisation, the registration of the LASER system and authorisation of its users with the office of the LASER Safety Officer (LSO) should be done. The forms for registration of the LASER and authorisations for LASER users are given in Appendix A.

7.3.2 Area Warning Signs and Equipment Labels

Equipment labels shall be attached on all the LASER equipment at conspicuous locations. In situations where attaching a label on a specific LASER equipment may not be feasible, e.g., in R&D labs and facilities which may contain unenclosed LASER under development or qualify as walk-in protective enclosures of LASER / LASER systems of higher hazard class than Class 1, an equipment label shall be placed at the entry of the lab or facility.

Equipment labels shall provide information regarding the type of the LASER, maximum output, class of the LASER, and appropriate cautionary statement, to avoid the hazards.

Area warning signs should be posted at the entry of the area, containing Class 3R LASER, and shall be posted at the entry of the area containing Class 3B or Class 4 LASER. The area warning signs shall prominently and conspicuously convey the presence of LASER hazard, severity of the hazard, spatial extent of the hazard where applicable, associated hazards and appropriate instructions, to avoid the hazard.

The details on area warning signs and equipment Labels are given in Annexure V. It includes the following:

(a) Blank template of LASER area warning sign or equipment label shown in Figure AN-V.1
(b) Samples of warning signs for different class of LASER are given in Figure AN-V.2
(c) The meaning and guidelines for the use of signal words on the warning signs and labels is given in the Table AN-V.1
(d) Information on the area warning signs and equipment labels.

7.3.3 Standard Operating Procedure (SOP)

Standard operating procedure (SOP) is a document that specifies operating, maintenance and service procedures, including appropriate safe work practices and information on the use of protective equipment. The In-charge or PLU of a Class 4 LASER / LASER system, or facility shall provide an SOP for approval by the LSO. An SOP is recommended for Class-3B LASER. The SOP shall be maintained with the LASER equipment, and used for reference by the operator, and the maintenance or service personnel.

Appendix C provides a sample format of the information that should be available in the SOP. The LSO shall assess and specify the complete information that may be required, as stated above, for approval, which may include alignment procedures (see sub section 7.3.4).

7.3.4 Alignment Procedures

Most of the LASER eye accidents occur during LASER alignment and beam handling operations. Such procedures must be performed with extreme caution. A written instruction is recommended for all recurring alignment tasks which may expose the operator to hazardous levels of radiation. Sample guidelines for LASER alignment and beam handling operations are given in Appendix E of this document.

Alignment of optical components, such as mirrors, prisms, lenses, beam splitters, etc., of Class 2, 3R, 3B or Class 4 LASER / LASER systems including the beam path to the application and thereafter within the NHZ, shall be performed with due and exhaustive attention to conceivable risks, such that the eyes of the operator, or other personnel, within the NHZ, are not exposed to radiation levels above the appropriate MPE, which may be produced by the primary beam, or specular or diffuse reflection of a beam, or any beam-induced secondary radiation. Such alignment tasks shall require the use of appropriate protective equipment, as deemed necessary by the LSO.

Documented outline of alignment methods should be included in the SOP for Class 3B LASER and Class 4 LASER, wherever access to the radiation is allowed during alignment. Wherever possible, the initial alignment of Class 3B or Class 4 LASER shall be performed, using appropriately attenuated beams, or using Class 1, Class 2, or Class 3R visible LASER as guide beams.

7.3.5 Personnel Training and Authorisation Requirements

Operation, the use, maintenance and servicing of Class 3B or Class 4 LASER / LASER systems, which may permit access to radiation levels, exceeding Class 3R AEL, shall be carried out only by authorised personnel who shall be provided appropriate education and training, to be confirmed by the LSO, prior to working on the LASER/ LASER system. Suitable education and training is recommended for personnel involved in operation, the use/maintenance and servicing of Class 1M, Class 2, Class 2M and Class 3R LASER, and Class 1 LASER, containing embedded Class 3B or Class 4 LASER.

General public or visitors shall not be permitted inside a LASER control area or a walk-in protective enclosure, containing operating Class 3B or Class 4 LASER, unless appropriate protective measures have been taken, preventing access to radiation levels above the applicable MPE during the period of the visit, the hazards including 'Do's and Don'ts, have been explained, and approval has been obtained from the Competent Authority, regarding the efficacy of the control measures.

Personnel who may be required to enter the NHZ of a LASER control area or a walk-in protective enclosure, for servicing, installing, or maintaining auxiliary systems, such as power supplies, associated equipment, utilities, etc., may be permitted, after obtaining approval from the supervisor, or appropriate user authority, such as the PLU, who shall confirm that such personnel shall not be exposed to radiation levels, exceeding the MPE, under any circumstances during such service work inside the area.

General features of education and training are provided in sub section 6.6.

7.4 Personal Protective Equipment

Personal protective equipment (PPE), in general, in the form of protective eyewear, clothing and gloves may be required to be worn by personnel only when all the prescribed engineering and administrative control measures are either not adequate, or deemed not reasonably practicable, to entirely prevent exposure to radiation levels above the applicable MPE. Thus, PPE shall not be used as the only or primary means for hazard control, and shall not replace or be used without engineering and administrative controls. PPE requirements for LASER beam hazards should generally arise within LASER control areas. PPE may have limitations, such as being damaged by the incident LASER radiation, and shall not be used as the only control measure where personnel may have access to high power Class 4 LASER / LASER systems, and shall be supplemented by other control measures per the decision/recommendations of the LSO.

PPE should be selected carefully, such that they do not excessively interfere with the normal functions that might potentially enhance some other hazard, as further indicated in the following sub sections.

Conditions for the use of PPE are specified below:

7.4.1 Protective Eyewear

Personally worn eye protection is generally in the form of ‘LASER safety goggles’ (secured with a head band) or ‘LASER safety spectacles’ (frames resting on ears) incorporating absorptive and/or reflective optical filters designed to reduce the transmission of the LASER radiation to levels below the applicable MPE.

Where protective eyewear has been specified as an appropriate and necessary method of risk reduction, its use within the corresponding NHZ shall be enforced through administrative requirement. In general, appropriate protective eyewear should be used within the NHZ of Class 3B LASER / LASER systems, and shall be used within the NHZ of Class 4 LASER / LASER systems. Working within the NHZ of Class 2, or Class 3R, LASER would generally not require use of protective eyewear except when intentional long term (>0.25 s) intra-beam viewing is required, or envisaged.

While selecting appropriate protective eyewear, the following factors shall be considered:

(a) Wavelength, multiple wavelengths, or wavelength band, of actual operation, as well as, operation capability of the LASER. This includes many LASER sources which may produce high brightness fluorescence, particularly when lasing threshold has not been crossed, and for which the accessible exposure level may exceed the applicable MPE, when observed close to the source.

(b) Worst case maximum effective exposure, for which protection is required, expressed in terms of irradiance or radiant exposure, averaged over the applicable limiting aperture and taking applicable exposure duration into account, as performed for hazard evaluation.

(c) Applicable ocular MPE expressed in same units as effective exposure.

(d) Optical density requirement as specified below:

(e) Actual worst case exposure and beam diameter, required to determine the ability of the eyewear to withstand a direct hit by the incident beam, when the applicable damage threshold is known (see sub section 7.4.1.1).

(f) Visible light transmittance at wavelengths, other than that/those for which protection is required, to enable tasks to be performed by personnel, using eyewear, including viewing of warning lights and other indicators. Ambient lighting should be increased, when visible transmittance is low, to minimise eye fatigue.

(g) Potentially hazardous specular reflection from the eyewear filter surface.

(h) Possibility of damage of the filter, when exposed directly to the maximum accessible level of radiation.

(i) Potential degradation or modification of the protective filtering effect, compromising its protective function, which may be caused, for example, by (i) nonlinear optical effects, such as saturated absorption, when exposed to high irradiances produced at the peak of ultra-short (e.g., femtoseconds) pulsed LASER; (ii) ageing effects produced by ambient conditions, such as high humidity, or cumulative effect of exposure to radiation.

(j) General design features, such as resistance to mechanical or thermo-mechanical shock and stress, wearing comfort and fit, ventilation to avoid fogging, peripheral vision, need for side shields, and damage possibility, or inflammability of frame material, when exposed to high power LASER irradiation.

7.4.1.1 Selection of Protective Eyewear

The LSO is required to approve the type and quality of the protective eyewear. The parameters of the eyewear which are required to be specified are:

(i) Optical density (OD**)**, D_λ, of the filter providing a measure of the transmittance of the filter at the LASER wavelength (λ). For sufficient protection, the value is given by,

$$D_\lambda = \log_{10}(H_{max}/MPE), \qquad \text{….. (eqn. 7.1)}$$

where H_{max} is the maximum reasonably foreseeable exposure (averaged over the applicable limiting aperture D_f, when the beam diameter is less than D_f), and expressed in the same units as that of the MPE. The OD should be sufficient to provide protection at all anticipated viewing angles and wavelengths.

For widely tunable LASER capable of producing an output having a narrow spectral line width, with its central wavelength tunable over a broad wavelength band, it may not be practicable to provide sufficient OD for protection over the entire wavelength band while retaining adequate transmission in some other part of the visible wavelength region. In such cases, alternative control measures for eye protection should be considered, including indirect viewing, through image converters, or remote viewing using cameras.

(ii) Damage threshold of the optical filter for direct exposure to the beam. The damage threshold depends on the type (pulsed or CW) and duration of the exposure, and may not be a well-qualified specification, except for a narrow range of LASER and exposure parameters. However, where protective eyewear is required for effective control of the hazard, it shall be necessary to ensure that the damage threshold meets the requirement. Some standards require both the filter and the frame to be designed to withstand a direct hit by the LASER, for some specified exposure conditions.

Special considerations for selecting LASER protective eyewear are provided in Appendix G. All the LASER protective eyewear shall be appropriately labeled, indicating the optical density and the wavelength(s) for which protection is intended.

Maintenance and inspection of LASER protective eyewear shall be performed periodically. Such tasks shall include cleaning of the filters, avoiding surface scratches, and inspection of the surface optical quality, discolouration, surface damage, and frame integrity. The frequency for periodic inspection and maintenance of LASER protective eyewear should be decided, based on an experienced assessment of its vulnerabilities, the potential of the accessible radiation level (irradiance in W/cm^2 and/or radiant exposure in J/cm^2, as appropriate) to cause damage by direct incidence, shelf life, and an estimate of the frequency of exposure, as well as, on the level of experience of the users. Whenever upon inspection the condition of an eyewear appears to be in doubt, it shall be tested thoroughly, before use, or discarded.

7.4.2 Skin Protection:

Where hazard evaluation for Class 3B or Class 4 LASER / LASER systems shows that engineering measures are not adequate to reduce the accessible emission levels to below the applicable MPE for skin damage, the use of appropriate skin protection measures shall be employed. This is of particular importance where chronic or repeated exposures to UV LASER radiation are anticipated, even if the exposure level is not significantly above the applicable MPE for skin. The protection measures may be in the form of skin covers, such as gloves, laboratory coats, and face covers, with consideration for flame retardant material, for Class 4 LASER. 'Sun screen' creams may be recommended for UV LASER, LASER welding/cutting applications.

7.5 Special Control Measures for Ultraviolet and Infrared LASER

UV and IR LASER are generally not visible, thereby increasing the hazard potential on account of difficulties in determining the beam path, or the areas exposed to diffusely scattered beams. Hence, in addition to the control measures, specified elsewhere in this document for UV and IR LASER and LASER systems, the control measures as specified below shall be incorporated, where considered necessary after a hazard evaluation by the LSO for Class 3R, 3B and Class 4 UV and IR LASER.

7.5.1 Special Control Measures for Infrared LASER

Surfaces which appear as diffuse reflectors in the visible region may act as specular reflectors of IR beams. Hence, appropriate IR absorbent materials should be used for termination of such IR LASER beams, or diffusely scattered radiation, where required. The material should also be fire resistant where Class 4 IR LASER radiation at levels exceeding the applicable MPE is accessible. IR absorbent materials should be inspected periodically, to determine possible degradation with use.

7.5.2 Special Control Measures for UV LASER

Surfaces which appear as good specular reflectors in the visible may scatter UV LASER beams significantly. Since exposure to UV radiation is harmful, it is important to contain UV radiation in the working environment as much as possible. While determining the protection measures, attention shall be given to the capability of the UV radiation to induce undesirable reactions on the exposed body parts of personnel, or in the working environment, producing hazardous contaminants, such as ozone and LGAC. Both skin and eye protection in the form of beam shields, gloves and long sleeves lab coats, when working near the beam, face and neck covers, and appropriate eyewear, shall be used to reduce the accessible radiation from UV LASER to levels below the applicable MPE. Proper ventilation shall be provided. Warning signs shall notify the possibility of enhanced hazard on chronic exposure to the persons under treatment with drugs that increase photosensitivity.

7.6 Special Control Measures for Fiber LASER/Fiber LASER Delivery System

Optical fibers are used in a variety of LASER systems and applications, for LASER generation as well as for delivery of the LASER beam to an application. Optical fiber cables/bundles and spliced components are also used in similar activities. Reference to optical fibers in this document includes all such systems. Control measures for widely used fiber-optic LASER delivery systems in optical fiber communication, healthcare facilities and LASER material processing industrial workstations require service level specifications, which are not within the scope of this document. Reference may be made to separate safety standards, such as ANSI Z.136.2, IEC-60825-2 (and latest revisions thereof), or other appropriate guidelines.

Generally, the control measures specified in this document also apply to the LASER radiation emitted from the output of fiber LASER and optical fiber LASER delivery systems. The fiber itself, with an appropriate sheath, provides a nominal protective enclosure to the radiation. However, special control measures are required because of the limitations arising from the use of fiber couplers, connectors and collimators in such systems, as well as occurrence of breaks in fiber/ sheath, which can provide access to radiation at levels above the applicable MPE. For example, while disconnecting the fiber from a collimating lens, direction of the emerging beam can change and also the beam may get focused, or reflected from the lens or from the coupler metal surface. The hazard level assignment applies to locations at which interruption of the fiber might occur under reasonably foreseeable conditions.

The special control measures nominally include the following:

(a) Warning notification is required on the device, indicating the hazard when the fiber is disconnected from a LASER, or a connector, enabling potential access to radiation at levels above the applicable MPE.

(b) R&D laboratories engaged in the development of fiber LASER, or fiber LASER delivery set-ups, involving disconnection and connection of fibers, and providing potential access to LASER radiation at levels exceeding the applicable MPE, shall be designated as LASER control areas, and appropriate control measures shall be applicable.

(c) Optical fibers shall not be connected to, or disconnected from Class 3B / Class 4 LASER systems, when the LASER are emitting at radiation levels exceeding the applicable MPE, unless a LASER control area or temporary LASER control area, is established, and all the associated control measures are in place.

(d) Particular care should be taken while manually manipulating optical fibers, if the radiation emitted from the fiber end exceeds the applicable MPE. Unlike fixed optical components, with precision mechanical control, commonly used for transporting or delivering a LASER beam, optical fibers, are flexible permitting unpredictable steering of the emitted beam, when handled manually.

(e) Care shall be taken to avoid stressing the fiber to an extent exceeding the manufacturer's recommendations, while handling and manipulating optical fibers, carrying LASER radiation in excess of the applicable MPE.

(f) Alignment of a Class 3R/ 3B or Class 4 LASER beam into an optical fiber shall be performed using fixed optical components, with precision controlled steering and focusing, and with appropriate eye protection.

(g) Glass windows shall be covered with shades, or filters of appropriate optical density whenever a fiber-optic LASER system is operational.

7.7 Control of Non-beam Hazards

Non-beam hazards associated with the use of LASER, as discussed in Section 3, are highly diverse in nature. Some of these hazards, e.g., electric shock, can be life threatening. Where such hazards cannot be eliminated by engineering design and written instructions in accordance with the provisions prescribed in applicable safety standards, competent experts on industrial hygiene and/or safety shall be involved to evaluate and specify the control measures, recommendations as well as mandatory requirements. Such situations may particularly arise in R&D labs, where, for example, a LASER may be used in a manner other than that intended by the manufacturer, or where a temporary power supply may be erected to energize a LASER. The nominal safety provisions recommended/required for the various non-beam hazards are provided below for following as a general practice, over and above those prescribed by standard safety practices. It should be noted that some of the hazards may fall into more than one category. Thus, a compressed toxic gas is both a chemical hazard and an explosion hazard.

7.7.1 Control of Electrical Hazards (nominal guidelines)

Although well-designed LASER products or associated power supplies, will not normally pose electrical hazards during operation, great care should always be exercised during installation, maintenance and servicing, or when other necessary work is undertaken, with the protective covers removed, and the interlocks overridden.

The following measures should be taken to control electrical hazards:

(a) All the electrical equipment used shall comply with the requirement of Indian Standard and maintenance schedule.

(b) Electrical safety training should be given to the operating and the maintenance personnel.

(c) All the personnel working with high voltage and/or current should be trained in cardiopulmonary resuscitation (CPR), and a CPR instruction chart should be conspicuously posted.

(d) When there is a possibility of exposure to high voltage, the following procedure should be followed:

    (i) Always follow the 'buddy system' while working.

    (ii) Label the LASER equipment with electrical ratings, frequency and watts.

(iii) Remove body-worn electrically conducting objects, such as rings, watches, bracelets, necklaces, etc.
(iv) Remove loose metallic objects from pockets.
(v) Work with one hand to eliminate the arm-to-arm electrical path.
(vi) Adhere to the lock-out/tag-out procedure during maintenance of the mains supply lines.
(vii) Ensure that the feet of operator, maintenance, or service person are not at ground potential.
(viii) Make sure the energy storage capacitors are fully discharged.
(ix) Employ a properly-designed grounding rod for discharging capacitors.
(x) Tools with insulated handles, should be used, while working on electrical equipment.

7.7.2 Control of Fire and Explosion Hazards (nominal guidelines)

Some safety standards specify CW average irradiances exceeding 10 W/cm^2, or beam power greater than 0.5 W, as possible ignition hazards. Average irradiances, exceeding 0.5W/cm^2, should be treated with caution.

(a) Fire retardant materials should be used for enclosures where the enclosure may be exposed to irradiance of more than 10 W/cm^2, or beam power exceeding 0.5 W.
(b) High pressure discharge lamps used in optically pumped LASER and high energy capacitor banks used in power supplies of pulsed LASER should be enclosed in suitable protective housings.
(c) While using high power LASER, all the components in the path of the LASER beam including beam steering mirrors should be checked for possible absorption and shattering, and enclosed accordingly.
(d) Avoid irradiation of electrical insulation and plastic tubing by intense beams, taking special care when the beam is not visible, or, for example, when the LASER protective eyewear interferes with clear viewing of the beam spot.
(e) Electrical sparks may cause ignition. Liquid circulation through insulated plumbing may produce electrical charge build-up, increasing the hazard, if the liquid is flammable, observed, for example, in liquid dye solution circulation systems.
(f) Limited quantities of flammable liquids and gases should be kept at work place. Secondary containment should be used, to prevent spreading of flammable liquids.
(g) Appropriate fire extinguishers should be available in the LASER laboratory.
(h) General safe practices for handling of gases and liquids should be followed, which include:
    (i) All plumbing for inflammable and hazardous fluids should be securely connected.
    (ii) Transfer of flammable liquids and gases should be done in a well-ventilated area, which is free from source of ignition.
    (iii) Gas cylinders should be placed in a suitable ventilated area, and held securely. Flammable and oxidizing gases should not be stored together. Standard operating procedures should be developed for safe handling of compressed gases.
    (iv) Circulation systems for flammable and toxic fluids shall incorporate emergency shutoff on detection of unacceptable level of leaks.

7.7.3 Control of Chemical Hazards (nominal guidelines)

The exposure limits for chemicals in various forms should be as per Permissible Limits of Exposure, as given in the Factories Act, 1948, or the Threshold Limit Values (TLV), as given in the booklet from American Conference of Governmental Industrial Hygienists (ACGIH) titled 'Threshold Limit Values (TLV) for Chemical Substances and Physical Agents' (latest version). Special control measures for handling LASER dyes and LASER dye solutions are provided in the next sub section.

(a) When toxic gases are used as lasing medium, exhaust ventilation shall be used to remove gases that could escape into occupied areas.
(b) Toxic gas cylinders should be placed in a ventilated (exhausted) cabinet. In the case of highly toxic gases, gas cleaning cartridges should be provided to the exhaust line.
(c) All gas cylinders used for the LASER system shall follow the requirements of the Gas Cylinders Rule, 2004.
(d) As far as possible, less toxic chemical should be substituted for one that is highly toxic.
(e) Where corrosive chemicals are handled, safety shower and eye-wash fountain should be installed.
(f) Necessary personal protective equipment, such as respirators, hand-gloves, lab coats etc., should be available, while handling hazardous chemicals.
(g) Material safety data sheets (MSDS) should be available for chemical safety information.
(h) LASER application processes, assessed to be capable of producing hazardous levels of LGAC, should be enclosed by physical barriers, and applications requiring manipulation should be handled inside such housings through master-slave manipulators, or remote control apparatus. These engineering measures are particularly important for LASER welding or cutting of targets, such as plastics, biological material, and coated metals. In addition, exhaust ventilation systems, including ducts, hoods, fans, etc., designed in accordance with the provisions prescribed in the applicable industrial hygiene norms, should be used. Respiratory personal protective equipment may be used for short duration exposures.
(i) Chemical waste generated in LASER operations should be disposed, as per the National Regulations.

7.7.4 Control Measures for Handling LASER Dyes and Dye Solutions (nominal guidelines)

(a) Do not eat/drink/smoke near work areas where dyes/solvents are used.
(b) Keep dye solution and solvent in tightly closed containers, with proper labeling.
(c) Dye solution and solvent should be kept away from sources of ignition.
(d) Dye solution circulation pumps and systems should be inspected, maintained, and tested on a regular basis for possible leaks, overheating, and improper electrical grounding.
(e) Liquid dye LASER should never be left / operating unattended.
(f) LASER dye powders should be handled in such a manner so as to prevent inhalation of airborne dust. Dye solution must be prepared only in a properly functioning fume hood.
(g) Protective gloves, facemask, apron and eye glasses must be used when handling / cleaning / disposing dye powder and dye solutions. The gloves being used should be resistant to the solvent being handled.
(h) Mixing of dyes and solvents should be done carefully, so as to avoid spilling. Any spills or leaks should be cleaned up immediately.

(i) Accumulation of dyes and solvent in the LASER facility should be avoided and the amount of the solution prepared by mixing dyes and solvent should be limited for the immediate use.

(j) All pumps and dye reservoirs must be placed in trays, with sufficient capacity to contain all of the dye/solvent, in case they leak.

7.7.5 Control Measures for Cryogenic Fluids (nominal guidelines)

(a) When handling cryogenic fluids, such as liquid nitrogen, protective equipment such as gloves, protective clothing and face shields must be used, to prevent freeze burns to the skin and eyes, or worse damage, such as sticking of the skin on contact with cold metal.

(b) Periodic monitoring of oxygen concentration should be carried out, depending on an assessment of the capacity of the cryogenic fluid to alter oxygen concentration, depending on its quantity, environment and mode of use.

(c) Sealed containers/reservoirs and piping of cryogenic fluids where used shall be qualified by competent experts to eliminate potential explosion hazards caused by boiling of the liquid due to faulty thermal insulation and inappropriate pressure relief valve, or other mechanisms.

7.7.6 Noise Protection

Appropriate hearing protection, in accordance with provisions prescribed in applicable safety standards, shall be used, if accessible noise level exceeds safe limits, depending on the exposure duration. personal protective equipment, in the form of ear plugs, or ear muffs, are generally used. When using PPE, consideration should be given to the PPE interfering with the ability to respond to audio alarms, abnormal sounds, or change in sound patterns, which would otherwise alert an operator to a hazard condition.

7.7.7 Control of Non-beam Radiation Hazards (nominal information)

Non-beam radiation hazards associated with production and the use of LASER (see Section 3) include (a) collateral radiation hazards, such as X-rays, UV, visible (bright fluorescence), microwave and RF generated by LASER system components or interaction of the LASER with materials and (b) plasma radiation, including broadband radiation and ionizing radiation (high energy charged particles, neutrons, high energy X-rays), produced as a result of interaction of high-intensity LASER radiation with matter. Control of non-beam radiation hazards includes engineering controls, administrative controls and personal protective equipment.

Engineering controls include shielding and isolation. Shielding is highly dependent on the shield material and construction for each spectral region for electromagnetic fields and characteristics of ionizing particles. Isolation may also be used to segregate the operator and process such as interlocked access door, in accordance with the provisions prescribed in applicable safety standards and guidelines.

Administrative controls include increasing distance and reducing exposure duration. Locating workstation or control panels, away from the source will decrease exposure levels. Exposure levels for RF and UV radiations should be below the safe limit exposure levels specified by the applicable safety standards and guidelines.

Personal protective equipment (PPE), if properly selected and used, is generally effective for optical radiation in the UV, visible, IR and, to some extent, for the X-ray region. This includes eye, face, hand and body protection. However, PPE may be inappropriate for microwave and RF fields.

Control of non-beam radiation hazards shall be implemented, in consultation with the LSO, and where necessary, with concerned experts, in accordance with the provisions prescribed in the applicable regulations and guidelines.

7.8 Guidance for Hazard Identification, Evaluation and Risk Assessment

Two types of document formats are generally used for LASER hazard identification, risk assessment, and assessing adequacy of control measures. One approach uses a checklist format that lists queries to determine whether the applicable safety control measures, for a specific LASER / LASER system, are implemented effectively or not. This is a 'LASER inspection/audit' based approach that relies on instructions regarding the applicable safety control measures as prescribed in safety standards or regulations, to audit the safety status and thereby bring out the deficiencies, if any. The other type of documented approach that may be referred to as 'LASER risk assessment', provides a stepwise-procedure pro-forma, to record an analysis and assessment of the foreseeable hazards, risks, and applied control measures vis-à-vis those prescribed, to assess the residual risks, if any. The second approach requires the risk to be assessed based upon a grading of the severity of the harm in three or four levels, e.g., minor, serious, major, extreme, and the probability of exposure to the hazard also graded in levels, such as certain, likely, unlikely, rare, etc. Thus, this risk assessment approach is qualitative using subjective judgments, to some extent.

Both approaches require brief description of the LASER system, and the application process and set-up including the beam delivery and beam path layout, the environmental conditions, the users, and identification of the parts of the life cycle relevant to risk assessment. Where the detailed information is not provided, as a part of the form, these should be provided in accompanying documents, such as the LASER Registration form, or the SOP.

It is recommended that both approaches be instituted as a part of policy requirements, or administrative control measures, in the following manner:

A 'LASER inspection form/checklist' is recommended for auditing the control measure requirements for an existing installation or set-up, for which a risk-assessment has been completed. A sample form is provided in Appendix B. The auditing shall be carried out periodically, listing any deficiencies and recommendations by a designated user, and assessed by the LSO, for approval, or initiating action.

A 'LASER risk assessment form' is recommended for assessing the risks, safety control requirements and effectiveness of control measures for new installations or set-ups, or whenever any modification to an existing set-up is envisaged. A sample form is provided in Appendix H. The risk assessment form shall be filled by a designated user, in consultation with the LSO, where necessary, and approved by the LSO.

The 'LASER risk assessment' approach is based on systematically addressing the different aspects of the hazards, risks and control measures, and can be grouped for convenience into a few broadly defined steps as outlined below, which are neither exhaustive nor exclusive, and should be applied iteratively in an integrated manner, to achieve an effective assessment. The first step in this iterative LASER risk assessment procedure would be to identify the hazards, assuming that the protection control measures are not available, followed by risk assessment vis-à-vis the existing control measures, and subsequent follow-up action.

Step1: LASER equipment & application hazard identification:

As a general rule, this step requires identification of every reasonably foreseeable hazardous situation, including the beam and the non-beam hazards that could arise during any, or all of the applicable stages of development, installation, operation, maintenance, servicing, and experimentation on, and with the LASER, as well as reasonably foreseeable misuse, or failure.

(a) LASER Equipment

Determine the hazard class of the LASER(s), corresponding to the accessible beam(s) exiting the equipment. This information may be provided by the manufacturer, with appropriate certification. For LASER / LASER systems, under development, prototypes, etc., the hazard class shall be certified by the LSO based on the system information provided by the designated user. (see Tables 4.2, 4.3 and Section 5).

In situations where there is a need to work on the LASER equipment, for example, while aligning a R&D LASER system, consider all the beam hazards that may arise from reflections from optical components, or specular/diffuse reflecting surfaces, particularly, for all possible orientations of the components that may be encountered in the course of work. Consider potential hazards arising from reflection from the personal wears, tools, beam viewing cards, or burn papers, particularly, while inspecting from a short distance. Consider potential alteration of beam characteristics such as wavelength, beam size, temporal characteristics, beam polarization that may produce a hazardous reflection from a polarizer. Consider possibility of occurrence of damage of components, while making adjustments which may produce hazardous reflections, or scattering from the damage spot.

Determine all non-beam hazards related with the production of the LASER beam. Consider hazards arising from the use of utilities, services and the use or generation of hazardous materials and radiation. Consider the hazards arising from potential failures of the equipment, or its sub-systems, such as leakage of cooling fluids, or hazardous gases/vapour, failure, or inadvertent shutdown of cooling pumps, failure of mechanical fixtures, explosion, or implosion of containments, etc.

(b) Beam Delivery

To start with, determine all beam related hazards, starting from the output aperture of the equipment to the beam stop, including the entire experimental set-up, assuming that the beam is accessible to persons working on the system, assisting, or watching, and can enter an unprotected eye, or be incident on the skin. Creating beam-path layout drawing, showing the boundary rays (1/e or $1/e^2$ of the irradiance spatial profile) of the beam, is highly recommended. Consider exposure conditions, such as duration of exposure, exposure to specular/diffuse reflections, not only from reflecting/opaque components, but also from transmitting lens surfaces, vacuum chamber windows, and the target itself where applicable, that may melt and produce a specular reflection, with uncharacterised beam characteristics, e.g., producing a reflected focused beam. Focused beams may enhance the hazard potential over a part of the beam path. Plane surfaces will produce a focused beam, if the incident beam is converging. Consider possibility of hazard enhancement by scattering from the LASER-induced surface/bulk damage in optical components, nonlinear optical processes that may become noticeable only at high irradiance, or potential malfunction of automated beam steering components, e.g., robotic arms used in LASER material processing workstations. Special considerations are required for fiber optic beam delivery systems, and beam delivery of UV and IR LASER.

Consider all associated non-beam hazards involved in beam delivery, such as electrical hazards from the use of electrical equipment for automated steering of the beam, in executing the experimental application, and the use, or generation, of hazardous materials.

(c) The LASER Application Process

Apart from the LASER beam hazards associated with the actual experimental system that are indicated in the step 1(b), consider additional beam hazards that may arise from production of coherent beams from the process itself in a direction same as, or different from, that of the incident beam; alteration of beam characteristics as stated in step 1(a); accidental movements of the components that may produce beam deflections, exposing personnel, or may introduce a hazardous, such as a flammable component, in the path of the beam. Consider non-beam hazards such as generation of collateral radiation, plasma radiation, gases, fumes, fires, material rupture, or explosion.

(d) The Environment

This involves analysis of the influence of the location of the LASER vis-à-vis the working area, on its hazard potential. Two situations are distinguished – indoor LASER operations where the use is within a control area, such as closed research laboratories, enclosed work stations, factory production lines, etc., and outdoor LASER operations such as free space communications, military field applications, outdoor engineering work, LASER remote sensing, environmental monitoring, etc.

Apart from location, some of the relevant issues in this category that influence the hazard evaluation are as follows: stability of the equipment support system such as a LASER platform; space congestion for operation, maintenance and application; illumination; operational complexity; presence of flat or curved specular reflecting objects other than those considered as a part of the beam path or enclosure (e.g., windows/ mirrors/polished surfaces in vehicles, buildings, constructions, free water surfaces, wet leaves, etc.); permanence of these objects near the beam path or the permanence of the beam path itself; whether the LASER is in an area, with or without public access.

An important task here is to determine the NHZ (see Section 5), wherever the output beam of a Class 3B, or Class 4, LASER is present, and the beam path is not enclosed. Due consideration should be given to the possibility of the use of optical instruments that may increase the hazard, or whether even diffuse reflection from any object could pose a hazard. Presence of curved objects, with concave specular reflecting surfaces, may need the NHZ to be estimated carefully.

Additionally, any possibility of the non-beam hazards being enhanced by the environmental factors should be considered.

Step 2: Consideration of persons at risk:

This step of risk assessment takes into consideration the number of the persons at risk, their level of awareness, training and availability of protection. Thus, the considerations for assessment would depend on whether the people at risk are, for example, skilled and trained scientists and operators or onlookers, visitors, contractor’s employees, other members of the public, or children, who may not understand warning signs, or labels, etc.

Assessment of the maturity of the judgment of the LASER users and even that of the other persons involved in the activity could play an important role in risk assessment and selection of control measures. One of the major responsibilities of such people would be to proactively anticipate and avoid aiming, or steering, the LASER beam at others, or at mirror-like surfaces, and applying their mind to avoid potential unforeseen exposures, when less-informed persons are present in the vicinity.

Consider how the persons might be exposed to the hazards under reasonably foreseeable misuse, or failures.

Step 3: Assessment of risk

In executing this step, the existing control measures are taken into consideration. For risk assessment, each of the potential hazards identified through the procedures outlined in steps 1 & 2 should be assessed separately, for the likelihood of exposure to the hazard vis-à-vis the existing control measures, and the severity of the injury. Owing to difficulties in quantifying these parameters, a qualitative or semi-quantitative graded risk assessment is applied, that combines the two factors, and produces the risk assessment in terms of three or four levels, such as low, medium, high and very high/extreme.

The classification of the hazard class of the LASER is itself based on a graded risk assessment. It needs to be supplemented with the assessment of the overall risk from the other factors discussed above.

The salient features of the risk assessment and its outcome must be documented for safety audits and for information of for the persons working on, or with, the LASER / LASER system. The sample form in Appendix H has provisions for recording the assessment.

Step 4: Identification of actions

The risk assessment form must have provisions for recording a set of recommendations and actions for implementation of the additional control measures required to remove the risks, or reduce the risks to an acceptable level. Specific dates, and the persons responsible for implementing the actions, should also be recorded.

Step 5: Review

The risk assessment exercise needs to be repeated, to review the residual risks, followed by selection of additional control measures until the risk from all the potentially harmful situations has been reduced to an acceptable level.

Thereafter, the safety audit or inspection should be carried out at regular intervals, and the risk assessment procedure should be repeated where necessary, as mentioned above.

The procedure for hazard evaluation and risk assessment should be carried out to a satisfactory level, before the LASER is used, with the control measures in place.

7.9 Product Safety Requirements for LASER / LASER Systems

The following safety control measures should be incorporated by design in a LASER / LASER system, and by contract where applicable, if it is to be handed over as a product to any other agency, for commercial or any other use.

(a) Protective Enclosure

Protective enclosure shall be provided to limit access to LASER radiation, other than the radiation emerging through the LASER aperture.

(b) Interlock

Interlock shall be provided to protect personnel from HV sources and LASER, or collateral radiation exceeding the applicable MPE if the protective enclosure is removed. Audio, or visual indication readily visible through protective eyewear, shall be used when the interlock is defeated for servicing, and interlock status shall be restored when the enclosure is put back after servicing.

(c) Identification Label

A durable identification label shall be permanently fixed to the protective housing of the device, so that it is readily accessible to view. The label should contain the full name and address of the manufacturer, the place, month and year of manufacture and serial number of the device.

(d) Location of Controls

Manual controls for operation and adjustment shall be located, so that exposure to LASER radiation, in excess of the appropriate MPE, is avoidable during operation.

(e) Emission Control

The device design, even after switching on, should disable LASER beam emission at levels exceeding the applicable MPE, except when enabled by intended operator action, for example, by opening a suitable beam shutter.

(f) Unspecified Modes of Operation

The design should preclude self-generation of unspecified modes of output over the entire range of rated operating parameters, such as mode-locking, or unwanted pulsing, when not specified explicitly in specifications. Where adjustment of operating parameters or internal components may produce modes of operation that are not part of the standard product specifications, or cause optical damage thereby enhancing the hazard, it should be stated in the operating manual and service manual.

(g) Secondary Radiation

The LASER, associated optics and enclosure should be so designed as to preclude emission of external secondary beams (such as reflection from polarizer, transmitting optics, or transmission of unconverted fundamental wavelength output beam, after frequency converters) or radiation (such as flash lamp or high brightness fluorescence) exceeding the applicable MPE that may be generated, but not required for functional use of the product.

(h) Beam Irregularities

Irregularities in the beam such as presence of irregular modulations in the irradiance profile (hot spots), should be minimised by design.

(i) View Ports

View ports should not be provided, unless necessary for functional use, and shall be designed to prevent access or attenuate accessible radiation levels to the applicable MPE.

(j) Warning Label

LASER hazard warning label vide Figure AN-V.2 shall be affixed near the emission aperture.

(k) User Manual

A suitable user manual, containing, among other information, the following information pertaining to the safe use of the product as applicable based on the hazard class of the LASER, and the corresponding control measures stated in this document shall be provided.

(i) Prominently stated information, regarding potential hazards arising from the LASER beam and its use, as well as from non-beam hazards.

(ii) Warning regarding modifications, or the use of a part of the system, not intended in the original design, as such actions may enhance the hazard.

(iii) Means for hazard control which have been incorporated in the system, and what has to be provided by the user, such as protective eyewear, including recommended sources.

(iv) Standard operating and maintenance procedure, including safe operating practices and emergency response actions.

(v) Requirement and availability of training programs suitable for the use of the LASER, as well as for LASER safety officer and servicing personnel.

(l) Class 3B or Class 4 LASER Product

In addition to satisfying the engineering control requirements stated in this Section for Class 3B or Class 4 LASER/ LASER systems, the following provisions shall be present:

(i) Emission indicator - A readily visible emission indicator at a suitable location to warn the operator, or other personnel, in the vicinity, when the LASER is energized.

(ii) Remote interlock connector, enabling the user to provide door switch interlock and emergency stop button outside the room in which the LASER product is located.

(iii) A secure key or some suitable control device, for starting the LASER, ensuring that LASER emission is not possible, with the key/device removed.

8. REGULATORY REQUIREMENTS

8.1 Introduction

The Section 87 of the Factories Act, 1948, gives the power to make rules for any manufacturing process, or operation, which exposes any person employed therein to a serious risk of injury, poisoning or disease, called as dangerous operation. Based on the provisions of this Section, ‘LASER and Optical Radiation’ is declared as dangerous operation under rule 88 of the Atomic Energy (Factories) Rules, 1996. The schedule XIV of the Rule 88 prescribes safety provisions for four hazard classes of LASER. This ‘safety guidelines’ may be used to supplement the rules, by providing a detailed procedure, to determine LASER hazard class, and apply the engineering and administrative control measures for safe design, installation and operation of LASER/LASER systems.

8.2 Regulatory Approach

The objective of this Section is to ensure compliance with the safety aspects with respect to LASER in R&D as well as industrial facility of DAE under the purview of AERB. The hazard evaluation procedure used is based on the ability of the LASER beam to cause biological damage to the eye, or skin during the intended use, and is related to the classification of the LASER / LASER system from Class 1, considered to be nonhazardous, to Class 4 that is highly hazardous.

The basic approach for hazard classification and evaluation are discussed in Section 4, whereas detailed procedure for evaluation and classification of LASER hazard is given in Section 5There should be well defined organisation system where in accordance with the recommendations in Section 6, the LASER / LASER system should be reviewed by LASER Safety Officer (LSO) or LASER Safety Committee, and the details shall be maintained in the register by LSO where LASER is allowed for use/operation.

If the hazard class of the LASER / LASER system is evaluated as Class 3B or Class 4, permission for operation of the LASER shall be taken from AERB. If there is significant hazard due to toxic and flammable chemicals used in the LASER/ LASER system or if there is ionizing radiation hazard, the licence shall be required from AERB for use/ operation of the LASER / LASER system.

8.3 Regulatory Clearances for LASER/ LASER System in DAE Facilities

The purpose of regulatory clearances, the In-charge/ Principal Laser User (PLU) of the LASER / LASER system shall submit the application along with a copy of Form-1 of Appendix-A and the list of authorised users to AERB. The regulatory clearances required for LASER / LASER system from AERB are given in the following sub sections:

8.3.1 Licence for LASER Facilities

Regulatory clearance in the form of the licence shall be required for:

(a) High power LASER which are capable of generating significant ionizing radiation due to interaction of LASER beam (such as Ti:Sapphire Terawatt/Petawatt LASER) with materials, or capable of inducing radioactivity in the material associated with LASER system.

(b) LASER used for processing/ enrichment/separation of nuclear/radioactive materials.

(c) LASER using highly flammable liquid or flammable gas, or toxic chemical, as active media for generation of LASER

The application for issue of the licence shall be submitted to AERB along with information mentioned in sub section 8.3 and the safety report of the LASER/ LASER system.

8.3.2 Authorisation for LASER Facilities

Regulatory clearance in the form of the authorisation shall be required for all LASER of hazard Class 3B or Class4. The application for the authorisation shall be submitted to AERB along with information mentioned in sub section 8.3.

8.3.3 Exemptions of LASER from Regulatory Clearances

All the Class 1, Class 2 and Class 3R LASER/LASER system designed/developed or used by DAE facilities under purview of AERB are exempted from taking any licence/ authorisation from AERB, considering the low hazard potential. However, LSO shall ensure that these LASER comply with administrative and engineering control measures specified in the 'safety guidelines', which would be subject to verification during regulatory inspection.

8.4 Suspension, Modification or Withdrawal of a Regulatory Clearance

In case of significant deviation from the control measures required as per the 'safety guidelines' or contravention of any stipulations mentioned in the regulatory clearance are observed, Chairman AERB may suspend the operation for a specified period of time, or modify or revoke the terms and conditions of the regulatory clearance.

APPENDIX A

(Sample – may need to be altered, in accordance with actual requirements, and approved by LSO)

LASER REGISTRATIONS AND USER AUTHORISATIONS

Form 1: Registration of LASER and/or LASER System

(1) Location (Building, Room No.): ___________________________

(2) Name of the In-charge/ Principal LASER User (PLU): ___________________________ ; Department: ____________;
Phone: _______ ; Email: ____________ Mobile : __________

(3) LASER / LASER system type & identification (name according to LASER medium & mode of operation, manufacturer / developer for R&D system, ID No. = model & serial number / designation by user):

____

(For LASER systems, comprising two or more LASER, provide description of each in the following table)

(4) LASER specifications

S. No.	LASER Type	ID No.	CW / Pulsed	Wavelength (s) (nm)	Diameter at Exit (mm)	Far field Divergence (mrad)	Radiant Power (W) or Radiant energy (J)	Pulse Duration (s)	Pulse Repetition frequency (Hz)	Beam Accessibility (during use / maintenance / service)	Hazard Class (by manufacturer / developer / LSO)	Date of Purchase / Installation

(5) Applications (List and brief description of all envisaged applications)

____

(6) Environment and enclosures (Describe briefly: enclosure, interlock features-local, remote, defeat. attach layout drawing showing usage of beams, optics and enclosures for beam/ secondary reflections, enclosure materials, windows, entryways, barriers, etc.):

____

____

(7) Chemicals used for the LASER and the LASER applications (gases, liquids, solutions, solid powders, biological materials; mode of use, whether circulating/once through-flow rate, pressure, and frequency of refurbishment.)

____

____

(8) Utilities / services (Cooling water – temperature, flow rate, pressure; electrical power – V, I, DC/AC, power; room temperature / humidity controllers- location & specifications; vacuum pumps – specifications; circulation pumps – type, location, fluid, purpose, safety features; UPS – type, specifications) : ______________________________ ______________________________

____

____

(9) People who may have access to beam (Trained / untrained workers, visitors, unrelated persons)

____

____

Submitted by ____________________________

Date:

Signature:

Signature of In-charge/ PLU ___________________)

Name of In-charge/ PLU

<u>For Use by LASER Safety Officer</u>: Registration Number: __________

- Does Safety Measures reviewed? Yes/ No .
- Date on which hazard evaluation and risk assessment was carried out: _______

Whether risk assessment is required? Yes/No

Date:

Signature of LSO __________________________

Name/Seal:

Form 2: Authorisations of LASER Users / Operators

(1) Name of LASER operators: ____

(2) Designation: ________________ (3) Division: ____________________

(4) Details of LASER system where the person is working

S. No.	LASER System (ID No. Max. Output, CW/ Pulsed, Wavelength and Type)	Location	Name of In-charge	Hazard Class of LASER

(5) Years of experience in LASER operation: ______

(6) Any training received in LASER safety: Yes/ No

(7) If Yes, then the dates on which training is received, and duration of training:
Dates: _________________ Duration: _________

(8) Date of medical test carried out (eye and skin) : _____________

(9) Date of issue of fitness certificate, with name of the Doctor:
____

(10) Declaration by the LASER operator

(i) Any use of photosensitizing drugs: ____________ (to be informed to LSO, if applicable at a later date)
(ii) Any history of eye or skin photo-sensitivity of self, or family, to ultraviolet light: ____
(iii) Any previous hazardous exposure to LASER: __________________________

Submitted by	**Forwarded by**	**Approved by**
Signature: (___________________) Name of LASER Operator	Signature: (_________________) Name of In-charge	Signature: (__________________) Name of LASER Safety Officer

APPENDIX B

(Sample – may need to be altered, in accordance with actual requirements, and approved by LSO)

LASER INSPECTION FORM / CHECKLIST

(a) LASER system: ____________________

(b) Location: ________________________

(c) Name of the In-charge of the facility: _________________

(d) Purpose and brief description of LASER system:

____

____

(e) Number of persons using LASER: _____________

(f) Inspection performed by: _______________________________ Date _________

S.No.	Item	Y	N	NA	Remarks
1.0	Administrative and Procedural				
1.1	LASER are classified appropriately (Class 2, Class 3R, Class 3B, Class 4)				
1.2	Standard operating procedures are available (Class 3B and Class 4)				
1.3	Alignment procedures are available(Class 2, Class 2M, Class 3R, Class 3B and Class 4)				
1.4	Viewing cards are used for alignment				
1.5	LASER users underwent appropriate training				
1.6	Registration of the LASER system and all its users (Class 3B and Class 4) with LSO				
2.0	Labeling and Posting				
2.1	Appropriate warning/danger sign at entrance to LASER area (Class 3B and 4)				
2.2	LASER status indicator outside room (Class 4)				
2.3	Class designation and appropriate warning label present (all)				
2.4	Radiation output information on the label				
2.5	LASER aperture label in place				
2.6	Warning posted for invisible radiation				

3.0	Control Measures				
3.1	General control measures				
3.1.1	Protective enclosure present and in good condition				
3.1.2	Interlock on enclosure				
	Interlock functioning appropriately				
3.1.3	Beam shutter/attenuator present				
3.1.4	LASER beams above/below the eye level				
3.1.5	Beam is enclosed as much as possible				
3.1.6	Beam not directed toward doors or windows				
3.1.7	Surfaces minimise specular reflections				
3.1.8	Beams are terminated with fire-resistant beam stops				
3.1.9	LASER system secured mechanically				
3.1.10	LASER/beam delivery optics secured mechanically				
3.1.11	Windows in the room covered				
3.1.12	Operators do not wear watches or reflective jewelry while working on/with LASER.				
3.2	Special control measures for Class 3B and 4 LASER				
3.2.1	Interlocks on protective housing				
3.2.2	Service access panel present				
3.2.3	Limited access to spectators				
3.2.4	Nominal hazard zone determined				
3.2.5	Controls are located so that the operator is not exposed to beam hazards				
3.3	Special control measures for Class 4 LASER				
3.3.1	Fail-safe interlocks at the entry to the control area				
3.3.2	Area restricted to authorised personnel				
3.3.3	LASER may be fired/operated remotely				
3.3.4	Area designed to allow rapid emergency exit				
3.3.5	Emergency shut-off available				
3.3.6	LASER activation indicator on console				
3.3.7	Pulsed- interlocks designed to prevent firing of the LASER by dumping the stored energy into a dummy load				
3.3.8	CW- interlocks designed to turn off power supply or interrupt the beam by means of shutters				

3.3.9	Height of the LASER beam and height of computer monitor from the laboratory floor should be different				
4.0	Personal Protective Equipment (Class 3B and Class 4)				
4.1	Protection eyewear is appropriate for LASER wavelength(s)				
4.2	Protection eyewear has adequate OD				
4.3	Alignment/adjustment eyewear has adequate OD at applicable wavelength(s)				
4.4	Warning/indicator lights can be seen through protective filters				
4.5	Proper skin protection available				
5.0	Non-beam Hazards				
5.1	High voltage equipment appropriately grounded				
5.2	High voltage equipment located away from wet surfaces or water sources				
5.3	High voltage warning label in place				
5.4	Compressed gases secured				
5.5	Toxic LASER media in use				
5.6	Fume hood for dye mixing				
5.7	Cryogens in use				
5.8	Collateral radiation hazard present				
5.9	Fire and explosion hazard				
5.10	LGAC production				

Recommendations/ Suggestions

____

____

____

Signature of the In-charge/ PLU
of the LASER System

Signature of the Person
carrying out inspection

Cc: LASER Safety Officer

APPENDIX C

(Sample – may need to be altered, in accordance with actual requirements, and approved by LSO)

FORMAT FOR LASER SYSTEM STANDARD OPERATING PROCEDURES

1 LASER System Description

Include brief description of LASER system, with principle, location and purpose. Also, include the layout of the LASER system.

2 LASER Information

(a) Date:
(b) Wavelength
(c) Beam diameter (mm): ______
(d) Beam divergence (milli-radian)
(e) Mode
(f) Continuous wave (CW):
Average power (watts): _____ Maximum power (watts): ____
(g) Pulsed or Q-switched
Pulse length (s): ______ Repetition rate (Hz):______
Average energy (joules/ pulse): _____ Maximum energy (J/pulse): ____
(h) LASER hazard class assigned: _______

3 Information on LASER Hazard and Control Measures

List all the hazards for this LASER system, such as unenclosed beams, invisible beams, scatter potential, hazardous materials (dyes, solvents), fumes/vapor, electrical hazards, ergonomic concerns, etc. Against each hazard, mention the applicable control measure, such as engineering control, administrative control and personal protective equipment, etc. The hazards and the control measures can be listed in the tabular form as shown below:

S.No.	Hazard	Controls
1	Beam Hazards	
1.1		
1.2		
2.0	Non-beam Hazards	
2.1	Electrical: _________	
2.2	Chemical: __________	
2.3		

4 **Alignment Procedure** (as per guidelines provided in Appendix E)

5 **General Operation Checkpoints (as applicable under normal operation or maintenance)**

a) Warning signs posted	Yes/	No / NA
b) Warning light turned on	Yes/	No
c) Doors secured	Yes/	No
d) Target area preparation complete	Yes/	No / NA
e) Protective equipment on (correct eyewear)	Yes/	No / NA
f) Beam stops in place	Yes/	No
g) Authorised operators	Yes/	No
h) LASER control area defined	Yes/	No / NA

6 Sequence of Operation

(a) Start-up

(i) ____________________________
(ii) ____________________________

(b) Regular Operation/ Experimentation

(i) ____________________________
(ii) ____________________________

(c) Normal Shutdown

(i) ____________________________
(ii) ____________________________

(d) Emergency Shutdown

(i) ___________________________
(ii) ___________________________

7 Contacts

Department: ------------------ ---------------------------------
LASER location: ---
Principal investigator’s phone: ------------------------------ email: ------------------
Primary LASER operator’s phone: --------------------------- email: ------------------
LASER safety officer’s phone: ------------------------------- email: ------------------
Maintenance/repair phone: --------------------------------
Emergency contact/phone: --------------------------------

Prepared By:

Signature:
Name and Designation: _______________

Reviewed by:

Signature:
Name and Designation: _______________

Approved and issued by:

Signature:
Name and Designation: __________________

APPENDIX D

(Sample – may be altered in consultation with appropriate authorities & LSO)

LASER EXPOSURE INCIDENT REPORT

(Submit the form, for each LASER exposure, to LASER Safety Officer)

(1) Name of the exposed individual: ____

(2) Date of incident: _______ Time of incident:_____________________

(3) Status of the exposed individual: Registered user/ Other staff / Student/ Visitor/ Other

(4) Location where exposure occurred: __________

(5) Registration number of the LASER: _________

(6) Name of the In-charge of the LASER facility: ___________________________

(7) Name of witnesses: __________________________________

(8) Nature and apparent cause of the incident: _________________________________
____

(9) Exposure:
Eye exposed: Left ___ Right _____ Both _________
Skin exposed: ____________________
Exposure duration: Minutes_______ s _______________

(10) Personal protective equipment (PPE) available: Yes/ No
Used: Yes / No (Submit PPE, if used)

(Name and Signature)
PLU/ In-charge

(11) Details of the medical treatment (to be filled in by attending doctor):
____
____

(Name and Signature)
Medical Officer

To
LASER Safety Officer

APPENDIX E

GUIDELINES FOR LASER ALIGNMENT AND BEAM HANDLING OPERATIONS

(Sample – may need to be altered, in accordance with actual requirements, and approved by LSO)

E.1 Procedural Considerations

E.1.1 Workers

(a) To reduce accidental reflections, watches, rings, dangling badges, necklaces, and reflective jewelry are taken off, before any alignment activity begin. The use of non-reflective tools should be considered.
(b) Access to the room or area is limited to authorised workers only.
(c) Consider having at least one other person present, to help with alignment.
(d) Persons conducting the alignment should be registered LASER operator.
(e) A NOTICE sign is posted at entrances, when temporary LASER control areas are set up, or unusual conditions that warrant additional hazard information to be made available to workers intending to enter the area.

E.1.2 Equipment

(a) All equipment and materials needed are present prior to beginning the alignment.
(b) All unnecessary equipment, tools, combustible materials (if the risk of fire exists) have been removed, to minimise the possibility of stray reflections and non-beam accidents.
(c) Beam blocks must be secured.
(d) Beam paths should be set at a safe height, below/above the eye level, when working.

E.2 LASER Beam Management

(a) There shall be no intentional intra-beam viewing. Intra-beam viewing is not allowed unless specifically evaluated and approved by the LSO.
(b) Collinear low power 'guide' LASER, or adequate attenuation or power reduction of the high power LASER beam by other means should be used as guide for alignment of a high power beam.
(c) The beam is enclosed as much as practical. The shutter is closed as much as practical during coarse adjustments. Optics and optics mounts are secured to the table. Beam stops are secured to the table, or optic mounts.
(d) Any stray or unused beams are terminated with appropriate materials.
(e) Invisible beams are viewed with IR/UV cards, or image converter viewers. Operators are aware that such materials may produce specular reflections, or may ignite.
(f) Pulsed LASER are aligned by firing single pulses when practical.
(g) Normal LASER hazard controls shall be restored when the alignment is completed. Controls include replacing all enclosures, covers, beam blocks, and barriers and checking affected interlocks for proper operation.

E.3 Personal Protective Equipment

(a) In accordance with requirements stated in this document (also see Appendix F), LASER protective eyewear shall be worn under applicable conditions at all times during the alignment of LASER, beam delivery optics, setting up LASER application and measurement steps.

(b) Wearing alignment/adjustment eyewear replacing protective eyewear during maintenance/alignment of operating visible LASER shall require an administrative procedure. Protective eyewear is to be worn again once the maintenance/alignment is complete. The adjustment / alignment eyewear and the protection eyewear are stored in different locations.

(c) Skin protection should be worn on the face, hands, and arms, when aligning LASER beams at UV wavelengths.

E.4 Precaution during Alignment of Class 3B and Class 4 LASER

(a) Exclude unnecessary personnel from the LASER area during alignment.

(b) Wherever possible, use low-power visible LASER for path simulation of higher power visible or invisible LASER.

(c) Wear protective eyewear and clothing.

(d) When aligning invisible LASER beams, use beam display devices, such as image converters viewers or phosphor cards, to locate the beams.

(e) Perform alignment tasks, that use high power LASER, at the lowest possible power level.

(f) Use a LASER rated shutter, or beam-block, to block high power beams at their source, except when actually needed during the alignment process.

(g) Use a LASER rated beam block to terminate high power beams after and close to the optics being aligned.

(h) Use beam blocks and/or LASER protective barriers in conditions where alignment beams could stray into areas, with uninvolved personnel.

(i) Place beam blocks behind optics, e.g. turning mirrors to terminate beams that might miss mirrors during alignment.

(j) Locate and block all stray reflections, before proceeding to the next optical component or section.

(k) Be sure all the beams and reflections are properly terminated, before high power operation.

APPENDIX F

SUMMARY OF CONTROL MEASURES FOR LASER

(For complete information also refer to Section 7)

TABLE AP-F.1
APPLICABILITY OF IMPORTANT ENGINEERING CONTROL MEASURES FOR BEAM HAZARDS*

(refer sub section 7.2)

Engineering Control Measures	LASER Classification						
	1	**1M**	**2**	**2M**	**3R**	**3B**	**4**
Protective enclosure	R	R	R	R	R	R	R
Interlocks on removable protective enclosures	SE	SE	SE	SE	SE	R	R
Master switch or Key control						S	R
LASER control area & NHZ analysis for partly/fully open beam path (Refer sub section 7.2.11)		S		S	LSO	R	R
Permanently attachable Beam stop / Attenuator						S	R
Remote interlock Connector						S	R
Supervised / controlled operation						S	R
LASER activation/operation warning system/sign						R	R

* Where alternative control measures are used in place of protective enclosure, interlocks, etc., LSO is required to assess and approve the same.

Legends

R: Shall be required
R#: Shall be required, but by using Class 1, Class 2 or Class 3R visible LASER (for alignment procedure)
SE: Shall if embedded Class 3B or Class 4
S: Suggested
Blank: Not required
LSO: Determined by LSO

TABLE AP-F.2

APPLICABILITY/REQUIREMENT OF IMPORTANT ADMINISTRATIVE AND PROCEDURAL CONTROL MEASURES FOR BEAM HAZARDS

(Refer sub sections 6.3 6.6, 7.3, 7.4, 7.8, and 7.9)

Administrative and Procedural Control Measures	**Classification**						
	1	**1M**	**2**	**2M**	**3R**	**3B**	**4**
LSO (sub section 6.3)					S	R	R
Registration of LASER System (sections 6.4.1 and 7.3.1 and Appendix A)		R		R	R	R	R
Authorisation of LASER users (sub section 7.3.5 & Appendix A)					**S**	R	R
Education and training of service/maintenance personnel (sub sections 6.3 & 6.6)	SE	R	R	R	R	R	R
Education and Training of users (sub sections 6.3 & 6.6)						R	R
LASER Warning Labels on equipment / at entry (sub section 7.3.2 & Annexure V)	R	R	R	R	R	R	R
Area Warning Signs at entry (sub section7.3.2 & Annexure V)					S	R	R
Standard Operating Procedure (sub sections 6.3, 7.3.3 & Appendix C)						S	R
Alignment Procedure (sub section 6.3, 7.3.5 and Appendix D)	SE	SE	R	R	R	R#	R#
User Safety Manual (sub section 6.3 7 .9-k)	R	R	R	R	R		
Protective eyewear (sub section 7.4 and Appendix G)						S	R
Skin Protection (sub section 7.4)		S		S		R	R
Hazard Evaluation and Risk Assessment (sub section 7.8 & Appendix H)		LSO		LSO	LSO	S	R

Legends

R: Shall be required

R#: Shall be required, but by using Class 1, Class 2 or Class 3R visible LASER (for alignment procedure)

SE: Shall if embedded Class 3B or Class 4

S: Suggested

Blank: Not required

LSO: Determined by LSO

APPENDIX G

LASER SAFETY EYEWEAR – SUPPLEMENTARY INFORMATION

All LASER safety standards and guidelines prescribe the requirement of appropriate optical density for protective eyewear, and mention the requirement that the optical filter and frame shall withstand a direct hit from the LASER. Some of the 'standards' and 'guidelines' also specify the 'damage threshold' of the filter, for direct irradiation by the LASER, as a more stringent control measure by requiring that the filters, while providing protection, shall also be able to withstand direct irradiation by:

(a) a continuous wave LASER for 10 s at the maximum accessible irradiance for which it is designed to provide protection, or

(b) a pulsed LASER for 100 pulses at the maximum accessible radiant exposure per pulse for which it is designed to provide protection.

Damage thresholds of only absorbing filters are clearly less than that of filters which are provided with a reflective dielectric coating on the outer surface. Plastic material based filters have damage thresholds lower than that of the glass-based filters. Another concern on choice of filters is for ultra-short LASER pulses with pico-seconds – femto-seconds pulse duration, for which nonlinear optical processes play an important role in determining the transmission of the filter. Thus, the related European safety standards (BS EN207:2009, BS EN207:2009, etc.) and LASER protection eyewear manufacturers specifically address these aspects, while specifying protective eyewear.

Protective eyewear generally has a high optical density (OD). OD 6 or higher is common, providing an attenuation factor of 10^6 or more. As a result, an otherwise visible LASER beam may become difficult to see, while carrying out alignment. Apart from the difficulty in alignment, this may make the work unsafe, as the operator cannot see where the beam is incident. For aligning LASER, with output wavelength outside the visible region, the beam locations are determined by using viewing surfaces made of materials that convert the wavelength into the visible region, for example, by fluorescence. The protective eyewear is designed to attenuate the LASER, but sufficiently transmitting the radiation in the visible wavelength region from the illuminated spot. However, for visible LASER, in order to see the beam spot on any surface, it would be necessary to provide a significant transmission at the same wavelength at which the protection is required.

To circumvent this problem, European standards, such as EN 208/60825, specify 'LASER adjustment' or 'LASER alignment' eyewear for LASER in the visible region (400 – 700 nm) which attenuates the beam to applicable accessible exposure limit for Class-2 LASER. As a result, the person wearing the alignment eyewear can see the beam spot, while the blink or aversion response is expected to provide protection against the hazard of accidental direct intra-beam viewing.

While using LASER safety eyewear, it must be understood that the protection is not provided for intentional intra-beam viewing.

APPENDIX H

FORMAT FOR HAZARD EVALUATION AND LASER/LASER SYSTEM RISK ASSESSMENT

(see sub section 7.8)

(Sample – may be altered in consultation with appropriate experts and LSO)

1.0 Background Information

1.1	Names of Assessor: ___________________	Date:______ ; Registration Number:______
1.2	LASER/LASER system description →	
1.3	Beam delivery system →	
1.4	Outline LASER application process →	
1.5	Environment of LASER and application→	
1.6	List people who use, maintain, service or affect operation of, the LASER, its power supply, utilities, including the application system →	
1.7	List & specify available PPE →	

Identify all parts of the life cycle relevant to the risk assessment: Planning, design, development, experimentation, manufacturing, testing, transport, installation, commissioning, normal operation, maintenance, servicing, modification, decommissioning, disposal

2.0 Risk Assessment

STEP 1	STEP 2		STEP 3		
List of Reasonably Foreseeable Hazards	**Persons at Risk (staff, contractor, visitor, others)**	**Hazard Exposure Mechanism / Mode**	**Existing / Proposed Controls**	**Residual Risk* (Low / Medium / High)**	**Further Actions Required (Yes/ No)**
(A) LASER / LASER System:					
(a) ___________					
(b) ___________					
(c) __________					
(B) Beam Delivery:					
(a) ___________					
(b) ___________					
(c) ___________					

STEP 1	STEP 2		STEP 3		
(C) LASER Application Process:					
(a) ___________					
(b) ___________					
(c) ___________					
(D) Environment:					
(a) ___________					
(b) ___________					
(c) ___________					

* Risk assessment may be carried out by applying a standard qualitative procedure – combining the probability of exposure to the hazard with the severity of the harm if exposed.

3.0 Follow-up Action (Step 4)

Hazards with Residual Significant Risks	Details of Additional Controls to Mitigate the Hazard and Actions Required to Implement	Date for Implement -ation	Person Responsi ble	Status /Date
(A) LASER / LASER system:				
(a) ________				
(b) _______				
(c) _______				
(B) Beam Delivery:				
(a) ________				
(b) _______				
(c) _______				
(C) LASER Application Process:				
(a) ________				
(b) _______				
(c) _______				
(D) Environment				
(a) ________				
(b) _______				
(c) _______				

ANNEXURE I

TABLES RELATED TO CALCULATION OF MAXIMUM PERMISSIBLE EXPOSURE (MPE) AND ACCESSIBLE EMISSION LIMITS (AEL)

TABLE AN-I.1
MPE for The Eye

Wavelength (nm)	Exposure Duration, t (s)	MPE		Restrictions
		J/cm^2 or	W/cm^2	
Ultraviolet				
Dual limits for 180 -600 nm ultraviolet LASER exposure at t > 1 ns				
Photochemical				
180 to 302	1 ns to 30 ks	$3\ mJ/cm^2$		Aperture sizes: 1 mm for t < 0.3 s $1.5\ t^{0.375}$ mm for 0.3 < t < 10 s 3.5 mm for t > 10 s
303	1 ns to 30 ks	$4\ mJ/cm^2$		
304	1 ns to 30 ks	$6\ mJ/cm^2$		
305	1 ns to 30 ks	$10\ mJ/cm^2$		
306	1 ns to 30 ks	$16\ mJ/cm^2$		
307	1 ns to 30 ks	$25\ mJ/cm^2$		
308	1 ns to 30 ks	$40\ mJ/cm^2$		
309	1 ns to 30 ks	$63\ mJ/cm^2$		
310	1 ns to 30 ks	$0.1\ J/cm^2$		
311	1 ns to 30 ks	$0.16\ J/cm^2$		
312	1 ns to 30 ks	$0.25\ J/cm^2$		
313	1 ns to 30 ks	$0.4\ J/cm^2$		
314	1 ns to 30 ks	$0.63\ J/cm^2$		
315 to 400	1 ns to 30 ks	$1\ J/cm^2$		
Thermal				
180 to 400	1 ns to 10 s	$0.56\ t^{0.25}\ J/cm^2$		
Visible				
400 to 700	100 fs to 10 ps	$0.015\ C_E\ \mu J/cm^2$		(all for 7 mm limiting aperture)
400 to 700	10 ps to 1 ns	$2.7\ C_E\ t^{0.75}\ J/cm^2$		
400 to 700	1 ns to 18 µs	$0.5\ C_E\ \mu J/cm^2$		
400 to 700	18 µs to 10 s	$1.8\ C_E\ t^{0.75}\ mJ/cm^2$		
Dual limits for 400 -600 nm visible LASER exposures at t > 10 s				(Use time T_1 given in Note 1 considering thermal and photochemical effect)
Photochemical[a]				
400 to 600	10 s to 100 s	$10\ C_B\ mJ/\ cm^2$		for $\alpha < 11$ mrad ($\gamma = 11$ mrad[a])
400 to 600	100 s to 30 ks		$0.1\ C_B$ mW/cm2	for $\alpha < 11$ mrad
400 to 600	100 s to 10 ks		$0.1\ C_B\ mW/cm^2$	for $\alpha > 11$ mrad ($\gamma = 1.1\ t^{0.5}$ mrad)
400 to 600	10 ks to 30 ks		$10\ C_B\ mW/(cm^2\ sr)$	(see Note 1 [a]) ($\gamma = 110$ mrad[a])
Thermal[a]				(all for 7 mm limiting aperture)
400 to 700	10 s to 30 ks		1.0 mW/cm2	for $\alpha < 1.5$ mrad
400 to 700	10 s to T2 s	$1.8\ C_E\ t^{0.75}\ mJ/cm^2$		for $\alpha > 1.5$ mrad
400 to 700	T_2 s to 30 ks		$1.8\ C_E\ T_2^{-0.25}\ mW/cm^2$	for $\alpha > 1.5$ mrad
Near Infrared IR-A				
700 to 1050	100 fs to 10 ps	$0.015 C_A\ C_E\ \mu J/cm^2$		7 mm limiting aperture
700 to 1050	10 ps to 1 ns	$2.7\ C_A\ C_E\ t^{0.75}\ \mu J/cm^2$		
700 to 1050	1 ns to 18 µs	$0.5\ C_A\ C_E\ \mu J/cm^2$		
700 to 1050	18 µs to 10 s	$1.8\ C_A\ C_E\ t^{0.75}\ mJ/cm^2$		
1051 to 1400	100 fs to 10 ps	$0.15\ C_C\ C_E\ \mu J/cm^2$		
1051 to 1400	10 ps to 1 ns	$27 C_C\ C_E\ t^{0.75}\ J/cm^2$		
1051 to 1400	1 ns to 50 µs	$5\ C_C\ C_E\ \mu J/cm^2$		
1051 to 1400	50 µs to 10 s	$9\ C_C\ C_E\ t^{0.75}\ mJ/cm^2$		

…..Table 1 contd.

MPE for the Eye

Wavelength (nm)	Exposure Duration, t (s)	MPE J/cm^2	MPE W/cm^2	Restrictions
700 to 1400	10 s to 30 ks		1.0 C_A C_C mW/cm^2	for α < 1.5 mrad
700 to 1400	10 s to T_2 s	1.8 C_A C_C C_E $t^{0.75}$ mJ/cm^2		for α > 1.5 mrad
700 to 1400	T_2 s to 30 ks		1.8 C_A C_C C_E $T_2^{-0.25}$ mW/cm^2 Not to exceed 100 mW/cm^2	for α > 1.5 mrad
Far infrared				Aperture sizes 1 mm for t < 0.3 s 1.5 $t^{0.375}$ mm for 0.3 < t < 10 s 3.5 mm for t > 10 s
1400 to 1500 nm	1 ns to 1 ms	0.1 J/cm^2		
1400 to 1500 nm	1 ms to 10 s	0.56 $t^{0.25}$ J/cm^2		
1500 to 1800 nm	1 ns to 10 s	1.0 J/cm^2		
1801 to 2600 nm	1 ns to 10 ms	0.1 J/cm^2		
1801 to 2600 nm	1 ms to 10 s	0.56 $t^{0.25}$ J/cm^2		
2601nm to 1mm	1 ns to 100 ns	10 mJ/cm^2		
2601 nm to 1mm	100 ns to 10 s	0.56 $t^{0.25}$ J/cm^2		
1400 nm to 1mm	10 s to 30 ks		100 mW/cm^2	

Reproduced from ICNIRP Guidelines

Note 1:

[a] – For small sources subtending an angle of 1.5 mrad or less, the visible dual limit MPE from 400 to 600 nm, for times greater than 10 s, reduces to the thermal limit, for times less than T_1, and to photochemical limits for longer times.

Where T_1, the exposure duration at which MPE based upon thermal injury are replaced by MPE based upon photochemical injury to retina, is determined as follows

$T_1 = 10$ s for $\lambda < 450$ nm;
$T_1 = 10 \text{ X } 10^{0.02(\lambda-450)}$ s for 450 nm $< \lambda <$ 500 nm; and
$T_1 = 100$ s for $\lambda > 500$ nm

The photochemical retinal hazard limit may also be expressed as an integrated radiance L = 100 C_B J/(cm^2.sr)

All the values of α and γ are in milli-radian (mrad). All the values of wavelengths are in nanometer (nm) unless specified.

Note 2: **Angular Subtense α of a source and limiting cone angle measuring a field of view γ.**

Angular Subtense (α) : The plane angle usually specified in milli-radian, subtended by the apparent source at a defined distance from the source

Alpha min (**α_{min}**): The angular subtense of a source below which the source can be effectively considered as a point source. The value of α_{min} is 1.5 milli-radian (mrad).

Alpha max (**α_{max}**): The angular subtense of an extended source beyond which additional subtense does not contribute to the hazard, and need not be considered. This value is 100 milli-radian (mrad), for retinal thermal effects, and 110 milli-radian (mrad), for the retinal photochemical effects.

Limiting Cone angle (γ): Angle of acceptance for measurement of photochemical hazard for extended sources with radiance and integrated radiance.
α_{min} is 1.5 milli-radian (mrad) for all thermal retinal hazard exposure limits.

$\gamma = 11$ mrad for $t \leq 100$ s,
$\gamma = 1.1\, t^{-0.5}$ mrad for $100 \text{ s} < t < 10{,}000$ s,
$\gamma = 110$ mrad for $t > 10{,}000$ s

Note 3: T_2, the exposure duration beyond which extended source (α > 1.5 mrad) MPE, based on thermal injury are expressed as a constant irradiance, is determined as follows

$T_2 = 10\ [10^{(\alpha-1.5)/98.5}]$ such that T_2 =10 s, for α < 1.5 mrad, and 100 s for α > 100 mrad

Note 4: **Spectral Correction Factor**

C_A :- Correction factor which increases the MPE values in the near infrared (IR-A) spectral band (0.7- 1.4 μm) based upon reduced absorption properties of the melanin pigment granules found in the skin and in the retinal pigment epithelium.

$C_A = 1$	for	λ = 400 to 700 nm
$C_A = 10^{0.002(\lambda - 700)}$	for	λ = 700 to 1050 nm
$C_A = 5$	for	λ = 1051 to 1400 nm

C_B :- Correction factor which increases the MPE in the red end of the visible spectrum (0.45- 0.6 μm) because of greatly reduced photochemical hazards.

$C_B = 1$	for	$400 \text{ nm} < \lambda \le 450$ nm
$C_B = 10^{0.02(\lambda-450)}$	for	$450 \text{ nm} < \lambda \le 600$ nm

C_C :- Correction factor which increases the MPE values for ocular exposure because of pre-retinal absorption of radiant energy in the spectral region 1050 - 1400 nm.

$C_C = 1$	for	$\lambda \le 1150$ nm
$C_C = 10^{0.0181(\lambda-1150)}$	for	$1150 < \lambda < 1200$ nm
$C_C = 8$	for	$1200 \le \lambda < 1400$ nm

Note 5: Extended Source Correction Factor **C_E**

C_E :- Correction factor used for calculating the extended source MPE for eye from the point source MPE, when the LASER source subtends a visual angle exceeding α_{min}.
For extended source viewing of LASER radiation (e.g. diffuse radiation) between 400 and 1400 nm, the thermal MPE includes the correction factor C_E, provided the angular subtense of the source (measured at the viewer's eye) is greater than α_{min}, where α_{min} is 1.5 mrad, for all thermal MPEs.

$C_E = 1.0$	for	$\alpha < \alpha_{min}$
$C_E = \alpha / \alpha_{min}$	for	$\alpha_{min} < \alpha < 100$ mrad
$C_E = \alpha^2 / (\alpha_{min} \times \alpha_{max})$	for	$\alpha > 100$ mrad, where α_{max} is 100 mrad

At and above α_{max}, the extended source MPE can be expressed as a constant radiance, using the last equation

$L_{MPE} = 8500\ MPE_{point\ source}$ J/ (cm²sr)	for t < 10 s
$L_{MPE} = 100\ C_B$ J/(cm²sr)	for t > 10 s

TABLE AN-I.2
MPE FOR THE SKIN

Wavelength (nm)	Exposure Duration, t (s)	MPE J/cm² or W/cm²	Restrictions
Ultraviolet			
180 - 400	1 ns to 30 ks	Same as eye MPE	
Visible and IR-A			
400 to 1400	1 ns to 100 ns	20 C_A mJ/cm²	3.5 mm limiting aperture
400 to 1400	100 ns to 10 s	1.1 $C_A\ t^{0.25}$ J/cm²	
400 to 1400	10 s to 30 ks	0.2 C_A W/cm²	
Far Infrared			
1400 nm to 1mm	1 ns to 30 ks	Same as eye MPE	3.5 mm limiting aperture

Reproduced from ICNIRP Guidelines

TABLE AN-I.3
LIMITING EXPOSURE DURATIONS FOR CW AND REPETITIVE PULSE MPE CALCULATIONS

(Recommended by ANSI-Z-136.1:2007)

Wavelength Range	Diffuse (s)	Intra-beam (s)
UV : 0.18 to 0.4 µm	30,000	30,000
Visible: 0.4 to 0.7 µm	600	0.25*
NIR: 0.7 to 1.4 µm	600	10
FIR: 1.4 µm to 1 mm	10	10

* For unintended or accidental viewing only. For other conditions, use the time of intended viewing.

Limiting Exposure Duration (T_{max}): An exposure duration which is specifically limited by the design or intended use(s).

Basis for Exposure times:

0.25 s	-	The human aversion time for a bright light stimulus
10 s	-	The optimum 'worst case' time period for ocular exposures to infrared LASER sources considering natural eye motion.
600 s	-	'Worst case' time period for viewing visible diffuse reflections during tasks such as alignment
30,000 s	-	Represents a full one day (8 hour) occupational exposures

TABLE AN-I.4
LIMITING APERTURES (IRRADIANCE AND RADIANT EXPOSURE) FOR HAZARD EVALUATION

Spectral Region (µm)	Exposure Duration (s)	Aperture Diameter (mm)	
		Eye	Skin
0.18 to 0.4	10^{-9} to 0.3	1.0	3.5
	0.3 to 10 *	1.5 $t^{0.375}$	3.5
	10 to 3 x 10^4	3.5	3.5
0.4 to 1.4	10^{-13} to 3 x 10^4	7.0	3.5
1.4 to 10^2	10^{-9} to 0.3	1.0	3.5
	0.3 to 10 *	1.5 $t^{0.375}$	3.5
	10 to 3 x 10^4	3.5	3.5
10^2 to 10^3	10^{-9} to 3 x 10^4	11.0	11.0

* Under normal conditions, these exposure durations would not be used for hazard evaluation.

TABLE AN-I.5
MEASUREMENT APERTURE AND TRANSMISSION FACTOR FOR OPTICAL AIDED VIEWING

Spectral Region (μm)	**Duration (s)**	**Aperture Diameter (mm)**	**Visible Optics transmission**
0.180 to 0.302	10^{-9} to 0.3 0.3 to 10 10 to 3 x 10^4	1.0 1.5 $t^{0.375}$ 3.5	< 2%
0.302 to 0.4	10^{-9} to 0.3 0.3 to 10 10 to 3 x 10^4	7.0 $11t^{0.375}$ 25.0	70%
0.4 to 0.7	10^{-9} to 3 x 10^4	50	90%
0.7 to 1.4	10^{-9} to 3 x 10^4	50	70%
1.4 to 2.8	10^{-9} to 0.3 0.3 to 10 10 to 3 x 10^4	7.0 $11t^{0.375}$ 25.0	70%
2.8 to 10^2	10^{-9} to 0.3 0.3 to 10 10 to 3 x 10^4	1.0 1.5 $t^{0.375}$ 3.5	<2%
10^2 to 10^3	10^{-9} to 3 x 10^4	11.0	<2%

TABLE AN-I.6
VALUES FOR t_{min} and F_{CR}

Wavelength Range	**t_{min}**	**F_{cr}**
315- 400 nm	1 ns	1 GHz
400- 1050 nm	18 μs	55kHz
1050 – 1400 nm	50 μs	20 kHz
1.4 – 1.5 μm	1 ms	1 KHz
1.5 – 1.8 μm	10 s	0.1 Hz
1.8 – 2.6 μm	1 ms	1 KHz
2.6 – 1000 μm	100 ns	10 MHz

t_{min} : For a pulse LASER, the maximum duration for which the MPE is the same as the MPE for a 1 ns exposure. For thermal biological effects, this corresponds to the 'thermal confinement duration' during which heat flow does not significantly change the absorbed energy content of the thermal relaxation volume of the irradiated tissue.

TABLE AN-I.7
ADDITIVE EFFECTS ON EYE (O) AND SKIN (S) OF RADIATION OF DIFFERENT SPECTRAL REGIONS

(Source: IEC Technical Report BSI 60825 Part 14:2004)

Spectral Region	UV-C and UV-B 180 to 315 nm	UV-A 315 to 400 nm	Visible and IR-A 400 to 1400 nm	IR-B and IR-C 1400 to 10^6 nm
UV-C and UV-B 180 to 315 nm	O S			
UV-A 315 to 400 nm		O S	S	O S
Visible and IR-A 400 to 1400 nm		S	O[a] S	S
IR-B nad IR-C 1400 to 10^6 nm		O S	S	O S

a Where Ocular MPE are being evaluated for time bases or exposure durations of 1 s or longer, then the additive photochemical effects (400 to 600 nm) and the additive thermal effects (400 to 1400 nm) shall be assessed independently and the most restrictive value used.

TABLE AN-I.8
REDUCTION FACTOR FOR THERMAL MPE IN SPECIAL EXPOSURE CONDITIONS

Exposure Duration T	Wavelength Range (nm)	MPE
$0.07s \leq T < 0.7s$	400-700	MPE(T = 0.07 s)
T > 0.7 s	400-600	MPE(T)/ 5.4
T > 0.7 s	600-700	MPE(T) / $10^{7.4(0.700-\lambda)}$ (λ in microns).

ANNEXURE II

LASER AND LASER SYSTEM HAZARD CLASSIFICATION DEFINITIONS

II.1 Classes 1 and 1M LASER and LASER Systems

(a) Any LASER, or LASER system, containing a LASER that cannot emit accessible LASER radiation levels during operation, in excess of the applicable Class 1 AEL for any emission duration within the maximum duration inherent in the design or intended use of the LASER / LASER system is a Class 1 LASER / LASER system during operation. The maximum exposure duration is assumed to be no more than 30,000 s, except for infrared system ($\lambda > 0.7$ μm), where 100 s shall be used.

(b) LASER / LASER systems intended for a specific use may be designated Class1 by the LSO on the basis that use for a limiting exposure duration of T_{max} is less than 100 s, provided that the accessible LASER radiation does not exceed the corresponding Class 1 AEL for any emission duration within the maximum duration inherent in that specific use.

(c) Any LASER / LASER system that cannot emit during operation, accessible LASER radiation levels in excess of the applicable Class 1 AEL under the conditions of measurement for the unaided eye, but exceeds the Class 1 AEL for telescopic viewing (Condition 1) and does not exceed the Class 3B AEL, for any emission duration, within the maximum duration inherent in the design or intended use of the LASER / LASER system is a Class 1M LASER / LASER system. The maximum exposure duration is assumed to be no more than 30,000 s.

II.2 Class 2 and 2M Visible LASER and LASER Systems

(a) Classes 2 and 2M LASER and LASER systems are visible (0.4 to 0.7 μm) CW and repetitive-pulse LASER and LASER systems which can emit accessible radiant energy exceeding the appropriate Class 1 AEL for the maximum duration inherent in the design or intended use of the LASER / LASER system, but not exceeding the Class 1 AEL for any applicable pulse (emission) duration < 0.25 s and not exceeding an accessible average radiant power of 1 mW. Class 2M LASER and LASER systems pose the same ocular hazards to the unaided eye as Class 2 LASER, but are potentially hazardous when viewed with optical aids.

(b) Any LASER / LASER system that cannot emit during operation accessible LASER radiation levels in excess of the applicable Class 2 AEL under the conditions of measurement for the unaided eye, but exceeds the Class 2 AEL for telescopic viewing (Condition 1) and does not exceed the Class 3B AEL, for any emission duration within the maximum duration inherent in the design or intended use of the LASER / LASER system is a Class 2M LASER / LASER system. The maximum exposure duration is assumed to be no more than 0.25 s.

II.3 Class 3R and 3B LASER and LASER Systems

(a) Class 3R LASER and LASER systems include LASER and LASER systems which have an accessible output between 1 and 5 times Class 1 AEL, for wavelengths shorter than 0.4 μm, or longer than 0.7 μm, or less than 5 times the Class 2 AEL for wavelengths between 0.4 and 0.7 μm.

(b) Class 3B LASER and LASER systems include:

(i) LASER and LASER systems, operating outside the retinal hazard region (i.e. <0.4 μm or > 1.4 μm) which can emit accessible radiant power in excess of the Class 3R AEL during any emission duration, within the maximum duration inherent in the design of the LASER / LASER system, but which (a) cannot emit an average radiant power in excess of 0.5 W for $T \geq 0.25$ s or (b) cannot produce a radiant energy greater than 0.125 J in an exposure time $T < 0.25$ μs.

(ii) Visible (0.4 to 0.7 μm) and near infrared (0.7 to 1.4 μm) LASER and LASER systems which can emit in excess of the AEL of Class 3R but which (a) cannot emit an average radiant power in excess of 0.5 W for $T \geq 0.25$ s and (b) cannot emit a radiant energy greater than 0.03 C_A J per pulse. For this limit, the pulses separated by less than t_{min} are to be considered one pulse.

II.4 Class 4 LASER and LASER Systems

Class 4 LASER and LASER systems are those that emit radiation that exceed the Class 3B AEL.

ANNEXURE III

EXAMPLES OF LASER ACCIDENTS

A few examples of LASER accidents, along with brief excerpts of case studies, are provided here:

III.1 Examples of LASER Accident

III.1.1 Face of a post-doctoral student was struck by a stray LASER beam from an optic polarizer. He was not wearing protective eyewear.

III.1.2 Two senior researchers were operating a femto-second LASER of 1 mJ pulse energy and 500 Hz pulse repetition frequency, with a beam size of several centimetres. The beam output power was not lowered as a mirror was inserted into the beam path. An IR viewer was also not used. One of the researchers was struck by a reflection while inserting the mirror, and immediately heard a popping sound from his eye. He then experienced swelling and near-blindness in the injured eye.

III.1.3 A research technician was working on a Class I XeCl excimer LASER that was housed in a protective enclosure to examine probable malfunction. The technician opened the enclosure, and was exposed to several LASER pulses that had reflected off a beam splitter which he was handling. Because he was wearing eye protection, the beam at a wavelength of 308 nm was not visible, the technician did not notice the exposure until hours later, when four burns appeared on his neck.

III.1.4 A researcher was exposed to the diffused radiation from a class 4 LASER source, which was situated in a neighbouring closed room access of which was restricted to a few trained persons. The beam was sent from the enclosed room to the other room through a small hole in the wall, so that the same source could be used simultaneously for several experiments. However, these holes were not protected by protective caps to shut the beam off, when the other experiment was not being performed.

III.1.5 A researcher was retrieving experimental data, without intending to work on the experimental set-up. However, he did not anticipate that someone might be working on the experimental set-up, and that the LASER might be in operation. He wasn't wearing his safety goggles, although they were correctly placed at the entry of the laboratory, and was exposed to hazardous levels of radiation.

III.2 Detailed Case Study of LASER Accidents

III.2.1 A Ph.D. student was working on a Class 4 Titanium-doped Sapphire LASER Oscillator. Instead of using a camera or infra-red sensor, he was doing alignment by directly observing the beam spot on a viewing card with naked eye in the dark, without safety goggles. The LASER was in operation in continuous mode at full power (700 mW).

As he had to elevate the beam to the same height as the rest of the experimental set-up, he first adjusted a periscope, with the two mirrors as close as possible and tightly fixed the bottom mirror, sending the beam to the ceiling. In order to be able to adjust the upper mirror, he did not fix it tightly. During the adjustment procedure, the student bent over the desk, thus placing his eye precisely over the periscope. His hand accidentally moved the upper mirror away from the beam, which briefly entered the student's eye. The retina was damaged and nerve cells of the macula were burnt. The incident caused a permanent and irreversible effect on his field of view, without loss of visual acuity.

This accident could have been avoided, if the following precautions had been taken:

(a) The student should have been wearing his safety goggles adapted to the pulsed LASER, which were placed next to him.
(b) While working with a LASER, the ambient light must always be over a certain level, in order to prevent the pupil from getting wide opened.
(c) Always work at minimum beam power when adjusting an optical system.
(d) Always tightly fix the optical elements, even if their positions may have to be optimised later.

III.2.2 During some experiments involving a femto second pulsed LASER, a researcher was measuring the beam width using a camera specially designed for this kind of measurements. The detection head was placed on a stand in order to be at the center of the beam, but was not properly fixed. He did his measurements, and then wanted to note down the results in his lab book, placed on a desk next to the experiment. A computer was situated on this desk. The experimentalist sat down on a chair, turning his back to the experimental set-up, aware that the beam was behind him. While he was writing on the book, the detection head tripped, and the beam was reflected from the computer screen situated at the same height, and entered his eye. Fortunately, due to the blink reflex of his eye, he did not experience permanent lesions.

This accident could have been easily avoided simply by correctly fixing the detection head. This protection is still not sufficient. The LASER beam should have been isolated from the desk by an opaque partition. Such a partition permits to isolate the experiment area of the room from the ‘desk work’ area.

III.2.3 A student was aligning two pulsed LASER, with different wavelengths, for his experiment. The first one was a dye LASER, emitting at 720 nm, delivering 10 ns pulses of energy 10 mJ, at a repetition rate of 10Hz. The second one was a pulsed Nd:YAG LASER, emitting at 266 nm, delivering pulses of same duration and at the same repetition rate, but of energy 50 mJ. In this experiment, the beam emitted by the first LASER was passing through a dichroic mirror, fully reflecting at 266 nm, and highly transparent at any other wavelength. The back side of the mirror was reflecting about 5% of the beam at 720 nm towards the ceiling. As he could not see the beam at 266 nm, nor the fluorescence spot on a viewing card while using the goggles, the student briefly worked without safety goggles. As he had totally forgotten the presence of the parasitic beam at 720 nm, he bent over the mirror, and received a LASER pulse from this reflection. He immediately noticed a blind spot in the central sight of his eye, while looking at some object in the laboratory, and was later diagnosed to have suffered a burn on the fovea. Surprisingly, the student was aware of the parasitic beam during a previous experiment, and had placed obstacles in the upward path, which were removed for setting up the new experiment.

The safety goggles, although specified at 266 nm, could probably have prevented the burn. More importantly, for any new experiment, the operator must evaluate the new hazard sources he may be exposed to.

ANNEXURE IV

SOLVED PROBLEMS FOR
LASER HAZARD EVALUATION

PART A
FORMULAS

(1) Class 1 AEL = MPE $\frac{\pi D_f^2}{4}$ watts

…..where D_f is limiting aperture diameter
(Refer sub section 4.3 of the document)

(2) Beam Diameter (D_L):

The beam diameter of a Gaussian-shaped beam changes with distance from LASER exit port.

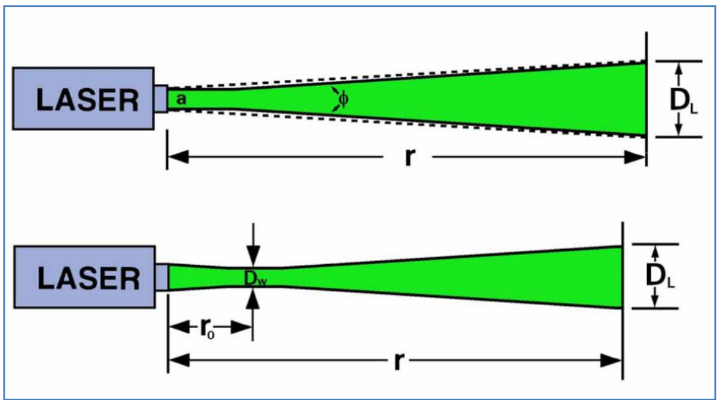


Figure AN-IV.1
BEAM EXPANSION WITH DISTANCE FROM LASER

2.1 When the beam waist occurs deep within the cavity of the LASER, the best approximation of the beam diameter with range is given by the equation

$$D_L = a + r\phi$$

2.2 If the beam waist for the LASER occurs at, or very near to the exit port, the beam diameter change with distance becomes more of hyperbolic function than the linear one for the internal beam waist, and is given by the equation

$$D_L = \sqrt{a^2 + r^2\phi^2}$$

2.3 There are instances where the beam waist occurs at a distance in front of the LASER exit port (refer Figure AN-IV.1). In this case, the beam diameter gets smaller than that at the exit port until the beam waist is reached, and then begins to expand.

$$D_L = \sqrt{D_w^2 + (r - r_0)^2 . \emptyset^2}$$

(Refer sub section 5.3.2 of the document for all formula of D_L)

(3) Parameters of LASER Beam Exposure (in terms of power / energy as applicable**)**

3(A)	Output Power (**Φ**)	3 (B)	Beam Output Energy (Q)
3.1 (A)	Peak Power = $\Phi_{pk} = Q_{pulse}/t$ Where t is duration of the pulse in time, expressed as Full Width at Half Maximum (FWHM) duration	3.1(B)	Total Beam Energy $Q_{0(group)}$ $Q_{0(group)} = Q_0.n$, where $n = F.T$ n = Number of Pulses (n), emitted by the LASER in exposure duration T (s) can be computed from the pulse repetition frequency (F) in hertz
3.2(A)	<u>Average Output Power $\Phi_{0(avg)}$</u> For pulsed LASER, it may be necessary to compute the average power for a given exposure duration T, or compute the individual pulse energy given this average power. Average output power can be computed by using Energy (Q_0) and the pulse repetition frequency (F) as per the following equation $\Phi_{0(avg)} = Q_0.F$		
3.3(A)	Accessible or Effective Power (Φ_m) The amount of power transmitted through a measurement aperture with diameter D_m. It is given by the following equations $\Phi_m = \Phi_0 \, \tau_\lambda \left[1 - e^{-\left(\frac{D_m}{D_L}\right)^2}\right]$ watts	3.3(B)	Accessible or Effective Energy (Q_m) The amount of energy (per pulse) transmitted through a measurement aperture with diameter D_m. It is given by the following equations $Q_m = Q_0 \, \tau_\lambda \left[1 - e^{-\left(\frac{D_m}{D_L}\right)^2}\right]$ joules It may be noted that the above equation is valid for Gaussian beam profile.
	Where Transmittance (τ_λ) values can be obtained from the manufacturer's specifications. In the absence of manufacturer's specification, the transmittance prescribed in Table AN-I.5, for different wavelength, can be used.		
3.4(A)	Irradiance (E) $E = \frac{4\Phi}{\pi D_L^2}$ Considering beam attenuation factor μ, the beam irradiance E at a distance r can be given by the following formula $E = \frac{4\,\Phi e^{-\mu r}}{\pi[\max(D_f, D_L)]^2}$	3.4(B)	Radiant Exposure (H) $H = \frac{4Q}{\pi D_L^2}$ Considering beam attenuation factor μ, the radiant exposure H at a distance r can be given by the formula $H = \frac{4\,Q e^{-\mu r}}{\pi[\max(D_f, D_L)]^2}$
3.5(A)	Beam irradiance of a reflected beam, using Lambert's law $E_{obs} = \frac{\Phi \rho_\lambda \cos\theta}{\pi r_1^2}$	3.5(B)	Radiant exposure for reflected beam, using Lambert's Law $H_{obs} = \frac{Q \rho_\lambda \cos\theta_v}{\pi r_1^2}$
	Where $\rho(\lambda)$ is the reflectance at given wavelength, Φ is the power of the incident beam, Q is the energy of the incident beam, θ is the angle of viewing with respect to normal, and r1 is the distance from the point of reflection to the point of observation. The Figure 5.6 shows the diffuse reflection of a LASER		

(4) MPE conversion using solid angle (Ω)

4.1 Where MPE values are expressed in radiance -L_e (W/cm^2/sr), it may be converted to irradiance E-(W/cm^2), by multiplying the radiance values by the source solid angle Ω,

$$\text{MPE: E} = \text{MPE: } L_e . \Omega_{(avg)}$$

4.2 Where MPE vales are expressed in integrated radiance- L_p (J/cm^2/sr), it may be converted to radiant exposure H-(J/cm^2), by multiplying the integrated radiance values by the source solid angle Ω,

$$\text{MPE: H} = \text{MPE: } L_P . \Omega_{(avg)}$$

4.3 In above 2 equation solid angle Ω is given by

$$\Omega_{(avg)} = \frac{\pi[\max(\alpha,\gamma)]^2}{4}$$

(5) Nominal Ocular Hazard Distance

By substitution of D_L from sub section 2.3 in sub section 4.1, and re-writing the equation

$$r = r_0 + \frac{1}{\phi}\sqrt{\frac{4\Phi}{\pi E} - D_W^2} \quad \text{or} \quad r = r_0 + \frac{1}{\phi}\sqrt{\frac{4Q}{\pi H} - D_W^2}$$

(Refer Figure AN-IV.1)

If E or H are replaced with MPE in order to obtain the range at which the irradiance equals the MPE, then "r" becomes "r_{NOHD}". The Nominal Ocular Hazard Distance in terms of irradiance (Φ) and radiant exposure (Q) is given by

$$r_{NOHD} = r_0 + \frac{1}{\phi}\sqrt{\frac{4\Phi}{\pi.\text{MPE: E}} - D_W^2} \quad \text{or}$$

$$r_{NOHD} = r_0 + \frac{1}{\phi}\sqrt{\frac{4Q}{\pi.\text{MPE: H}} - D_W^2}$$

For a small source, r_0 can be taken as approximately zero, and the equation becomes

$$r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{4\Phi}{\pi.\text{MPE: E}} - D_W^2} \quad \text{or} \quad r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{4Q}{\pi.\text{MPE: H}} - D_W^2}$$

5.1 NOHD for optically aided viewing

The use of optical aides for intra-beam viewing will increase the viewing hazard by as much as the square of magnifying power (Optical gain) of the optical system. From sub section 5.3.10(b) of Section 5, we can write

$$G_{eff} = \tau(\lambda)\, P^2$$

The maximum increased hazard can then be written as

$$H_{max} = MPE / G_{eff}$$

Hence, with the help of H_{max}, the NOHD should be extended because of the use of optical system. The extended ocular hazard distance is given by the formulas

$$r_{NOHD} = r_0 + \frac{1}{\phi}\sqrt{\frac{4\Phi G_{eff}}{\pi.\,MPE:E} - D_W^2} \qquad \text{or}$$

$$r_{NOHD} = r_0 + \frac{1}{\phi}\sqrt{\frac{4QG_{eff}}{\pi.\,MPE:H} - D_W^2}$$

5.2 NOHD for reflected beam

From sub section 5.3.10(a) in the main text, r_{NOHD} for reflected diffuse beam can be given by equation

$$r_{NOHD-diffuse} = \sqrt{\frac{\Phi\rho_\lambda \cos\theta_v}{\pi.\,MPE:E}} \qquad \text{or} \qquad r_{NOHD-diffuse} = \sqrt{\frac{Q\rho_\lambda \cos\theta_v}{\pi.\,MPE:H}}$$

Similarly for specular reflection of point source r_0 and D_W becomes zero. Also replacing Φ with $\Phi_0\rho(\boldsymbol{\lambda})$ and Q by $Q_0\,\rho(\boldsymbol{\lambda})$ for reflected beam, the Nominal Ocular Hazard Distance is given by the formula.

$$r_{NOHD-specular} = \frac{1}{\phi}\sqrt{\frac{1.27\rho(\lambda)\Phi_0}{MPE:E}}\ \text{cm} \quad \text{or}$$

$$r_{NOHD-specular} = \frac{1}{\phi}\sqrt{\frac{1.27\rho(\lambda)Q_0}{MPE:H}}\ \text{cm}$$

PART B
SOLVED PROBLEMS

DETERMINATION OF BEAM PARAMETERS

(1) An Nd-YAG LASER emits near infra-red radiation 1060 nm in wavelength at a power level of 10 W CW. The exit aperture is 3 mm and beam divergence is 5 mrad. Find

(a) the $1/e^2$ diameter,

(b) $1/e^2$ diameter at a distance of 10 m, and

(c) the irradiance at a distance of 10 m.

Solution:

(a) The aperture area is $A = \pi d^2/4 = \Pi (3\text{ mm})^2/4 = 7.069\text{ mm}^2$

The $1/e^2$ diameter of LASER beam is the diameter of a circle that intercepts 0.865 of the energy in the LASER beam. Hence,

$\pi d^2/4 = 0.865 \times 7.069\text{ mm}^2$

$d = 2.79\text{ mm}$

(b) The diameter D_L of a LASER beam at distance r from the aperture diameter (a) and beam divergence ϕ radians is given by

$$D_L = \sqrt{a^2 + r^2\phi^2}$$

$$D_L = \sqrt{(0.00279)^2 + (10)^2(0.005)^2} = 0.05\text{ m} = 5\text{ cm}$$

(c) The irradiance at a distance of 10 m =

$$\text{Irradiance} = \frac{\text{Power}}{\left(\frac{\pi D_L^2}{4}\right)} = \frac{4\text{ X}10\text{ W}}{3.14\text{ X }0.05^2} = 509\text{ mW/cm}^2$$

(2) A 0.1 J Ruby LASER has an aperture of 7 mm and a beam divergence of 1 mrad.

(a) What is the radiant exposure at distance of 5 and 10 m from the aperture ?

(b) How far behind the LASER aperture is the virtual focal point from where the LASER light seems to originate?

Solution:

a) Radiant Exposure

$$\text{Radiant Exposure } H(r) = \frac{\text{Radiant Energy}}{\text{Irradiated Area}} = \frac{Q}{\frac{\pi}{4}\left(\sqrt{a^2 + r^2\phi^2}\right)^2}$$

where Q = radiant energy = 0.1 J, a = aperture diameter = 0.7 cm = 7 mm
r = distance 5 m and 10 m , and ϕ = beam divergence = 0.001 radian

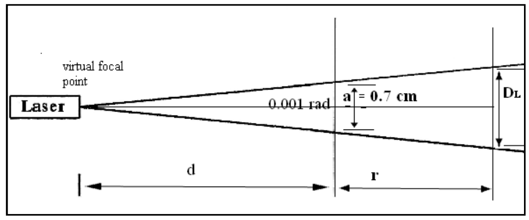
H (5m) = 0.172 J/cm^2 and H (10m) = 0.085 J/cm^2

b) Virtual Focal Point

The virtual focal point is the point where backward projection of the beam borders intersect, as shown in the Figure below:

$a = d\,\phi$

d = (a / ϕ) = 0.7 cm / 0.001 rad
= 700 cm = 7 m



(3) The output of a CW ND:YAG LASER is Q switched at a pulse repetition frequency of 10 kHz. If each pulse is 50 ns wide, and if the mean power output is 10 W, calculate (a) Duty cycle, (b) the peak power per pulse, (c) the energy per pulse.

Solution:

(a) Duty cycle = fraction of time lasing occurs = F (pulses/s) x T (s/pulse)
Duty cycle = 10×10^{3} pulses/ s x 50×10^{-9} s /pulse = 5×10^{-4}

(b) Peak power per pulse:

Mean power = duty cycle x peak power

P_{mean} = 10 W, duty cycle = 5×10^{-4}
P_{peak} = P_{mean}/ duty cycle = 10 W / 5×10^{-4} = 2×10^{4} W

(c) the Energy per pulse = peak power x time of pulse

E = 2×10^{4} W x (1 J/s / 1W) x 50×10^{-9} s/ pulse = 0.0001 J per pulse

(4) From a Gaussian-shaped beam, calculate the maximum central beam irradiance and the central beam irradiance averaged over a 7 mm aperture from a LASER with a 5 mW output and 8 mm beam diameter.

Solution:

(a) Maximum Irradiance E_0

$$\textbf{Max Irradiance}: \mathbf{E} = \frac{\mathbf{4\Phi}}{\mathbf{\pi D_L^2}} = \frac{\mathbf{1.27 X\ 5\ X\ 10^{-3}}}{\mathbf{(0.8)^2}} = \mathbf{9.9\ X10^{-3}\ W/cm^2}$$

(b) Maximum beam Irradiance over 7 mm
Fraction of the power transmitted = $_f$ / Φ_0

$$= \left[\mathbf{1 - e^{-\left(\frac{D_f}{D_L}\right)^2}}\right] = \left[\mathbf{1 - e^{-\left(\frac{0.7}{0.8}\right)^2}}\right]$$

Fraction of the power transmitted = 0.535

The beam irradiance averaged over 0.7 cm diameter aperture is given by
E = (5 mW x 0.535)/ 0.385 cm^2 = 6.95 mW/ cm^2

DETERMINATION OF MPE

CW and Single Pulse MPE

(5) Determine the MPE for accidental direct exposure to a visible LASER.

Solution:

The time to use for 'accidental exposure' in the visible region is 0.25 s, the blink reflex. Visible LASER are those that emit light of wavelengths between 400 and 700 nm. From Table AN1.1 , we find:

$MPE = 1.8\ t^{3/4}\ mJ/cm^2$
For $t = 0.25$ s, this is equal to a radiant exposure MPE:H = 0.636 mJ /cm^2 .

If we want the MPE in terms of irradiance, we use the formula:

$$E = \frac{H}{t} = \frac{0.636\ \text{mJ/cm}^2}{0.25\ \text{s}}$$

$E = 2.55\ mW / cm^2$

Finally, if we consider the limiting aperture of the eye in the visible region, 7 mm, then, the area over which the visible radiation will be viewed is $\pi/4 \times 0.7^2 = 0.385\ cm^2$. Hence, the maximum flux of a visible LASER to avoid harm due to accidental exposure should be $2.55 \times 0.385 = 1.0$ mW.

As you may recall, this is the upper power limit for a class II LASER device.

(6) With a single pulse near-infrared LASER, find the MPE for a 1.064-μm (Nd:YAG) LASER with a $7x10^{-4}$ s pulse.

Solution:

For exposure duration of $7 X 10^{-4}$ s, the MPE formula from Table AN-I.1 is given by
MPE:H = $9.0\ C_c\ t^{0.75}\ x\ 10^{-3}$ J x cm^{-2}

MPE:H = $9.0 x (7x10^{-4})^{0.75} x 10^{-3}$ J x cm^{-2} = $3.87 x 10^{-5}$ J x cm^{-2}

MPE:E = ($3.87 x 10^{-5}$ J x cm^{-2}) / ($7 x 10^{-4}$s) = $5.5 x 10^{-2}$ W x cm^{-2}

(7) Calculate the MPE for intentional, direct ocular exposure to the fundamental mode of a CW Nd:YAG LASER.

Solution:

The fundamental mode of a Nd:YAG LASER is at 1064 nm. The appropriate value is read directly from Table AN-I.1: For intentional viewing, take the time of exposure to be 100 s, so the

MPE = $5C_C X10^{-3}$ W / cm^2, or 5 mW / cm^2 (C_C = 1.0 for 1050 to 1150 nm).

(8) A GaAs near infrared LASER operates at room temperature at a peak λ=0.904 μm. What is the MPE for a 180 ns pulse?

Solution:

From Table AN-I.1, The MPE for exposures of 1 ns to 18 μs are given by:

MPE:H = 0.5 C_A $\mu J/cm^2$ = 0.5 x $(10^{0.002(904 - 700)})$ $\mu J \times cm^{-2}$
MPE:H = 0.5 X 2.56 $\mu J/cm^2$ = 1.28 $\mu J/cm^2$

(9) Calculate the MPE for accidental exposure to a Xe:Cl excimer LASER.

Solution:

The wavelength of emission from a Xe:Cl Excimer is 308 nm. Since this is invisible to the human eye, the time period for accidental exposure should be taken as t = 10 s. From Table AN-I.1, the

MPE = 40 mJ/cm^2 .

Note: from Table AN-I.1 that this MPE applies to all exposure times. Unlike the visible and near-IR region, where the eye can tolerate a small but constant irradiance, in the UV radiation damage is cumulative. Thus the longer the exposure time, the lower should be safe operating power.

(10) Ruby LASER with wavelength 694 nm and exposure duration is 1 ms, What is the MPE for eye and skin ?

Solution:

From Table AN-I.1, $MPE_{eye} = 1.8\ t^{0.75} = 1.8 \times (0.001)^{0.75}\ mJ/cm^2 = 0.1\ J/m^2$

From Table AN-I.2, $MPE_{skin} = 1.1\ C_A\ t^{0.25}\ J/cm^2 = 1.1 \times (1) \times (0.001)^{0.25} = 0.1956$ J/cm^2

(11) Determine the emergent beam diameter necessary to preclude a skin hazard for a 1.0 watt He-Ne LASER operating at 0.543 μm.

Solution:

The MPE for visible wavelength skin exposures greater than 10 s is found from Table AN-I.2

$MPE_{skin} = 0.2 \times C_A\ W/cm^2$ (with a limiting aperture of 3.5 mm)

For a visible LASER, C_A = 1.0, so the …. $MPE_{skin} = 0.2\ W/cm^2$

Where the output is greater than 0.5 W, which is lower boundary of Class-4 LASER, the beam would have to be large enough to reduce the irradiance to below 0.2 W/cm^2, i.e. MPE_{skin}.

MPE $_{skin}$ = E_0 = 4Φ /πa^2, and assume a is larger than 3.5 mm so…..

$$\mathbf{a} = \sqrt{\frac{\mathbf{4\ \Phi}}{\boldsymbol{\pi}\ (\mathbf{0.2})}} = \sqrt{\frac{\mathbf{4\ (1)}}{\boldsymbol{\pi}\ (\mathbf{0.2})}} = \mathbf{2.52\ cm}$$

The beam diameter must be greater than 2.5 cm to preclude a skin hazard.

(12) Does a He-Ne LASER at 632.8 nm, with a 1 mm exit beam diameter and a specified maximum output power of 1.25 mW exceed the MPE for a 0.25 s exposure near the exit?

Solution:

MPE for a visible LASER for 0.25 s is 2.55 x 10^{-3} W/cm^2

Near the LASER exit port, the increase in beam diameter may be ignored here. For the retinal hazard region, D_f is 7 mm. This represents a fully dilated pupil in daylight. The irradiance of the LASER is:

$$\mathbf{E} = \frac{\mathbf{1.27.\Phi}}{\mathbf{max}\ (\mathbf{a}, \mathbf{D_f})^{\mathbf{2}})} = \frac{\mathbf{1.27X\ 1.25\ X10^{-3}}}{\mathbf{0.7^2}}$$

E = 3.24 x 10^{-3} W x cm^{-2}

As 3.24 x 10^{-3} W/cm^2 is greater than 2.55 x 10^{-3} W/cm^2

⇨ This LASER does exceed the MPE.

MPE FOR REPETITIVELY PULSED LASER

(13) Calculate the MPE for a XeCl excimer LASER (308 nm), with a pulse length t = 20 ns, operating at a frequency F = 120 Hz.

Solution:

Assume an exposure time of 10 s (no blink reflex).
Refer sub section 5.2.1.2 for determination of MPE

Values of t_{min} are not specified for LASER below 315 nm. Hence, the flow chart in Figure 5.3 cannot be applied. In this case, all three values MPE limits are to be calculated, and the lowest should be taken as MPE.

Rule 1: The MPE for a single pulse of 20 ns at 308 nm, found in Table AN-I.1, is the lower of $MPE_{thermal}$ = 0.56 $t^{0.25}$ J/cm^2
= 0.56 (20X 10^{-9})$^{0.25}$ = <u>6.7 mJ/cm^2</u>

Rule 2: The $MPE_{Photochemical}$ of a continuous source for a 10 s exposure, found in Table AN-I.1, is 40 mJ/cm^2. The total number of pulses n = 1200, so the MPE per pulse = 40 mJ/cm^2 / 1200 = 33 µJ/cm^2
$MPE_{thermal}$ is same as in Rule 1.

Rule 3: Using the MPE for a single pulse = 6.7 mJ/m^2 (from limit 1), and

the number of pulses 10 s, n = 1200 (from limit 2), the calculated
MPE per Pulse = 6.7 (mJ/cm^2) X $(1200)^{-0.25}$
= 6.7 / 5.89 mJ/ cm^2 = 1.1 mJ/cm^2

So the MPE/pulse is defined by Rule-2-photochemcial is 33 $\mu J/cm^2$.

To express this in terms of irradiance, multiply the result by the repetition frequency F:

$$E = H/t = H.F = 0.033\ (mJ/cm^2) \times (120)\ (/s) = 4\ mW/cm^2$$

(14) Calculate the MPE for accidental exposure to a pulsed Nd:YAG LASER operating in its doubled mode of 532 nm, with an pulse length t = 1 ns and a repetition frequency F = 20 Hz.

Solution:

Assume an exposure time of 0.25 s (blink reflex) for accidental exposure
t = 1 ns < t_{min} (18 µs for 532 nm from Table AN-I.6)
F= 20 Hz, $F_{cr} = 10^6 / 18 = 55.56$ kHz
From the flow chart of Figure 5.3 → MPE is the lowest between the Rule-1 for thermal and Rule-2 for photochemical

Rule 1: The $MPE_{thermal}$ for a single pulse of 1 ns at 532 nm, found in Table AN-I.1, is
MPE single pulse = 0.5 $\mu J/cm^2$.

Rule 2: Thermal MPE is applicable as exposure duration is less than 10 s.
The MPE of a continuous source for a 0.25 s exposure, found in Table AN-I.1, is
$MPE_t = 1.8x\ t^{0.75} = 0.636\ mJ/cm^2$.
The total number of pulses, n = FT = 20 x (0.25) = 5, so the
$MPE_{per\ Pulse}$ = 0. 636 (mJ/cm^2) /5 = 0.127.2 mJ/cm^2

Rule 3: Using the MPE for a single pulse = 0.5 $\mu J/cm^2$ (from limit 1), and the number of pulses in 0.25 s, n = 5 (from limit 2), the calculated
MPE per Pulse= 0.5 X $(5)^{-0.25}$ = 0.33 $\mu J/cm^2$

Here though MPE/pulse using Rule 3 is the lowest, it cannot be taken as MPE. MPE is lowest of Rule-1 thermal and Rule-2 photochemical. Hence, MPE= 0.5 $\mu J/cm^2$

To express this in terms of irradiance, multiply the result by the repetition frequency F:

$$E = H/t = H.F = 0.0005\ mJ/cm^2 \times 20\ s = 0.01\ mW/cm^2 = 10\ \mu W/cm^2$$

15) What is the MPE for an eye exposed to LASER radiation at 488 nm from Argon LASER source emitting pulses of 10 ns duration at a repetition rate of 1 MHz.

Solution:

Wavelength = 488 nm, F = 1 MHz, t = 10 ns, exposure duration T = 0.25 s, as it is visible,
T_{min} = 18 µs F_{cr} = 55 kHz (from Table AN-I.6)

From Figure 5.3 the MPE is to be selected from lower of Rule-2 for thermal and Rule-2 for photochemical. However as exposure duration is less than 10 s, the applicable limit is from Rule-2 Thermal MPE

Rule 1: Single Pulse MPE: from Table AN-I.1 $MPE_{pulse} = 0.5\ \mu J/cm^2$

Rule 2: Average Power MPE for 0.25 s exposure duration

$MPE_{avg} = 1.8\ (t)^{0.75} = 1.8 \times (0.25)^{0.75} = 0.636\ mJ/cm^2$

The total number of pulses, $n = FT = 10^6\,(0.25) = 25 \times 10^4$, so the

MPE per Pulse = $0.636 / (25 \times 10^4)\ (mJ/cm^2) == 2.55 \times 10^{-6}\ mJ/cm^2$

$MPE_{avg} = 2.55 \times 10^{-6} \times 10^{-3} / 10^{-4}\ J/m^2 = 2.55 \times 10^{-5}\ J/m^2$

Hence the MPE/pulse is defined by Rule 2, i.e., MPE = $2.55 \times 10^{-5}\ J/m^2$.

16) For a near infrared repetitive pulsed LASER, find the MPE for a 905 nm GaAs LASER, with a 100 ns pulse width (1×10^{-7}) and a PRF of 1 kHz

Solution:

For wavelength λ = 905 nm, the recommended maximum duration of exposure is 10 s. The total number of pulses, in a 10 s is $n = FT = 10^4$ pulses.

The MPE reduction factor for repetitive pulse wave $C_P = n^{-0.25} = 0.1$

The spectral correction factor λ is given by $C_A = 10^{0.002(\lambda-700)} = 10^{0.410} = 2.57$

t = 100 ns

$t_{min} = 18\ \mu s$ F_{cr} = 55 kHz (from Table AN-I.6)

From Figure 5.3, the MPE Limit is the lowest amongst Rule-2 photochemical or Rule-3, with $T = t_{min}$

Rule 1: Single Pulse MPE:

$MPE_{sp} = 0.5\ C_A \times 10^{-6}\ J \times cm^{-2} = 1.29 \times 10^{-6}\ J \times cm^{-2}$

Rule 2: Average Power MPE : The MPE for a 10 s exposure is :

$$MPE{:}H_{group} = \frac{1.8 \times 10^{-3}\ C_A\ t^{0.75}\ J \times cm^{-2}}{10^4 \text{ pulses}} = 2.6 \times 10^{-6}\ J/cm^2$$

Rule 3: Repetitive Pulse Limit:

$$\begin{aligned} MPE/pulse &= n^{-0.25}\ MPE_{sp} \\ &= 10{,}000^{-0.25} \times 1.29 \times 10^{-6}\ J \times cm^{-2} \\ &= 1.3 \times 10^{-7}\ J \times cm^{-2} \end{aligned}$$

Here, MPE is selected for $t_{min} = 18\ \mu s$

Rule 3 yields the lowest value and is selected as the MPE/pulse = 1.3×10^{-7} joule/ cm^2.

Now the cumulative exposure MPE for the entire pulse train is found:

$$\begin{aligned} MPE{:}H_{group} &= T \times F \times MPE/pulse = (10\ s)\ (10^3\ Hz)\ (1.3 \times 10^{-7}\ J \times cm^{-2}) \\ &= 1.3 \times 10^{-3}\ J \times cm^{-2} \end{aligned}$$

In terms of average irradiance this is:

$$MPE:E = \frac{\underline{MPE:H\ group}}{T} = \frac{1.3 \times 10^{-7}\ J \times cm^{-2}}{10\ s} = 1.3 \times 10^{-4}\ W \times cm^{-2}$$

17) Find the MPE of a 0.643 μm Q-switched LASER, with three 200 ps pulses 100 ns apart.

Solution:

This is a visible wavelength (643 nm), where the pulse train isn't more than 0.25 s. and
t = 200 ps, from Table AN-I.6 - t_{min} = 18 μs and F_{cr}= 55 KHz

Here there is no pulse repetition frequency; It has only 3 pulses of 200 ps separated by 100 ns. The total duration of pulse will be little more than 200 ns which is less than t_{min}. Hence all three pulses should be considered as single pulse

Rule 1: Single Pulse Limit: Table AN-I.1, single pulse MPE
$MPE_{sp} = 2.7 \times t^{0.75}$ J/ cm^2 =$2.7 \times (200 \times 10^{-12})^{0.75} = 1.44 \times 10^{-7}$ J x cm^{-2}

Rule 2: Average Power Limit. The Pulse train of 200 ns is less than t_{min} of 18 μs (from Table AN-I.5),
$$MPE:H\ group = \frac{5 \times 10^{-7}\ J \times cm^{-2}}{3\ pulses} = 1.67 \times 10^{-7}\ J \times cm^{-2}$$

Rule 3: Repetitive Pulse Limit. Where exposure duration 'T' is less than t_{min}, all the pulses are considered the same as 1 pulse, so sum the energies of all the three pulses. C_P is 1.0.
The MPE for t_{min} is 5×10^{-7} J /cm^2 and

MPE/pulse = based on Rule 3 is the same as for Rule 2
= 1.67×10^{-7} J / cm^2

The lowest MPE is from Rule 1: MPE/pulse = 1.44×10^{-7} J x cm^{-2}

18) A argon fluoride excimer LASER operating at 193 nm is used at PRF= 400 Hz and each pulse is 20 ns in length . What is exposure limit for 10 s exposure duration?

Solution:

λ= 193 nm, F = 400 Hz, t_{min} = Not specified in standard. t = 20 ns and T= 10 s
Principle of thermal confinement for biological effect is not applicable below 315 nm, therefore, all three rules are to be applied for determination of MPE.

- The MPE for UV LASER (< 400 nm) are based on both thermal effects and photochemical effects and most restrictive limit should be considered.

Rule 1: Single Pulse Limit
$MPE_{SP} = 0.56\ (20 \times 10^{-9})^{0.25}$ J/cm^2 = 6.66 mJ/cm^2
Photochemical limit of 3mJ/cm^2 (from Table AN-I.6) is lowest as per rule 1.

Rule 2: Average Power Rule – For thermal effects

- Thermal MPE_{group} = 0.56 $(10)^{0.25}$ = 1 J/cm^2
  In 10 s exposure, an individual could be exposed to n =FT= 400 x 10= 4000 pulses
  Thermal MPE/ pulse = 1/ 4000 J/cm^2 = 2.5 x 10^{-4} J/cm^2/pulse
- MPE for photochemical effect per pulse = 3x 10^{-3}/ 4000 = 7.5 x 10^{-07} J/cm^2/ pulse
- As per rule 2, MPE photochemical = 7.5 x 10^{-7} J/cm^2

Rule 3: Repetitive Pulse Limit

- Repetitive pulse correction factor is to be applied to thermal MPE_{SP} but not to photochemical limit.
- As per rule 1, thermal MPE_{SP} = 6.6 mJ/cm^2
  For 10 s exposure will have 4000 pulse
  $MPE_{RP} = MPE_{SP}$ x $(n)^{-0.25}$ = 6.66 x 0.126 = 8.4 x 10^{-4} J/cm^2

Comparing MPE from all 3 rules, the photochemical MPE/pulse of 7.5 X 10^{-7} J/cm^2 is the lowest
Exposure limit for T= 10 s is given by

MPE:H_{group} = T x F x MPE/pulse = (10 s) (400 Hz) (7.5 x 10^{-7} J/cm^2) = 3 mJ/cm^2

MPE FOR EXTENDED SOURCE

19) A user observes a diffuse reflection from a CW Nd:YAG LASER operating at 532 nm with an energy of 2 W. The distance is 40 cm and the angle of observation 20º to the normal. Is the user safe?
Let the diameter of the beam at the surface of the reflector *a* = 8 mm. Is the beam observed as an extended source?

Solution:

λ = 532 nm, exposure duration T = 0.25 s,
Hence MPE from Table AN-I.1, MPE = 1.8 $t^{0.75} C_E$ = 0.636 mJ / cm^2
Assume a perfect reflector (ρ = 1) and ignore the angle of observation. The energy observed by the user is:

Energy = Power x time = 2 W x 0.25 s = 0.5 J

The radiant exposure of the reflected beam is given by $H_{obs} = \frac{Q\rho_\lambda \cos\theta_v}{\pi r_1^2}$

H_{obs} = (0.5*10^3 mJ Cos 20)/ 3.142 x (40 cm)^2 = 0.093 m J/cm^2
Yes, the user is safe.

To determine the angle subtended by the beam's image at the point of observation, we require the distance (*r* = 40 cm) the angle (θ = 20º) and the beam diameter (0.8 cm). The angle subtended is given by:

Yes, the beam does represent an extended source. The correct MPE, after application of extended source correction factor (α/α_{min}),

MPE = 0.636 **x** 19/1.5 = 8.06 mJ /cm^2 .

CALCULATIONS FOR NHZ

20) CW CO_2 LASER, intra-beam case average power Φ = 2000 W, beam divergence ϕ= 4 mrad = 0.004 radians, emergent beam diameter (a) = 1.0 cm, λ = 10.6 μm. Calculate NOHD

Solution:

For intra beam viewing as per Table AN-I.3, exposure duration = 10 s
From Table AN-I.1; MPE = 100 mW/cm^2 or MPE = 0.1 W/cm^2
From Equation 5.23 Nominal Occular Hazard Distance is given by

$$r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{4\Phi}{\pi.\text{MPE: E}} - D_W^2}$$

$$r_{NOHD} = \frac{1}{0.004}\sqrt{\frac{4\text{x } 2000}{\pi \text{ x } 0.1} - 1^2}$$

r_{NOHD} = 39,900 cm = 399 m

21) Find the hazardous viewing distance for 10 s exposure for looking at a diffuse target having a reflectivity of 0.9 illuminated by a laboratory argon LASER (514 nm) with 2 W power and aperture diameter is 2 mm.

Solution:

T= 10 s , $\rho_\lambda = 0.9$; λ = 514 nm, Φ = 2W

Worst case diffuse reflection will be at 0 degree and
From Table AN-I.1 read along with Note-1, only thermal MPE is applicable
MPE = 1 x 10^{-3} W/cm^2

$$r_{NOHD-diffuse} = \sqrt{\frac{\Phi\rho_\lambda \cos\theta_v}{\pi.\text{MPE:E}}} = \sqrt{\frac{2 \text{ W X } 0.9 \text{ X } \cos 0}{3.14 \text{ X } (1 \text{ X } 10^{-3} \text{W/cm2})}}$$

$\mathbf{r}_{NOHD-diffuse}$ = 24 cm

CLASSIFYING THE LASER

22) What is the LASER class for a single pulsed Q-switched ruby LASER, with a manufacturer's listed peak power output of 25 MW for 32 ns?. The LASER rod diameter is 5/8 inch.

Solution:

For Ruby LASER λ = 694.2 nm, and given that Φ = 25 MW, t =32 ns,
D_L= 5/8 inch = 0.62x 2.54 cm = 1.57 cm

First find the output energy per pulse using formula

$Q = \Phi \times t = (25 \times 10^6 W)(3.2 \times 10^{-8} s) = 0.8$ J

From Table AN-I.1, MPE = 0.5 μ J/cm^2

AEL1= MPE x πD_f^2/ 4 watts= 0.5 x10^{-6} x 3.142 x $(1.54)^2$/ 4 =0.93 X10^{-6} J

Using the flow-chart of Figure 5.9 and comparing Q with AEL-1 or using the Class 3B limit from definition given in Annexure II is : 0.03 x C_A joule / pulse = 0.03 J (C_A = 1)

Comparing Q with Class 3B limit 0.8 J/ 0.03J = 26.6

This LASER is 27 times this limit! (0.8J/0.03J = 26.66) So it is a Class 4 LASER.

23) Classify the following LASER: A dye LASER with a peak λ= 0.580 μm. Power output is 10 mJ for a 5 mm beam for a 1 μs burst.

Solution:

t = 1 μs, λ = 580 nm, D_L= 0.5 cm

The MPE can be selected from Table AN-I.1 as

$MPE = 5 \times 10^{-7}$ J /cm^2 and C_A =1.0 at 580 nm

Limiting aperture is 7 mm and Area of limiting aperture is 0.385 cm^2 (Table AN-I.4)

The Class 1 AEL = MPE x Area of limiting aperture

$$\textbf{Class 1 AEL} = \textbf{MPE X} \frac{\pi D_f^2}{4} \ \mathbf{J/cm^2}$$

Class 1 AEL = 5 x 10^{-7} J /cm^2 x 0.385 cm^2 = 1.9 x 10^{-7} J

- The Class 3R AEL is 5 times the Class 1 AEL or 9.6 x 10^{-7} J
- The Class 3B limit from Annexure II or flow chart in Figure 5.6 is 0.03x C_A J/ pulse or 30mJ/pulse.

The 10 mJ output lies between the limits of 0.96 μJ and 30 mJ. Therefore, it's a Class 3B LASER.

CALCULATION FOR OPTICAL DENSITY OF LASER PROTECTIVE EYE-WEAR

24) A pulsed ruby LASER, λ = 694.3 nm, is operated in a laboratory at a level of 5 x 10^{-4} J/pulse, 100 μs pulse width, and a PRF of 60 pulses per second. The beam exit aperture is 1 mm in diameter, and the beam divergence is 0.1 mrad. What optical density is required for protective goggles for incidental exposure for as long as 2 s?

Solution:

λ = 694.3 nm Q = 5 x 10^{-4} J/pulse t_{pulse} = 100 μs

F = 60 Hz D_L = 1 mm = 0.1 cm   ɸ = 0.1 mrad
OD for t = 2s

Calculating MPE using 3 rule method

Rule 1: Single pulse limit
MPE for single pulse of 100 µs from Table AN-I.1 is
MPE = $1.8\ t^{0.75} = 1.8\ (10^{-4})^{0.75} = 1.8\ X10^{-3}$ mJ/cm^2

Rule-2: MPE average power limit
MPE for 2 s from table AN-I.1 is $1.8\ (2)^{0.75} = 3.02$ mJ/cm^2
Number of pulse in 2 s are 120
MPE per pulse is = 3 /120 mJ/cm^2 = 0.025 mJ/cm^2
As exposure is less than 10 s, only thermal limit is applicable

Rule 3 : Repetitive pulse limit
Single Pulse limit = $1.8\ X10^{-3}$ mJ/cm^2
Number of pulses 120
Repetitive pulse limit = $1.8\ X10^{-3}$ mJ/cm^2 X $(120)^{-0.25} = 0.54\ X\ 10^{-3}$ mJ/cm^2

From Figure 5.3 only limit of rule 3 is applicable MPE

MPE = 0.54 µJ/cm^2/ pulse

MPE for 2 s = F.T. MPE/pulse = 60 X 2X 0.54 X 10^{-3} mJ/cm^2
= 64.8 X 10^{-3} mJ/cm^2

In this LASER, pulse energy is Q = 5 x 10^{-4} J/pulse, Hence radiant exposure can be given by

$$H = \frac{4Q}{\pi D_L^2} = \frac{4\ X\ 0.5\ X\ 10^{-4}}{\pi\ 0.1^2}$$

H= 6.37 x 10^{-2} J/cm^2/pulse

OD = log (H / H_{MPE}) = log [(6.37 x 10^{-2}J /cm^2)/ (64.8 x10^{-7} J/cm^2)] = 5.1
Hence the required optical density for 2 s exposure is 5.1

25) A He-Ne LASER, λ = 632.8 nm, is operated at a power level of 3 W in CW mode. The beam aperture is 0.9 mm (0.09 cm) in diameter, and the beam divergence is 0.9 mrad. If the possibility exists for momentary accidental intra-beam ocular exposure not exceeding 0.25 s, calculate the minimum required optical density of protective goggles for exposure (a) at the LASER, and (b) at a distance of 100 m.

Solution:

a) Calculation at exit port of the LASER:

The power density at the aperture;

$$E = \frac{\text{Power}}{\text{Area}} = \frac{4\Phi}{\pi D_L^2} = \frac{4x\ 3}{\pi.(0.09)^2}$$
E= 472 W/cm^2

From Table AN-I.1
MPE:H = 1.8 (t)$^{3/4}$ x 10^{-3} J/cm^2 = 1.8 (0.25)$^{3/4}$ x 10^{-3}J/cm^2 = 6.36 x 10^{-4} J/cm^2

MPE :E = MPE:H / t = [(6.36 x 10^{-4} J/cm^2) / (0.25 s)]
= 2.54 x 10^{-3} W/cm^2

OD = log (E/ E_{MPE}) = log [(472 W/cm$^{2)}$ /(2.5 x 10^{-3} W/cm^2)] = 5.3

Hence Optical Density of 5.3 is required at LASER exit port for accidental viewing.

b) Calculation at a distance of 100 m:

The irradiance at a distance r is given the equation

$$E = \frac{4\Phi}{\pi[(a)^2 + r^2\phi^2)} = \frac{4x\ 3}{\pi[(0.09)^2 + (10000)^2.(0.9X10^{-3})^2]}$$

E(100m) = 4.72 x 10^{-2} W/cm^2
MPE = 2.5 x 10^{-3} W/cm^2 …. From part (a)

OD = log (E/ E_{MPE}) = log [(4.72x 10^{-2} W/cm$^{2)}$ /(2.5 x 10^{-3} W/cm^2)]

OD = 1.3 is required at a distance of 100 m.

26) An Nd:YAG LASER with a power of 40 watts is projected onto a fully dilated human eye pupil of 7-mm diameter. The eye is exposed for a duration of 10 s. Calculate the minimum optical density OD of a LASER safety goggle needed to protect the eye from damage.

Solution:

λ = 1064 nm, duration of exposure T = 10 s, Eye diameter = 7 mm

- MPE = 0.005 W/cm^2 (from Table AN-I.
- Φ = 40 W,

Area of pupil = $\pi D^2/4$ = (3.14)(0.7 cm)^2 /4 = 0.38 cm^2

Using eqn. OD = $\log_{10}(E_0/ \text{MPE})$ and
$E_0 = \Phi / A$ = 40 / 0.38 cm^2 = 105.26 W/cm^2
OD= $\log_{10}$[(105.26W/cm^2) /(0.0051 W/cm^2)] = 4.3
The required optical density for the LASER safety goggles would be 4.3 or larger.

ANNEXURE V

DETAILS OF AREA WARNING SIGNS AND EQUIPMENT LABELS

TABLE AN-V.1
MEANING AND GUIDELINES FOR USE OF SIGNAL WORDS ON THE LASER WARNING SIGNS AND LABELS

Signal Word	Meaning	Use
CAUTION	Indicates a potentially hazardous situation, which if not avoided, may result in minor or moderate injury. It may also be used to alert against unsafe practices.	The signal word “Caution” shall be used with all signs and labels associated with Class 2 and Class 2M LASER and LASER systems, which do not exceed the applicable MPE for irradiance.
DANGER	Indicates an imminently hazardous situation, which, if not avoided, will result in death or serious injury. This signal word is to be limited to the most extreme conditions	The signal word “Danger” shall be used with all signs and labels associated with all LASER and LASER system that exceed the applicable MPE for irradiance, including all Class 3R, Class 3B and Class 4 LASER and LASER systems. The optical density of protective eyewear and wavelength shall be shown on the sign for a location requiring the use of eyewear.
NOTICE	Indicates a statement of facility policy as the message relates directly or indirectly to the safety of personnel or the protection of property. This signal word shall not be associated directly with a hazard or hazardous situation and must not be used in place of “DANGER” or “CAUTION”.	The signal word “Notice” shall be used on signs posted outside a temporary LASER control area such as during periods of service.

Figure AN-V.1
BLANK TEMPLATES FOR LASER WARNING SIGNS / EQUIPMENT LABELS

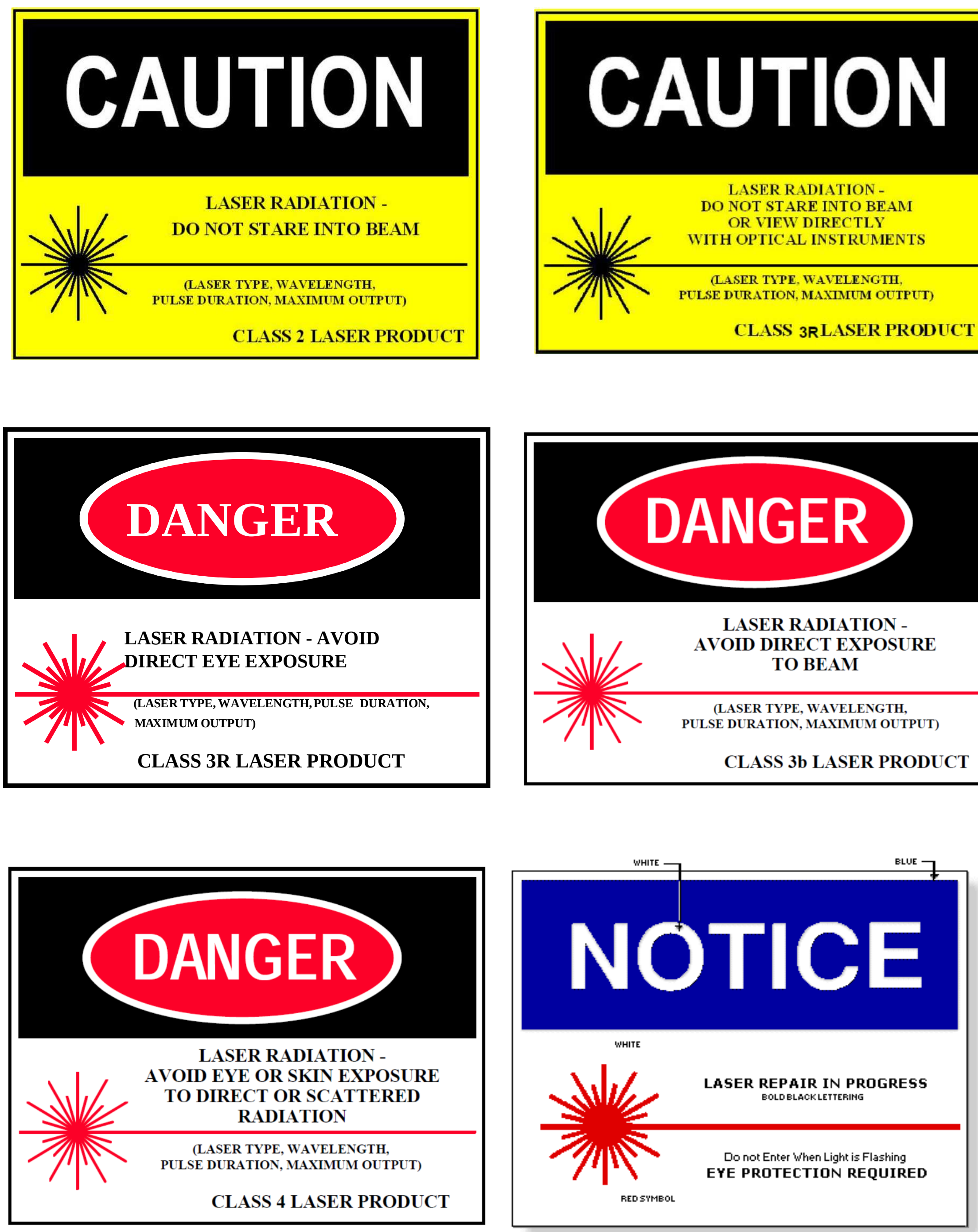


Figure AN-V.2
SAMPLE LASER WARNING SIGNS / EQUIPMENT LABELS

V.1 Information on Area Warning Signs [refer Figure AN-V.1 and AN-V.2]

The area warning sign shall conform to the following specifications

(a) The appropriate signal word (Danger, Caution, or Notice) shall be located in the upper panel.

(b) Adequate space shall be available on all signs to allow for the inclusion of pertinent information. Such information may be included during the printing of the sign or may be handwritten in a legible manner, and shall include the following:

   (1) At position 1 above the tail of the sunburst, special precautionary instructions or protective action that may be applicable. For example,

      (i) LASER protective eyewear required
      (ii) Invisible LASER radiation
      (iii) Knock before entering
      (iv) Do not enter when light is on
      (v) Restricted area

   (2) At position 2 below the tail of the sunburst, the type of LASER (Nd:YAG, Helium-Neon, etc.), or the emitted wavelength, pulse duration (if appropriate), and maximum output; and

   (3) At position 3, the class of the LASER / LASER system

The word "Radiation" on signs and labels may be replaced by the word "light" for LASER operating in the visible range at wavelengths greater than 0.4 μm and equal to or less than 0.7 μm. For LASER operating outside of this visible range, the word "Invisible" shall be placed prior to the words "LASER Radiation".

V.2 Information on Equipment Label

(a) At position 1 above the tail of the sunburst, special precautionary instructions or protective actions required by the reader, such as

   (1) For Class 2 LASER and LASER systems, 'LASER Radiation – Do Not Stare into Beam'

   (2) For Class 2M and 3R LASER and LASER systems where the accessible irradiance does not exceed the applicable MPE based upon a 0.25 s exposure for wavelengths between 0.4 and 0.7 μm 'LASER Radiation – Do Not Stare into Beam, or View Directly with Optical Instruments'

   (3) For all other Class 3R LASER and LASER systems, 'LASER Radiation – Avoid Direct Eye Exposure'

   (4) For all Class 3B LASER and LASER systems, 'LASER Radiation – Avoid Direct Exposure to Beam'

   (5) For Class 4 LASER and LASER systems, 'LASER Radiation –Avoid Eye or Skin Exposure to Direct or Scattered Radiation'

(b) At position 2 below the tail of the sunburst, type of LASER (Nd:YAG, Helium-Neon, etc.), or the emitted wavelength, pulse duration (if appropriate), and maximum output; and

(c) At position 3, the class of the LASER / LASER system

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LIST OF PARTICIPANTS

EXPERT COMMITTEE FOR PREPARATION OF SAFETY GUIDELINES FOR 'DEVELOPMENT AND APPLICATION OF LASER'

Dates of meeting	:	October 30, 2007 September 1, 2009[#] November 2, 2010 January 5, 2011 January 29, 30 and 31, 2011 February 13 and 14, 2011 October 12, 2011[*] April 9, 2013[*]

Members and invitees of the Expert Committee:

Dr. K. Dasgupta (Chairman)	:	BARC
Prof. T. Kundu,	:	IIT, Bombay
Dr. Lala Abhinandan	:	RRCAT
Dr. Suranjan Pal	:	ECS, DRDO Headquarters, Delhi
Dr. Alok Ray	:	BARC
Shri Nidhip Chodankar (Member-Secretary)	:	AERB

\# It was decided in the first meeting that there was a requirement to refer to the 'American National Standard for Safe Use of LASER (ANSI-Z-136.1-2007)' in order to produce the draft document. The second meeting took place after procuring the same through RRCAT, Indore, and preparing the draft.

* In view of the diversity of LASER and the complexity of hazard analysis, it was decided to provide comprehensive but simplified procedures covering the entire gamut of hazard evaluation, risk assessment and control measures including organisational requirements. Apart from the earlier meetings which deliberated on these aspects, produced a detailed understanding of the various complexities and quantitative procedures, and created the first draft, this approach also required several sections to be re-written breaking down the reasoning and procedures in well-defined steps, as well as new figures and flow charts to be prepared and incorporated with due attention to accuracy of the logic involved. As availability of all members for the subsequent meetings could not be assured, the revised drafts were circulated among members through e-mails and their consent taken before submission.

LIST OF SAFETY STANDARD AND SAFETY GUIDELINES ON INDUSTRIAL SAFETY

Safety Series No.	Title	Year of Publication
AERB/NF/SS/FPS (Rev.1)	Fire Protection System for Nuclear Facilities	2010
AERB/SG/IS-1	Control of Works	2011
AERB/SG/IS-2	Preparation of Safety Report of Industrial Plants other than Nuclear Power Plants in the Department of Atomic Energy	2001
AERB/SG/IS-3	Personal Protective Equipment	2004
AERB/SG/IS-4	Pre-employment Medical Examination and Fitness for Special Assignments	2005
AERB/SG/IS-5	Accelerators	2005
AERB/NF/SG/ IS-6	Safety in Thorium Mining and Milling	2006
AERB/SG/ IS-7	Safety in Design and Application of LASER	2015
AERB/SG/EP-3	Preparation of On-site Emergency Preparedness Plans for Non-Nuclear Installations	2000
AERB/SG/EP-4	Preparation of Off-site Emergency Preparedness Plans for Non-Nuclear Installations	2000