Doc 9815
AN/447

Manual on Laser Emitters and Flight Safety

Approved by the Secretary General
and published under his authority

First Edition — 2003

International Civil Aviation Organization

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AMENDMENTS

The issue of amendments is announced regularly in the *ICAO Journal* and in the monthly *Supplement to the Catalogue of ICAO Publications and Audio-visual Training Aids*, which holders of this publication should consult. The space below is provided to keep a record of such amendments.

RECORD OF AMENDMENTS AND CORRIGENDA

AMENDMENTS		
No.	Date	Entered by

CORRIGENDA		
No.	Date	Entered by

FOREWORD

Adequate lighting is necessary for all visual tasks. An excess of light, however, can detrimentally affect vision to the extent of rendering it ineffective. In aviation, a pilot may experience high levels of lighting when flying into the sun or looking at very bright artificial light sources such as searchlights. The invention (in 1957) of the laser* is a significant addition to the known aviation-related problems associated with high-intensity lights.

Laser is an acronym for *light amplification by stimulated emission of radiation*; this technique can produce a beam of light of such intensity that permanent damage to human tissue, in particular the retina of the eye, can be caused instantaneously, even at distances of over 10 km. At lower intensities, laser beams can seriously affect visual performance without causing physical damage to the eyes. There are, however, many useful applications of laser technology, such as high-speed automatic scanning of bar codes, laser printing, welding and cutting, micro-surgery, communication by means of fibre optics, recording of music, gyroscopes, light displays and the ubiquitous laser pointer used by lecturers worldwide. Lasers are associated with almost every aspect of modern life.

Whilst protection of the pilot against deliberate or accidental laser beam strikes has been of interest to military aviation medicine specialists for many years, it was only with the advent of the laser light display for entertainment or commercial purposes and subsequent accidental illumination of civil aircraft from such displays that civil aviation medicine specialists have become more concerned.

By 2001, many pilots had experienced incapacitation following accidental laser beam strikes. Over 600 incidents have been recorded worldwide, the majority of reports coming from the United States (see Chapter 4, page 4-1 for a summary of two significant incidents). It may be expected that most civil aircraft laser beam strikes will be inadvertent, but powerful laser emitters that can be accurately targeted are now available at relatively low cost, so the possibility of malicious use of such devices in the future cannot be ignored.

In view of the increasing risk to flight safety posed by the more widespread use of laser emitters around airports, ICAO formed a study group in 1999 to evaluate the laser risk and consider whether new Standards or Recommended Practices (SARPs) were necessary.

The study group consisted of experts in ophthalmology and vision care, light engineering and physics, flight operations and regulatory aviation medicine. These experts were nominated in part by four Contracting States: Canada, Netherlands, United Kingdom and United States and in part by the Aerospace Medical Association and the International Federation of Airline Pilots' Associations.

At the first meeting of the study group, documentation was presented indicating that there was considerable international concern that lasers might pose a significant and increasing risk to flight safety and that without ICAO action, development of necessary controls in individual Contracting States would be inconsistent, insufficient or worse, non-existent.

During 1999 and 2000, the Aviation Medicine Section of the ICAO Secretariat, with the assistance of the study group, developed the laser-related SARPs that are now included in Annexes 11 and 14 to the Convention. However, these SARPs do not provide the necessary practical guidance for implementation of relevant regulations in States. The study group, therefore, recommended that a manual be written focussing on the medical, physiological and psychological effects on flight crew of exposure to laser emissions.

The information and guidance material provided in this manual is primarily directed to decision-makers at government level, laser operators, air traffic control officers, aircrew, aviation medicine consultants to and medical officers of the regulatory authorities, and doctors involved in clinical aviation medicine, occupational health and preventive medicine. The manual is aimed both at reducing the need for regulatory authorities to seek individual expert advice and at reducing inconsistencies between Contracting States in the implementation of national regulations.

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* The term laser has more than one meaning, see Glossary.

In addition, it can be used to support training provided by operators to flight crew with respect to the effect of laser emitters on operational safety. It is recommended that the information contained in Chapter 4, particularly in relation to preventative procedures, be included in the operations manual.

This manual contains information and guidance provided by the study group. Comments from States and other parties outside ICAO would be appreciated. They should be addressed to:

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International Civil Aviation Organization
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Montréal, Quebec H3C 5H7
Canada

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GLOSSARY

Note.— The definitions of the terms listed below are based on a pragmatic approach. The terms defined are therefore limited to those actually used in this manual. This listing is not intended to constitute a dictionary of terms used in the laser field as a whole.

Absorption. Transformation of radiant energy to a different form of energy (usually heat) by interaction with matter.

Accessible emission limit (AEL). The maximum accessible emission power or energy permitted within a particular laser class.

Accessible radiation. Optical radiation to which the human eye or skin may be exposed in normal usage.

Actinic radiation. Electromagnetic radiation in the visible and ultraviolet part of the spectrum capable of producing photochemical changes.

Aerodrome reference point (ARP). The designated geographical location of an aerodrome.

After-image. An image that remains in the visual field after an exposure to a bright light.

Attenuation. The decrease in the laser beam power or energy as it passes through an absorbing or scattering medium.

Average power. The total energy imparted during exposure divided by the exposure duration.

Aversion response. Closure of the eyelid or movement of the head to avoid an exposure to a noxious stimulant or bright light. In laser safety standards, the aversion response (including blink reflex time) is assumed to occur within 250 milliseconds (0.25 s).

Beam. A collection of rays that may be parallel, divergent or convergent.

Beam diameter. For the purpose of this manual, the beam diameter is the radial distance across the centre of a laser beam where the irradiance is 1/e times the centre-beam irradiance (or radiant exposure for a pulsed laser).

Beam waist. The minimum dimension of a cross section of the beam.

Buffer angle. An angle added to the beam divergence or intended laser projection field in order to ensure a protection zone.

Buffer zone. A volume of air surrounding the laser beam, all potential locations of the laser beam and all hazardous diffuse or specular reflections, where the maximum permissible exposure (MPE) or visual interference levels are exceeded. It includes the beam divergence or scanning extent of the laser beam plus the buffer angle and the full range of the laser beam to the point where the MPE or any applicable visual interference level is not exceeded. Natural terrain or beam masks may truncate part of this volume.

Cavity. The optical assembly of a laser usually containing two or more highly reflecting mirrors which reflect radiation back into the active medium of the laser.

Collateral radiation. Any electromagnetic radiation emitted by a laser, except the laser beam itself, which is necessary for the operation of the laser emitter or is a consequence of its operation.

Collimated beam. A beam of radiation with very low divergence or convergence and therefore effectively considered parallel.

Continuous wave (CW). The output of a laser which is operated in a continuous rather than a pulsed mode. In laser safety standards, a laser operating with a continuous output for a period greater than 0.25 s is regarded as a CW laser.

Critical level. The minimum effective irradiance from a visible laser beam which can interfere with critical task performance due to transient visual effects.

Diffraction. Deviation of part of a beam, determined by the wave nature of radiation and occurring when the radiation passes the edge of an opaque obstacle.

Diffuse reflection. The component of a reflection from a surface which is incapable of producing a virtual image such as is commonly found with flat finish paints or rough surfaces. A matt surface will reflect the laser beam in many directions. Viewing a diffuse reflection from a matt surface may produce either a small or a large retinal image, depending on the viewer distance and the size of the illuminated surface.

Divergence (φ). For the purpose of this manual, the divergence is the increase in the diameter of the laser beam with distance from the exit aperture, based on the full angle at the point where the irradiance (or radiant exposure for pulsed lasers) is 1/e times the maximum value.

Electromagnetic radiation. The flow of energy consisting of orthogonally vibrating electric and magnetic fields. Electromagnetic radiation includes optical radiation, X-rays and radio waves.

Electromagnetic spectrum. The range of frequencies or wavelengths over which electromagnetic radiations are propagated. The spectrum ranges from short wavelengths, such as gamma rays and X-rays, through visible radiation to longer wavelength radiations of microwaves, and television and radio waves.

Energy. The capacity for doing work. Energy content is commonly used to characterize the output from pulsed lasers and is generally expressed in joules (J).

Excited state. The state of an atom or molecule when it is in an energy level with more energy than in its normal or "ground" state.

Exposure duration. The duration of a pulse or a series or a train of pulses, or of continuous emission of laser radiation incident upon the human body.

Flash-blindness. The inability to see (either temporarily or permanently) caused by bright light entering the eye and persisting after the illumination has ceased.

Free radical. An atom or group of atoms in a transient chemical state containing at least one unpaired electron. Free radicals may be produced within or introduced into biological tissue where they may cause damage.

Gaussian beam profile. The bell-shaped profile of a laser beam when the laser is operating in the simplest mode.

Glare. A temporary disruption in vision caused by the presence of a bright light (such as an oncoming car's headlights) within an individual's field of vision. Glare is unassociated with biological damage and lasts only as long as the bright light is actually present within the individual's field of vision.

Hazard. Something with the potential to cause harm to people, property or the environment.

Hazard zone. The space within which the level of radiation during operation of a laser emitter exceeds the applicable exposure limit. See also ***nominal hazard zone (NHZ).***

Infrared radiation. For the purpose of this manual, electromagnetic radiation with wavelengths that lie within the range 700 nm to 1 mm.

Instrument flight rules (IFR). A set of rules governing the conduct of flight under instrument meteorological conditions.

Interlock. See ***safety interlock.***

Invisible laser beam. A laser emission with a wavelength either shorter than 400 nm or longer than 700 nm. Laser sources near these defining limits may be capable of producing a visual stimulus.

Irradiance (E). The power per unit area, expressed in watts per square centimetre (W/cm^2) or watts per square metre (W/m^2).

Laser. 1) An acronym for light amplification by stimulated emission of radiation. 2) A device that produces an intense, coherent, directional beam of optical radiation by stimulating emission of photons by electronic or molecular transitions to lower energy levels.

Laser-beam critical flight zone (LCFZ). See ***protected flight zones a).***

Laser-beam free flight zone (LFFZ). See ***protected flight zones b).***

Laser-beam free level. The maximum level of visible optical radiation which is not expected to cause any visual interference to an individual performing critical tasks.

Laser-beam sensitive flight zone (LSFZ). See ***protected flight zones c)***.

Laser emitter. Same as ***laser 2).***

Laser safety officer (LSO). An individual who is knowledgeable in the evaluation and control of laser hazards and has responsibility for oversight of the control of those hazards.

Laser source. See ***source.***

Light (visible radiation). A form of electromagnetic radiation capable of producing a visual stimulus to the human eye. Its wavelength range is approximately from 400 nm to 700 nm (between ultraviolet and infrared). Laser sources of an equivalent power slightly outside this range may be capable of producing less intense visual stimuli.

Limiting aperture (D_f). The diameter of a circle over which irradiance or radiant exposure is averaged for comparison to the maximum permissible exposure (MPE).

Local laser working group (LLWG). A group, convened to assist in evaluating the potential effect of laser emissions on aircraft operators in the vicinity of the proposed laser activity. Participants may include, but are not limited to, representatives from the aerodrome tower, area control centre, aerodrome management, airspace users, local officials, military representatives, qualified subject experts, laser manufacturers and the laser proponent.

Maximum permissible exposure (MPE). The internationally accepted maximum level of laser radiation to which human beings may be exposed without risk of biological damage to the eye or skin.

Mitigation. Use of control measures aimed at neutralizing the effect of laser beams on flight safety.

Nominal hazard zone (NHZ). The space within which the level of the direct, reflected or scattered radiation during operation of a laser emitter exceeds the applicable maximum permissible exposure (MPE). Exposure levels beyond the boundary of the NHZ are below the applicable MPE level.

Nominal ocular hazard distance (NOHD). The distance along the axis of the laser beam beyond which the appropriate maximum permissible exposure (MPE) is not exceeded (i.e. an indication of the "safe viewing" distance). An equivalent term for skin exposure is "skin hazard distance".

Normal flight zone (NFZ). See ***protected flight zones d).***

Optical density (OD). A physical property of a material that quantifies the attenuation of the laser beam.

Optical radiation. Part of the electromagnetic spectrum comprising infrared, visible and ultraviolet radiations.

Photon. In quantum mechanics, the smallest particle of optical radiation.

Pointing accuracy. The maximum angle of expected error in beam direction during all projected uses of the laser emitter.

Population inversion. The condition needed for light amplification to occur whereby the number of atoms in an excited state is greater than the number of atoms in a lower energy state.

Power. The rate at which energy is emitted, transferred or received. Unit: watts (joules per second).

Proponent. The legal entity (corporation, company, individual) applying to conduct an outdoor laser operation at a specific time and location.

Protected flight zones. Airspace specifically designated to mitigate the hazardous effects of laser radiation.

a) ***Laser-beam critical flight zone (LCFZ).*** Airspace in the proximity of an aerodrome but beyond the laser-beam free flight zone (LFFZ) where the irradiance is restricted to a level unlikely to cause glare effects.

b) ***Laser-beam free flight zone (LFFZ).*** Airspace in the immediate proximity to the aerodrome where the irradiance is restricted to a level unlikely to cause any visual disruption.

c) ***Laser-beam sensitive flight zone (LSFZ).*** Airspace outside, and not necessarily contiguous with, the LFFZ and LCFZ where the irradiance is restricted to a level unlikely to cause flash-blindness or after-image effects.

d) ***Normal flight zone (NFZ).*** Airspace not defined as LFFZ, LCFZ or LSFZ but which must be protected from laser radiation capable of causing biological damage to the eye.

Pulsed laser. A laser that delivers its energy in individual pulses lasting less than 0.25 s. See ***repetitively-pulsed laser***.

Pulse duration. The duration of a laser pulse, usually measured as the time interval between the half-power points on the leading and trailing edges of the pulse.

Pulse repetition frequency (PRF). The number of pulses that a laser produces over an applicable time frame divided by that time frame. For uniform pulse trains lasting over 1 s, the PRF is the number of pulses emitted by the laser in 1 s. Unit: hertz (Hz).

Radian. A unit of angular measure equal to the subtended angle at the centre of a circle by an arc whose length is equal to the radius of the circle. 1 radian = 57.3 degrees; 2π radians = 360 degrees.

Radiant energy (Q). Energy emitted, transferred or received as radiation. Unit: joule (J).

Radiant exposure (H). The laser beam energy per unit area, expressed in joules per square centimetre (J/cm^2) or joules per square metre (J/m^2).

Radiant power (Φ). Power emitted, transferred or received as radiation. Unit: watt (W).

Reflection. Deviation of radiation following incidence on a surface. A reflection can be either diffuse or specular. See ***diffuse reflection*** and ***specular reflection.***

Refraction. The redirection of light as it passes from one medium to another.

Repetitively-pulsed laser. A laser producing multiple pulses of radiant energy occurring in sequence with a pulse repetition frequency (PRF) greater than 1 Hz.

Retinal hazard region. Wavelengths between 400 nm and 1400 nm.

Safety interlock. 1) A device which is activated upon entry to a laser laboratory or enclosure, which terminates laser operation or reduces personnel exposure to below the maximum permissible exposure (MPE). 2) A device that is activated upon removal of the protective housing of a laser in such a way as to prevent exposure above the maximum permissible exposure (MPE).

Scanning laser beam. Laser radiation that moves, i.e. has a time-varying direction, source or pattern of propagation with respect to a stationary frame of reference.

Scintillation. Rapid changes in irradiance levels in a cross-section of a laser beam, caused by variations of the index of refraction in a medium as a consequence of temperature and pressure fluctuations.

Sensitive level. The minimum effective irradiance from a visible laser beam, which can cause temporary vision impairment and therefore interfere with performance of vision-dependent tasks. Illumination at this level may cause after-images or flash-blindness.

Source. A laser emitter or a laser-illuminated reflecting surface.

Specular reflection. A mirror-like reflection that usually maintains the directional characteristics of a laser beam.

Terminated beam. An output from a laser which is directed into airspace but is confined by a suitable object that blocks the beam or prohibits the continuation of the beam at levels capable of producing psychological effects or visual disruption.

Transmission. Passage of radiation through a medium. If not all the radiation is absorbed, that which passes through is said to be transmitted.

Ultraviolet radiation. Electromagnetic radiation with wavelengths shorter than those of visible radiation, for the purpose of this manual: 180 to 400 nm.

Vestibular apparatus. The organ of equilibrium in the inner ear. Because of its complicated anatomy, it is also called the labyrinth. It consists of the semicircular canals and the otolith organs.

Visible radiation. See ***light***.

Visual flight rules (VFR). A set of rules governing the conduct of flight under visual meteorological conditions.

Visual interference level. A visible laser beam, with an irradiance less than the maximum permissible exposure (MPE), that can produce a visual response which interferes with the safe performance of sensitive or critical tasks by aircrew or other personnel. This limit varies in accordance with the particular zone where the laser is operating. A generic term for critical level, sensitive level or laser-free level.

Wavelength (λ). The distance between two successive points on a periodic wave that have the same phase. It is commonly used to provide a numeric description of the colour of visible laser radiation.

LIST OF ABBREVIATIONS, SYMBOLS AND UNITS

ADI	attitude direction indicator
AEL	accessible emission limit
AGL	above ground level
ANSI	American National Standards Institute
ARP	aerodrome reference point
ATC	air traffic control
ATIS	automatic terminal information service
CIE	International Commission on Illumination (Commission Internationale de l'Éclairage)
CW	continuous wave
CZED	critical zone exposure distance
D_f	limiting aperture
DME	distance measuring equipment
FAA	Federal Aviation Administration
FDA	U.S. Food and Drug Administration
FLIR	forward looking infrared
FSEL	flight safe exposure limits
H	radiant exposure
HSI	horizontal situation indicator
HUD	head-up display
Hz	hertz
IFR	instrument flight rules
ILS	instrument landing system
IMC	instrument meteorological conditions
IR	infrared
J	joule
λ	wavelength
laser	light amplification by stimulated emission of radiation
LCFZ	laser-beam critical flight zone
LED	light emitting diode
LEP	laser eye protection
LFED	laser free exposure distance
LFFZ	laser-beam free flight zone
LIDAR	light detection and ranging
LLWG	local laser working group
LSA	loss of situational awareness
LSFZ	laser-beam sensitive flight zone
LSO	laser safety officer
MFD	multifunction display
MIL	maximum irradiance level
MOVL	minimal ophthalmoscopically visible lesion
MPE	maximum permissible exposure
mrad	milliradian
MSL	mean sea level
navaid	aid to air navigation
Nd:YAG	neodymium yttrium-aluminium-garnet
NFZ	normal flight zone
NHZ	nominal hazard zone
NIR	near infrared
nm	nanometre
NM	nautical mile
NOHD	nominal ocular hazard distance
NOTAM	notice to airmen
NSHD	nominal sensitivity hazard distance
NVD	night vision device
NVG	night vision goggles
OD	optical density
PCP	pre-corrected power
φ	beam divergence
Φ	radiant power
PRF	pulse repetition frequency
Q	radiant energy
SAE	Society of Automotive Engineers
SD	spatial disorientation
SIAP	standard instrument approach procedure
STAR	standard terminal arrival route
SZED	sensitive zone exposure distance
TVI	temporary visual impairment
TVL	temporary vision loss
UTC	coordinated universal time
UV	ultraviolet
VCF	visual correction factor
VCP	visually corrected power
VED	visual effect distance
VFR	visual flight rules
VMC	visual meteorological conditions
W	watt
YAG	yttrium-aluminium-garnet

Definitions of units

e. A term for the irrational number that corresponds to the base of natural logarithms: 2.71828183… .

Hertz (Hz). The unit that expresses the frequency of a periodic oscillation in cycles per second.

Joule (J). A unit of energy. Joules = watts × seconds.

Milliradian (mrad). A unit of angular measure used for beam divergence. A milliradian is about 0.057 degree (one seventeenth of a degree) or 3.44 minutes of arc.

Watt (W). A unit of power. 1 watt = 1 joule per second.

Chapter 1

PHYSICS OF LASERS

1.1 INTRODUCTION TO LASER EMITTERS

1.1.1 A basic insight into how a laser works helps in understanding the hazards incurred when a laser emitter is used. As shown in Figure 1-1, electromagnetic radiation is emitted whenever a charged particle (e.g. an electron) gives up energy. This happens every time an electron drops from a higher energy state, Q_1, to a lower energy state, Q_0, in an atom or ion as occurs in a fluorescent light. This can also happen from changes in the vibrational or rotational state of molecules.

1.1.2 The colour of light is determined by its frequency or wavelength. The shorter wavelengths are the ultraviolet (UV) and the longer wavelengths are the infrared (IR). The smallest particle of light energy is described in quantum mechanics as a photon. The energy in joules, E, of a photon is determined by its frequency, v in hertz (Hz), and Planck's constant, h (6.63×10^{-34} J . s), as follows:

$$E = h \times v$$

1.1.3 The velocity of light in a vacuum, c, is 3×10^8 metres per second (m/s). The wavelength, λ, of light is related to the frequency as follows:

$$\lambda = \frac{c}{v}$$

1.1.4 The difference in energy levels across which an excited electron drops determines the wavelength of the emitted light. As the energy increases, the wavelength decreases.

1.2 COMPONENTS OF A LASER

1.2.1 As shown in Figure 1-2, the three basic components of a laser are:

- Lasing medium (crystal, gas, semiconductor, dye, etc.)

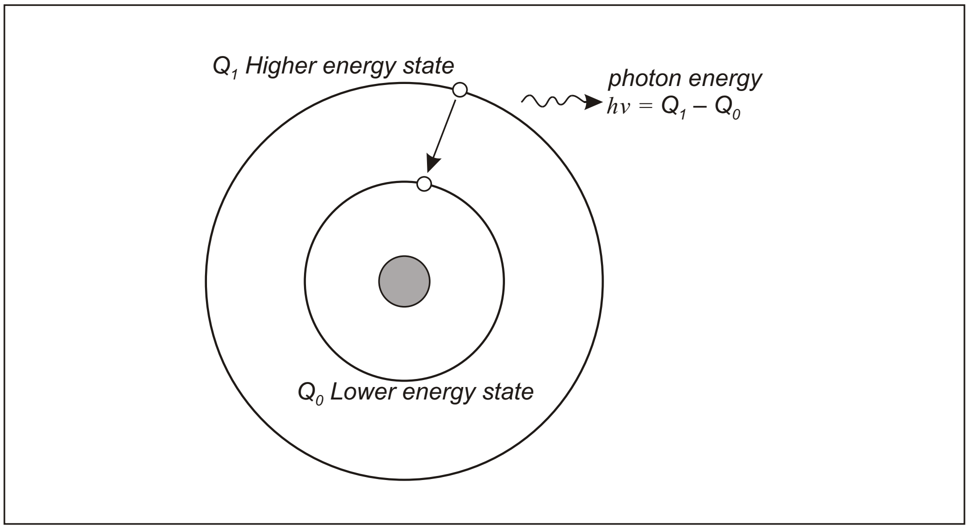

Figure 1-1. Emission of radiation from an atom by transition of an electron from a higher energy state to a lower energy state

- Pump source (adds energy to the lasing medium, e.g. xenon flash lamp, electrical current to cause electron collisions, radiation from another laser, etc.)

- Optical cavity (typically bound by reflectors to act as the feedback mechanism for light amplification)

1.2.2 Electrons in the atoms of the lasing medium normally reside in a steady-state lower energy level. When energy from a pump source is added to the atoms of the lasing medium, the majority of the electrons are excited to a higher energy level, a phenomenon known as population inversion. This phenomenon must occur in order to achieve light amplification.

1.2.3 The excited state is an unstable condition for these electrons. They will stay in this state for a short time and then decay back to their original energy state. This decay can occur in two ways — spontaneously or by stimulation. If, before an excited electron spontaneously decays, it is hit with a photon with a certain wavelength, the electron will be stimulated into decay and will emit a photon of the same wavelength and in the same direction as the incident photon. If the direction of this reaction is parallel to the optical axis of the cavity, the emitted photons travel back and forth in the cavity stimulating more and more transitions and releasing more and more photons all in the same direction and with the same wavelength. The light energy is therefore amplified. Since one of the mirrors is a partial reflector, part of the amplified energy is emitted as a laser beam.

1.2.4 In practice, it is very difficult to obtain a population inversion when utilizing only one excited energy level. Electrons in this situation have a tendency to decay to their ground state very quickly. As shown in Figure 1-3, a lasing medium typically has at least one excited (metastable) state where electrons can be trapped long enough (microseconds to milliseconds) to maintain a population inversion so that lasing can occur. Although laser action is possible with only two energy levels, most lasers have four or more levels.

1.3 TYPES OF LASERS

1.3.1 There are a number of methods used in producing laser energy. Common methods include the use of semiconductors, liquid dye, solid state, gas and metal vapour. Although the technology behind each type can be quite different, the resulting laser energy has the same basic characteristics (see Table 1-1).

1.3.2 In recent years, the semiconductor laser (laser diode) has become the most prevalent laser type. The laser diode is a light emitting diode (LED) with an optical cavity to amplify the light emitted from the energy band gap that exists in semiconductors.

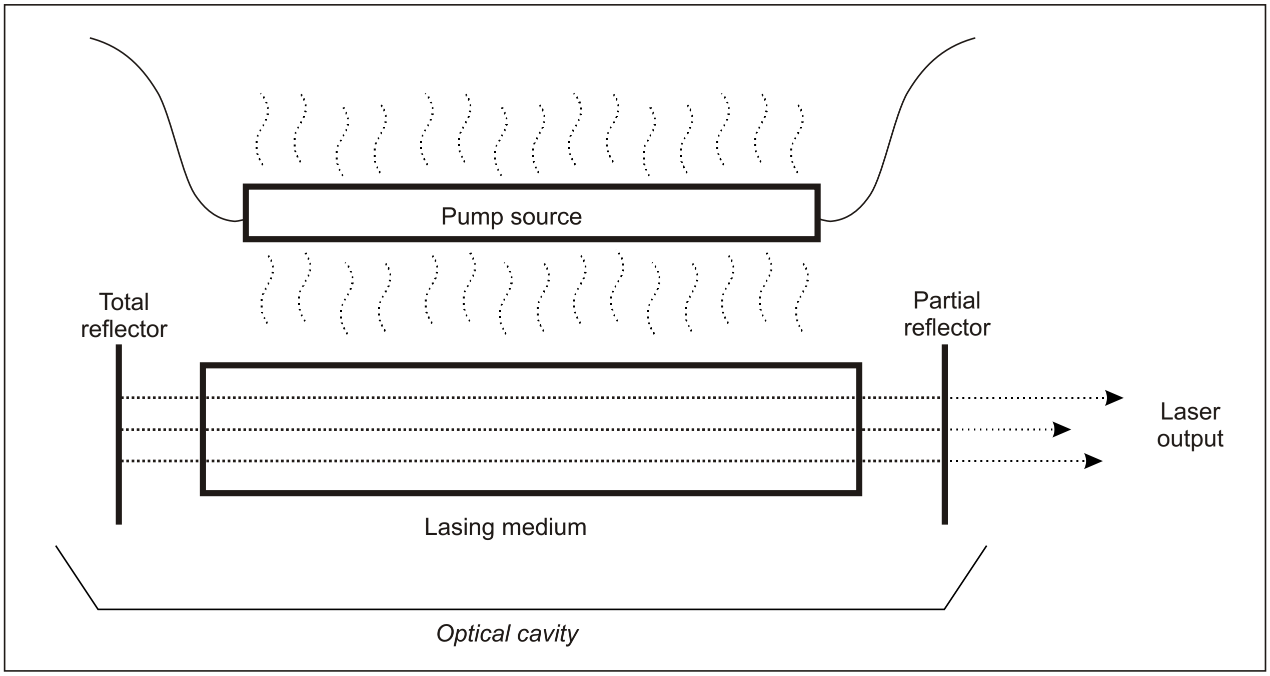

Figure 1-2. Diagram of solid state laser

Table 1-1. Examples of common lasers

Lasing medium	*Laser method*	*Spectral region*	*Wavelength*
Argon fluoride	Gas	UV	193 nm
Xenon chloride	Gas	UV	308 nm
Helium cadmium	Gas	UV Blue	325 nm 442 nm
Argon	Gas	Blue Green	488 nm 514 nm
Krypton	Gas	Blue Green Yellow Red	476 nm 528 nm 568 nm 647 nm
Copper vapour	Metal vapour	Green Yellow	510 nm 578 nm
Frequency-doubled Nd:YAG	Solid state	Green	532 nm
Helium neon	Gas	Green Yellow Orange Red Near IR	543 nm 594 nm 612 nm 633 nm 1.15 µm
Rhodamine 6G	Liquid dye	Visible	550–650 nm
Gold vapour	Metal vapour	Red	628 nm
Gallium aluminium arsenide	Semiconductor	Visible – near IR	670–830 nm
Ruby	Solid state	Red	694 nm
Alexandrite	Solid state	Near IR	700–815 nm
Gallium arsenide	Semiconductor	Near IR	840 nm
Titanium sapphire	Solid state	Near IR	840–1 100 nm
Nd:YAG	Solid state	Near IR	1.06 µm
Erbium:glass	Solid state	Mid IR	1.54 µm
Erbium:YAG	Solid state	Mid IR	2.94 µm
Carbon dioxide	Gas	Far IR	10.6 µm

1.3.3 Lasers can operate continuously (continuous wave or CW) or may produce pulses of laser energy. Pulsed laser systems are often repetitively pulsed. The pulse rate or pulse repetition frequency (PRF) as well as pulse duration and peak power are extremely important in evaluating potential biological hazards. Due to damage mechanisms in biological tissue, repetitively pulsed lasers can often be more hazardous than a CW laser with the same average power.

1.4 BEAM PROPERTIES

Laser output intensity

1.4.1 Lasers either emit continuously or produce discrete pulses of optical radiation. When dealing with continuous wave (CW) lasers, beam power is used. Beam energy is used for single pulse lasers. However, when dealing with repetitively pulsed lasers, either parameter can be used. Care must be taken to ensure that the correct parameter is considered when comparisons with safety thresholds are made.

1.4.2 Laser power is the rate with which laser energy is emitted. This means that at any given instant, a laser can produce a certain quantity of laser power. Laser energy is a measure of the amount of optical radiation received in a given period of time (such as a single laser pulse). Power is typically given in watts (W) and energy is typically given in joules (J). They are mathematically related as follows:

$$1 \text{ watt} = \frac{1 \text{ joule}}{1 \text{ sec}}$$

Irradiance and radiant exposure

1.4.3 With the exception of what is absorbed by the atmosphere, the amount of energy available at the output of the laser will be the same amount of energy contained within the beam at any point downrange. Figure 1-4 illustrates a typical laser beam with a sampling area smaller than the cross-sectional area of the beam. The amount of energy available within the sampling area will be considerably less than the amount of energy available within the total beam. Irradiance describes the power per unit area, and radiant exposure describes the energy per unit area of a laser beam.

Laser modes (laser power distribution)

1.4.4 Laser beams can have complex patterns and shapes. The optical power distribution within a laser beam (called the laser mode) is typically expressed with either a single bell-shaped (Gaussian) power density profile or a

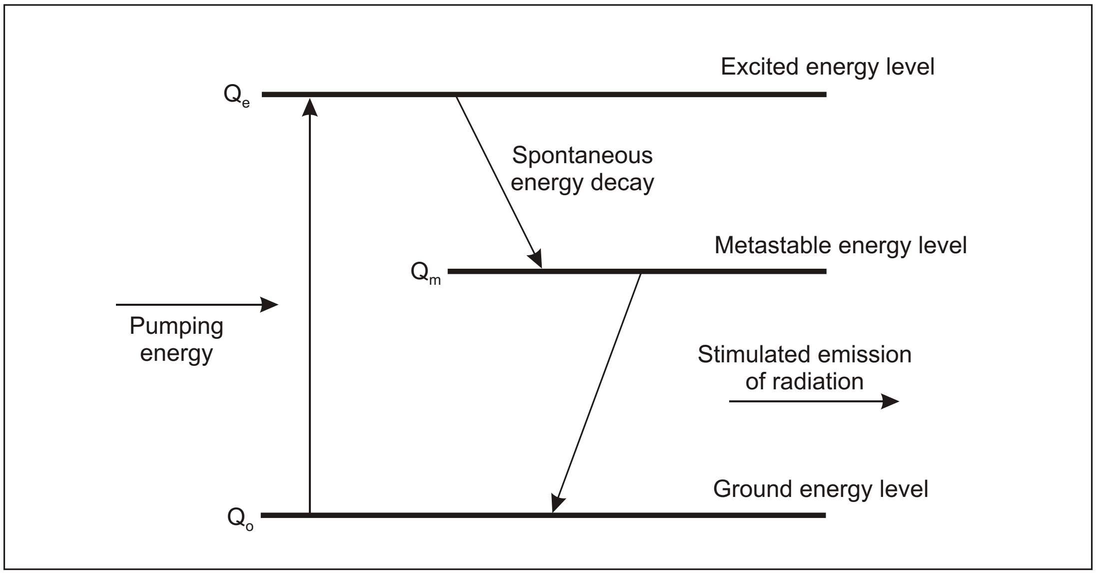

Figure 1-3. Diagram of three-level laser energy

combination of multiple bell-shaped profiles. A uniform (constant) power mode is actually a combination of many Gaussian profiles overlapping each other. The ideal laser is considered to have a single Gaussian profile for most laser applications. This mode is often assumed in order to simplify laser hazards analyses.

1.4.5 Since a Gaussian distribution has no mathematical beginning or ending (see Figure 1-5), defining the diameter of a laser beam can be difficult. To solve this problem, one can define the diameter of a laser beam by determining the diameter of an aperture that would allow only a certain percentage of the total beam output to pass through. The 1/e beam diameter is defined as the size of an aperture that would block 36.8 per cent (1/e) of the beam output (allowing 63.2 per cent to pass). This is the method most often used for laser safety evaluations. Some laser manufacturers will specify their laser beam diameters assuming an aperture that blocks 13.5 per cent ($1/e^2$) of the output (allowing 86.5 per cent to pass). The 1/e beam diameter is equal to the $1/e^2$ beam diameter divided by the square root of 2 (i.e. 1.414).

Line width

1.4.6 Light from a conventional light source is extremely broadband (containing wavelengths across the electromagnetic spectrum). If one were to place a filter that would pass only a very narrow band of wavelengths (e.g. a green filter) in front of a white or broadband light source, only that colour or wavelength region would be seen exiting the filter (see Figure 1-6).

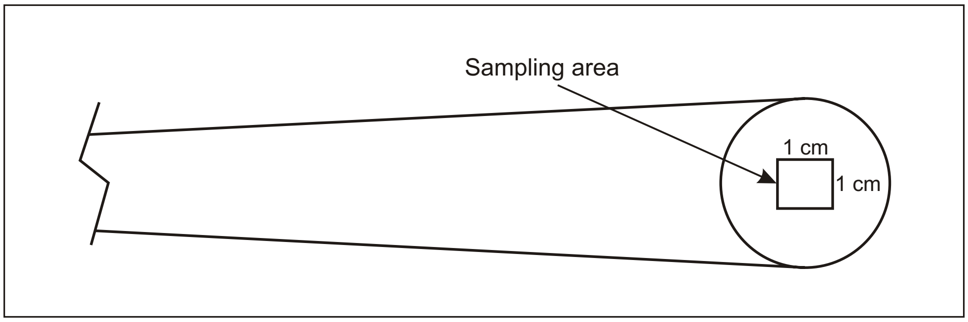

Figure 1-4. Illustration of irradiance

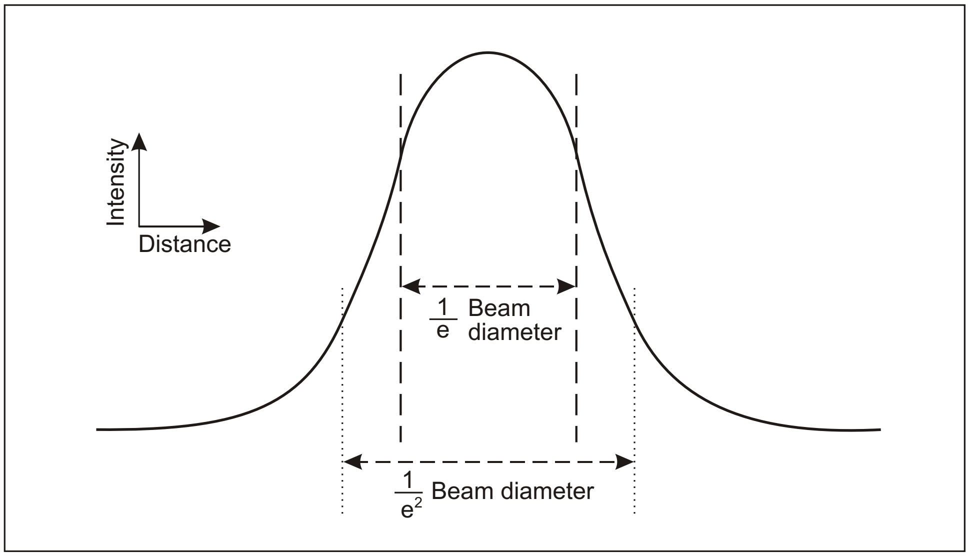

Figure 1-5. Beam diameter

1.4.7 Light from the laser is similar to the light seen from the filter. However, instead of a narrow band of wavelengths, none of which is dominant as in the case of the filter, there is a much narrower bandwidth about a dominant centre frequency emitted from the laser. The colour or wavelength of light being emitted depends on the type of lasing material being used. For example, if a neodymium:yttrium aluminium garnet (Nd:YAG) crystal is used as the lasing material, light with a wavelength of 1 064 nm will be emitted. Certain materials and gases are capable of emitting more than one wavelength. The wavelength of the light emitted in such a case is dependent on the optical configuration of the laser.

Divergence

1.4.8 Light from a conventional light source diverges (spreads rapidly) as illustrated in Figure 1-7. The power or energy per unit area may be large at the source, but it decreases rapidly as an observer moves away from the source. In contrast, the output of the laser shown in Figure 1-8 has a very small divergence and the beam irradiance or radiant exposure at shorter distances is almost the same at the observer as at the source. Thus, within a narrow beam, relatively low-power lasers are able to project more energy than can be obtained from much more powerful conventional light sources.

1.4.9 The divergence, φ, of a laser beam used in laser safety calculations is defined as the full angle of the beam spread measured between those points which include laser energy or irradiance equal to 1/e of the maximum value. As a laser beam propagates through space, it produces a profile as shown in Figure 1-9. The beam diameter, D_L, is a function of range, r, from the exit port or beam waist and can be calculated as:

$$D_L = \sqrt{a^2 + r^2\varphi^2}$$

where a is the 1/e beam diameter at the exit port or beam waist.

1.5 CHARACTERISTICS OF MATERIALS

Reflection

1.5.1 Materials can reflect, absorb and transmit light rays. Reflection of light is best illustrated by a mirror. If light rays strike a mirror, almost all of the energy incident on the mirror will be reflected. Figure 1-10 illustrates how a plastic or glass surface will act on an incident light ray. The sum of energy transmitted, absorbed and reflected will equal the amount of energy incident upon the surface.

1.5.2 A surface is specular (mirror-like) if the size of surface imperfections and variations are much smaller than the wavelength of incident optical radiation. When irregularities are randomly oriented and are much larger than the wavelength, then the surface is considered diffuse. In the intermediate region, it is sometimes necessary to regard the diffuse and specular components separately.

1.5.3 A flat specular surface will not change the divergence of the incident light beam significantly. Curved specular surfaces, however, will change the beam divergence. The amount that the divergence is changed is

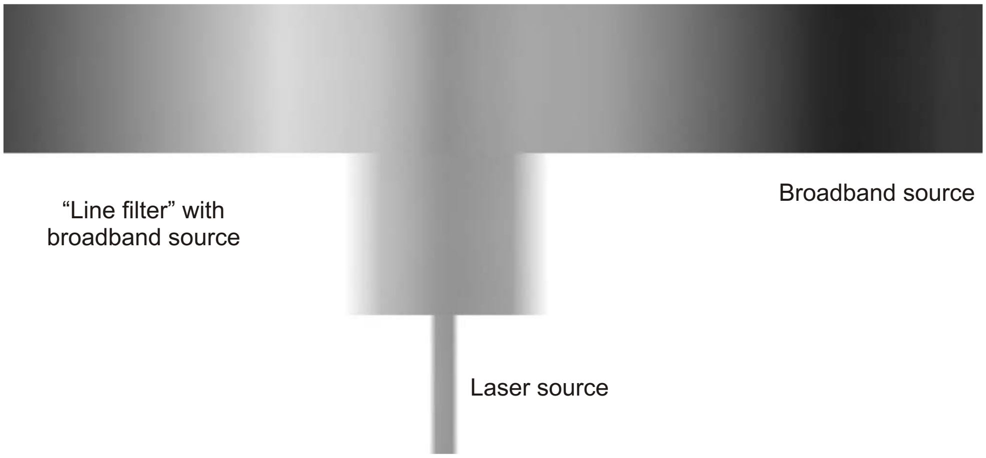

Figure 1-6. Laser line width

dependent on the curvature of the surface. Figure 1-11 demonstrates these two types of surfaces and how they will reflect an incident laser beam. The divergence and the curvature of the reflector have been exaggerated to better illustrate the effects. The value of irradiance measured at a specific range from the reflector will be less after reflection from the curved surface than after reflection from the flat surface, unless the curved reflector focuses the beam near or at that range.

1.5.4 A diffuse surface will reflect the incident laser beam in all possible directions. The beam path is not maintained when the laser beam strikes a diffuse reflector. Whether a surface is a diffuse reflector or a specular reflector will depend upon the wavelength of the incident laser beam. A surface that would be a diffuse reflector for a visible laser beam might be a specular reflector for an IR laser beam. As illustrated in Figure 1-12, the effect of various curvatures of diffuse reflectors makes little difference on the reflected beam. The phenomenon known as scatter is the diffuse reflection from very small particles in the air.

Refraction

1.5.5 Refraction is the deflection of a ray of light when it passes from one medium into another. If light is incident upon an interface separating two transmitting media (such as an air-glass interface), some light will be

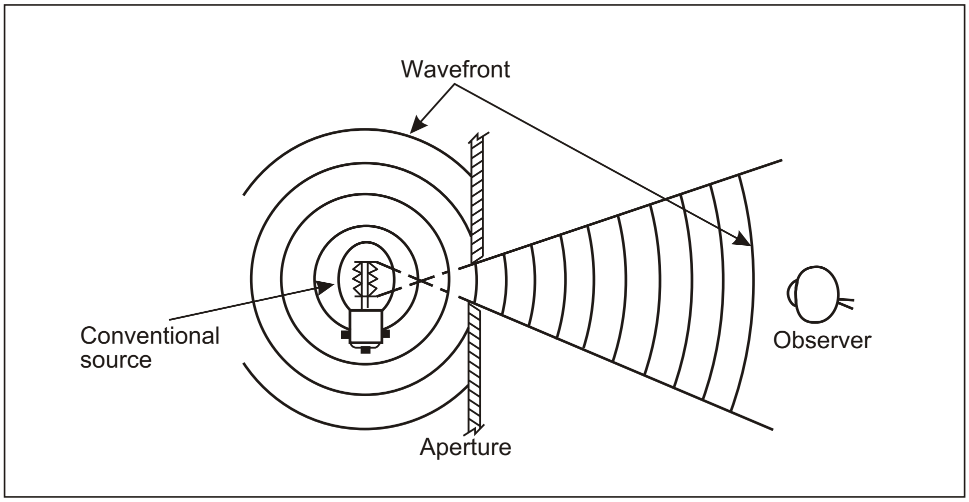

Figure 1-7. Divergence of conventional light beam

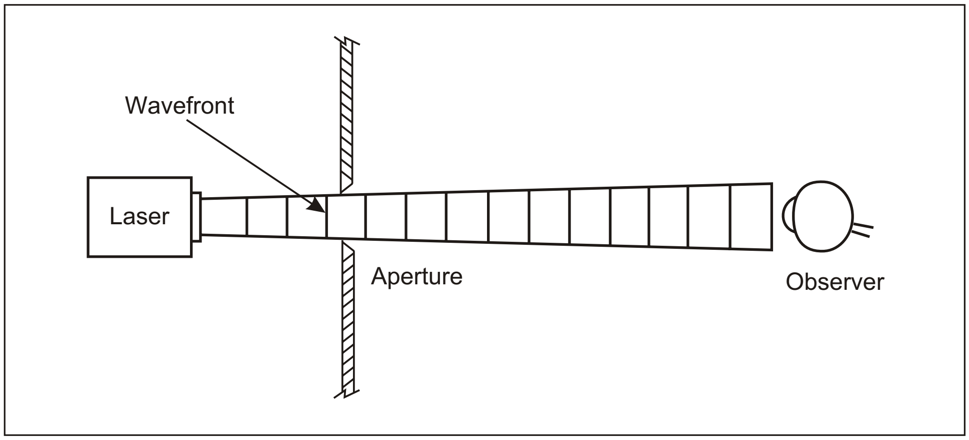

Figure 1-8. Divergence of laser beam

transmitted while some will be reflected from the surface. If no energy is absorbed at the interface, $T + R = 1.00$ where T and R are the fractions of the incident beam intensity that are transmitted and reflected. T and R are called the transmission and reflection coefficients, respectively. These coefficients depend not only upon the properties of the material and the wavelength of the radiation but also upon the angle of incidence.

1.5.6 The angle that an incident ray of radiation forms with the normal (perpendicular) to the surface will determine the angle of refraction and the angle of reflection (the angle of reflection equals the angle of incidence). The relationship between the angle of incidence (θ) and the angle of refraction (θ') is:

$$n \sin(\theta) = n' \sin(\theta')$$

where n and n' are the indices of refraction of the media that the incident and transmitted rays move through, respectively (see Figure 1-10).

1.5.7 Since refraction can change the irradiance or radiant exposure, it can either increase or reduce a laser hazard.

Absorption

1.5.8 As light propagates through the atmosphere or any medium, its total power or energy is attenuated by absorption and scattering. After propagating a distance, *r*, through the atmosphere, intensity, I, is given by:

$$I = I_0 e^{-\mu r}$$

where I_0 is the initial intensity and μ is the atmospheric attenuation coefficient. The units of μ must be the inverse to that of *r*, that is, if *r* is represented in cm, then μ must be represented in cm^{-1} so that the term μr is dimensionless.

1.5.9 This equation shows that the intensity falls off exponentially as a function of the distance from the laser source. The attenuation coefficient is dependent on the wavelength of the laser. Because of the combination of absorption and scattering effects, the attenuation coefficient is a complex function of wavelength having a large value at some wavelengths and a small value at others.

Scintillation

1.5.10 Scintillation is caused by random variations in the index of refraction of the atmosphere through which the beam is passing. These index variations are caused by localized temperature and pressure fluctuations. This results in a focusing effect which creates hot spots in the beam pattern, most pronounced at long ranges. Scintillation of a laser beam creates a flickering pattern of light similar to what one might expect at the bottom of a swimming pool when the water surface is not calm and the sun shines into it.

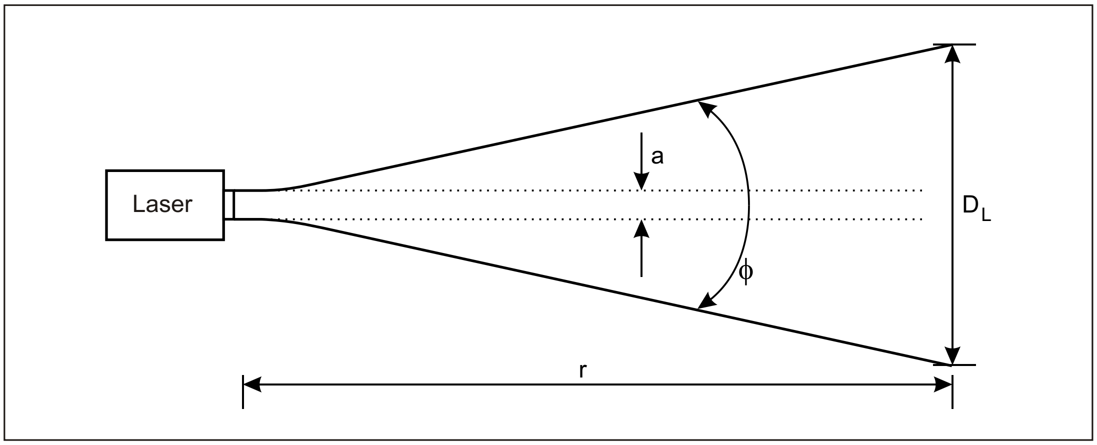

Figure 1-9. Geometry of laser beam

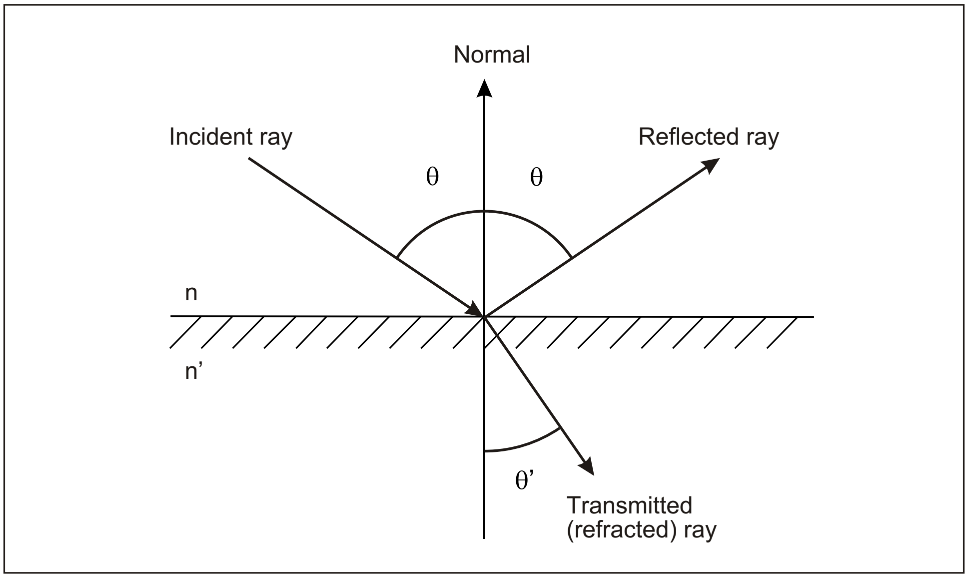

Figure 1-10. Light ray incident to a glass surface

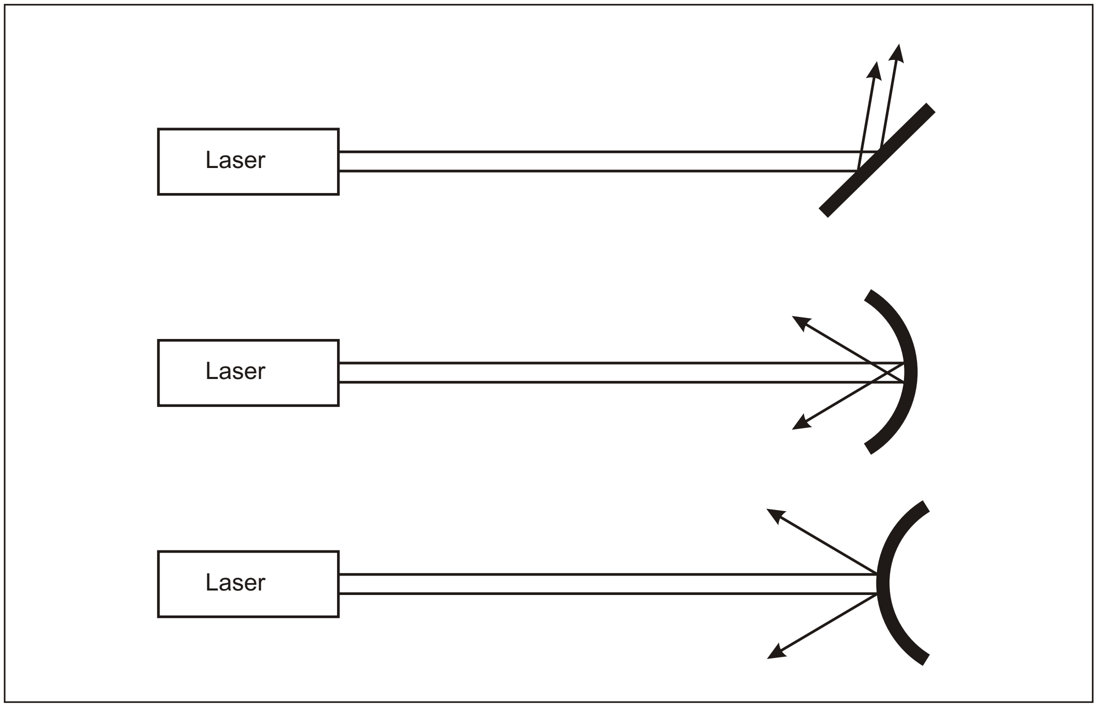

Figure 1-11. Specular reflectors

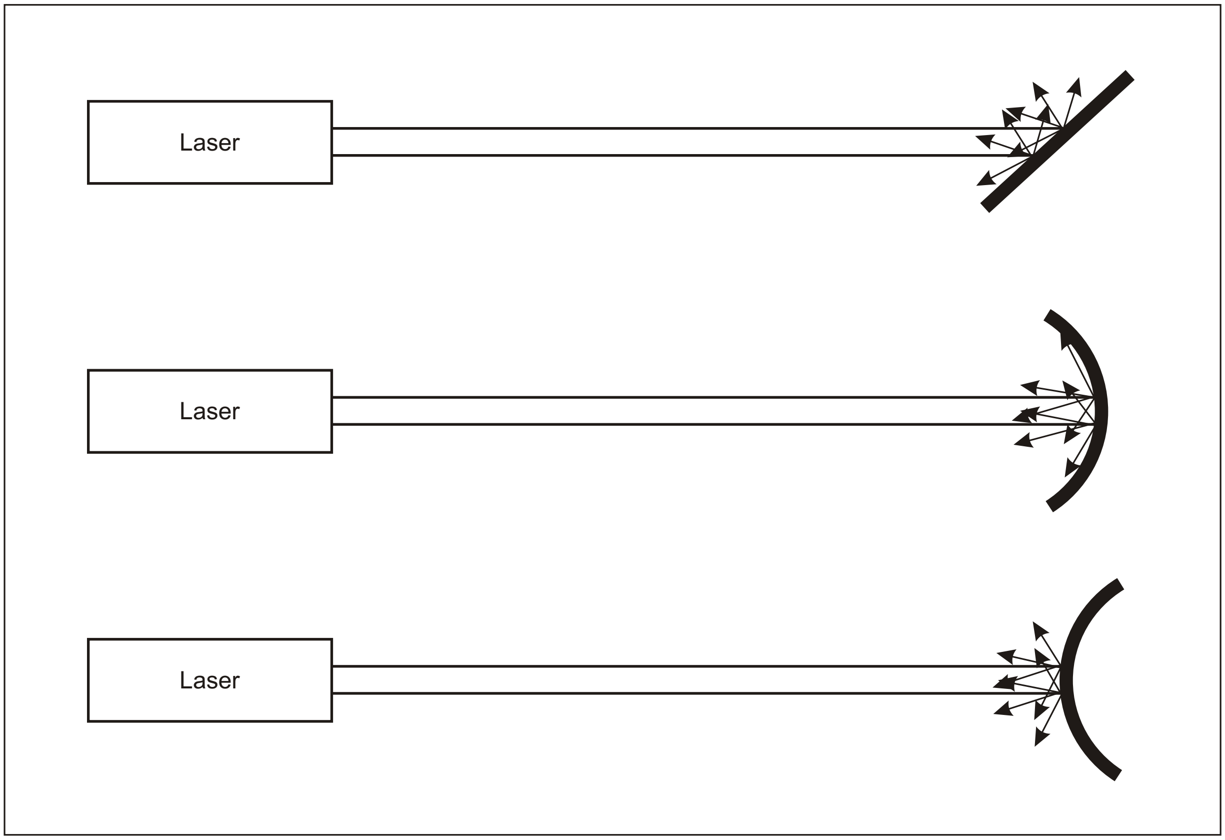

Figure 1-12. Diffuse reflectors

Chapter 2

LASER HAZARD EVALUATION

2.1 PURPOSE

The purpose of a laser hazard evaluation is to minimize the potential for injury to personnel from a laser emitter. As part of this evaluation, the accessible emission limit (AEL), laser classification, nominal ocular hazard distance (NOHD) and optical density (OD) required for personnel protection are determined. In addition, engineering and administrative control measures should be considered.

2.2 BACKGROUND

2.2.1 The retina is especially sensitive to laser light beams for two reasons:

a) irradiance from a conventional source, such as a light bulb, is reduced with increasing distance from the source according to the inverse square law, i.e. the irradiance is reduced as a function of the square of the distance from the source. Since a laser beam is collimated, it does not follow the inverse square law and its irradiance for a given power output is usually far greater at a given distance than that from a conventional light source; and

b) if light from a conventional source is focused by means of a reflecting surface, as in a searchlight, the irradiance downrange of the source is greater than would be expected according to the inverse square law. However, it is not possible to collimate conventional light energy. For a given power output, a conventional light source cannot, therefore, produce a light beam which has an irradiance similar to that of a laser beam.

2.2.2 Collimated light rays reaching the eye are focused by the cornea and lens onto a very small area of the retina similar to the way parallel light rays from the sun can be focused by a magnifying glass into a spot of sufficient irradiance to burn paper. A laser beam can have an irradiance which exceeds that of the sun, even if the laser is of relatively low power (e.g. 5 milliwatt) and the observer is at a considerable distance from the source. In this context, the focusing ability of the eye is very important. Laser light passing through a pupil of 7 mm diameter can be focused into a spot on the retina only 2–20 µm big. It can be calculated that the irradiance of collimated light is increased up to 100 000 times from the cornea to the retina.

2.3 ACCESSIBLE EMISSION LIMIT (AEL)

2.3.1 The AEL is defined as the maximum accessible emission power or energy permitted within a particular class. The class 1 AEL is the value to which laser output parameters are compared. The class 1 AEL is calculated by multiplying the maximum permissible exposure (MPE) by the area of the limiting aperture.

Maximum permissible exposure (MPE)

2.3.2 The MPE is a function of wavelength, exposure time and the nature of exposure (intrabeam, diffuse reflection, eye or skin). MPE values are determined from biological studies and are published in regional, national (e.g. American National Standards Institute ANSI Z136.1) and international (e.g. International Electrotechnical Commission IEC 60825-1) laser safety standards.

2.3.3 MPE values are expressed in terms of irradiance or radiant exposure and are given in W/cm^2 or J/cm^2 (W/m^2 or J/m^2). They represent the maximum levels to which a person can safely be exposed without incurring biological damage. However, sub-damage threshold effects may be significant at exposure levels below the MPE.

Limiting aperture (D_f)

2.3.4 The limiting aperture (D_f) is the maximum diameter of a circle over which irradiance or radiant exposure can be averaged. It is a function of wavelength and exposure duration. These values are provided in national and international laser safety standards. The limiting aperture is a linear measurement and is thus expressed in terms of cm or mm.

2.3.5 The MPE for eye exposure in the 400 to 1 400 nm band (retinal hazard region) is based upon the total energy or power collected by the night-adapted human eye, which is assumed to have an entrance aperture of 7 mm in diameter. This diameter is the limiting aperture. To determine the potential hazard, the maximum energy or power that can be transmitted through this aperture must be determined. This amount is compared to the class 1 AEL. For lasers with wavelengths outside the retinal hazard region and for the skin, other limiting apertures may apply (see applicable national or international standards).

2.4 LASER HAZARD CLASSIFICATION

2.4.1 Laser hazard classifications are used to indicate the level of laser radiation hazard inherent in a laser system and the extent of safety controls required. These range from class 1 lasers, which are safe for direct beam viewing under most conditions, to class 4 lasers, which require the most strict controls.

2.4.2 Classification is based only on unaided and 5-cm-aided viewing conditions. This means that the power or energy that can pass through the limiting aperture (known as the effective power or energy) is compared to the appropriate AEL when determining hazard classification. The laser classification system is summarized below (for a full description, reference should be made to the applicable national or international standards).

Class 1 lasers

2.4.3 Class 1 lasers are lasers which cannot emit radiation in excess of the class 1 AEL (based on the maximum possible duration inherent in the design or intended use of the laser) or which have adequate engineering controls to restrict access to the laser radiation from an embedded higher class of laser. This does not, however, necessarily mean that the system is incapable of doing harm. Since only unaided and 5-cm-aided viewing conditions are considered, hazards may still be posed when viewing optics with a greater optical gain than 7.14 (5-cm optics) are used or if access to the interior of the laser emitter is possible.

Class 2 lasers

2.4.4 Class 2 lasers are low-power visible (400 to 700-nm wavelength) lasers and laser systems that can emit an accessible output exceeding the class 1 limits but not exceeding the class 1 AEL for a 0.25 second exposure duration. The class 1 AEL for a 0.25 second exposure duration is 1 mW. Invisible lasers cannot be class 2.

Class 3 lasers

2.4.5 Class 3 is subdivided into 3a and 3b (3A and 3B in international standards). Class 3a lasers are medium-power lasers with an output between 1 and 5 times the class 1 AEL (class 2 AEL for visible lasers) based on the appropriate exposure duration. All other lasers at any wavelength not classified as class 1 or class 2 with a power less than 500 mW and unable to produce more than 125 mJ in 0.25 seconds are defined as class 3b (3B). The International Electrotechnical Commission (IEC) international standard also has a limit on irradiance for class 3A lasers of 25 Wm^{-2} (2.5 $\mathrm{mW\ cm}^{-2}$).

Class 4 lasers

2.4.6 Class 4 lasers are high-power lasers including all lasers in excess of class 3 limitations. These lasers can often be fire hazards. Both specular and diffuse reflections are likely to be hazardous.

2.5 NOMINAL OCULAR HAZARD DISTANCE (NOHD)

2.5.1 The *NOHD* is the maximum range at which the power or energy entering the limiting aperture can exceed the class 1 *AEL*. This value expresses the minimum safe distance from which a person can directly view a laser source without a biological damage hazard. The class 1 *AEL* is calculated by multiplying the *MPE* by the area of a circle with a diameter of the limiting aperture (D_f).

$$AEL = MPE \times \left[\pi \times \left(\frac{D_f}{2}\right)^2\right] = \frac{MPE \cdot \pi \cdot D_f^2}{4}$$

2.5.2 The following equation describes the relationship between energy through a limiting aperture, Q_f, (effective energy) to total energy, Q_o, of a Gaussian laser beam, given the 1/e beam diameter, D_L, the aperture diameter, D_f, and neglecting atmospheric losses.

$$\frac{Q_f}{Q_o} = \left[1 - e^{-\left(\frac{D_f}{D_L}\right)^2}\right]$$

2.5.3 When including the effects of divergence, atmospheric attenuation and viewing aids (see 1.4.9, 1.5.8 to 1.5.10 and 3.7.7, respectively, for further explanation), this equation becomes:

$$\frac{Q_f}{Q_o \cdot \tau \cdot e^{-\mu \cdot r}} = \left[1 - e^{-\left(\frac{G \cdot D_f^2}{a^2 + r^2 \cdot \varphi^2}\right)}\right]$$

where G represents the effective optical gain and τ represents the transmission of viewing aids.

2.5.4 If the class 1 AEL (the maximum safe level of exposure) is substituted for Q_f (the actual exposure that could be received), the range, r, becomes the $NOHD$. Making these substitutions and solving for $NOHD$ results in the following:

$$NOHD = \frac{1}{\varphi}\sqrt{\frac{-D_f^2 \times G}{1\mathrm{n}\left(1 - \frac{AEL}{Q_o \cdot \tau \cdot e^{-\mu \cdot NOHD}}\right)} - a^2}$$

2.6 OPTICAL DENSITY (OD)

2.6.1 Since some lasers or laser systems may produce energy or power millions of times that of the class 1 AEL, the use of logarithms is the preferred method to express personnel protection requirements. To fully specify the eye protection requirements for a particular laser system, unaided and aided OD values are calculated.

2.6.2 To determine the OD of eyewear required to protect personnel from incident laser radiation, the ratio of the effective energy, Q_f, to the class 1 AEL is used as shown:

$$OD = \log_{10}\left(\frac{Q_f}{AEL}\right)$$

2.6.3 To consider the effects of binoculars or other viewing aids, the change in the effective energy will produce different OD values and must be considered if those viewing conditions are possible. However, the maximum OD will never be more than:

$$OD = \log_{10}\left(\frac{Q_o}{AEL}\right)$$

2.6.4 This equation assumes that all laser energy is concentrated into the limiting aperture with no transmission loss through optics. This is the worst case condition.

2.7 OTHER FACTORS

2.7.1 In performing a laser hazard evaluation, other issues must be considered. Things such as critical task impairment, properly working safety interlocks, standard operating procedures, and signs and labels are integral factors in establishing a safe environment for laser operation. The significance of specific control measures depends upon the laser hazard classification. A start-up delay, for example, should not be necessary for a class 2 laser device. Applicable national or international laser safety standards list the control measures required for each laser hazard class.

Buffer zones

2.7.2 With outdoor lasers, a buffer zone should be established and utilized for each laser system. A buffer zone is a conical volume centered on the laser's line of sight with its apex at the laser aperture using a specified buffer angle. Within the buffer zone, the beam will be contained with a very high degree of certainty. The laser system's buffer zone depends on the aiming accuracy and boresight retention of the laser system. Typically, the laser system's buffer zone is equal to five times the system's aiming accuracy. The typical buffer angles for lasers used outdoors are 10 mrad for hand-held lasers and 5 mrad for lasers on a stable platform.

Nominal hazard zone (NHZ)

2.7.3 The volume of space defined by all locations capable of exceeding the class 1 AEL (including the buffer zone) is known as the nominal hazard zone (NHZ). Anyone outside the NHZ is considered to be safe from laser hazards. Anyone within the NHZ should be protected by either procedural safeguards or personnel protection equipment (e.g. laser safety goggles). Small specular reflectors in the laser beam path can create unwanted beams and should be considered in determining the NHZ.

Laser-beam sensitive, laser-beam critical and laser-beam free flight zones

2.7.4 Biologically safe exposure of the eye to a visible laser beam can create unwanted effects that can reduce or destroy the ability of a person to perform a task. These effects can be very hazardous if the task is safety-critical (e.g. landing an aircraft). Three visual interference levels have been defined and are described in 2.7.5 and in greater detail in 3.8. These values are as follows:

- sensitive level — 100 μW/cm^2
- critical level — 5 μW/cm^2
- laser beam free level — 50 nW/cm^2

2.7.5 The sensitive level approximates the level at which a person could experience severe, lingering after-effects from exposure to a laser beam. The critical level approximates the level to which a person could experience significant loss of vision during exposure to a laser beam and some residual, lingering after-effects. The laser beam free level approximates the level at which a person would receive a distracting glare but no after-effects. The laser beam sensitive, critical and free flight zones are the respective volumes of space where levels above these are prohibited.

2.7.6 Determining the distances associated with these visual interference levels is done the same way as when evaluating the NOHD values. The values mentioned in 2.7.4 are substituted for the appropriate MPE, new AEL values are determined, and the range is recalculated. Note that these values are only relevant to visible laser beams. These values have no meaning for wavelengths outside the visible spectrum (400–700 nm).

Non-beam hazards

2.7.7 Although laser radiation is the most obvious hazard associated with laser systems, many other hazards should be considered in a laser hazard evaluation. These are known as non-beam hazards. The following list shows several non-beam hazards common to laser use:

- collateral radiation
- compressed gases
- confining space
- cryogenics
- electrical
- electromagnetic interference
- ergonomics
- explosion
- fire
- laser dyes
- mechanical
- noise
- toxic materials
- trailing cables/pipes
- waste disposal
- X-rays

Chapter 3

LASER BEAM BIOEFFECTS AND THEIR HAZARDS TO FLIGHT OPERATIONS

3.1 INTRODUCTION

3.1.1 The development of the laser and the industrial application of laser technology stand out as some of the most significant scientific contributions of the 20th century. Presently, lasers are found virtually everywhere, from supermarkets and schools to satellites and operating rooms, and have become fundamental components in consumer products and complex industrial devices, including sophisticated weapon systems. The accessibility of the technology and the significant reduction in cost place lasers at almost everyone's disposal. Furthermore, the application of laser technology to modern society is still emerging and its future potential appears boundless.

3.1.2 However, if used improperly, laser energy also poses a significant biohazard. Consequently, even the most innocuous laser pointer can become a safety hazard, either through direct bioeffects or by causing a disruption of critical performance tasks in hazardous situations.

3.1.3 Not surprisingly, as lasers proliferate, an ever-increasing number of laser beam-related incidents, some from misadventure and others caused by intentional misuse, have been reported. A significant number of these incidents involve aircraft operations, both civil and military. Low-flying helicopters, as used by police and for medical evacuation, are particularly vulnerable, not only because of their proximity to the ground but also because of their proximity to ground-based lasers. In some aviation environments, even the most trivial of laser beams have the potential to become a lethal threat, e.g. by distraction of aircrew during a critical phase of flight. This chapter will elaborate on the bioeffects and damage mechanisms of laser beam energy particularly from the perspective of its effects on aircraft operations. However, the ongoing development of new lasers and the continued advances in research associated with lasers and their effects make this a vast and still evolving area of biological science. Therefore, this chapter will only serve to be an overview of particular aspects of those effects, namely their bioeffects and how they relate to aircraft operations. Other technical publications exist that cover this topic more comprehensively, some of which are listed in the bibliography at the end of this chapter.

3.1.4 Depending on power and other physical characteristics, laser beams have the potential to generate a variety of bioeffects, including the capacity to vapourize biological tissue, either in part or in full, sometimes destroying the entire organism. This chapter, however, will be limited to those laser beam bioeffects likely to be encountered within civilian aircraft operations and primarily those affecting the skin and the eye. The major part of this chapter will address this risk from the perspective of its potential effect on vision, since this is the primary aeromedical concern.

3.2 THE HAZARD

3.2.1 The spectrum of electromagnetic radiation ranges from the shortest of cosmic rays at 10^{-5} nm to very long waves in the order of 10^{14} nm (100 km), as associated with communications and power sources. Each of these wavelengths is associated with photons of varying energy. The shorter the wavelength, the higher the energy associated with the photons at that specific wavelength. For tissue interactions at the atomic level, the higher the level of energy associated with these photons, the higher the risk for biological effects. Therefore, radiation of shorter wavelengths has the greatest potential to be biologically hazardous.

3.2.2 The sun is the source for most of the natural electromagnetic radiation reaching the earth. Fortunately, the atmosphere protects the surface of the planet from many of these wavelengths and their associated hazards, but a significant portion of the electromagnetic spectrum still penetrates this protective barrier to become an environmental biohazard. In addition, industrial sources can create hazardous radiation in any environment.

3.2.3 The optical radiation portion of the electromagnetic spectrum can interact with the human eye and skin. Optical radiation extends from the shortest ultraviolet wavelength, at 100 nm, through the visible spectrum up to and including longer IR wavelengths around 1 mm (10^6 nm), such as those associated with radar. The optical radiation portion of the electromagnetic spectrum can be a biohazard when associated with visible and invisible laser beams.

3.2.4 The International Commission on Illumination (CIE) has divided the optical radiation portion of the spectrum into the bands listed in Table 3-1, which include IR, visible (VIS) and UV wavelengths:

3.2.5 The atmospheric contents normally shield the surface of the planet from UVC radiation. Wavelengths below 180 nm are completely blocked by the atmosphere. Without this protection, biological life on the planet would not be possible. Although not a naturally occurring biological threat, any of these wavelengths can be artificially generated and exploited by means of laser-based technology.

Table 3-1. Optical radiation spectral bands

Spectral band	Wavelength (nm)
UVC	100–280
UVB	280–315
UVA	315–400
VISIBLE	400–700*
IRA	700–1 400
IRB	1 400–3 000
IRC	3 000–1 000 000

* Although the visible range can be regarded to extend beyond 700 nm, usually up to 770 nm or even higher in some individuals, by convention and to maintain consistency with other accepted international standards, the visible range will be limited to 400–700 nm in this manual.

3.3 BIOLOGICAL TISSUE DAMAGE MECHANISMS

3.3.1 In order for phototoxic damage to occur in a biological tissue, radiation must be absorbed by some molecular constituent of that biological tissue. If the radiation passes through the tissue without molecular absorption, no biological damage occurs. However, most molecules have the ability to absorb at least some portion of the electromagnetic spectrum. It is possible to plot, for any given tissue, those ranges of radiation (wavelengths) to which that individual tissue is sensitive. That tissue plot represents a summation of the individual sensitivities of all of its constituent molecules and is known as the *action spectrum*. In many cases, the action spectra of different individual tissues have been precisely calculated and they are associated with very specific wavelengths. Most action spectra have been well described for the different tissue types. A classic example of this is the action spectrum for photokeratitis (inflammation of the cornea), which is related to excessive ultraviolet exposure (see Figure 3-1).

3.3.2 In order for biological damage to occur, a molecule must absorb the photons emitted by the radiation source. The Grotthus-Draper Law states that photons must be absorbed by a molecule before a photochemical effect can occur. The Stark-Einstein Law states that only one photon has to be absorbed by a molecule to cause an effect. If a photon is absorbed, then biological damage may occur as a consequence of one of three main damage mechanisms or any combination thereof: **photochemical** (photolytic), **thermal** (photocoagulative) and **acoustico-mechanical**.

3.3.3 Within any given biological tissue, the amount of damage that occurs represents a summation of all these mechanisms as well as other propagated local tissue effects; therefore, tissue damage will usually extend beyond the immediate confines of individual molecular locations. In some cases, tissue damage can be induced at a considerable distance from the location of the absorbing molecules, e.g. from oedema or vascular disruption.

Photochemical damage

3.3.4 Photochemical (photolytic) damage occurs when the energy of an incoming photon is high enough to break (lyse) existing chemical bonds within individual molecules. The effect of this is to alter or destroy the absorbing molecules and to transform them into unwanted free radicals. A considerable amount of research and interest continues regarding the acute and chronic tissue effects from the generation of free radicals, regardless of cause. A large portion of an organism's ability to resist the long-term consequences of tissue-free radicals that are generated on a daily basis involves many chemical mediators that repair this damage and remove these free radicals from individual tissues in order to neutralize their potential negative effects. When these damage repair mechanisms or mediators cannot compensate for the rate of free-radical generation, many acute and chronic diseases are known to follow. Examples of these include cataracts, macular degeneration, corneal degenerations and a variety of degenerative skin conditions, from loss of elasticity (wrinkles) to skin cancers.

3.3.5 The shorter the wavelength, the higher the energy associated with those particular photons. High-energy photons, for example UVC, have sufficient energy to break carbon-to-carbon bonds, which are some of the strongest biochemical bonds in living tissue. This is why atmospheric UVC absorbers, such as oxygen, ozone, water, carbon dioxide and other atmospheric constituents, are critically linked to human survival on earth. Thus, it is the energy associated with these shorter UV wavelengths that accounts for a significant portion of the photochemical damage seen in both the skin and the eye. In fact, wavelengths shorter than 320 nm are regarded as the active actinic ultraviolet range. Lasers can provide a concentrated source of photons at virtually any wavelength and thus are quite efficient at causing photochemical damage, either from low-intensity long exposures or high-intensity short exposures.

Thermal damage

3.3.6 When an inorganic or organic molecule absorbs a photon, this additional new energy drives the molecule into one of several types of unstable excited states, the most unstable of which is often referred to as a triplet state. These states are very unstable. The newly acquired level of excess energy is usually shed quickly and these states, therefore, are of extremely short duration. In some cases, the release of energy occurs visibly by re-radiation of the energy as light at another wavelength, either as phosphorescence or fluorescence. Generally, however, this energy is released as an exothermic reaction by giving off heat. Depending on the amount of heat generated and the thermal sensitivity of the surrounding tissues, if normal thermal dissipating mechanisms fail to compensate or are overloaded, this thermal process will then induce thermal damage. The heat can damage surrounding proteins and other tissues well beyond the immediate surrounds of the absorbing molecules. This explains why the visual effects of a retinal burn from a laser beam can be much larger than expected from the size of the visible retinal lesion.

Acoustico-mechanical damage

3.3.7 Acoustico-mechanical damage occurs as a consequence of high energy, short-duration exposures to laser beams. This damage mechanism consists of several sub-processes. These include acoustic shock waves induced by the impact of the laser beam itself and several consequences thereof. For example, ultra-fast elevations of tissue temperature can generate steam bubbles in the tissue. Mechanically, this can either destroy surrounding tissue as

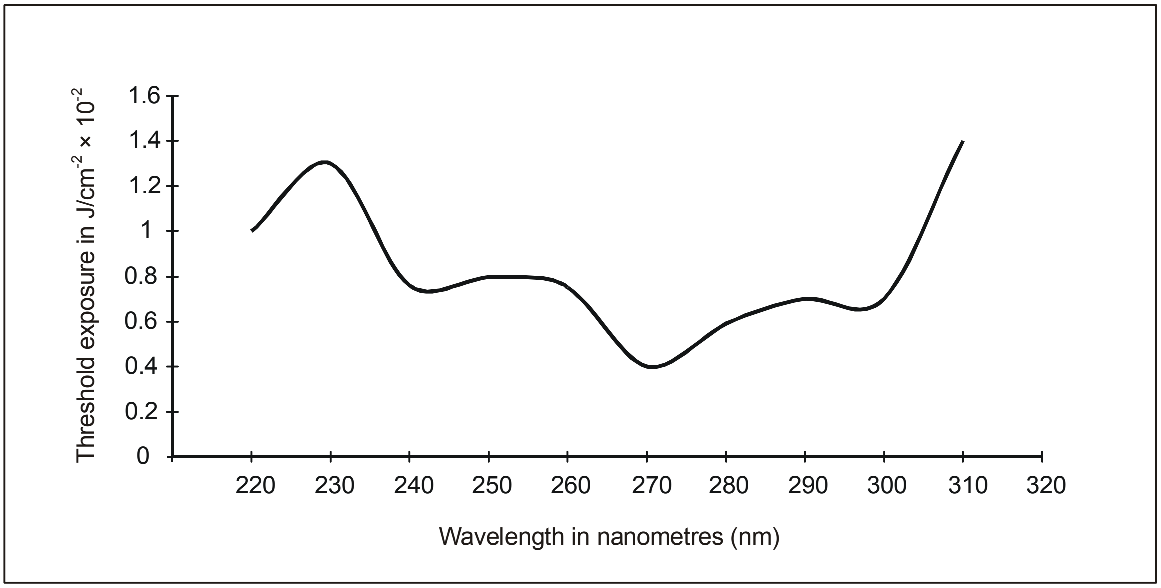

Figure 3-1. Action spectrum for photokeratitis

a function of being a space-occupying lesion or by inducing additional shock waves, which then propagate into and through various neighbouring tissues inducing even further structural damage. In addition, the ability of radiation to create a highly ionized state of matter (plasma) in combination with this steam-generating process can result in a cavitation process with formation of bubbles that can further disrupt delicate tissue structures. Such effects can be very dramatic and may affect areas up to 200 times larger than the thermal damage area. This cavitation process, also called an optical breakdown, can be used quite effectively, e.g. by a Nd:YAG laser, to create mechanical disruption of tissue. This effect is used clinically by ophthalmologists to cut through opacifications of the posterior capsule of the lens (capsulotomy) which may form after extracapsular lens extraction, to lyse tissue bands deeper in the eye and to create holes in the iris (iridotomy) to treat angle closure glaucoma.

3.3.8 The types of bioeffects and related tissue damage induced by a laser beam in either the skin or the eye are dependent on many variables, including the physical characteristics of the laser emitter itself, the environmental setting and the biological characteristics of the target tissue and its surrounding structures.

3.3.9 The physical characteristics related to the laser emitter itself are discussed in depth in Chapter 1. The most important are:

- wavelength
- initial beam size
- power and power density
- beam divergence
- output mode (pulsed or CW)
- pulse properties (PRF, pulse width, etc.)

3.3.10 The ability of any given laser beam to induce bioeffects and generate damage can be tempered or enhanced by environmental factors. This is particularly germane with respect to the eye. Such environmental factors include:

- ambient luminance (which determines the level of light adaptation)
- distance from laser source
- atmospheric conditions
- angle of incidence
- intervening optical interfaces
- viewing conditions (unaided or with magnification device)

3.3.11 The individual sensitivity of any biological tissue to any given radiation can be artificially increased (damage threshold decreased) by the use of certain photosensitizing agents or medications. There is a large and growing list of assorted pharmaceutical agents, both topical and systemic, that can make an individual more vulnerable to biological damage in some tissues in any given setting. In some cases, this can elevate tissue sensitivity to such a degree that a known non-damaging level of a particular radiation can suddenly and unexpectedly become a significant biohazard. A list of some common photosensitizers is provided in Table 3-2.

3.4 THE SKIN

3.4.1 The wavelength sensitivity range of the skin and the eye to optical radiation are generally very similar. While the likelihood of a skin injury is statistically higher because the skin has a much larger vulnerable surface area than the eye, the actual operational consequences of such skin effects are generally trivial. Furthermore, this vulnerability of the skin can easily be diminished by simple protective measures, such as covering the exposed areas with garments or chemical blocking agents. Nonetheless, when exposed to optical radiation, the skin can suffer the consequences, both acute and chronic, of all three biological tissue-damage mechanisms. The typical acute skin injury is likely to be a surface burn that may be severe enough to require medical management. Cumulative effects manifest themselves later in life as chronic conditions, such as wrinkles, skin folds (e.g. cutis rhomboidalis nuchae) and skin cancers. It is estimated that 80 per cent of the lifetime carcinogenic exposure to UV radiation occurs before age 21. Proper UV protection should be diligently followed from the earliest possible age; especially important is the protection of infants.

3.4.2 It is possible to disrupt skin and entire organisms with more powerful lasers such as those developed for military, industrial and scientific use. It is, however, unlikely that acute skin damage from a laser beam will disable aircrew, either physically or psychologically, and thus play a role in the disruption of safe air operations. Additional information is available in technical publications dealing with induced skin damage. Unnecessary exposure to radiation, particularly UV, should be avoided to reduce potential toxic cutaneous effects, both acute and chronic. The amount of UV radiation increases with altitude, as a general rule increasing three to four per cent for every 300 m (1 000 ft) gain in altitude.

Table 3-2. Common photosensitizing agents

- Antibiotics (tetracyclines)
- Chlordiazepoxide (Librium®)
- Chlorthiazides
- Cyclamates
- Furocoumarins (psoralens)
- Griseofulvin
- Nalidixic acid
- Oestrogens/progesterones
- Phenothiazines
- Porphyrins (porphyria)
- Sulfonamides
- Sulfonylurea
- Tretinoin (retinoic acid, vitamin A acid, Retin-A®)
- Triacetyldiphenolisatin (laxative)

3.5 THE EYE

3.5.1 It is the acute disruption in visual performance and the potential of laser beams to induce ocular damage that are of paramount importance to aircrew in the performance of their duties and which implies a threat to flight safety.

3.5.2 Optical radiation can be divided into two general regions with respect to the potential of a laser beam to cause damage: the retinal hazard region and the non-retinal hazard region. The wavelengths of the retinal hazard region include the visible and near infrared (NIR) band and represent those wavelengths that are transmitted through the optical media of the eye (cornea, aqueous humour, lens and vitreous body) and are focused on the retina. This band includes the entire visible range between 400 and 700 nm, up to the end of the near infrared (IR-A) range at 1 400 nm.

3.5.3 The non-retinal hazard region refers to those wavelengths that are mostly absorbed by anterior ocular tissues (cornea and lens) without significant transmission posteriorly to the retina. This band includes UV and the longer IR bands, those greater than 1 400 nm (IR-B and IR-C). Although some of the non-retinal hazard radiation can be transmitted through some ocular tissues, almost all of it is normally absorbed before it reaches the retina. This absorption process, however, can also have acute and chronic effects on the absorbing tissues themselves, especially if normal repair capabilities are exceeded. The classical example of this is the crystalline lens, which is the final tissue barrier to UV radiation. It absorbs virtually all of the residual UV radiation that passes through the cornea and the aqueous humour.

3.5.4 This absorption process induces changes within the lens, such as yellowing, which make it a more effective blue-wavelength and UV filter. But the absorption may also result in increasing opacification of the lens in the form of nuclear and cortical sclerosis (senile cataract) that eventually disrupts overall visual performance. Once the lens is removed surgically, this normal barrier to UV radiation is also removed and thus retinal tissue is now exposed to higher levels of UV that normally would have been absorbed by the natural lens. This necessitates additional sun protection even in individuals with implanted intraocular lenses (IOL) containing UV radiation-absorbing additives because such lenses do not reliably protect the retina against UV radiation.

3.5.5 The characteristics of each ocular tissue with respect to optical radiation will now be discussed in more detail. Figure 3-2 is provided to facilitate the discussion.

The cornea

3.5.6 The multi-layered cornea is a clear ocular structure, which contributes the bulk of the light-bending power (refractive power) of the eye as it naturally focuses incoming light rays on the retina. The cornea can absorb virtually 100 per cent of UV wavelengths shorter than 280 nm (UVC). This is usually of little importance as the atmosphere already absorbs almost all of the natural UVC, even at the highest flight levels. Artificial sources that generate UVC within the environment are a different matter. The overall absorption of the UV radiation band by the cornea decreases as the wavelength increases, so that more and more UV radiation is gradually passed on through the aqueous humour to the lens. At 360 nm, the cornea absorbs about 34 per cent of the UV radiation. On the other hand, the cornea absorbs very little of the visible and NIR portions of the spectrum, passing over 95 per cent of this range on to the retina as a more concentrated or focused beam.

3.5.7 Absorption of excessive UV radiation by the cornea can cause corneal tissue damage as a function of its action spectrum. The classic example of this is photokeratitis associated with arc-welding, artificial suntanning or exposures to high levels of environmental UV radiation, such as that typical of snow and water activities. UV radiation has also been identified as causing several types of corneal degeneration often referred to as climatic droplet keratopathies, such as Bietti's corneal degeneration and Labrador Keratopathy. Damage repair mechanisms and the replicating nature of the corneal epithelium generally limit such effects to only a temporary condition, albeit an extremely painful one. Such exposures can be epidemic as described by Xenophon in *Anabasis* where large multitudes of Greek soldiers at altitude were incapacitated by "solar blindness" during an organized military retreat. However, with very high-intensity laser beams, it is possible to induce stromal damage deep in the cornea. This would cause formation of a permanent corneal scar with the potential loss of vision depending on its location. Fortunately, such powerful UV radiation laser emitters are not readily available.

3.5.8 UV radiation-induced corneal injury is usually superficial, temporary and reversible. Nonetheless, it can be very disabling and painful. A severe acute corneal lesion could render aircrew visually incapacitated.

The aqueous humour

3.5.9 The aqueous humour is a transparent fluid with very few floating cellular elements. It does, however, absorb some of the UV radiation that gets through the cornea but not in any appreciable quantities. Similarly, it passes IR and visible radiation virtually unattenuated through to the lens.

The lens

3.5.10 The crystalline lens provides the final focusing element of the optical structures of the eye. While it provides substantially less refractive power than the cornea, it is the only dynamic focusing element with the ability to refine the final focus on the retina. It does so automatically and almost instantaneously. It is also, essentially, the last tissue barrier to any of the UV radiation that penetrates the cornea and aqueous humour. The lens absorbs increasing amounts of UV radiation above 300 nm (UVB), such that it absorbs approximately 50 per cent of UV radiation at 360 nm (UVA). As addressed earlier, the penalty for providing this final barrier of UV radiation protection for the retina is increasing yellowing and other changes that eventually result in opacification and cataract formation (cataractogenesis).

3.5.11 The UV radiation absorption capability of the anterior segment of the eye results in virtually no UV radiation shorter than 300 nm being passed into the vitreous body and only about one to two per cent of UVB and UVA passing through the lens. A unique window of UV radiation transmission has been identified in the lens through which a disproportionate amount of UV radiation at 320 nm (UVA) is transmitted. This is of some interest but does not represent a significant vulnerability. Since the lens is an avascular and encapsulated structure, its ability to dissipate heat and other damage effects is very limited, a factor which ultimately contributes to cataract formation later in life. The lens transmits visible and near IR radiation virtually unattenuated but with some scatter. However, the lens will absorb mid-infrared energy (IRB) such that it is possible to induce lenticular damage with levels of IR energy that are not high enough to induce corneal damage. The lens will also absorb increasing amounts of short, visible wavelengths (violet and blue) as it yellows with age.

The vitreous humour

3.5.12 The vitreous humour or vitreous body (corpus vitreum) is an optically clear structure composed of gelatinous and aqueous material with few structural fibres and cells. It does, however, have some very limited ability to absorb UV radiation and by design passes visible and NIR radiation to the retina virtually without attenuation.

The retina

3.5.13 The retina contains the neural elements and photoreceptors (rods and cones) of the visual system and it is the prime concern with respect to phototoxic damage induced by any optical radiation.

3.5.14 Retinal susceptibility to photolytic damage increases as the wavelength decreases. Furthermore, the absorption of the retinal pigment epithelium is higher in the near UV range than in the visible range. Therefore, thermal retinal damage can occur if UV reaches the retina in significant amounts. While normally protected from UV by the anterior segment of the eye, the retina is vulnerable to UV exposure, especially from 320 nm radiation. The retinal sensitivity to UVA radiation has also been demonstrated in aphakic eyes.

3.5.15 The retina is uniquely configured to respond to the narrow band of solar radiation that typically reaches the surface of the planet, namely the visible spectrum. As mentioned previously, that spectrum generally extends from 400–700 nm, but the retina is particularly more sensitive to certain wavelengths within that range. That sensitivity peaks at approximately 555 nm (yellow-green) due to cone sensitivity under photopic conditions (daylight) but shifts down towards shorter wavelengths, reaching approximately 510 nm (blue-green) at twilight, which coincides with the peak rod sensitivity under scotopic conditions (night). This shift between cone sensitivity and rod sensitivity is known as the Purkinje Shift.

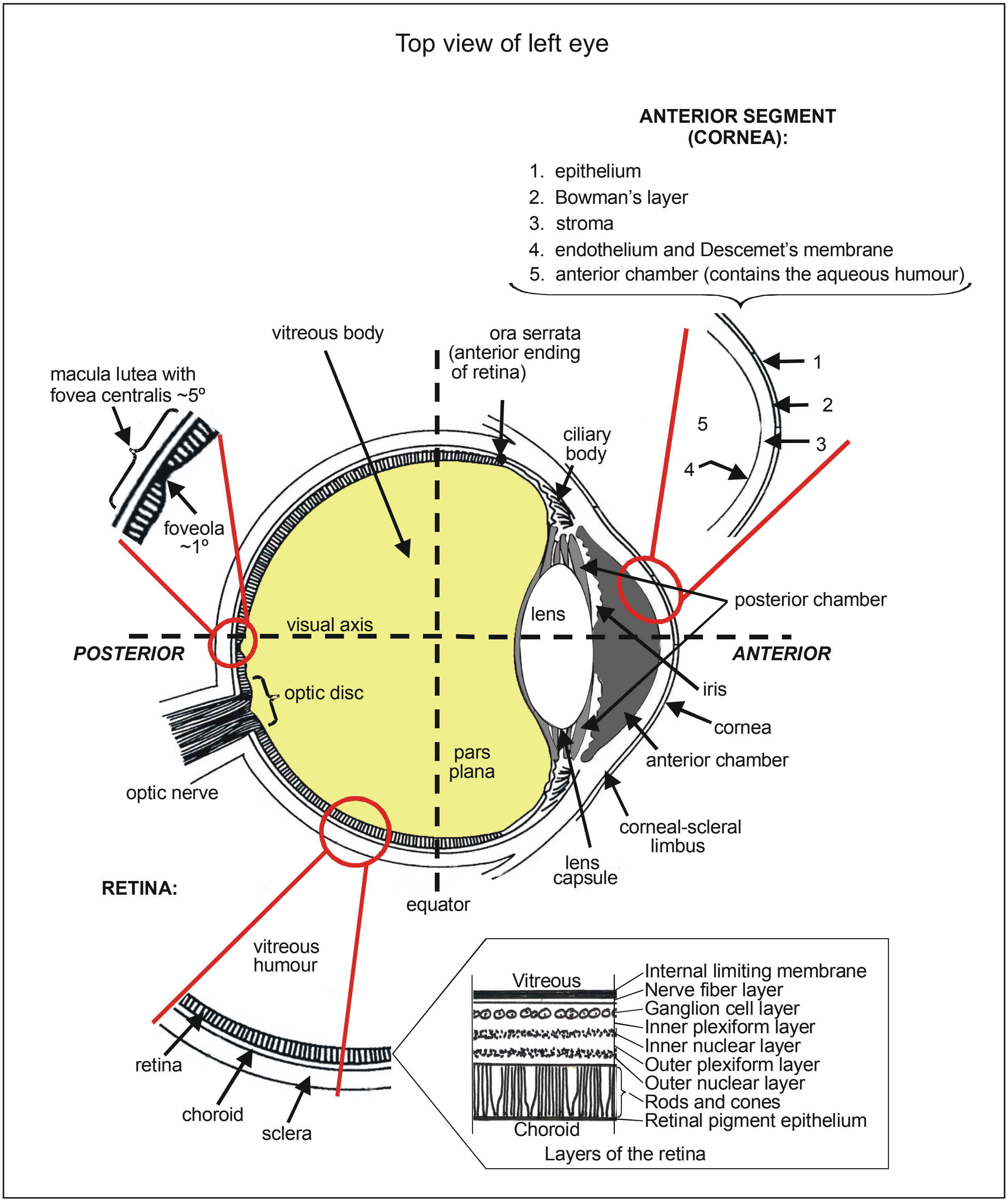

Figure 3-2. The anatomy of the eye

3.5.16 In some cases, a physiological retinal reaction to UV and IR radiation can be documented. While IR radiation is generally invisible, it has been possible to demonstrate spectral sensitivity in the human eye as high as 1 064 nm (Sliney, et al., 1976).[1]

3.5.17 To initiate the visual process, the retina must absorb visible radiation. The retina is also capable of absorbing IR radiation. This absorbable radiation (visible and IR) defines the **in-band** range and classifies those lasers that emit photons within this band as having **in-band** laser threat wavelengths.

3.5.18 As mentioned previously, the potential for any given laser beam to induce bioeffects is not only a function of the physical characteristics of the laser beam itself, but also of assorted environmental or atmospheric conditions present at the time. To these variables, certain biological characteristics of the eye must be added that also modify damage thresholds in the eye. These include:

- pupil size
- age
- photosensitivity level
- tissue vascular supply
- clarity of the ocular media (transmission and scatter)
- level of light adaptation
- type of tissue exposed

3.6 OCULAR LASER BEAM DAMAGE TERMINOLOGY

There are a few specific terms relevant when addressing laser-beam damage in an eye. These are:

a) ***Maximum permissible exposure (MPE).*** The MPE is that level of laser beam energy below which exposure to a laser beam is not expected to produce adverse biological damage. There are differences in MPE calculations depending on whether the laser beam is pulsed or continuous. MPEs for the skin and eye for any laser beam and exposure condition are available in the American National Standards Institute ANSI Z136-1-2000,[2] the International Electrotechnical Commission (IEC) 60825-1: 1998[3] and other related international documents.

b) ***Nominal ocular hazard distance (NOHD).*** The NOHD is the distance from a laser beam beyond which the MPE is not exceeded. Within the NOHD, the MPE may be exceeded and biological damage may be expected. It therefore defines the so-called "safe range" from any given laser emission. That "safe range" relates to actual biological damage and not necessarily to disruptions in visual performance.

c) ***Minimal ophthalmoscopically visible lesion (MOVL).*** The MOVL can be defined as the minimal lesion caused by a laser beam exposure, which can be seen by direct ophthalmoscopy. Tissue damage may not be immediately apparent and it may take over 24 hours for a lesion to become visible. In general, the energy required to produce an MOVL increases as a function of distance from the fovea on the retina. Radiant exposure and irradiance thresholds capable of creating MOVLs have been determined for most common laser beam wavelengths.

3.7 LASER BEAM BIOEFFECTS

3.7.1 The range of potential bioeffects associated with laser beam illumination is a continuum of reversible and irreversible histological damages dependent on the physical laser beam characteristics, environmental factors and vulnerability of the tissue.

3.7.2 It is therefore possible to define a broad range and continuum of potential bioeffects, involving the optical radiation range, that include both pathological damages (either reversible or irreversible) and performance impacts, all of which represent a threat to safe air operations (Figure 3-3). This ranges from distraction, glare and dazzle through flash-blindness, assorted after-images and residual scotomas, to retinal burns, retinal hemorrhages and even an ocular hole. It also includes physical and psychological phenomena that may further disrupt visual and cognitive function during a particular task. Consequently, it is not necessary for the MPE to be exceeded or the NOHD to be violated before a potentially significant effect will occur.

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[1] Sliney, D.H., R.T. Wangemann, J.K. Franks and M.L. Wolbarsht. "Visual Sensitivity of the Eye to Infrared Laser Radiation". *Journal of the Optical Society of America*, 66(4): pp. 339–341.

[2] American National Standards Institute ANSI Z136.1-2000. "American National Standard for the Safe Use of Lasers".

[3] International Electrotechnical Commission IEC 60825-1: 1998. "Safety of Laser Products, Part 1; Equipment Classification, Requirements, and User's Guide".

3.7.3 At the very minimum, any visible laser beam can be potentially distracting and psychologically disruptive. During a critical phase of flight, even a low-powered laser beam could prove lethal to crew and passengers while not having the power to cause any biological tissue damage.

3.7.4 A single exposure to a laser beam may induce several effects at the same time. Such an exposure can be distracting (on occasion even terrifying), induce glare or dazzle effects, cause flash-blindness and create after-images and scotomas, as well as being capable of creating a retinal burn or hole or inducing an intraocular haemorrhage.

3.7.5 A laser beam capable of inducing a retinal burn will also induce a surrounding area of oedema and other related biological tissue damage or bioeffects that will encompass a much broader area beyond the confines of the actual visible lesion itself. The MOVL refers to the smallest laser beam induced lesion that is ophthalmoscopically visible and refers only to lesions visible with direct view examination devices and does not extend to microscopic examination techniques. Specialized equipment is needed to see areas of microscopic damage induced by laser beam exposure. However, it can be anticipated that these changes are an ever-present part of the tissue bioeffect continuum and are invariably present in and around any discrete laser beam induced focal lesion. This collateral damage is primarily due to other tissue damage mechanisms, such as distal effects from occlusion of proximal blood supply or oedema that disrupts adjacent cell structures and compresses local blood vessels.

3.7.6 Generally, the susceptibility of the human eye to actual damage is also a function of the environmental luminance and level of light adaptation at the time of exposure. For example, any given laser beam would have to be significantly more powerful to induce similar photopic (daylight) bioeffects, such as flash-blindness, glare, dazzle and distraction, than such an illumination under mesopic (twilight) or scotopic (night) conditions. For the same average power, a pulsed laser beam will have a higher peak power and is therefore more hazardous than a CW laser beam. However, when it comes to many of the potential bioeffects common to all laser beams, the clinical and subjective difference between pulsed and CW beams is irrelevant.

3.7.7 Due to their light-collecting capability, viewing aids, such as periscopes, telescopes and binoculars, have a potential to increase the amount of laser radiation entering

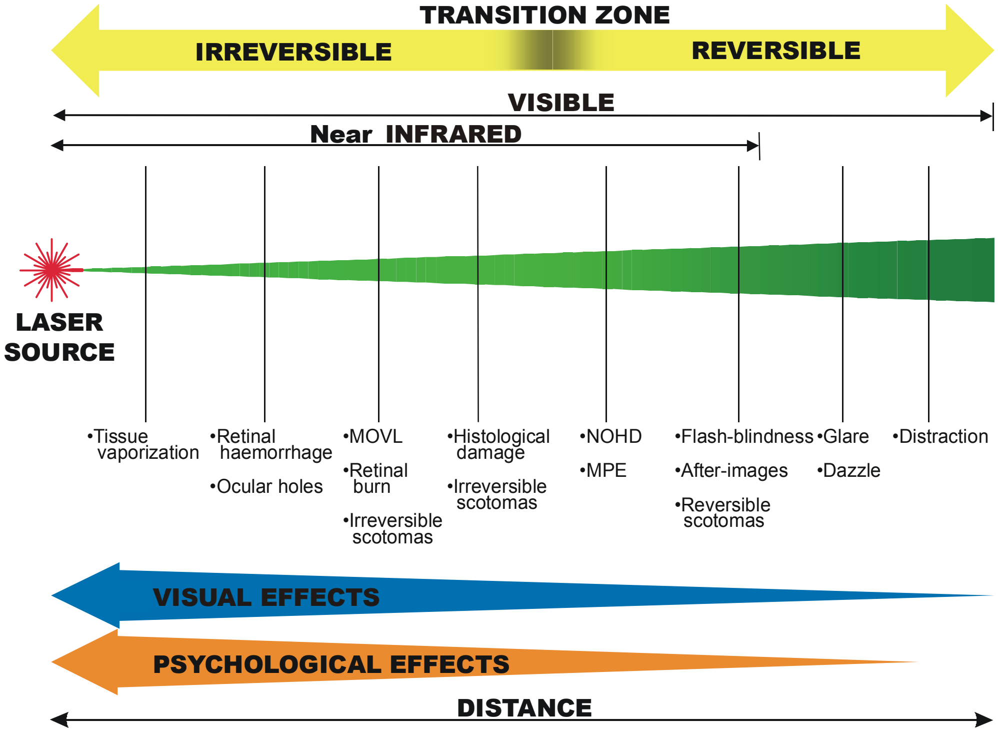

Figure 3-3. Ranges of laser beam bioeffects

the eye, thus increasing the hazard. This would increase the NOHD and OD requirements for eye protection. When the beam diameter is made 50 per cent smaller, the power density of the beam is quadrupled.

3.7.8 Imaging devices that do not provide direct viewing of a laser beam, such as night vision goggles (NVG) or forward looking infrared (FLIR) sensors, do not transmit the incoming laser photons directly to the human eye. These devices use visible photons that have been newly generated and then multiplied using photosensitive materials. The output of these devices is not a laser beam. The new photons emitted out of the viewing port of such devices are considerably different from those that actually enter the light-gathering device. Consequently, although such sensors and their data can be disturbed or destroyed by a laser beam, they do provide a significant level of laser beam eye protection along their line of sight.

3.8 LASER BEAM BIOEFFECTS AND AIR OPERATIONS

3.8.1 This section will elaborate on the individual features of the bioeffects continuum as they relate to the eye and air operations. These bioeffects include:

- distraction
- glare (also referred to as dazzle)
- flash-blindness
- after-images
- scotomas
- retinal burns
- retinal haemorrhages
- globe rupture
- other

Distraction

3.8.2 When a person sees a bright light, particularly at night, the natural reaction is to look at it. While in flight, aircrews are particularly sensitive to unexpected bright lights. Such a light may be perceived as representing a potential threat, such as the prospect of a collision with another aircraft or a ground obstacle. Pilots, because of their extensive training in combination with normal biological reflexes, instinctively divert their attention toward any new unexpected light in order to assess its significance. A distraction that occurs during a critical phase of flight could have serious consequences unrelated to the light source's ability to induce actual ocular damage. If the light is a laser beam illumination that exceeds the MPE, then even a brief direct visualization of the laser beam before a compensatory blink occurs could result in irreversible biological damage, as well as acute disturbances in visual performance.

3.8.3 Due to the strobe effect of some pulsed laser beams, they can be more distracting than CW laser beams of the same average power.

3.8.4 If the light proves to only be a trivial distraction, attention can be rapidly refocused to the aeronautical task at hand with little more than perhaps an inconsequential time penalty. However, if the light is bright enough, residual psychological and visual bioeffects can prevent resumption of normal visual and cognitive function and related performance tasks.

3.8.5 When a suspected laser beam exposure occurs, experience has shown that there will be an immediate psychological reaction as a direct consequence of what may initially be perceived as a serious eye injury, especially if the light is strong enough to induce persistent visual effects. The resulting mindset will persist until some functional vision returns but will not completely dissipate until it resolves completely or assurances are given that no permanent damage has occurred. Therefore, there may be a period of time during which the exposed aircrew members may be functionally disabled, visually and/or psychologically. Reactions to such events are an unpredictable aspect of human nature, but experience has taught us that significant exposures to laser beams under these conditions can result in serious psychological disruptions, inciting panic and necessitating transfer of control of the aircraft to the other flight crew members.

Glare and dazzle

3.8.6 Glare and dazzle are two terms often used interchangeably that refer to temporary disruptions in visual acquisition without biological damage. Glare can be caused by virtually any light and is particularly disruptive under scotopic viewing conditions, especially when the eyes are fully dark-adapted. However, any glare source in the cockpit is undesirable. Glare is regarded to be a source-fixed effect, meaning that as the position of gaze shifts away from the light source, glare effects are diminished. Glare only occurs when the light source is on. The length of time during which glare is in effect is not only a function of how long the light is viewed but also of the overall dark-adaptation state and pupil size in the target eye. Glare can be divided into discomfort glare and disability glare. Discomfort glare refers to glare of high enough illumination that forces the viewer to turn away. Discomfort glare tends to be exacerbated when the overall ambient illumination is low. Disability glare refers to the inability to see an object because of the light. Veiling glare represents the ability of glare to impede visualization of structures around the glare source beyond the actual size of the glare source itself and is a more functional representation of the true level of visual performance degradation.

3.8.7 Disability glare from an external light can be reduced by any intervening interfaces, such as windscreens, canopies or other optical media that scatter incident light. Scratched or dirty spectacles, contact lenses, as well as the cornea and crystalline lens, may also attenuate the disability glare. However, the more scatter that occurs, the greater the degrading effect from veiling glare.

3.8.8 Some interface materials can also reradiate at different wavelengths; thus an invisible laser beam can cause reradiation at a visible wavelength. This effect is not likely to be significant outside the NOHD for the invisible laser beam.

3.8.9 It has been shown that glare sensitivity increases with age as it is a function of age-related changes in the optical media, particularly the crystalline lens. In general, a visible laser beam is a very bright light that can be an extremely effective cause of disability glare. Laser beam induced glare can be initiated by both CW and pulsed laser beams, although it tends to be more of a concern with a CW laser beam source. It also appears that within the visual spectrum, all wavelengths have approximately the same scattering characteristics. Consequently, all colours have the capacity to induce glare.

Flash-blindness

3.8.10 Flash-blindness is a visual interference effect caused by a bright light that persists after the light is terminated. Flash-blindness persists while an eye attempts to recover from an exposure to the bright light. The ability of any given light source to induce flash-blindness is directly related to the brightness of the light and the level of dark adaptation in the target eye at the time of the exposure. It can be shown that the brighter the environmental luminance levels to which an eye is adapted at the time of the exposure, the brighter the light needed to induce flash-blindness. The corollary to this is that the brighter the light in any given situation, the longer the ensuing flash-blindness period. This relates directly to the ability of the eye to recover from bleaching of the photosensitive pigments caused by the new bright extrinsic light. During the period of recovery, the luminance conditions of the objects being viewed as a primary task will also determine how long it takes to recover functionally from the flash-blindness. If the visual task being undertaken at the time of exposure is well illuminated, recovery times will be shorter than recovery from poorly illuminated visual tasks. These recovery times reflect differences between the photochemical rejuvenation rate of rods and that of cones.

3.8.11 Flash-blindness can last from several seconds to several minutes and has been shown to be more prolonged in older individuals, largely based on the speed and efficiency of recovery mechanisms and richness of vascular supply available in the target ocular tissue. CW and pulsed laser beams are equally adept at inducing flash-blindness.

After-images

3.8.12 After-images refer to perceptions, or so-called after-effects, which persist following illumination with a bright light. They are often described as light, dark or coloured spots following exposure. Such after-images are essentially a type of flash-blindness, although after-image effects may last for more prolonged periods of time, often well beyond recovery of the ability to perform visual tasks required while in the cockpit. After-image effects may include colour distortion that represents selective cone pigment depletion similar to those induced with flash-blindness. However, after-images may persist for much longer periods than flash-blindness and can persist from minutes to hours or several days. They can also have different effects depending on the characteristic of the background under observation. Like flash-blindness, after-images also tend to last longer in older individuals. Their intensity, density and duration are in direct proportion to the intensity of the instigating light.

3.8.13 After-images can occur following illumination with both visible and invisible radiation. The latter reflects normal retinal sensitivity to some of these wavelengths, i.e. to some limited UV or IR bands, or is an expression of actual biological damage.

Scotomas

3.8.14 A scotoma is an after-effect which is either temporary (reversible) or permanent. A scotoma in its most benign form represents a resolving residual after-image. However, it can also be permanent and may thus reflect the earliest sign of permanent biological tissue damage. Scotomas typically follow flash-blindness reflecting normal biochemical recovery of photosensitive pigments in both rods and cones. The typical scotoma can be caused by exposure to a bright light but can also be caused by some non-visible wavelengths.

3.8.15 A permanent scotoma can be either relative or absolute. A relative scotoma is an area of the visual field in which objects of a certain size, brightness or colour may be seen while other objects that are smaller, less bright or of a different colour are not seen. This indicates damage to the retina but not complete loss of function. It is a reflection of the degree of tissue damage in the immediate area or to its vascular supply at a more distant location.

3.8.16 An absolute scotoma, on the other hand, is a more pronounced manifestation of visual damage and essentially represents an area of the visual field where no object, regardless of size, colour or luminance, is visible. In effect, it represents a part of the retina where there is no longer any functioning neural retina remaining as a result of direct localized tissue damage or disruption of vascular supply or neural pathways elsewhere.

3.8.17 The visual performance ramifications of such scotomas are related to their size and location. Even the smallest of absolute scotomas can have devastating visual consequences if it occurs directly in the fovea (central vision), as opposed to a few degrees away.

3.8.18 Retinal cones mediate fine visual acuity and are maximally concentrated in and around the fovea, achieving their densest population in a specialized area called the foveola. Here the visual acuity is maximal as illustrated in Figures 3-4 and 3-5. This highest level in cone-mediated visual acuity at that location is known as **central vision**. Cone population density, however, quickly drops off as a function of distance from the fovea, especially outside a 10-degree radius from the fovea.

3.8.19 This cone distribution accounts for the fact that 6/6 or better visual acuity occurs within the central one degree of the fovea, in the foveola. By five degrees away, visual efficiency has dropped off to approximately 6/12 to 6/18 and by 10 degrees away, visual degradation reaches 6/18 to 6/24. Vision outside the fovea is referred to as **peripheral vision**, which typically degrades to 6/60 to 6/120 levels as cones become less common and more widely spaced.

3.8.20 Therefore, it is the precise location of any permanent ocular damage relative to the fovea that will determine the resulting level of functional visual acuity. Any focal lesion in the eye will produce a scotoma. Permanent scotomas are usually associated with observable retinal lesions, but the area of scotoma may be much larger than the size of the retinal lesion suggests because of collateral histological damage in surrounding tissue. Consequently, the size and location of the retinal lesion will determine the overall visual effect of any given lesion in an eye.

Retinal burns

3.8.21 A retinal burn represents more significant and permanent damage induced by intense radiation and is very characteristic of laser beam induced phototoxic damage. A laser beam focused on the retina is more likely to cause injury than a non-focused beam. The ability of a laser beam to induce such damage is used as a surgical tool to treat certain ophthalmological disorders, such as retinal tears and diabetic retinopathy. In the latter case, approximately 1 500 deliberate retinal burns are created with an argon laser beam to reduce the risks of retinal neovascularization that occurs in about five percent of diabetes mellitus cases. However, such laser beam induced events in normal eyes are otherwise significant, unwanted occurrences. It is also possible that other histological damage, occurring at levels not observable ophthalmoscopically, can account for surprising amounts of visual damage without an apparent retinal burn. As mentioned previously, the size of any area of retinal damage will generally extend beyond the confines of the visible lesion because of the other tissue-damage mechanisms. A small retinal burn that closes or interrupts vascular supply or neural pathways can affect a much larger area of retina, although collateral blood flow may temper this effect to some degree.

3.8.22 It is the ability of a laser beam to induce a retinal burn that is one of the most ominous unwanted effects in a normal eye, and any resultant visual consequences will be a direct function of the size and location of the lesion.

3.8.23 Direct viewing of a high-powered laser beam on the visual axis will cause burns that have greater visual ramifications than off-axis burns. The retina can sustain many small burns in the periphery without any obvious physiological consequence. These peripheral lesions, while not usually symptomatic, indicate the presence of a significant laser beam exposure in the given operational environment. In addition, a laser beam has the ability to remain quite powerful even after reflection from shiny surfaces, so that those whose visual attention are directed away from the primary laser beam may still receive an on-axis reflection from an unexpected quadrant of gaze. In some cases, certain reflective sources, such as concave mirrors, may concentrate the laser beam even further. Other observations related to the ability of a laser beam to induce a retinal burn reveals that the energy requirements to induce such a lesion generally increase as the distance from the fovea increases. Similarly, it has been shown that repetitive re-exposures (multiple subthreshold exposures) in any given area may reduce the threshold for inducing biological damage at that location. This further supports the need to redirect gaze immediately away from any laser beam that enters the eye.

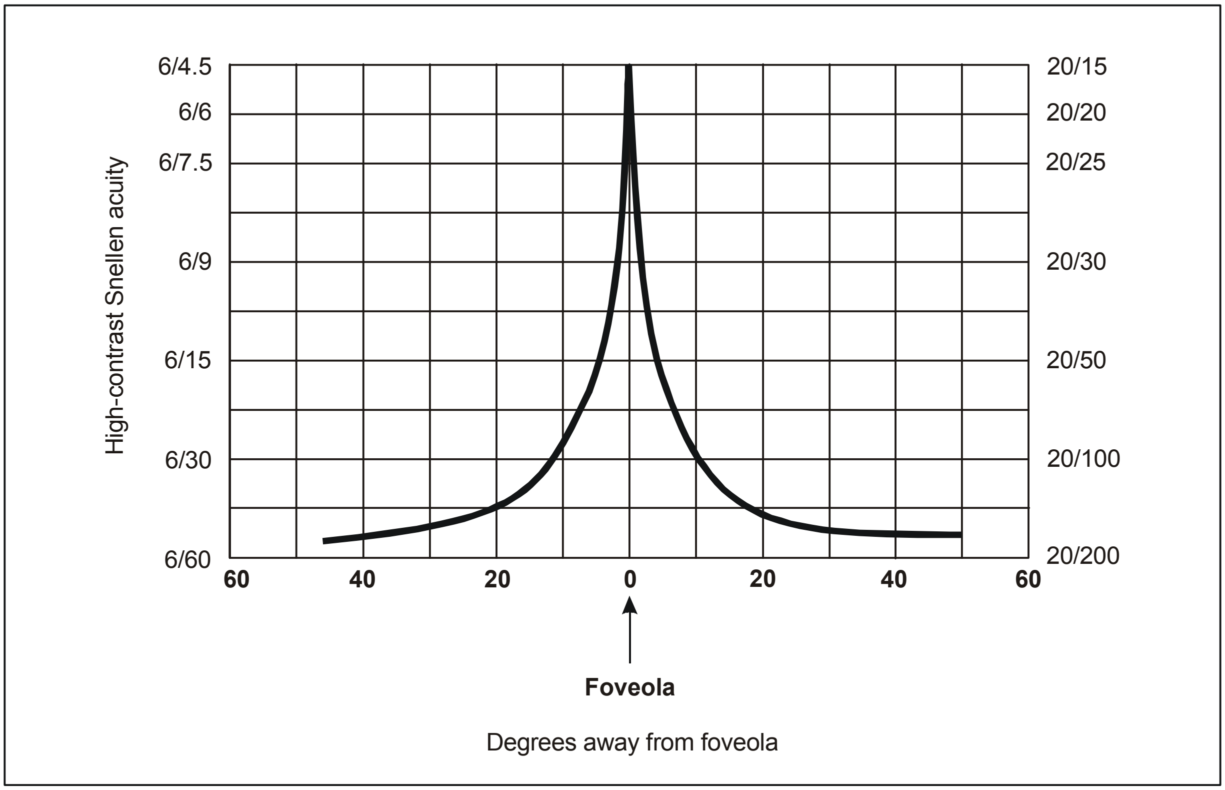

Figure 3-4. Visual acuity as a function of cone distribution

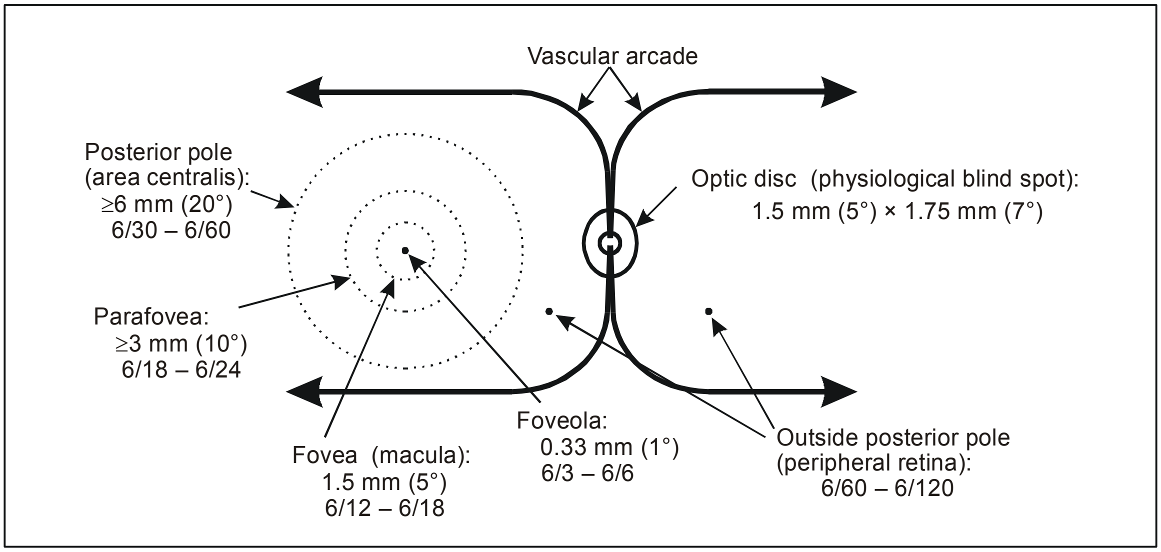

Figure 3-5. Visual acuity as a function of retinal location

Retinal haemorrhages

3.8.24 A retinal haemorrhage will occur if a laser beam disrupts a blood vessel somewhere in the eye. The characteristics of that haemorrhage will depend on the location of the damaged blood vessel within the retina, its distribution and the orientation of the cell structure at the disruption site. Haemorrhages involving superficial retinal vessels will tend to follow the nerve fibre layer and assume a flame-shaped configuration as the blood follows the nerve fibres out radially from the optic nerve. Haemorrhages in retinal layers deeper than the nerve fibre layer tend to be dot- or blot-shaped. This blood can originate from deeper vascular supplies, such as from the choroid (middle layer) of the eye. It is also possible to disrupt a vessel or vascular plexus to the extent that a large intraocular bleed occurs. This blood may either collect on the retinal surface as a preretinal haemorrhage or diffuse into the vitreous cavity. Blood that enters the vitreous body will tend to remain localized, particularly in younger individuals, but with increasing age, the jelly-like vitreous body liquefies and will allow blood to diffuse throughout the entire vitreous cavity. This change in the vitreous body with age is a normal aging process known as vitreal liquefaction, but it may also occur as a result of other pathological processes such as trauma.

3.8.25 A haemorrhagic event can have significant visual impact. Recovery will depend on the location of the bleed and other induced cytoarchitectural disruptions, as well as the rate of reabsorption of the blood, e.g. from the vitreous body, where it acts as a light-blocking filter. In general, blood in the vitreous cavity will take approximately six to twelve months to resolve spontaneously but will not always do so. In many cases, removal of the cloudy vitreal contents will be required surgically (vitrectomy) to restore a clear ocular medium within the vitreous cavity. In some cases, blood in the vitreous body will fibrose into localized areas of vitreal opacification or induce fibrous strands that can produce retinal traction or retinal tears.

Globe rupture

3.8.26 It is possible with a laser beam to disrupt tissue to such an extent that neither a burn nor a haemorrhage occurs, but rather a tear in the tissue is caused. This can be a deleterious effect from exposure to high-peak power laser beams of certain wavelengths. But this can also be used therapeutically to disrupt unwanted membranes or traction bands within the eye. Such tissue disruption may be complete, either extending through an entire tissue layer, such as the retina and choroid, or with more powerful laser beams, to create a tear or hole in the entire outer coat of the eye, the sclera-globe rupture. Such laser beams would need to be very powerful to retain that capability at considerable distances and would not likely be associated with laser beams routinely encountered in civil aviation. Furthermore, lasers of this peak power at extended ranges are likely to have other much more significant effects that would overshadow the eye and vision considerations.

Other bioeffects

3.8.27 In addition to the previous discussion of the psychological and ocular effects associated with laser beam exposures, there are other bioeffects that need to be addressed. It is quite common in response to a perceived bright light, particularly if it induces symptoms or a lesion, for those affected to rub their eyes. This can induce mechanical trauma to the cornea and conjunctiva that is unrelated to the biological damage mechanisms of laser beams. For example, excessive rubbing can induce conjunctival haemorrhages and superficial epithelial lesions of the cornea or even corneal abrasions that can induce further symptoms and discomfort that are unrelated to, but often attributed to, the laser beam itself. This can become even more problematic if the rubbing occurs over contact lenses, especially lenses made from rigid materials.

3.8.28 As a result, best corrected visual acuities and any ocular damage must be carefully recorded in the medical record so that a determination can be made, either by on-scene medical examiners or by subject matter experts who later review such cases as to cause and effect. A corneal and retinal drawing should always be made to show the precise location and configuration of any lesions related to the event. This is extremely important especially since these events invariably become medical, occupational, legal and political controversies at some point.

3.8.29 Beyond the description of biological damage mechanisms and related bioeffects associated with laser beams, consideration should be given to the visual performance ramifications of this damage from a different perspective. Those categories of visual performance that are related to either temporary or permanent laser beam effects include: central visual acuity, peripheral visual acuity, colour perception, contrast sensitivity and stereopsis. Therefore, the consequences of specific laser beam induced lesions must also be viewed with regard to their ability to affect these other areas of visual performance. In many cases, these visual functions will be tested to determine deviations from normal and to monitor recovery. It should be noted that colour perception screening (which should include both red/green and yellow/blue testing) can be particularly useful in identifying phototoxic retinal damage and may indicate laser beam damage even when the Amsler grid and Snellen visual acuity tests are normal. This ability to identify phototoxic events with colour vision tests has been shown to exceed the ability of the Amsler grid to identify the presence of an actual laser beam related injury. Therefore, colour vision testing (including red/green and blue/yellow testing) remains a significant tool to assess the level and degree of potential damage related to any light or laser beam exposure.

3.8.30 Individual variations in affected eyes make accurate prediction of rate and degree of recovery almost impossible. The closer the lesion to the macula, the greater the likelihood of significant visual impairment, but appearance alone is not always a good indicator of function. Some eyes with significant lesions seen with the ophthalmoscope have surprisingly good visual function. Other eyes may have significantly reduced visual function with very little to see ophthalmoscopically. The normal retina is transparent and it is only with some of the newer instruments, such as the confocal scanning ophthalmoscope that subtle retinal changes can be studied. The most subtle lesions may be impossible to detect except with electron microscopy. Corneal lesions are somewhat easier to evaluate clinically. As with the retina, location is critical. A small corneal scar in the visual axis will affect vision severely, while a dense peripheral corneal scar may have no effect on visual acuity.

3.9 THE FUTURE

3.9.1 Although much is known about laser beam bioeffects, the proliferation of laser technology mandates continued research as new laser beam wavelengths and laser characteristics are developed. Several areas of concern related to laser beam exposure remain to be defined, such as cumulative effects as a result of repetitive low-intensity exposures and age-related sensitivities.

3.9.2 Another area of interest is neuroprotective drugs. While no effective neuroprotective agents have yet been identified, several types are being pursued in the hopes of eliminating or decreasing retinal sensitivity to injury from laser beam exposure.

3.9.3 On the other hand, the increasing use of a variety of medications can potentially photosensitize the skin and the eyes, increasing their susceptibility to phototoxic damage. Research in this area remains difficult. It is expensive, complicated, time consuming and would need to encompass a huge and ever-expanding pharmacopoeia of both natural and synthetic drugs.

3.10 MEDICAL EVALUATION OF LASER BEAM INCIDENTS

3.10.1 The medical tools and methodologies recommended for evaluating suspected laser beam induced injuries are described in Chapter 7. It is extremely important that every effort be made to promptly record all relevant details of the exposure at the earliest opportunity as this may have critical occupational, medical, legal and operational value to all parties concerned. Experience shows that in many such exposures, damage attributed to laser beam illuminations has, in fact, another cause. The following report gives an example of this.

> On 29 November 1996, at about 6:50 p.m. local time, the captain of an Embraer 120 sustained an eye injury when hit by a laser beam during approach to Los Angeles, California (United States). The aircraft was at 6 000 feet MSL in VMC on right base for a visual approach to runway 24R. The captain was looking for other traffic through the right window of the cockpit when he was struck in his right eye by a bright blue beam of light. As the flight continued, it became more difficult for the captain to see with his right eye because of increasing pain and tearing. By the time the aircraft was established on final approach, the captain was in so much discomfort that he relinquished the control to the co-pilot who completed the landing. The captain requested immediate medical attention, and examination at a local hospital revealed multiple flash burns to his right cornea. The captain was also examined by specialists at Armstrong Laboratory, Brooks AFB, San Antonio, Texas. This examination revealed no evidence of permanent effects from the exposure. Investigators from the FDA attempted without success to identify the source of the laser beam. There were no NOTAMs in effect for laser light activity in the Los Angeles area at the time of the incident.
>
> (Summary of NTSB Full Narrative Report LAX97IA056)

3.10.2 In this report, the initial diagnosis of corneal damage (“multiple flash burns to his right cornea”) cannot be directly attributed to a visible laser beam because light passes through the cornea without affecting it. The damage to the cornea was most likely caused by rubbing of the eye in response to the light beam exposure.

3.10.3 The inability of some examiners to correctly diagnose an injury following laser beam exposure can be attributed to a lack of understanding of the significance of the events involved and inadequate experience with this kind of injury. It is common for people to vigorously rub their eyes in response to an insult they may have received, whether it was from radiation or particulate matter. They often do so instinctively, sometimes in a state of panic and in such a coarse way that they induce ocular damage to the conjunctiva and cornea. This damage can be misconstrued as caused by the laser beam itself when, in fact, it was a self-induced mechanical trauma after the event. It is therefore absolutely critical, when such events occur, that these patients be examined by subject-matter experts with adequate experience and knowledge of laser beam injury patterns and source characteristics. Only such experts can definitively establish whether or not such events are related to a laser beam exposure.

3.10.4 Physical characteristics and other historical details related to the laser beam and exposure setting need to be evaluated carefully. For the most part, this will be beyond the capability of ordinary medical practioners who lack a comprehensive background in lasers and their bioeffects. In the absence of national laser injury management centres, an international point of contact should be established to help facilitate the recording of such incidents.

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Chapter 4

OPERATIONAL FACTORS AND TRAINING OF AIRCREW

4.1 BACKGROUND

4.1.1 An increasing incidence of in-flight laser beam illuminations of flight crew personnel has been reported in recent years. Incidents have occurred primarily near airports located in close proximity to large cities, resort destinations and entertainment venues. Such illuminations have resulted in aversion responses (blinking, squinting, head movement), temporary visual impairment (TVI), temporary vision loss (TVL), a variety of psychological effects and evasive actions.

> On 19 November 1993, at 10 p.m. local time, a B-737 departing Las Vegas, Nevada (United States) was struck by a green laser beam at 500 feet AGL. The beam entered the cockpit through the co-pilot's window, flash-blinding both pilots for 5-10 seconds. The co-pilot reported problems with his right eye and needed medical attention at the end of the flight. The captain of the flight stated as his opinion that if the laser beam had passed through the front windshield illuminating both pilots at a more direct angle, they would have lost control of the aircraft. The laser beam source was reported to have been located at one of the hotels near the airport.
>
> (Summary of *Report of Irregularity*, dated 24 November 1993)

4.1.2 During the following two years in the vicinity of Las Vegas airport, there were more than 150 laser beam illuminations of air carriers, regional carriers, military aircraft and local helicopter operators, including emergency and law enforcement operators.

> On 30 October 1995, at 6:10 p.m. local time, a B-737 was climbing through 4 500 feet AGL on departure from Las Vegas when the first officer, who was the flying pilot, was hit by a laser beam. He immediately experienced eye pain and was completely blinded in the right eye. After-image effects also impaired vision in his left eye. He reported that his inability to see lasted 30 seconds and for an additional period of two minutes he was unable to interpret any instrument indications. The captain assumed control of the aircraft and continued the climb.
>
> (Summary of NTSB Aviation Accident/Incident Database Report LAX96IA032)

4.1.3 These incidents made it clear that TVI at illumination levels much lower than those normally associated with physical eye injury could affect flight safety. On 11 December 1995, a moratorium on all outdoor laser activities in Las Vegas was declared.

4.1.4 There are two situations where outdoor laser operations may compromise aviation safety. The first is where the MPE is exceeded and physical injury to the eye can occur. The second is the situation where the MPE is not exceeded, but where there is a potential for functional impairment, such as flash-blindness, after-image and glare that can interfere with the visual tasks of the pilots during critical phases of flight. The two excerpts above are believed to be examples of the second situation.

4.1.5 There are obvious flight safety risks associated with laser beam illumination during critical phases of flight (especially procedures requiring steady-state turns). These are caused by ocular, vestibular and psychological effects, which individually or combined may lead to loss of situational awareness (LSA). TVI leaves the pilot reliant upon other sensory input, which may provide inadequate but compelling information, resulting in incorrect decisions. TVI can lead to startle, distraction, disruption, disorientation and in extreme cases, complete incapacitation.

4.1.6 Pilots receive most of their flight information visually, and in order to maintain situational awareness in a dynamic environment, they rely on frequent reference to their instruments. This reliance is greater at night and becomes total in instrument meteorological conditions (IMC).

4.1.7 It is important to understand how trained pilots interpret, integrate and process information without visual reference to the outside world. Thorough instrument flight training is a prerequisite for maintaining normal task performance, information integration and situational awareness when operating under instrument flight rules (IFR).

4.1.8 Pilots use a visual scan technique of glancing at, rather than dwelling upon, the flight instruments. Pilots construct mental images of their position in space from information provided by the flight instruments. Spatial orientation is maintained through the brain's comparison of visual inputs with a pre-existing mental model. When conditions permit, this model is continually updated with reference to the outside world for comparison and processing.

4.2 SITUATIONAL AWARENESS

4.2.1 Situational awareness (SA) is the accuracy by which a person's perception of his environment mirrors reality. SA is determined by several factors. Anything that leads to a loss of SA can create a flight safety hazard. One of the most critical factors, and the one most likely to be affected by laser beam illumination, is spatial orientation.

4.2.2 Loss of spatial orientation is called spatial disorientation (SD). It can be classified into three types:

- Type I (unrecognized SD) occurs when a person is unaware of being disorientated;
- Type II (recognized SD) occurs when a person is aware of being disorientated and is able to compensate for it; and
- Type III (incapacitating SD) occurs when a person is aware of being disorientated but is unable to compensate for it.

4.2.3 A laser beam illumination may cause all three types of SD but is most likely to cause Types II and III.

4.3 ORIENTATION IN FLIGHT

4.3.1 Orientation in flight is determined primarily by cues provided by the following four senses:

a) ***Sight (vision).*** This is the single most important sense for maintaining spatial orientation during flight. When vision is impaired, spatial orientation is degraded because motion and position cues provided by other senses are not reliable during flight.

   Vision can be divided into peripheral and central vision. Peripheral vision provides low resolution but is highly sensitive to movement and light. It is primarily concerned with the question of "where", thus supporting spatial orientation. Central vision provides high resolution and colour perception but is less sensitive to light. It is primarily concerned with the question of "what". With the loss of visual orientation cues, inadequate but compelling information from other senses causes a variety of illusions, sometimes leading to overwhelming SD.

b) ***Vestibular sense (sense of equilibrium).*** The vestibular apparatus provides information from the inner ear about motion and balance. In addition, the middle ear provides information about ambient pressure changes. Normally, visual input will suppress input from other senses. Because flight motion is different from that of everyday activities, the loss of visual input is critical, as vestibular information alone may result in illusory perception of flight attitude and motion. For example, to stimulate the inner ear, an angular acceleration of 0.5 to 2.2 degrees per second per second is required. When the angular acceleration ceases, such as when a constant rate turn has been established, the vestibular apparatus is no longer able to detect the turn. If visual input is absent, pilots will not recognize that the aircraft continues to turn.

c) ***Proprioception (kinaesthetic sense).*** A variety of sensory nerve endings in the skin, the capsules of joints, muscles, ligaments and deeper supporting structures are stimulated mechanically and, hence, are influenced by the forces acting on the body. These proprioceptive mechano-receptors provide useful equilibrium information based on sensation of position and movement. The kinaesthetic sense is better known to pilots as "seat-of-the-pants". Alone, the kinaesthetic perception of an aircraft's attitude in space is unreliable but can easily be overcome by more vital sensory input.

d) ***Hearing (audition).*** The auditory system provides information about sound level, pitch and direction.

Pilots learn to recognize certain sounds during flight. For example, airflow over the windscreen during acceleration and deceleration of the aircraft and the change in pitch as the engine power-setting changes can be detected.

4.3.2 Loss of visual references caused by a laser beam illumination, coupled with inadequate information from the vestibular apparatus, the proprioceptive mechano-receptors and the auditory system, may result in SD (often referred to by pilots as "vertigo"), which can lead to accidents. Disorientation demonstration courses and laser-awareness training are therefore recommended.

4.4 PREVENTATIVE PROCEDURES

Pre-flight procedures

- Notices to airmen (NOTAMs) should be consulted for location and operating times of laser activities and alternate routes should be considered.
- Aeronautical charts should be consulted for permanent laser activities (theme parks, research facilities, etc.).

In-flight procedures prior to entering airspace with known laser activity

- Exterior lights should be turned on to aid ground observers in locating and identifying aircraft.
- The autopilot should be engaged.
- One pilot should stay on instruments to minimize the effects of a possible illumination.
- Flight deck lights should be turned on.

In-flight procedures during and after laser beam illumination of the cockpit

4.4.1 If a pilot is exposed to a bright light suspected to be a laser beam, the following steps are recommended to reduce the risk unless the specific action would compromise flight safety:

- Look away from the light source.
- Shield eyes from the light source.
- Declare visual condition to other pilots.
- Transfer control of the aircraft to another pilot.
- Switch over to instrument flight.
- Engage autopilot.
- Manoeuvre or position the aircraft such that the laser beam no longer illuminates the flight deck.
- Assess visual function, e.g. by reading instruments or approach charts.
- Avoid rubbing eyes.
- Notify air traffic control (ATC) of a suspected in-flight laser beam illumination and, if necessary, declare an emergency.

4.4.2 It is important to notify appropriate authorities of a suspected in-flight laser beam illumination. Upon landing, the pilot should notify the authorities and provide details about the incident, then seek immediate medical evaluation, preferably by a qualified vision specialist. Documentation of incidents and medical examinations are covered in Chapters 6 and 7, respectively.

Chapter 5

AIRSPACE SAFETY

5.1 GENERAL

5.1.1 This chapter provides guidance for determining and minimizing the potential adverse effects of outdoor laser operations on aviation safety. Provisions* concerning laser emitters and protected flight zones are contained in:

Annex 11 — *Air Traffic Services*

"2.17.5 Adequate steps shall be taken to prevent emission of laser beams from adversely affecting flight operations."

Annex 14 — *Aerodromes*, Volume I — *Aerodrome Design and Operation*

"Laser emissions which may endanger the safety of aircraft

"5.3.1.2 **Recommendation.—** *To protect the safety of aircraft against the hazardous effects of laser emitters, the following protected zones should be established around aerodromes:*

— *a laser-beam free flight zone (LFFZ)*
— *a laser-beam critical flight zone (LCFZ)*
— *a laser-beam sensitive flight zone (LSFZ)*

"Note 1.— Figures 5-10, 5-11 and 5-12 may be used to determine the exposure levels and distances that adequately protect flight operations.

"Note 2.— The restrictions on the use of laser beams in the three protected flight zones, LFFZ, LCFZ and LSFZ, refer to visible laser beams only. Laser emitters operated by the authorities in a manner compatible with flight safety are excluded. In all navigable air space, the irradiance level of any laser beam, visible or invisible, is expected to be less than or equal to the maximum permissible exposure (MPE) unless such emission has been notified to the authority and permission obtained.

"Note 3.— The protected flight zones are established in order to mitigate the risk of operating laser emitters in the vicinity of aerodromes".

5.1.2 Contracting States may be guided by the following text examples when controlling the hazards of laser beam emissions or enacting regulations in accordance with Annexes 11 and 14:

a) No person shall intentionally project, or cause to be projected, a laser beam or other directed high intensity light at an aircraft in such a manner as to create a hazard to aviation safety, damage to the aircraft or injury to its crew or passengers.

   Note.— Also see Annex 14, Volume I, 5.3.1.1.

b) Any person using or planning to use lasers or other directed high-intensity lights outdoors in such a manner that the laser beam or other light beam may enter navigable airspace with sufficient power to cause an aviation hazard shall provide written notification to the competent authority.

c) No pilot-in-command shall deliberately operate an aircraft into a laser beam or other directed high-intensity light beam unless flight safety is protected. This may require mutual agreement by the operator of the laser emitter or light source, the pilot-in-command and the competent authority.

5.2 AIRSPACE RESTRICTIONS

5.2.1 To protect the safety of aviation in the vicinity of aerodromes, heliports and certain other areas, such as low-level visual flight rules (VFR) corridors, it is necessary to protect the affected airspace against hazardous laser

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* The provisions are not intended to confer any responsibility onto airport operators.

beams. For non-visible laser beams, the nominal ocular hazard distance (NOHD) value is the sole consideration. For visible laser beams, in addition to the NOHD, visual disruption must also be considered.

5.2.2 According to 5.3.1.2 in Annex 14, airspace around aerodromes should be designated as laser-beam sensitive flight zones, laser-beam critical flight zones, and laser-beam free flight zones, in order to prevent visible laser beams from interfering with a pilot's vision, even if the maximum permissible exposure (MPE) is not exceeded. The beam from a visible laser must not enter any zone, when the irradiance is greater than the corresponding visual interference level, unless adequate protective means are employed to prevent personnel exposure. Lasers with beam irradiances less than the MPE but exceeding the sensitive level or critical level, may be operated in the sensitive zone or critical zone, respectively, if adequate means are used to prevent aircraft from entering the beam path.

Laser-beam free flight zone (LFFZ)

5.2.3 The LFFZ is the airspace in the immediate proximity to the aerodrome, up to and including 600 m (2 000 ft) above ground level (AGL), extending 3 700 m (2 NM) in all directions measured from the runway centre line, plus a 5 600 m (3 NM) extension, 750 m (2 500 ft) on each side of the extended runway centre line of each useable runway. Within this zone, the intensity of laser light is restricted to a level that is unlikely to cause any visual disruption. The following conditions are applicable to LFFZ:

a) parallel runways are measured from the runway centre line toward the outermost edges, plus the airspace between runway centre lines;

b) within this airspace, the irradiance is not to exceed 50 nW/cm^2 unless some form of mitigation is applied. The level of brightness thus produced is indistinguishable from background ambient light; and

c) to allow laser operations below the arrival path, a 1:40 slope may be applied to the 5 600 m extensions. This slope is calculated from the runway threshold.

Laser-beam critical flight zone (LCFZ)

5.2.4 The LCFZ is the airspace within 18 500 m (10 NM) of the aerodrome reference point (ARP), from the surface up to and including 3 050 m (10 000 ft) AGL (see Figures 5-1, 5-2 and 5-3). This zone may have to be adjusted to meet air traffic requirements. Within this airspace the irradiance is not to exceed 5 $\mu\text{W/cm}^2$ unless some form of mitigation is applied. Although capable of causing glare effects, this irradiance will not produce a level of brightness sufficient to cause flash-blindness or after-image effects.

Laser-beam sensitive flight zone (LSFZ)

5.2.5 The LSFZ is the airspace outside the LFFZ and LCFZ where the irradiance is not to exceed 100 $\mu\text{W/cm}^2$ unless some form of mitigation is applied. The level of brightness thus produced may begin to produce flash-blindness or after-image effects of short duration; however, this limit will provide protection from serious effects. The LSFZ need not necessarily be contiguous with the other flight zones.

Normal flight zone (NFZ)

5.2.6 The NFZ is any navigable airspace not defined as LFFZ, LCFZ or LSFZ. The NFZ must be protected from laser radiation capable of causing biological damage to the eye.

5.2.7 Figures 5-1 through 5-3 define the zones established to protect aircraft in navigable airspace. The dimensions indicated are given as guidance but have been found to protect safety well.

5.2.8 The amount of airspace affected by a laser operation varies with the laser systems output power, which is measured in watts or joules. The following maximum irradiance levels (MILs) can be used for evaluating laser activities in close proximity to an aerodrome:

a) LFFZ: MIL is equal to or less than 50 nW/cm^2;

b) LCFZ: MIL is equal to or less than 5 $\mu\text{W/cm}^2$;

c) LSFZ: MIL is equal to or less than 100 $\mu\text{W/cm}^2$; and

d) NFZ: MIL is equal to or less than the MPE for CW or pulsed lasers.

Note.— Items a), b) and c) refer to visible laser emissions only.

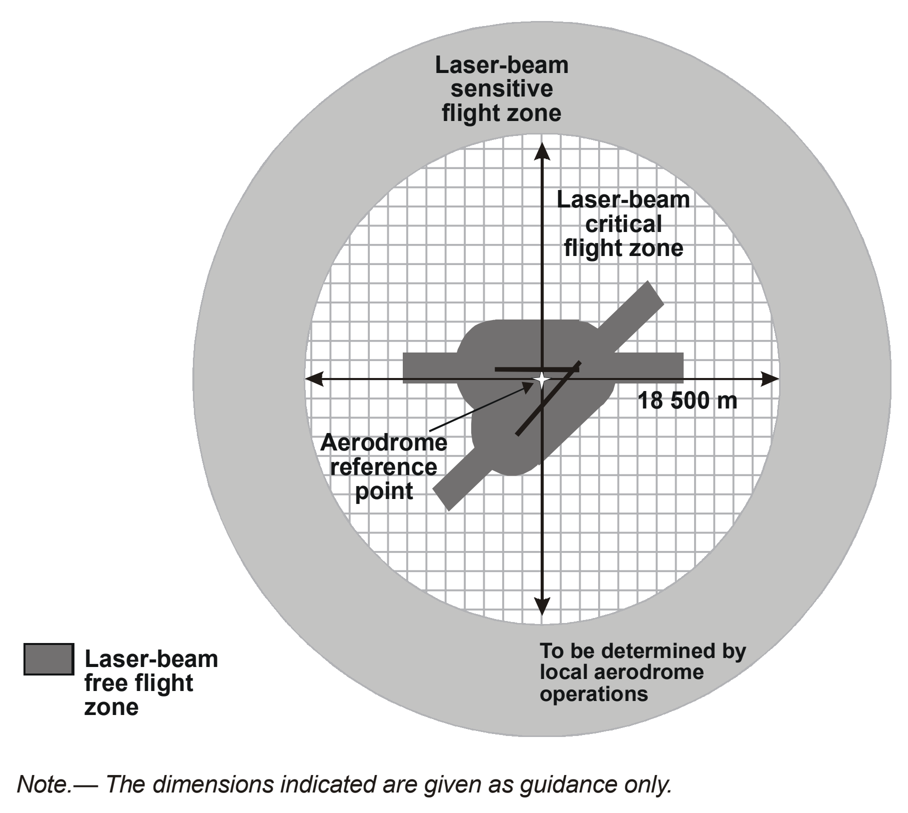

Figure 5-1. Protected flight zones

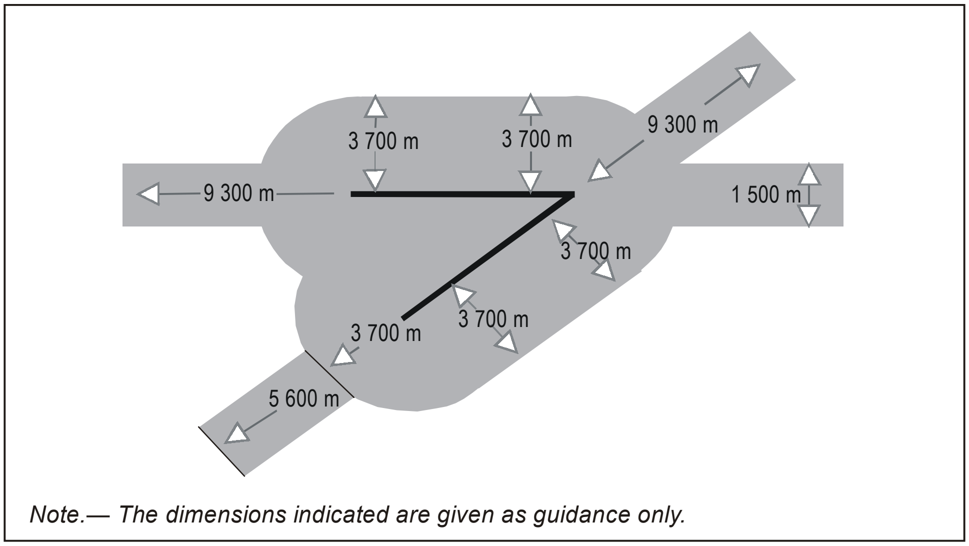

Figure 5-2. Multiple runway laser-beam free flight zone (LFFZ)

5.2.9 Protective means (mitigation) are required to protect pilots and other personnel when the visual interference level is exceeded. Redundant systems are advisable in locations noted for heavy air traffic.

5.3 AERONAUTICAL ASSESSMENT

5.3.1 The procedures outlined below may be used to evaluate the potential effect of laser activity on aircraft operations. The proponent should notify the competent authority in sufficient time to allow an aeronautical assessment to be completed.

5.3.2 A Contracting State may provide a submission form which, when completed, will provide sufficient information for an aeronautical assessment to be completed. A sample "Notice of Proposal to Conduct Outdoor Laser Operations" form and instructions are attached in Appendix A. The competent authority should:

a) determine the location of the laser activity and the laser MPE and NOHD;

b) plot the LFFZs, LCFZs and LSFZs at aerodromes;

c) establish additional LSFZs, if required, to protect locations of aviation activity that may also be affected, such as substantial helicopter traffic operating below 300 m (1 000 ft), VFR corridors, the airspace around high-energy lasers used to support astronomical observatories, active training areas, etc.;

d) consider the laser operations in relationship with the established zones. Use the MILs established by the competent authority when evaluating laser activities in proximity to an aerodrome;

e) review airspace and aircraft operations that may be affected by the proposal;

f) coordinate with local officials, e.g. aerodrome managers, air traffic managers, military representatives, local police organizations;

g) convene a local laser working group (LLWG) if the operations appear to be complex or controversial;

h) consider the proponent's proposed mitigation measures and any additional measures taken to

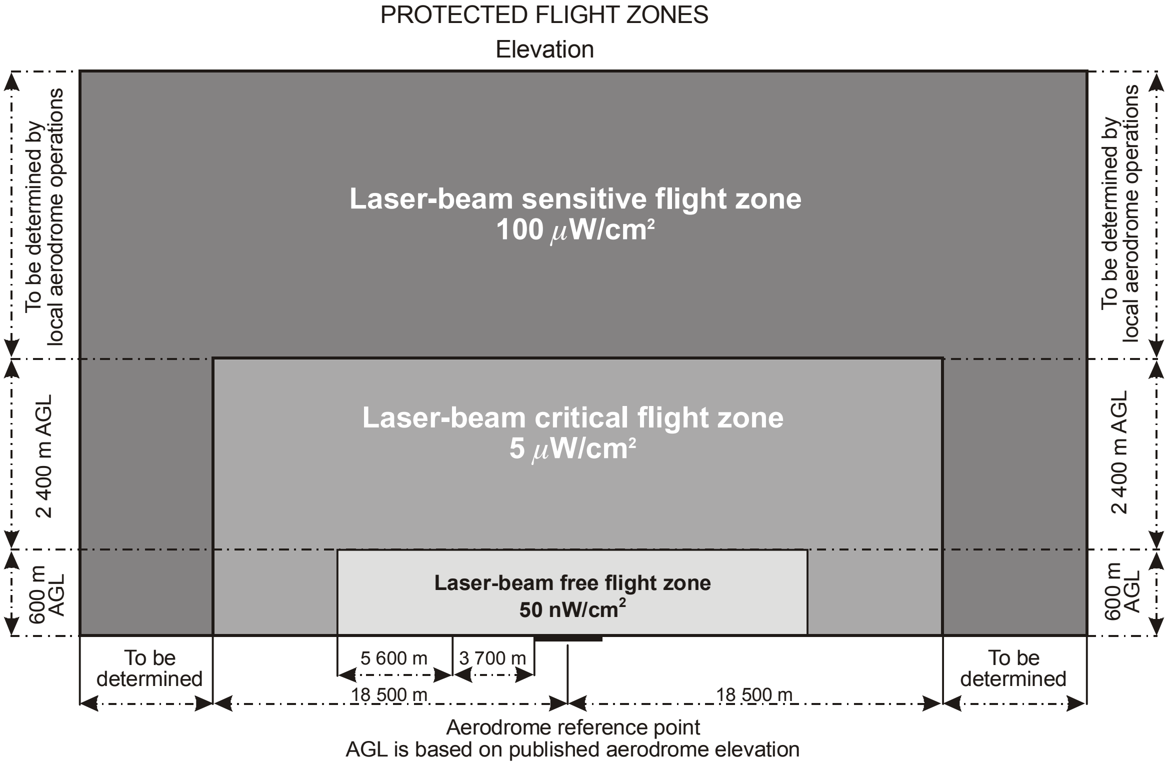

Figure 5-3. Protected flight zones with indication of maximum irradiance levels for visible laser beams

ensure that aircraft operators will not be exposed to laser emissions that have the potential to impair their performance of duties. Such measures include, but are not limited to, physical, procedural, manual and automated control measures;

i) compile a cumulative impact assessment on permanent or long-term laser operations effects on local operations;

j) assess the capability of the affected ATC facilities to provide real-time management of air traffic to ensure no cockpit illuminations by the laser beams;

k) coordinate with the proponent, identify objectionable effects and negotiate appropriate mitigation to protect aviation safety; and

l) communicate to the proponent and all participating authorities the completed aeronautical assessment. If the proposal is complex or controversial, the competent authority should document all pertinent information and disseminate copies as appropriate.

5.4 CONTROL MEASURES

Physical, procedural and automated control measures established to ensure that aircraft operations will not be exposed to levels of illumination greater than the respective MILs considered acceptable should meet one or more of the descriptions listed below:

a) ATC control measures:

   1) NOTAM;

   2) Voice advisory (e.g. automatic terminal information system (ATIS), pilot-controller communications);

   3) Airspace restrictions;

whereas the proponent must ensure that the operator control measures are in accordance with one or more of the following:

b) Operator control measures:

   1) The laser beam may be physically blocked (terminated beam) to prevent laser light from being directed into protected volumes of airspace.

   2) The laser beam divergence and output power or pulse energy emitted through the system aperture may be adjusted to meet appropriate exposure levels.

   3) Beams can be directed in a specific area. Directions should be specified by giving bearing in the azimuth scale 0–360 degrees and elevation in degrees ranging from 0–90 degrees, where 0 degrees is horizontal and 90 degrees is vertical. Both true and magnetic bearings should be given.

   4) Manual operation of a shutter or beam-termination system can be used in conjunction with airspace observers. Observers should be trained and able to see sufficient airspace surrounding beam paths to terminate the beam prior to illumination of aircraft.

   5) Scanning the laser beam may reduce the level of illumination; however, it may increase the potential risk of illumination.

   6) Automated systems designed to detect aircraft and automatically terminate or redirect the beam or shutter the system may be used. The proponent should include detailed information that describes the operation of the automated system, its effectiveness and how it can be tested for full functionality prior to each use.

5.5 DETERMINATIONS

5.5.1 If the proponent's notification satisfies the requirements of the aeronautical assessment, the competent authority should issue, as a minimum, the following:

a) a statement advising the proponent that his notification satisfies the requirements of the competent authority and is approved subject to conditions or limitations (such as aircraft spotter requirements), as applicable;

b) a statement to the proponent that changes should not be incorporated into the proposed activity once permission has been granted, unless approved by the competent authority in writing;

c) a statement that the proponent notify the appropriate authority or their designated representative of any changes to show start/stop times or cancellation 24 hours in advance;

d) a statement that approval does not relieve the sponsor or operator of responsibility for complying with the mitigation agreed upon, the laws, ordinances or regulations of any relevant authority; and

e) NOTAM. (See examples in 5.5.4.)

5.5.2 If the proponent's notification does not satisfy the requirements of the aeronautical assessment, the competent authority should issue a statement advising the proponent that an objection is being issued. Specifically, it should indicate why the proponent does not satisfy safety requirements, and that new data or other appropriate information may be submitted for consideration. If negotiations to resolve any objectionable effects have not been successful, the objection should stand.

5.5.3 To enhance aviation safety, a NOTAM should be prepared alerting pilots of known laser activities. It is important to emphasize the hazardous effects and other related phenomena that may be caused by laser beams.

5.5.4 The competent authority should provide information for the publication of a NOTAM* as shown in the following sample formats. Laser activities that last more than 180 days should be considered permanent (e.g. annual ongoing activities). Information pertaining to such activities should be published in applicable aviation publications.

Sample publication format of temporary laser activity

LASER LIGHT DEMONSTRATION WILL BE CONDUCTED AT (place, city, province or state), (NAVAID ID, type, radial) RADIAL (dist.) NAUTICAL MILES, (lat./long.). BEAMS FROM SITE PROJECTING (direction) BETWEEN RADIALS (xxx-xxx), ON (dates), BETWEEN (time/UTC). LASER LIGHT BEAMS MAY BE INJURIOUS TO PILOTS/AIRCREW AND PASSENGERS EYES WITHIN (nominal ocular hazard distance) VERTICALLY AND/OR (nominal ocular hazard distance) LATERALLY OF THE LIGHT SOURCE. FLASH-BLINDNESS OR COCKPIT ILLUMINATION MAY OCCUR BEYOND THESE DISTANCES.

LASER RESEARCH WILL BE CONDUCTED AT (place, city, province or state, lat./long.), ON/FROM (dates), BETWEEN (times/UTC), AT AN ANGLE OF (degree), FROM THE SURFACE, PROJECTING UP TO (height) MSL AVOID AIRBORNE HAZARD BY (NM). THIS LASER LIGHT BEAM MAY BE INJURIOUS TO PILOTS/AIRCREW AND PASSENGERS EYES.

AIRBORNE TO GROUND LASER ACTIVITY WILL BE CONDUCTED ON (dates), BETWEEN (lat./long., altitude) AND BELOW. AVOID AIRBORNE HAZARD BY (NM). THIS LASER BEAM MAY BE INJURIOUS TO PILOTS/AIRCREW AND PASSENGERS EYES.

AIRBORNE LASER ACTIVITY WILL BE CONDUCTED ON/FROM (dates), AT/FROM (times/ UTC), BETWEEN (NAVAID ID, type, radial) RADIAL (dist.) NAUTICAL MILES, (lat./long.), AND (NAVAID ID, type, radial) RADIAL (dist.) NAUTICAL MILES, (lat./ long.), BETWEEN (altitude) MSL AND (altitude) MSL (or the surface). AVOID AIRBORNE HAZARD BY (NM). THE LASER LIGHT BEAM MAY BE INJURIOUS TO PILOTS/AIRCREW AND PASSENGERS.

Sample publication format of a permanent laser site

(place, city, province or state).

UNTIL FURTHER NOTICE A LASER LIGHT DEMONSTRATION WILL BE CONDUCTED NIGHTLY BETWEEN SUNDOWN AND DAWN AT THE (place, city, province or state) (NAVAID ID, type radial) RADIAL AT LAT./LONG. RANDOM BEAMS ILLUMINATING (directions indicated) QUADRANTS. THE BEAM MAY BE INJURIOUS TO EYES IF VIEWED WITHIN (NOHD dist.) VERTICALLY AND (NOHD dist.) LATERALLY OF THE LIGHT SOURCE. FLASH-BLINDNESS OR COCKPIT ILLUMINATION MAY OCCUR BEYOND THESE DISTANCES.

NOTAMs concerning temporary laser activity at Harboøre in København FIR (issued by the Civil Aviation Administration, Denmark)

XXXXX/XX NOTAMN
Q) EKDK/QWXXX/V/B/W/000/103/
A) EKDK B) 0006091900 C) 0006102200
D) DAILY 1900-2200
E) TEMPO NAV WRNG. LASER LIGHTSHOW WILL TAKE PLACE AT HARBOOERE PSN 563713N 0081130E. THE LASERBEAM MAY CAUSE BLINDNESS IF VIEWED WITHIN A VERTICAL DISTANCE OF 500FT AND HORIZONTAL DISTANCE

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* More information about the NOTAM format can be found in Annex 15.

OF 0.5NM OF THE LIGHT SOURCE. FLASHBLINDNESS OR COCKPIT ILLUMINATION MAY OCCUR WITHIN A VERTICAL DISTANCE OF 8300FT AND A HORIZONTAL DISTANCE OF 8NM
F) GND
G) 8300FT MSL

XXXXX/XX NOTAMN
Q) EKDK/QWXXX/V/B/W/000/103/
A) EKDK B) 0006091900 C) 0006102200
D) DAILY 1900-2200
E) TEMPO NAV WRNG. AIRBORNE TO GROUND LASER ACTIVITY WILL TAKE PLACE WITHIN A 10NM RADIUS OF HARBOOERE PSN 563713N 0081130E. THE LASERBEAM WILL OPERATE FROM 10,000FT MSL DOWNWARD AND MAY CAUSE BLINDNESS IF VIEWED WITHIN A VERTICAL DISTANCE OF 5000FT AND HORIZONTAL DISTANCE OF 2.5NM OF THE LIGHT SOURCE. FLASHBLINDNESS OR COCKPIT ILLUMINATION MAY OCCUR WITHIN A VERTICAL DISTANCE OF 5300FT AND A HORIZONTAL DISTANCE OF 8NM
F) GND
G) 8300FT MSL

5.6 INCIDENT-REPORTING REQUIREMENTS

Contracting States may wish to establish an incident-reporting system to provide a means of monitoring unauthorized use of lasers in airspace. Rapid notification of an incident will assist in the investigation and possible enforcement action against the offender. Sample incident report formats are found in Appendix B.

Chapter 6

DOCUMENTATION OF INCIDENTS AFTER SUSPECTED LASER BEAM ILLUMINATION

6.1 BACKGROUND

Laser beams with the potential to compromise flight safety may be visible or invisible. Laser beams may cause damage to the retina, especially at higher levels of exposure. The bright light from visible laser beams can cause glare, after-images and flash-blindness. Exposure to invisible laser beams may result in pain, vision loss or skin burns, but they are not normally associated with glare and flash-blindness. Damage to the tissue of the eye's cornea and conjunctiva requires a higher exposure level than that required to cause damage to the retina. This is due, in part, to the eye's natural focusing mechanism that can increase the energy per unit area delivered to the retina. Besides glare, flash-blindness and after-images, other symptoms of laser beam light exposure may include pain, eye fatigue, tearing, eye irritation and headache. Laser beam light can and has interfered with safe and efficient performance of flight procedures by causing temporary distraction, disorientation and visual incapacitation.

6.2 PROCEDURES

Whenever an unexpected illumination by an unknown source occurs, a laser incident should be suspected and reported. It is recommended that all suspected laser beam incidents be reported to the national aviation medicine and flight safety authorities. In general, individuals should, without delay, consult an optometrist, ophthalmologist or designated medical examiner whenever they have experienced a suspected laser beam exposure. Those with persistent symptoms or abnormal clinical findings may require referral to an ophthalmologist for further medical evaluation and treatment.

Note.— Chapter 7, entitled "Medical Examination Following Suspected Laser Beam Illumination", provides guidance for evaluating aircrew and other aviation personnel who may have been injured or incapacitated by a laser beam illumination.

6.3 DOCUMENTATION

6.3.1 Documentation of a suspected laser beam illumination incident has three important functions. First, it provides information on the effectiveness of current policies and procedures used to protect the navigable airspace against hazardous laser beams. Second, it provides a protocol for medical assessment. Third, it provides updates on new devices or sources of hazardous laser beams that may affect visual performance.

6.3.2 Guidance on how to document suspected laser beam illumination incidents is provided in Appendix B. The two forms (Suspected Laser Beam Incident Report and Suspected Laser Beam Exposure Questionnaire) may be used for investigation of illumination incidents. The report should be completed by the illuminated persons as soon as possible after the incident. The questionnaire may be used by an official of the competent authority during the initial interview.

Chapter 7

MEDICAL EXAMINATION FOLLOWING SUSPECTED LASER BEAM ILLUMINATION

7.1 GENERAL

7.1.1 All cases of suspected laser beam exposure should be promptly reported to the medical section of the competent authority. In cases of suspected laser beam exposure, two forms should be used:

a) Suspected Laser Beam Incident Report. This form is to be completed by the persons illuminated.

b) Suspected Laser Beam Exposure Questionnaire. This form may be used by the competent authority during the initial interview of an exposed person.

Note.— Samples of these two forms can be found in Appendix B.

7.1.2 The following information provides guidance for the medical examination and evaluation of those who may have been exposed to a laser beam.

7.2 PROCEDURE

7.2.1 A basic ocular examination should be performed on any person suspected of having been exposed to a laser beam to verify that no permanent damage has occurred and to confirm normal ocular health. An optometrist, ophthalmologist or a designated medical examiner may complete the basic examination.

Basic ocular examination

- History (review Suspected Laser Beam Exposure Questionnaire, if available)
- External examination
- Best corrected visual acuity (near and far) in each eye separately
- Amsler grid for each eye separately (see Appendix C)
- Stereopsis (specify test used)
- Colour-vision testing with pseudoisochromatic plates of each eye separately
- Confrontation visual fields of each eye separately
- Nondilated funduscopy on each eye separately

7.2.2 If the results of this examination are normal and the person does not have persistent visual complaints, further examinations are not necessary.

7.2.3 If the results of the basic examination are abnormal or questionable, an intermediate ocular examination to assess the condition of the person's eyes should be performed. An optometrist or an ophthalmologist may complete the intermediate examination.

Intermediate ocular examination

- Pupils of each eye separately
- Slit lamp of each eye separately
- Automated visual fields of each eye separately
- Motility (ductions and versions; cover test)
- Dilated funduscopy on each eye separately

7.2.4 If the results of this examination are normal and the person does not have persistent visual complaints, further examinations are not necessary.

7.2.5 If the results of the intermediate ocular examination are abnormal or if visual complaints persist, the person should be referred to an ophthalmologist (preferably a retinal specialist), as advised by the aviation medicine section of the competent authority. This ophthalmologist should conduct an advanced ocular examination.

Advanced ocular examination

- Retinal photography
- Comprehensive testing of colour vision (to include blue/yellow tests)
- Electrodiagnostic tests, as needed
- Scanning laser ophthalmoscopy, as needed
- Fluorescein angiography, as needed

Appendix A

NOTICE OF PROPOSAL TO CONDUCT OUTDOOR LASER OPERATION(S)

Note.— The sample form below was adapted by ICAO and reproduced with the permission of the Federal Aviation Administration.

NOTICE OF PROPOSAL TO CONDUCT OUTDOOR LASER OPERATION(S)

To: *(Competent Authority)*	From: *(Applicant)*	Report date:

1. GENERAL INFORMATION

Event or facility		
Customer	Site address	
GEOGRAPHIC LOCATION		
Latitude ________ *deg (°)* ________ *min (′)*________ *sec (″)*	Longitude ________ *deg (°)* ________ *min (′)*________ *sec (″)*	
Ground elevation at site *(above Mean Sea Level)*	Laser elevation above ground *(if on buildings, etc.)*	Determined by: ☐ GPS ☐ Map ☐ Other *(specify)*
DATE(S) AND TIME(S) OF LASER OPERATION		
Testing and alignment	Operation	

2. BRIEF DESCRIPTION OF OPERATION

3. ON-SITE OPERATION INFORMATION

Operator(s)	
On-site phone #1	On-site phone #2
BRIEF DESCRIPTION OF CONTROL MEASURES	

4. ATTACHMENTS

Number of laser configurations *[Fill out one copy of page 2 of this notice (“Laser Configuration”) for each configuration.]*
List any additional attachments needed to evaluate this operation *(could include maps, diagrams, and details of control measures).*

5. DESIGNATED CONTACT PERSON *(if further information is needed)*

Name	Position	
Phone	Fax	E-mail
STATEMENT OF ACCURACY To the best of my knowledge, the information provided in this Notice of Proposal is accurate and correct.		
Name *(if different from contact person)*	Position	
Signature	Date	

LASER CONFIGURATION

Fill out one copy of this form for each laser or laser configuration used at the Outdoor Laser Operations site.

1. CONFIGURATION INFORMATION

Name of event/facility	This page is configuration number _____ of _____	Report date
Brief description of configuration		

2. BEAM CHARACTERISTICS AND CALCULATIONS *(check one Mode of Operation only, and fill in only that column)*

Mode of Operation	☐ Single pulse	☐ Continuous wave	☐ Repetitively pulsed
Laser Type *(lasing medium)*			
Power *Watts (W)*	*(not applicable)*	*Maximum power*	*Average power*
Pulse Energy *Joules (J)*		*(not applicable)*	
Pulse Width *Seconds (s)*		*(not applicable)*	
Pulse Repetition Frequency *Hertz (Hz)*	*(not applicable)*	*(not applicable)*	
Beam Diameter @ 1/e points *Centimetres (cm) (not mm)*			
Beam Divergence 1/e @ full angle *Milliradians (mrad)*			
Wavelength(s) *Nanometres (nm)*			
MAXIMUM PERMISSIBLE EXPOSURE (MPE) CALCULATIONS *(will be used to calculate NOHD)*			
MPE *W/cm^2*	(not applicable)		
MPE per pulse *J/cm^2*		(not applicable)	
VISUAL EFFECT CALCULATIONS *(will be used only for visible lasers to calculate SZED, CZED and LFED)*			
Pre-corrected Power (PCP) *Watts (W)*	Pulse Energy (J)*4	Maximum Power (from above)	Average Power OR Pulse Energy (J) x PRF (Hz)
Visual Correction Factor (VCF) *Enter "1.0" or use Table 5*			
Visually Corrected Power *PCP x VCF*			

3. BEAM DIRECTION(S)

Azimuth *(degrees)* ☐ True ☐ Magnetic	Magnetic variation *(degrees)*
Minimum elevation angle *(degrees, where horizontal = 0°)*	Maximum elevation angle *(degrees)*

4. DISTANCES CALCULATED FROM ABOVE DATA

(Fill in all three columns for NOHD. If a visible laser, fill in all three columns for SZED, CZED, and LFED.)

	Slant range *(ft)*	Horizontal distance *(ft)*	Vertical distance *(ft)*
NOMINAL OCULAR HAZARD DISTANCE			
NOHD *(based on MPE)*			
VISUAL EFFECT DISTANCES If the laser has no wavelengths in the visible range (400–700 nm), enter "N/A (non-visible laser)" in all blocks below. For visible lasers, if the calculated visual effect distance is less (shorter distance) than the NOHD, you must enter "Less than NOHD".			
SZED *(for 100 μW/cm^2 level)*			
CZED *(for 5 μW/cm^2 level)*			
LFED *(for 50 nW/cm^2 level)*			

5. CALCULATION METHOD

☐ Commercial software (print product name) ☐ Other [describe method (spreadsheet, calculator, etc.)]

INSTRUCTIONS FOR FILLING OUT NOTICE OF PROPOSAL FORM (page 1)

The information in this form will be used by the Competent Authority to perform an aeronautical study to evaluate the safety of a proposed laser operation. Provide all information that the Authority may need to perform the study. If additional details are necessary, list these in the "Attachments" section of this form.

To: Enter the name, address, phone and fax of the Competent Authority's Office responsible for the area which includes the laser operation site. (A list of Offices is available at the end of these instructions.)

From: Enter the name, address, phone, fax, and E-mail of the applicant. This is the party primarily responsible for the laser safety of this operation. In some cases, the applicant is a manufacturer or a governmental agency, and the laser is located at a different site. In such a case, list the applicant here; the site location is filled in elsewhere in the form.

Report date: This is the date the report is prepared or sent to the Authority. It is *not* the date of the laser operation.

1. GENERAL INFORMATION

Event or facility: Enter the event name (for temporary shows) or the facility name (for permanent installations).

Customer: If the laser user is different from the applicant, fill in the "Customer" section; if not, enter "Same as applicant".

Site address: Street address, city, province or state.

GEOGRAPHIC LOCATION

Latitude and longitude: Be sure that latitude and longitude are specified in degrees, minutes and seconds. Some maps or devices may give this information in "Degrees.Decimal" form; this must be converted into degrees, minutes and seconds.

Ground elevation at site: This is the elevation in feet above Mean Sea Level, at the show site. It can be found on a topographic map or other resource.

Laser elevation above ground: If the laser is on a building or other elevated structure, enter the laser's height in feet above the ground.

Note.— For lasers on aircraft or spacecraft, attach additional information on the flight locations and altitudes.

DATE(S) AND TIME(S) OF LASER OPERATION

Testing and alignment: Enter the date(s) and time(s) during which testing and alignment procedures will take place.

Operation: Enter the date(s) and time(s) during which laser light will enter airspace.

2. BRIEF DESCRIPTION OF OPERATION

This should be a general overview. Specific laser configurations at the operation are described in detail using the Laser Configuration form on page 2. If necessary, attach additional pages.

3. ON-SITE OPERATION INFORMATION

Operator(s): List names and/or titles of operators.

On-site phones: There should be at least one working, direct phone link to the operator, or equivalent way of quickly reaching the operator (e.g. phoning to a central station that reaches the operator via radio). Two telephone numbers are listed on the form, so one can be used as an alternate or backup.

BRIEF DESCRIPTION OF CONTROL MEASURES

Describe the control measure(s) used to protect airspace; for example, termination on a building (where the beam path is not accessible by aircraft including helicopters), use of observers, use of radar and imaging equipment, physical methods of limiting the beam path, etc. The more that the operation relies on the control measures to ensure safety, the more detailed the description should be.

4. ATTACHMENTS

Number of laser configurations: List how many "Laser Configurations" you are submitting with this proposal. If a particular set-up operates with more than one laser, with different beam characteristics (power settings, pulse modes, divergence, etc.) or has multiple output devices (example: projector heads), then each should be analysed as a separate Laser Configuration using the form on page 2.

List additional attachments: You may need to add attachments such as maps, diagrams and details of control measures. Include whatever materials you feel are necessary to assist the Authority in sufficiently evaluating your proposal.

5. DESIGNATED CONTACT PERSON

This is the person whom the Authority will contact if additional information is needed. This should be the person with the most knowledge about laser safety at this operation. However, it could also be a central contact person who interfaces between the Authority and the laser operation personnel. The Designated Contact Person *must* work for or represent the applicant listed in the "From:" area at the top of the form.

STATEMENT OF ACCURACY

The Designated Contact Person should sign the form. However, in some cases the responsibility for the accuracy of the information may rest with another person, such as a Laser Safety Officer who is not acting as the contact. Therefore, the person who has the authority to bind the applicant must sign the form.

INSTRUCTIONS FOR FILLING OUT LASER CONFIGURATION FORM (page 2)

A single outdoor operation may have a number of lasers or "laser configurations" — power settings, pulse modes, divergence, etc. On the Notice of Proposal form (page 1), in the first row of the Attachments table, enter the number of different laser configurations for the outdoor operation. Then, fill out one Laser Configuration form (page 2) for each different configuration to be analysed.

Alternative analysis: This form and accompanying tables must cover a wide variety of laser configurations. They are necessarily simplified, and they make conservative assumptions. Some laser configurations may warrant a more complex analysis. Any such alternative analysis should be based on established methods. *Both the methods and the calculations must be documented*. (See ICAO Doc 9815 for further information.)

1. CONFIGURATION INFORMATION

Brief description of configuration: Describe the beam projecting or directing system. Include description of site layout. Attach additional information if more space is required.

2. BEAM CHARACTERISTICS AND CALCULATIONS

This section requires data about the laser beam's characteristics. The data can be obtained from direct measurement, manufacturer specifications or specialized instruments. You can also derive data by making reasonable, conservative assumptions (for example, that a certain value makes the beam more hazardous than it would be in reality). All data should err on the side of safety. *In borderline situations where data accuracy is crucial to compliance, provide additional data on measurement techniques, data sources and assumptions.*

Mode of operation: Determine the mode of operation for this configuration: Single Pulse, Continuous Wave, or Repetitively Pulsed. Put a check in the appropriate column. Fill out *only* that column for the remainder of this Beam Characteristics and Calculations section.

- **Single Pulse:** Lasers that produce a single pulse of energy with a pulse width <0.25 seconds or a pulse repetition frequency <1 Hz.
- **Continuous Wave:** A laser that produces a continuous (non-pulsed) output for a period ≥0.25 seconds.
- **Repetitively Pulsed:** Lasers that produce recurring pulses of energy at a frequency of 1 Hz or faster.

Note on "repetitively pulsed" vs. scanning: "Repetitively pulsed" refers to lasers that naturally emit repetitive pulses, such as Q-switched lasers. The form and tables are not intended for analysing pulses due to scanning the beam over a viewer or aircraft (examples: graphics or beam patterns used in laser displays; scanned patterns used for LIDAR). Pulses resulting from scanning are often extremely variable in pulse width and duration. Therefore, for a conservative analysis, assume the beam is static (non-scanned). *Should you rely on scanning to be in compliance, you must 1) provide a more comprehensive analysis, documenting your methods and calculations, and 2) document and use scan-failure protection devices.*

Laser Type: Enter the lasing medium, for example, "Argon", "Nd:YAG", "Copper-vapour", "CO_2", etc.

Power: If a continuous wave laser (Column 2), fill in the power in watts. If a repetitively pulsed laser (Column 3), fill in the average power in watts [energy per pulse (J) × pulse repetition frequency (Hz)]. For both types of power, this is the maximum power during the operation that enters airspace.

For simplicity and safety you can enter a higher value, the maximum power of the laser; this ignores any additional losses in optical components in the beam path, before the beam enters airspace.

Pulse Energy and Pulse Width: If a single pulse laser (Column 1) or repetitively pulsed laser (Column 3), fill in the pulse energy in joules and the pulse width in seconds. This is the maximum power that enters airspace. For simplicity and safety you can enter a higher value, the maximum pulse energy of the laser; this ignores any additional losses in optical components in the beam path, before the beam enters airspace.

Beam Diameter: Provide the beam diameter using the 1/e peak-irradiance points.

Note.— Diameter is often expressed in millimetres; however, in this form you must enter the diameter in centimetres.

Beam Divergence: The beam divergence is the full angle given at the 1/e points. If you know the diameter or divergence measured at the $1/e^2$ points instead, multiply by 0.707 to convert to 1/e diameter or divergence.

Note.— Diameter and divergence measurements can be complex. You can use simplifying assumptions for safety. It is safer to assume the beam divergence is smaller than it really is.

For example, as a beam travels from the laser through a laser show projector, the divergence generally increases. To be conservative (safer), use the smaller divergence of the beam at the laser, before it goes through the projector. This will assume the beam is tighter (and thus more hazardous) than it really is.

Wavelength(s): Enter the wavelengths of laser light that enter airspace.

If the laser emits multiple wavelengths, each wavelength will need to be analysed separately to find their MPEs and NOHDs. In addition, for lasers emitting visible wavelengths, each wavelength can be analysed separately to find the Visual Effect Distances (SZED, CZED, and LFED corresponding to LSFZ, LCFZ, and LFFZ). This process is described in more detail in the Visual Effect Distances instructions below.

In all cases of multiple-wavelength lasers, you must document your methods and calculations. If you do not analyse all wavelengths in full, then you must explicitly state your simplifying, conservative assumptions.

MAXIMUM PERMISSIBLE EXPOSURE CALCUATIONS

MPE and MPE per pulse: Provide the Maximum Permissible Exposure (MPE) calculation results in the applicable block. This will be used later to determine the Nominal Ocular Hazard Distance (NOHD).

The easiest way to find the MPE is to use Tables 1 to 4 as described immediately below. These tables provide a simple, conservative method. *If you require less conservative levels, use the American National Standards Institute (ANSI) Z136 series of standards or other established methods. Both the methods and calculations must be documented.*

- **Single Pulse (Column 1):** Use Table 1 to find the MPE. Fill in the “MPE per pulse” block in the Single Pulse column.
- **Continuous Wave (Column 2):** Use Table 2 to find the MPE. Fill in the “MPE” block in the Continuous Wave column.
- **Repetitively Pulsed (Column 3):** Lasers that produce recurring pulses of energy can produce an additional hazard above that of a single pulse or continuous wave laser. The MPE is adjusted for repetitively pulsed lasers based on its pulse repetition frequency. The adjusted MPE is designated as MPE_{PRF}. The MPE_{PRF} can be determined using either the per-pulse energy or the average power. This document provides a simplified method for calculating the MPE_{PRF} for average power with wavelengths in the visible and infrared region. (ANSI Z136 series can provide a less conservative value in some cases.) Although designated MPE_{PRF}, the values should be placed in either the “MPE” or “MPE per pulse” blocks of the repetitively pulsed column. Following are the simplified methods for determining the MPE_{PRF} for:

  1. Ultraviolet wavelengths: Reference the American National Standards Institute ANSI Z136 series.
  2. Visible wavelengths: Use Table 3 to determine the MPE_{PRF}. Table 3 results have already applied the correction factor to the CW MPE. Fill in the “MPE” block in the Repetitively Pulsed column.
  3. Infrared wavelengths:
     a) Use Table 2 to find the CW MPE.
     b) Use Table 4 to find the infrared pulse repetition correction factor.
     c) Multiply the CW MPE times the infrared pulse repetition correction factor to give the MPE_{PRF}. Fill in the “MPE” block in the Repetitively Pulsed column.

Note for Repetitively Pulsed lasers: The simplified methods of Tables 2 to 4 use the Average Power to determine the MPE in W/cm^2. It is possible with other methods to use the Pulse Energy to determine the MPE per pulse in J/cm^2. Only one of the two MPEs is required.

VISUAL EFFECT CALCUATIONS (for visible lasers only)

If the laser has no wavelengths in the visible range (400–700 nm), enter “N/A — non-visible laser” in these blocks and go to the next section (Beam Directions).

For visible lasers, the Authority is concerned about beams that are eye-safe (below the MPE) but are bright enough to distract aircrews. In accordance with ICAO Recommendations (see Annex 14, Volume I — *Aerodrome Design and Operations*, 5.3.1.2), the Authority has therefore established Laser-beam Sensitive, Laser-beam Critical and Laser-beam Free Flight Zones where aircraft should not be exposed to light above 100 μW/cm^2, 5 μW/cm^2, and 50 nW/cm^2, respectively. Because apparent brightness varies with wavelength — green is more visible than red or blue — a visual correction factor can be applied if desired. This has the effect of allowing more power for red and blue beams than for green beams. For any visible laser, you must submit Visual Effect Calculations.

Pre-Corrected Power: The PCP is the power before applying any visual correction factor. The method used to determine the PCP depends on which type of laser you are using:

- **Single Pulse (Column 1):** Multiply the Pulse Energy (J) by 4, and enter in the form. *Note.— This technique averages the pulse's energy over the 0.25 sec maximum pulse duration and is a conservative approximation of the visual effect of a pulse. If you use less conservative calculations, you must document your methods and calculations.*

- **Continuous Wave (Column 2):** The Pre-Corrected Power is the same as the maximum power of the laser. Enter the same value you previously filled out in the Power (W) block of the form.

- **Repetitively Pulsed (Column 3):**

  A) If you filled out the Power (W) block on the form, enter that value.

  B) If you filled out the Pulse Energy (J) block on the form, multiply that value times the Pulse Repetition Frequency (Hz) to determine the average power.

Visual Correction Factor and Visually Corrected Power: The VCF takes into account the beam's apparent brightness, which varies depending on wavelength. Once you find the VCF, you can then determine the VCP. You have a choice of methods, depending on how precise you want to be:

1) **For the simplest, most conservative analysis of a single- or multiple-wavelength beam:** Assume there is no correction factor at all — the laser is at maximum apparent brightness (VCF of 1.0). In the Visual Correction Factor block of the form, enter "1.0 (assumed)" for the Visual Correction Factor. In the Visually Corrected Power block, enter the same value you filled out for the Pre-Corrected Power.

2) **For a single-wavelength beam:** To find the Visual Correction Factor, use Table 5. To find the Visually Corrected Power, multiply the Visual Correction Factor by the Pre-Corrected Power. (An example calculation is provided at Table 5, example 1.)

3) **For a beam with multiple wavelengths,** choose one method:

   A) Make a simplifying, conservative assumption. Use Table 5 to determine which wavelength has the largest Visual Correction Factor (is the most visible). Enter this in the Visual Correction Factor block of the form. To find the Visually Corrected Power, multiply this Visual Correction Factor by the Pre-Corrected Power of the laser (all wavelengths). *Note.— You must attach data and calculations showing how you arrived at the Visually Corrected Power.*

   B) Analyse each wavelength separately, then sum them. First, determine the Pre-Corrected Power for each wavelength. Next, use Table 5 to find the Visual Correction Factor for each wavelength. Multiply each wavelength's Pre-Corrected Power by its Visual Correction Factor, to find the Visually Corrected Power (VCP) for that wavelength. Add all the VCPs together to determine the total VCP. Enter the total VCP in the "Visually Corrected Power" block of the form. (An example calculation is provided in Table 5, example 2.) *Note.— You must attach data and calculations showing how you arrived at the Visually Corrected Power.*

3. BEAM DIRECTIONS

Provide the pointing directions of the beam projections for this configuration.

Azimuth: If the beam is moved horizontally during the operation, enter the movement range under "Azimuth"; for example, "20 to 50 degrees". Make sure you give the range going clockwise; otherwise your data will be interpreted as directing the beam everywhere but where you intend. Specify if azimuth is in true or magnetic readings.

Magnetic Variation: Provide the magnetic variation for the location if this is known (this *must* be done if you mark the "Magnetic" check box or if you are using a compass as part of your control measures).

For some configurations, additional information about the beam direction may be needed. For example: lasers that are very widely separated at the Geographic Location listed on page 1, or a laser used on an aircraft or spacecraft which is moving and/or shoots downwards. If this additional information is useful for the Authority to evaluate the proposal, then attach the information to this form.

4. DISTANCES CALCULATED FROM ABOVE DATA

There are four distances that are important in evaluating the safety of outdoor operations. Here are brief definitions:

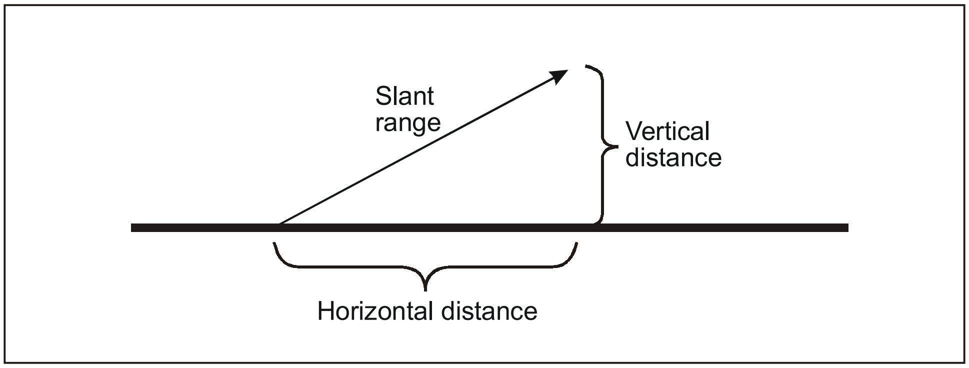
- **Nominal Ocular Hazard Distance (NOHD):** The beam is an eye hazard (is above the MPE), from the laser source to this distance.

- **Sensitive Zone Exposure Distance (SZED):** The beam is bright enough to cause temporary vision impairment, from the source to this distance. Beyond this distance, the beam is 100 $\mu W/cm^2$ or less.

- **Critical Zone Exposure Distance (CZED):** The beam is bright enough to cause a distraction interfering with critical task performance, from the source to this distance. Beyond this distance, the beam is 5 $\mu W/cm^2$ or less.

- **Laser-Free Exposure Distance (LFED):** Beyond this distance, the beam is 50 nW/cm^2 or less — dim enough that it is not expected to cause a distraction.

For each of these four distances, it is important to know the distance directly along the beam (the Slant Range) as well as the ground covered (the Horizontal Distance) and the altitude (the Vertical Distance). The diagram shows these three distances.



NOMINAL OCULAR HAZARD DISTANCE

NOHD Slant Range: Use Equation 6.1 for Single Pulse, or for Repetitively Pulsed if you calculated the Pulse Energy and $\mathrm{MPE}_{\mathrm{PRF}}$. Use Equation 6.2 for Continuous Wave, or for Repetitively Pulsed if you calculated the Average Power and MPE.

Equation 6.1 $$\mathrm{SR}_{\mathrm{NOHD}} = \sqrt{\frac{1366 \times Q}{\varphi^2 \times \mathrm{MPE}_H}}$$

Where:
$\mathrm{SR}_{\mathrm{NOHD}}$ = NOHD Slant Range in feet
Q = Pulse Energy (J)
φ = Beam Divergence (mrad)
MPE_H = MPE per pulse in J/cm^2
1366 = Conversion factor used to convert centimetres into feet and radians into milliradians

Equation 6.2 $$\mathrm{SR}_{\mathrm{NOHD}} = \sqrt{\frac{1366 \times \Phi}{\varphi^2 \times \mathrm{MPE}_E}}$$

Where:
$\mathrm{SR}_{\mathrm{NOHD}}$ = NOHD Slant Range in feet
φ = Beam Divergence (mrad)
Φ = Power (W)
MPE_E = MPE in W/cm^2
1366 = Conversion factor used to convert centimetres into feet and radians into milliradians

Example: A 40-watt CW laser has a beam divergence of 1.5 milliradians
Given:
φ = 1.5 mrad
Φ = 40 W
MPE_E = 0.00254 (2.54 mW/cm^2, from Table 2)
Solve Equation 6.2:

$$\mathrm{SR}_{\mathrm{NOHD}} = \sqrt{\frac{1366 \times 40}{1.5^2 \times 0.00254}} = \sqrt{\frac{54640}{0.005715}} = \sqrt{9560804} = 3092 \text{ ft}$$

NOHD Horizontal Distance is the distance along the ground. Note that the horizontal distance uses the *minimum* elevation angle. Calculate the horizontal distance using the equation:

$$\mathrm{HD} = \mathrm{SR}_{\mathrm{NOHD}} \times \cos(\text{Minimum Elevation Angle})$$

Where:
HD = Horizontal distance along the ground. The units are the same as for the Slant Range. If SR is in feet, then HD will also be in feet.
$\mathrm{SR}_{\mathrm{NOHD}}$ = NOHD Slant Range
Minimum Elevation Angle = Data from “Minimum elevation angle” block on form.

Example: The NOHD Slant Range is 1000 feet, and the beam is elevated at 30 degrees above horizontal. The Horizontal Distance along the ground is $1000 \times \cos(30)$, or 866 feet.

NOHD Vertical Distance is the distance above the ground. Note that the vertical distance uses the *maximum* elevation angle. Calculate the vertical distance using the equation:

$VD = SR_{NOHD} \times \sin(\text{Maximum Elevation Angle})$

Where:
VD = Vertical distance (altitude). The units are the same as for the Slant Range. If SR is in feet, then VD will also be in feet.
SR_{NOHD} = NOHD Slant Range
Maximum Elevation Angle = Maximum elevation angle of laser beam as provided on form.

Example: The NOHD Slant Range is 1000 feet, and the beam is elevated at 30 degrees above horizontal. The Vertical Distance (altitude) is 1000 × sin(30) or 500 feet.

VISUAL EFFECT DISTANCES

Fill in this section only if one or more of the laser wavelengths are visible (in the range 400–700 nm).

- If the laser is outside the visible range, enter "N/A — non-visible laser" in all SZED, CZED, and LFED blocks.
- If the laser is visible, then perform the SZED, CZED, and LFED calculations below.

Important: For some visible pulsed lasers, the SZED, CZED, and LFED may be calculated to be less (shorter distance) than the NOHD. If this is the case, for safety reasons do *not* enter the distance numbers in the applicable block. Instead, you *must* enter that the distance is "Less than NOHD". This is because in this case, the NOHD (eye-damage distance) would be the most important for calculating safety distances and airspace to be protected.

SZED Slant Range: Use the following equation:

Equation 6.3 $$SR_{SZED} = \frac{3700}{\varphi} \times \sqrt{\Phi_{VCP}}$$

Where:
SR_{SZED} = SZED Slant Range
φ = Beam Divergence (mrad)
Φ_{VCP} = Visually Corrected Power (from form)
3700 = Conversion factor used to convert centimetres into feet and radians into milliradians

SZED Horizontal Distance: Use the following equation. For details, see the NOHD Horizontal Distance instructions above.

$HD = SR_{SZED} \times \cos(\text{Minimum Elevation Angle})$

SZED Vertical Distance: Use the following equation. For details see the NOHD Vertical Distance instructions above.

$VD = SR_{SZED} \times \sin(\text{Maximum Elevation Angle})$

CZED Slant Range, Horizontal Distance and Vertical Distance: Multiply the SZED values above by 4.5. Example: If SZED Slant Range was 5 000 feet, HD was 866 feet, and VD was 500 feet, then the CZED SR is 22 500 feet, HD is 3 897 feet and VD is 2 250 feet.

LFED Slant Range, Horizontal Distance and Vertical Distance: Multiply the SZED values above by 45.

5. CALCULATION METHOD

List the method by which the calculations were performed.

Source note for equations: The equations above are derived from ANSI Z136.1 and have been re-expressed to a simpler form as follows: Beam divergence (φ) is entered in milliradians, making the first ANSI fraction 1000/φ instead of 1/φ. The radical (square root) sign is used instead of raising to a power of 0.5. Under the radical, the expression 4/π is reduced to 1.27, while beam diameter (a^2) is not used since its contribution to the overall slant range distance is negligible. ANSI results are in cm; to convert to feet, a conversion factor of 0.0328 is used (1 cm = 0.0328 ft). There are now two numeric constants, 1 000 (from the milliradians fraction) and 0.0328, which are multiplied into a single constant, 32.8, to give results in feet. For results in cm, use “1 000” as the constant; for results in metres, use “10”.

Note.— The assumption that a constant can be used to derive the CZED and LFED from the previously-calculated SZED is valid only if atmospheric attenuation is ignored. Should you be relying on atmospheric attentuation for a safety factor, you must use a more detailed analysis which independently calculates these three Visual Effect Distances.

Table 1. Single Pulse Selected Maximum Permissible Exposure (MPE) Limits

Wavelength (nm)	**Exposure Duration** (sec)	**MPE** (J/cm^2)
Ultraviolet		
180 to 400	10^{-9} to 10	Reference American National Institute Standard (ANSI) Z136 series
Visible		
400 to 700	$<10^{-9}$ 10^{-9} to 18×10^{-6} 18×10^{-6} to 10 0.25	Reference ANSI Z136 series 0.5×10^{-6} $1.8 \times t^{0.75} \times 10^{-3}$ 0.64×10^{-3}
Infrared		
700 to 1 050	$<10^{-9}$ 10^{-9} to 18×10^{-6} 18×10^{-6} to 10 0.25 10	Reference ANSI Z136 series $0.5 \times C_A \times 10^{-6}$ $1.8 \times C_A \times t^{0.75} \times 10^{-3}$ $0.64 \times C_A \times 10^{-3}$ $10 \times C_A \times 10^{-3}$
1 050 to 1 400	$<10^{-9}$ 10^{-9} to 50×10^{-6} 50×10^{-6} to 10 10	Reference ANSI Z136 series $5.0 \times C_C \times 10^{-6}$ $9 \times C_C \times t^{0.75} \times 10^{-3}$ $50 \times C_C \times 10^{-3}$
1 400 to 1 500	$<10^{-9}$ 10^{-9} to 10^{-3} 10^{-3} to 10 10	Reference ANSI Z136 series 0.1 $0.56 \times t^{0.25}$ 1.0
1 500 to 1 800	$<10^{-9}$ 10^{-9} to 10 10	Reference ANSI Z136 series 1.0 1.0
1 800 to 2 600	$<10^{-9}$ 10^{-9} to 10^{-3} 10^{-3} to 10 10	Reference ANSI Z136 series 0.1 $0.56 \times t^{0.25}$ 1.0
2 600 to 10 000	$<10^{-9}$ 10^{-9} to 10^{-7} 10^{-7} to 10 10	Reference ANSI Z136 series 10×10^{-3} $0.56 \times t^{0.25}$ 1.0

To find C_A:

For wavelength = 700 to 1050 nm, $C_A = 10^{0.002\,(\text{wavelength} - 700)}$

Example 1: Laser wavelength is 850 nm; $C_A = 10^{0.002(850 - 700)} = 10^{0.002*150} = 10^{0.3} = 1.995$

Example 2: Laser wavelength is 933 nm; $C_A = 10^{0.002(933 - 700)} = 10^{0.002*233} = 10^{0.466} = 2.924$

To find C_C:

For wavelength = 1050 to 1150 nm, $C_C = 1.0$

For wavelength = 1150 to 1200 nm, $C_C = 10^{0.018\,(\text{wavelength} - 1150)}$

For wavelength = 1200 to 1400 nm, $C_C = 8.0$

Example 3: Laser wavelength is 1175 nm; $C_C = 10^{0.018(1175 - 1150)} = 10^{0.018*25} = 10^{0.45} = 2.8$

To find t: “t” is the pulse duration in seconds.

Table 2. CW Mode Maximum Permissible Exposure (MPE) Limits

Values are for selected wavelengths for unintentional viewing.

Wavelength (nm)	**MPE** (W/cm^2)
Ultraviolet	
180 to 400	Reference American National Standards Institute ANSI Z136 series
Visible	
400 to 700	2.54×10^{-3}
Infrared	
700 to 1 050	$(10^{0.002(\text{wavelength} - 700)})(1.01 \times 10^{-3})$
1 050 to 1 150	5×10^{-3}
1 150 to 1 200	$(10^{0.018(\text{wavelength} - 1150)})(5 \times 10^{-3})$
1 200 to 1 400	4.0×10^{-2}
1 400 to 10 000	0.1

Example 1: Laser wavelength is visible; MPE = 0.00254 W/cm^2

Example 2: Laser wavelength is 850 nm; MPE = $(10^{0.002(850 - 700)})(1.01 \times 10^{-3}) = (10^{0.002*150})(0.00101) = (10^{0.3}) \times 0.00101 = 1.995 \times 0.00101 = 0.002$ W/cm^2

Example 3: Laser wavelength is 1175 nm; MPE = $(10^{0.018(1175 - 1150)})(5 \times 10^{-3}) = (10^{0.018*25})(0.005) = (10^{0.45}) \times 0.005 = 2.818 \times 0.005 = 0.01409$ W/cm^2

"Unintentional viewing": Exposure durations used for unintentional viewing of a CW exposure are 0.25 seconds or shorter for visible lasers, and 10 seconds or shorter for infrared lasers. (For visible light, it is assumed that within 0.25 seconds, the person will blink or will move to avoid the light. For infrared, it is assumed that the laser will not stay in the same spot for more than 10 seconds, due to normal body movement.)

Source: ANSI Z136.1 Table 5 for CW Exposure.

Table 3. Maximum Permissible Exposure — Pulse Repetition Frequency (MPE_{PRF}) Limits for Visible Lasers

For unintentional viewing of repetitively pulsed visible (400–700 nm) laser light with pulse width between 1 ns and 18 µs.

Pulse Repetition Frequency (Hz)	**MPE_{PRF}** (W/cm^2)
1	7.07×10^{-07}
2	1.19×10^{-06}
3	1.61×10^{-06}
4	2.00×10^{-06}
5	2.36×10^{-06}
6	2.71×10^{-06}
7	3.04×10^{-06}
8	3.36×10^{-06}
9	3.67×10^{-06}
10	3.98×10^{-06}
15	5.39×10^{-06}
20	6.69×10^{-06}
25	7.91×10^{-06}
30	9.06×10^{-06}
40	1.12×10^{-05}
50	1.33×10^{-05}
75	1.80×10^{-05}
100	2.24×10^{-05}
150	3.03×10^{-05}
200	3.76×10^{-05}
250	4.45×10^{-05}
500	7.48×10^{-05}
1 000	1.26×10^{-04}
1 500	1.70×10^{-04}
2 000	2.11×10^{-04}
2 500	2.50×10^{-04}
5 000	4.20×10^{-04}
10 000	7.07×10^{-04}
15 000	9.58×10^{-04}
20 000	1.19×10^{-03}
25 000	1.41×10^{-03}
30 000	1.61×10^{-03}
40 000	2.00×10^{-03}
50 000	2.36×10^{-03}
55 000	2.54×10^{-03}
100 000	2.54×10^{-03}

If the laser's pulse repetition frequency falls between two table entries, use the more conservative (smaller) value of the two resulting MPE_{PRF} values.

Note.— This table for MPE_{PRF} is based on repetitively pulsed lasers with a pulse width between 1 ns and 18 µs. These MPE_{PRF} numbers can be used to estimate larger pulse widths, and will provide a conservative (safer) result.

Not intended for scanning analysis: This table is intended for lasers that naturally emit repetitive pulses, such as Q-switched lasers. It is not intended for analysing "scanned" pulses, caused by moving the beam quickly over a viewer or aircraft. (Examples: graphics or beam patterns used in laser displays, or scanned patterns used for atmospheric analysis.) Pulses resulting from scanning are often extremely variable in pulse width and duration, and thus require a more stringent analysis.

Table 4. Correction Factors (MPE_{pulsed} / MPE_{cw}) for Repetitively Pulsed Infrared Lasers

Use to find MPE_{PRF} of repetitively pulsed infrared (700–1 400 nm) laser light with pulse width between 1 ns and 18 µs.

Pulse Repetition Frequency (Hz)	**Correction Factor** For wavelengths 700–1 050 nm	**Correction Factor** For wavelengths 1 050–1 400 nm
1	2.8×10^{-4}	5.5×10^{-4}
5	9.4×10^{-4}	1.8×10^{-3}
10	1.6×10^{-3}	3.1×10^{-3}
15	2.1×10^{-3}	4.2×10^{-3}
20	2.6×10^{-3}	5.2×10^{-3}
25	3.1×10^{-3}	6.2×10^{-3}
50	5.3×10^{-3}	1.0×10^{-2}
75	7.1×10^{-3}	1.4×10^{-2}
100	9.0×10^{-3}	1.7×10^{-2}
150	1.2×10^{-2}	2.4×10^{-2}
200	1.5×10^{-2}	2.9×10^{-2}
250	1.8×10^{-2}	3.5×10^{-2}
500	3.0×10^{-2}	5.9×10^{-2}
1 000	5.0×10^{-2}	1.0×10^{-1}
2 000	8.0×10^{-2}	1.7×10^{-1}
3 000	1.1×10^{-1}	2.3×10^{-1}
4 000	1.4×10^{-1}	2.8×10^{-1}
5 000	1.7×10^{-1}	3.3×10^{-1}
10 000	2.8×10^{-1}	5.6×10^{-1}
15 000	3.8×10^{-1}	7.5×10^{-1}
20 000	4.7×10^{-1}	9.3×10^{-1}
21 000	4.8×10^{-1}	9.7×10^{-1}
22 000	5.0×10^{-1}	1.00*
23 000	5.2×10^{-1}	1.00
24 000	5.4×10^{-1}	1.00
25 000	5.5×10^{-1}	1.00
30 000	6.3×10^{-1}	1.00
40 000	7.9×10^{-1}	1.00
50 000	9.3×10^{-1}	1.00
55 000	1.00*	1.00

*The MPE for lasers which operate at a PRF greater (faster) than 55 000 Hz for wavelengths 700–1 050 nm (or 22 000 Hz for wavelengths 1 050–1 400 nm) is the same as for continuous wave lasers, so the correction factor is 1.

To find the MPE for repetitively pulsed infrared lasers, multiply the CW Mode MPE by a correction factor from this table. If the laser's pulse repetition frequency falls between two table entries, use the more conservative (smaller) value of the two resulting correction factors.

Example: A laser operating at a pulse repetition frequency (PRF) of 12 000 Hz emits infrared light at 850 nm. First, go to Table 2 and find the CW Mode MPE for the 850 nm wavelength, which is 0.002 W/cm^2 (see example 2 from Table 2). Next, from the table above determine which of the right two columns should be used; in this case, the column labelled "For wavelength 700–1 050 nm". The laser's PRF of 12 000 Hz falls between the 10 000 and 15 000 rows, so use the more conservative (smaller) value of the 10 000 Hz PRF: 2.8×10^{-1}. The correction factor is thus 0.28. Multiply this by the CW Mode MPE found from Table 2 to get a MPE_{PRF} of 0.28×0.002 W/cm^2 = 0.00056 W/cm^2 = 5.6×10^{-4} W/cm^2.

Table 5. Visual Correction Factor for Visible Lasers

Use for visible lasers only (400–700 nm).

Laser Wavelength (nm)	**Visual Correction Factor** (VCF)
400	4.0×10^{-4}
410	1.2×10^{-3}
420	4.0×10^{-3}
430	1.16×10^{-2}
440	2.30×10^{-2}
450	3.80×10^{-2}
460	5.99×10^{-2}
470	9.09×10^{-2}
480	1.391×10^{-1}
490	2.079×10^{-1}
500	3.226×10^{-1}
510	5.025×10^{-1}
520	7.092×10^{-1}
530	8.621×10^{-1}
540	9.524×10^{-1}
550	9.901×10^{-1}
555	1.0×10^{0} (VCF = 1)
560	9.901×10^{-1}
570	9.524×10^{-1}
580	8.696×10^{-1}
590	7.576×10^{-1}
600	6.329×10^{-1}
610	5.025×10^{-1}
620	3.817×10^{-1}
630	2.653×10^{-1}
640	1.751×10^{-1}
650	1.070×10^{-1}
660	6.10×10^{-2}
670	3.21×10^{-2}
680	1.70×10^{-2}
690	8.2×10^{-3}
700	4.1×10^{-3}

To find the Visually Corrected Power (VCP) for a specified wavelength, multiply the Visual Correction Factor (VCF) for the wavelength (from the table above) by the Average Power. If the laser's wavelength falls between two table entries, use the more conservative (larger) value of the two resulting VCFs.

Example 1: A frequency-doubled YAG laser emits 10 watts of 532 nm continuous wave light. From the table, 532 is between 530 and 540; use the more conservative (larger) Visual Correction Factor of 540 nm: 9.524×10^{-1}. Multiply the VCF of 0.9524 by the Average Power of 10 watts to obtain the Visually Corrected Power of 9.524 watts.

Example 2: An 18-watt argon laser emits 10 watts of 514 nm light, and 8 watts of 488 nm light, both continuous wave. Calculate each wavelength separately, then add the resulting Visually Corrected Powers together.

10 watts at 514 nm: From the table, 514 is between 510 and 520; use the more conservative (larger) VCF of 520 nm: 7.092×10^{-1}. Multiply the VCF of 0.7092 by the Average Power of 10 watts to obtain the Visually Corrected Power of 7.092 watts.

8 watts at 488 nm: From the table, 488 is between 480 and 490; use the more conservative (larger) VCF of 490 nm: 2.079×10^{-1}. Multiply the VCF of 0.2079 by the Average Power of 8 watts to obtain the Visually Corrected Power of 1.6632 watts.

Finally, add the two VCPs together: 7.092 + 1.6632 = 8.7552. The 18-watt laser in this example has a Visually Corrected Power of only 8.7552 watts. *Note that the 10-watt YAG in Example 1 appears brighter to the eye (9.5* W_{VCP}*) than an 18-watt argon (8.8* W_{VCP}*).*

Source: The Visual Correction Factor used in this table (C_F) is the CIE normalized efficiency photopic visual function curve for a standard observer. The luminance ($\text{lm} \cdot \text{cm}^{-2}$) is the measured irradiance multiplied by C_F and 683. The effective irradiance is the actual (measured) irradiance multiplied by C_F. The effective irradiance ($\text{W} \cdot \text{cm}^{-2}$) multiplied by 683 $\text{lm} \cdot \text{W}^{-1}$ is the illuminance ($\text{lm} \cdot \text{cm}^{-2}$). The term “Visually Corrected Power” divided by the area of the laser beam is the “effective irradiance”, as used in this document.

Appendix B

SUSPECTED LASER BEAM INCIDENT REPORT AND SUSPECTED LASER BEAM EXPOSURE QUESTIONNAIRE

SUSPECTED LASER BEAM INCIDENT REPORT

This form may be used by local ATC or airline authorities to report a suspected laser beam exposure. When completed, the report should be forwarded to the competent authority as soon as possible for further investigation.

Name ______________________ Age ______________

Position (pilot, co-pilot, controller, etc.) ______________ Phone ______________

Type of vision correction worn at time of incident (spectacles/contact lenses) ______________

Type of aircraft ______________

Aircraft ID or call ______________

Date and time of incident (UTC) ______________

Date and time report is being completed (UTC) ______________

Environmental factors:

Weather conditions ______________

VMC/IMC ______________

Ambient light level (day, night, sunlight, dawn, dusk, starlight, moonlight, etc.) ______________

____

Location of incident:

Near (aerodrome/city/NAVAID) ______________

Radial and distance ______________

Phase of flight ______________

Type/name of approach or departure procedure ______________

Heading/approximate heading if in turn ______________

Altitude (AGL) ______________ (MSL) ______________

Aircraft bank and pitch angles ______________

Angle of incidence:

Did the light hit your eye(s) directly or from the side? ______________

____

Light description:

Colour ____________________

Nature of beam (constant/flicker/pulsed) ____________________

Light source (stationary or moving) ____________________

Do you feel you were intentionally tracked? ____________________

Relative intensity (flashbulb, headlight, sunlight) ____________________

Duration of exposure (seconds) ____________________

Was the beam visible prior to the incident? ____________________

Position of light source (relative to geographical feature or aircraft) ____________________

____

Circle the window where the light entered the cockpit:

Left left-front centre right-front right other ____________

Elevation of the beam from horizontal (degrees) ____________________

Effect on individual:

Describe visual*/psychological/physical effects ____________________

____

____

Duration of visual effects (seconds/minutes/hours/days) ____________________

Do you intend to seek medical attention? ____________________

____

Note.— This is recommended if even minor symptoms were experienced.

Effect on operational or cockpit procedures: ____________________

____

____

* Examples of common visual effects:

After-image. An image that remains in the visual field after an exposure to a bright light.

Blind spot. A temporary or permanent loss of vision of part of the visual field.

Flash-blindness. The inability to see (either temporarily or permanently) caused by bright light entering the eye and persisting after the illumination has ceased.

Glare. A temporary disruption in vision caused by the presence of a bright light (such as an oncoming car's headlights) within an individual's field of vision. Glare lasts only as long as the bright light is actually present within the individual's field of vision.

— — — — — — — —

SUSPECTED LASER BEAM EXPOSURE QUESTIONNAIRE

This questionnaire may be filled out by the competent authority during interviews with persons exposed to laser beams. This information will be used to aid in any subsequent investigation and provide important medical and statistical data for the review of regulatory and enforcement issues associated with new laser beam applications and threats to aviation safety. The completed form should be forwarded to the appropriate aviation authority as soon as possible.

1. Did anyone else see the light beam? ____________________

2. What was the colour(s) of the light? ____________________

   Did the colour(s) change during the exposure? ____________________

3. Did the light come on suddenly, and did it become brighter as you approached it? ____________________

   ____

4. Was the light continuous or did it seem to flicker? ____________________

   If it flickered, how rapidly and regularly? ____________________

5. Did the light fill your cockpit or compartment? ____________________

6. How would you describe the brightness of the light? ____________________

   Was it equally bright in all areas or was it brighter in one area? ____________________

7. Did you attempt an evasive manoeuvre? ____________________

   If so, did the beam follow you as you tried to move away? ____________________

   How successful were you in avoiding it? ____________________

8. Do you know the source of the light emission? ____________________

9. Can you estimate how far away the light source was from your location? ____________________

   Was the source moving? ____________________

10. What was between the light source and your eyes — windscreen, glasses, contact lenses, etc.? ____________________

    Did any of these sustain damage by the light? ____________________

11. Was the light coming directly from its source or did it appear to be reflected off other surfaces? ____________________

    Were there multiple sources of light? ____________________

12. Did you look straight into the light beam or off to the side? ____________________

13. How long was the exposure? ____________________

    Did the light seem to track your path or was there incidental contact? ____________________

14. At what time of the day did the incident occur? ____________________

15. What was the visibility? ____________________

    What were the atmospheric conditions — clear, overcast, rainy, foggy, hazy, sunny? ____________________

16. What tasks were you performing when the exposure occurred? ____________________

    Did the light prevent or hamper you from doing those tasks, or was the light more of an annoyance? ____________________

17. What were the visual effects you experienced (after-image, blind spot, flash-blindness, glare*)? ____________________

18. How long did any symptoms you experienced from the exposure last? ____________________

    Are any symptoms (tearing, light sensitivity, headaches, etc.) still present? ____________________

19. Did you touch or rub your eyes at the time of the incident? ____________________

20. Did you have your eyes examined after the incident? ____________________

    If so, when and by whom? ____________________

    What were the results of this visit? ____________________

21. Did you report the incident? ____________________

    If so, to whom (ATC, medical personnel, safety officer, etc.) and when? ____________________

* Examples of common visual effects:

After-image. An image that remains in the visual field after an exposure to a bright light.

Blind spot. A temporary or permanent loss of vision of part of the visual field.

Flash-blindness. The inability to see (either temporarily or permanently) caused by bright light entering the eye and persisting after the illumination has ceased.

Glare. A temporary disruption in vision caused by the presence of a bright light (such as an oncoming car's headlights) within an individual's field of vision. Glare lasts only as long as the bright light is actually present within the individual's field of vision.

Appendix C

AMSLER GRID TESTING PROCEDURE

The Amsler grid test is designed to detect defects in the central visual field of an eye, corresponding to retinal lesions as small as 50 micrometres.

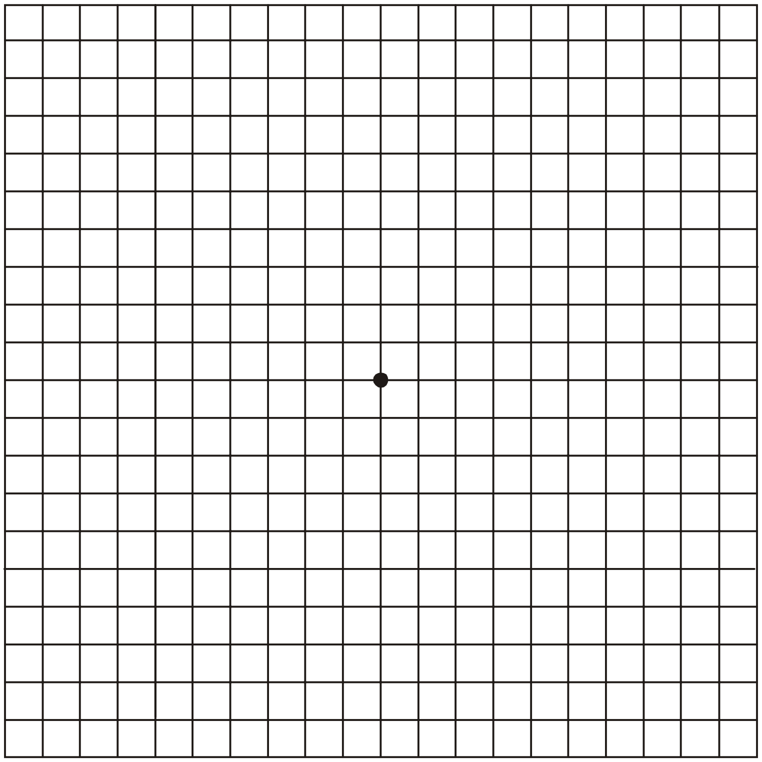
The chart below is sized to be viewed at a distance of 28–30 cm, the usual distance for reading tests. At this distance the test will examine the central 20 degrees of the patient's field of vision for abnormalities, with each small square equivalent to 1 degree. Before using this chart:

a) the refraction of the eye in question must be exactly corrected for this distance;

b) the chart must be clearly and evenly illuminated as for a reading test;

c) all artificial mydriasis and any ophthalmoscopy immediately before the examination must be avoided; and

d) the other eye should be covered, preferably with an occluder.



While continually urging the patient to look steadily upon the central point, ask the following questions. Record the responses and ask the patient to carefully draw any abnormal results on the grid chart.

1. Do you see the spot in the centre of the square chart?

2. Keeping your gaze fixed upon the spot in the centre, can you see the four corners of the big square? Can you also see the four sides of the square? In other words, can you see the whole square?

3. Keeping your gaze fixed upon the spot in the centre, do you see the network intact within the whole square? Are there any interruptions in the network of squares, such as holes or spots? Is it blurred in any place? If so, where?

4. Keeping your gaze fixed upon the spot in the centre, are both the horizontal and vertical lines straight and parallel? In other words, is every small square equal in size and perfectly regular?

5. Keeping your gaze fixed upon the spot in the centre, do you see any movement of certain lines? Is there any vibration or wavering, shining or colour tint? If so, where?

6. Keeping your gaze fixed upon the spot in the centre, at what distance from this point do you see the blur or distortion? How many small intact squares do you find between the blur or distortion and the centre point where your gaze is fixed?

— END —

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