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Laser Safety

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Introduction

Laser is the acronym for Light Amplification by Stimulated Emission of Radiation. Laser light is a form of electromagnetic radiation, but most laser light does not fall in the ionizing section of the spectrum. Lasers are used for a variety of applications throughout the Reed College campus and may cause injury if improperly used. Therefore a basic knowledge of laser safety is necessary before one uses a laser. Everyone associated with laser operations needs to be aware of the hazards they may encounter. Lasers can cause serious eye injury if a person looks directly into the beam, and even diffuse reflections can blind, burn flesh, ignite flammable materials, and/or activate toxic chemicals. Lasers may also bring hazards associated with high voltage, high pressure, noise, radiation, and toxic gases.

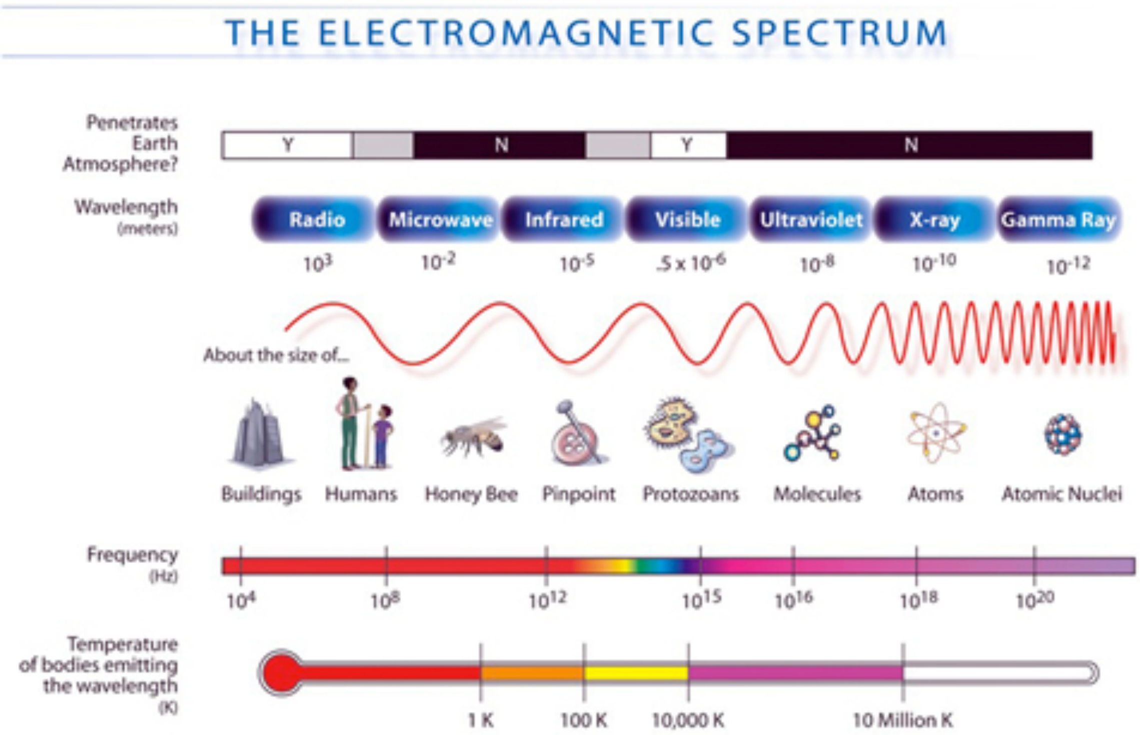

Figure 1: Electromagnetic Spectrum

Chapter 1: Laser Basics

Here are some basic characteristics for laser light:

- Lasers produce a very narrow, intense beam of light. Light from a light bulb spreads out as it travels, so much less light hits a given area as the distance from the light source increases (the inverse square law). Laser light travels as a parallel beam spreading very little, so the inverse square law does not apply.
- Laser light is monochromatic and coherent. White light is a jumble of colored light waves, each color is a different wavelength. If all the wavelengths or colors except one were filtered out, the remaining light would be monochromatic.
- White light propagates in all directions and is a jumble of phases. If light waves are all parallel and in phase with one another they are said to be coherent (i.e. the wave crests and troughs coincide). Therefore these waves reinforce one another.
- Not all lasers emit visible light. Some lasers produce infrared or ultraviolet light. This light is still capable of producing injuries. Most laser systems are made of three basic components:
    - A pumping system or energy source: this can be a flash lamp, microwaves, chemical reaction, another laser, etc.
    - The lasing medium may be a gas, liquid, solid, semiconductor, electron beam, etc.
    - A resonant cavity, which amplifies the intensity of the light. Lenses, mirrors, absorbers, shutters, and other accessories may be added to the system to obtain more power, shorter pulses, or special beam shapes, but only these three basic components are necessary for laser action.

Lasers use a process called stimulated emission to amplify light waves. Many substances give off light by spontaneous emission. Consider what occurs when one of the electrons of an atom absorbs energy. While it possesses this energy, the atom is in an excited electronic state. If the orbital electron gives off this energy in the form of electromagnetic radiation, such as light, with no outside impetus, spontaneous emission has occurred. If a wave emitted by one excited atom strikes another atom, it may stimulate the second atom to emit energy in the form of a second wave that travels parallel to and in step (or phase) with the first wave.

The stimulated emission results in the amplification of the first wave. If the two waves strike other excited atoms, a very intense coherent beam can be built up. But if these waves strike unexcited atoms, the energy is absorbed and some intensity is lost. In the normal state of matter on the earth, the great majority of atoms are not excited. As more than the usual number of atoms become excited, the probability increases that stimulated emission, rather than absorption, will take place.

1.1 Ruby Lasers

The ruby laser was the first laser invented in 1960. Ruby is an aluminum oxide crystal in which some of the aluminum atoms have been replaced with chromium atoms. Chromium gives ruby its characteristic red color and is responsible for the lasing behavior of the crystal. Chromium emits green and blue light and reflects only red light. For a ruby laser, a crystal of ruby is formed into a cylinder. A fully reflecting mirror is placed on one end and a partially reflecting mirror on the other. A high intensity lamp is spiraled around the ruby cylinder to provide a flash of white light that triggers the laser action. The green and blue wavelengths in the flash excite electrons in the chromium atoms to a higher energy level. Upon returning to their normal state, the electrons emit their characteristic ruby-red light. The mirrors reflect some of this light back and forth inside the ruby crystal, stimulating other excited chromium atoms to produce more red light, until the light pulse builds up to high power and drains the energy stored in the crystal.

The laser flash that escapes through the partially reflecting mirror lasts for only about 300 millionths of a second (roughly the duration of the flash lamp's flash), but it is very intense. Early lasers could produce peak powers of some ten thousand watts. Modern lasers can produce pulses that are billions of times more powerful.

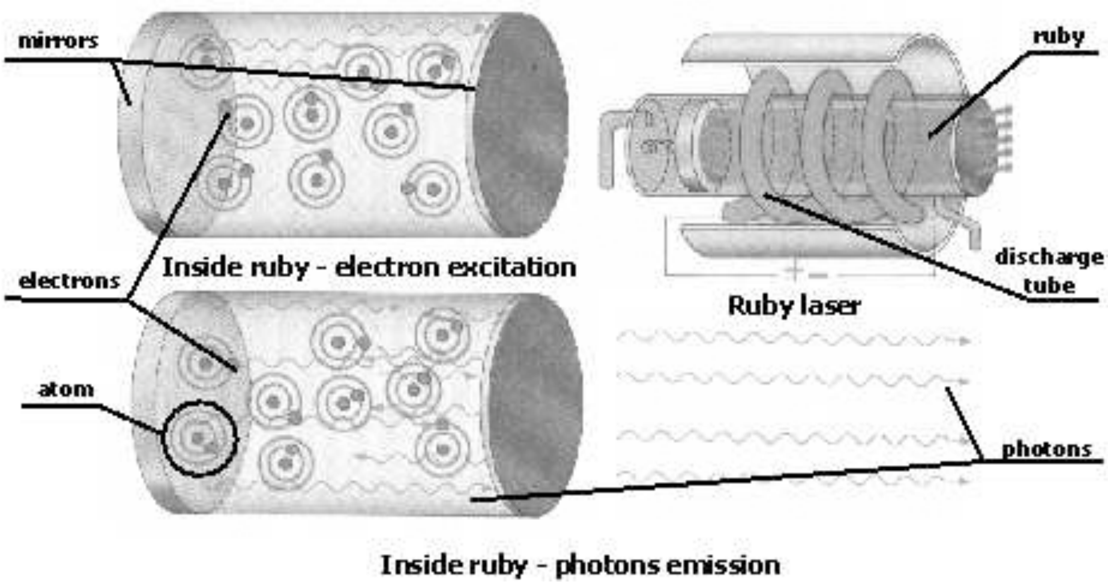

Figure 1.1: Ruby Laser

1.2 Helium-Neon Lasers

One of the most common lasers used is the helium-neon laser. Let us review this system, comparing and contrasting the way that it functions with the more simple ruby laser we just described. At the heart of the helium-neon laser system is an optical cavity comprised of a tube which is sealed with mirrors at each end. One mirror is 100% reflective while the other is greater than 95% reflective but not quite 100% reflective. A gas discharge in the tube is created by a brief 6 to 15 kV trigger and maintained with 2 to 6 kV DC, at 4 to 10 milliamps, applied across the electrodes.

Electrons strike the helium atoms and excite some of them to metastable states from which their subsequent decay is restricted to processes which do not produce radiation. Neon possesses several energy levels which lie just below helium's decay-restricted states. An excited helium atom which passes very near a neon atom may transfer its energy, through a form of resonant coupling, to the neon. This process allows the helium to decay to the ground state where it may, once again, be excited by the electric field. Meanwhile, the excited neon atoms may loose their energy in several ways; one such pathway is the spontaneous emission of visible light at 632.8 nm (orange).

Laser activity becomes possible when a population inversion exists (i.e. when the number of neon atoms capable of 632.8 nm emission exceeds the number of atoms which are in the relaxed state). The helium metastable atoms produce neon's population inversion. Some of the 632.8 nm radiation will induce other excited neon atoms to emit light, a process called stimulated emission, and that light is coherent with the stimulating light. Energy losses may occur as a result of spontaneous emission, diffraction, scattering, and collisional relaxation (resulting in heat). The mirrors create a optical path along the entire length of the glass tube, which is needed for sufficient amplification, by stimulated emission of radiation, to occur.

If this amplification exceeds energy losses (including the light exiting the laser from the partially reflecting mirror) then energy density at the desired frequency will rise exponentially and the laser quickly enters into oscillation. In this condition the population inversion decreases and so does amplification. When amplification balances energy losses then a stable operating environment is achieved.

1.3 Other Lasers

Helium-neon lasers the most common gas lasers. They have a primary output of visible red light; although other colors - most often green - are also available.
CO2 lasers emit energy in the far-infrared region, and are used for cutting hard materials. Nitrogen lasers emit ultraviolet light. Excimer lasers (the name is derived from the terms excited and dimers) use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton or xenon. When electrically stimulated, a pseudo molecule (dimer) is produced. When lased, the dimer produces light in the ultraviolet range. Dye lasers use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths. Semiconductor lasers, sometimes called diode lasers, are solid state lasers. These electronic devices are generally very small and use low power. They may be built into larger arrays, such as the writing source in some laser printers or CD players. Nd:YAG lasers (neodynium doped yittrium aluminum garnet lasing medium) are solid state lasers that emit in the infrared

region. They are very powerful and the output can be frequently doubled, tripled, and quadrupled to produce green and ultraviolet laser beams.

Chapter 2: Terms and Definitions

Although a form of electromagnetic radiation, because of its characteristics, lasers present us with a new set of terms and definitions. Some of these pertain to laser systems and some pertain to the eye, the organ of primary concern for laser injury. Each is important for understanding the hazard that a particular laser system may pose.

2.1 Radiation Characteristics

The pulse duration is the duration (usually msec, **μ**sec, or nsec) of a pulsed laser flash, usually measured as the time interval between the half-peak-power points on the leading and trailing edges of the pulse. If the energy is delivered over a shorter period of time, say nanoseconds, instead of milliseconds, the potential for tissue damage is greater because the tissue does not have sufficient time to dissipate the deposited energy.

The pulse repetition rate describes how often during a time period (i.e., Hz, kHz) the laser is allowed to emit light. If the pulse repetition rate is low, tissue may be able to recover from some of the absorbed energy effects. If the repetition rate is high, there are additive effects from several pulses (rather than from a single pulse) over a period of time.

The wavelength, is the distance between two peaks of a periodic wave. It is inversely related to the frequency, f, the number of waves per second, and is also inversely related to the energy (i.e., the shorter the wavelength, the greater the energy; E = h = hc/). Table 2.1 lists the various optical band designations along with some of the common laser systems. Tissue penetration of electromagnetic energy depends upon wavelength. Some wavelengths in the infrared region penetrate deeper into the tissue than certain wavelengths in the UV region. Theoretically, every wavelength has its own penetration characteristics. Other considerations pertaining to penetration include percentage of water in an organ, the reflectivity or focusing characteristics at the surface of the tissue, etc.

Table 2.1: Optical Spectral-Band Designation

Spectral Band	Wavelength	Designation	Laser	Wavelength (nm)
Vacuum-Ultraviolet	10-200 nm			
Near-Ultraviolet	100-280 nm	UV-C	Argon-Fluoride	193
			Neodymium:YAG (quadrupled)	255

	280-315 nm	UV-B	Xenon-Chloride	308
	315-400 nm	UV-A	Helium-Cadmium	325
			Ruby (Doubled)	347.1
			Kyrpton	350.7, 365.4
			Nd:YAG (Tripled)	355
			Nitrogen	337
			Argon	351.1, 363.8
Visible	400-700 nm		Helium-Cadmium	441.6
			Argon	497.9, 467.5, etc.
			Helium-Selenium	460.4-1260
			Nd:YAG (doubled)	532
			Helium-Neon	632.8
			Krytpon	647.1, 530.9, etc.
			Ruby	694.3
			Rhodamine 6G (dye laser)	450-650
Near-Infrared	700-1400 nm	IR-A	Gallium-Arsenide	905
			Nd:YAG	1064
			Helium-Neon	1080, 1152
Mid-Infrared	1400 nm-3 µm	IR-B	Erbium:Glass	1540
Far-Infrared	3 µm-1 mm	IR-C	Carbon-Monoxide	3390
			Helium-Neon	4000-6000
			Hydrogen-Fluoride	5000-5500
			Carbon Dioxide	10,600
			Water Vapor	118,000

Lasers are characterized by their output. The output of a continuous-wave laser is normally expressed in watts, W, of power and the output of a pulsed laser is expressed as energy in joules, J, per pulse. For pulsed systems, multiplying the output by the number of pulses per second (repetition frequency) yields the average power in watts (W = J/s). The peak power for a pulsed laser depends upon the pulse duration. The shorter the duration, the higher the peak power. Peak powers for very short duration pulsed lasers can be in the terawatt (TW or 1012 W) range.

Pulsed laser output is normally characterized by the radiant exposure or energy density which is the magnitude of the energy flux and describes the quantity of energy across the face of the beam that is arriving at a tissue surface at any one point in time, expressed in joules/cm2. The greater the energy, the greater the potential for damage. CW laser beams are characterized by the irradiance or power density, the rate of energy flow per unit area in the direction of wave propagation, typically measured in units of mW/cm2 or W/m2. This is a factor of both the output and beam diameter (usually expressed in mm).

2.2 Components of the Eye

From the laser effects viewpoint, the eye is composed of several subsystems: light transmission and focusing, light absorption and transduction, and maintenance and support systems.

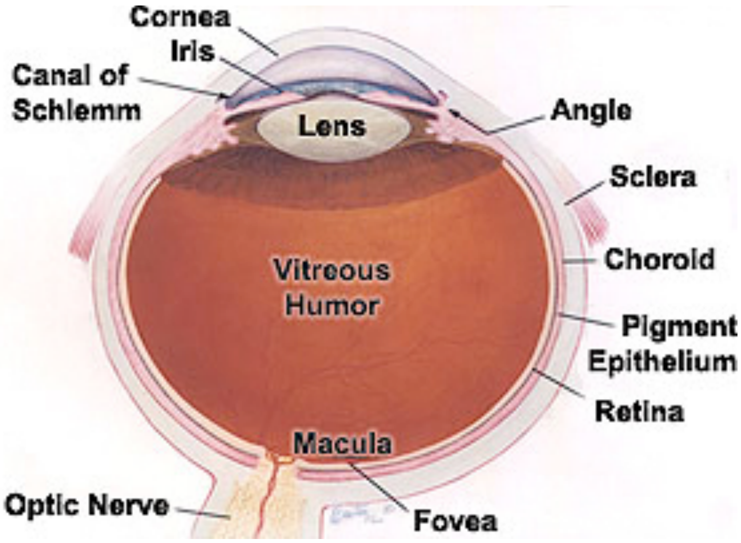

Figure 2.1: Eye Components

Transmission and Focusing System

The cornea is the transparent membrane which forms part of the front of the eye and separates it from the air. It covers the colored portion (iris) and the pupil of the eye. The cornea is continuous with the sclera (white of the eye). The greatest amount of refraction of the laser beam takes place in the cornea. The cornea transmits most laser wavelengths except ultraviolet and far-infrared irradiation which, at high energies, may burn it.

The sclera or the "white of the eye" is the white membrane which forms the outer envelope of the eye, except its anterior (front) sixth which is occupied by the cornea. The iris and pupil are the colored diaphragm with an aperture (pupil) in its center. The iris is composed in large part of muscular tissue which controls the amount of light entering the eye by widening (dilating) the pupil at twilight, night, and dawn; narrowing (constricting) the pupil at daylight. Therefore, eye-hazard lasers are much more dangerous under low light conditions; more wavelengths enter the eye through the wide pupil hitting the retina.

The lens is a transparent structure located immediately behind the iris and pupil which focuses light on the retina. It thus forms one of the refractive media of the eye. Visible and near-infrared light pass through the lens, but near-ultraviolet light is absorbed by it. The aqueous humor is the water-like liquid between the cornea and the iris. The vitreous humor, the jelly-like substance filling the eye between the lens and the retina, is transparent to both visible and near-infrared radiation. The vitreous humor also serves as a structural support for the retina.

Absorption and Transduction System

The retina lines the inside of the eyeball and consists primarily of photoreceptors and nerve cells. The nerve cell layer lies on top of the photoreceptor cells but is transparent, so light entering through the pupil actually passes through the nerve cell layer before reaching the photoreceptor cells. Beneath the nerve cells is the pigmented epithelium of the eye, it is a layer of cells in which pigment able to absorb scattered light and stop light reflection is formed. Light is focused by the cornea, lens, and various fluids of the eye onto the layer of rods and cones of the retina. These photoreceptor cells convert the energy of absorbed light into nerve impulses. These impulses are received by the nerve cells which transmit them along nerve fibers from layer to layer through the retina to a nerve complex, the optic nerve, that leads to the brain through the back of the eye.

The retina is particularly sensitive to laser irradiation since the laser beam is well focused on it. This is true for visible and near-infrared laser beams. For example, all the light entering a 5 mm pupil is converted to an image 0.05 mm or smaller in diameter on the retina, multiplying the energy density 10, 000-times or more. If the beam enters the eye through binoculars or other magnifying optics, it is more dangerous since the energy concentration may increase up to a million times. The retina is composed of the macula, fovea, and retinal periphery.

The macula lutea or macula, is the area in the retina that is in direct line with the visual axis. The eyes are fixed in such a manner that the image of any object looked at is always focused on the macula. In the macular region, the inner layers of the retina are pushed apart, forming a small central pit, the fovea centralis, or fovea. The fovea is the central 1.5 mm area at the back of the eye. The fovea is the only part of the eye in which precise vision takes place, enabling location of small and distant targets and detection of colors. If an object is looked at directly, imaging takes place at the fovea inside of the macula. If the object happens to be a laser beam sufficiently strong to cause tissue damage, sharp vision is lost and the person may be blinded;

barely able to see the top letters on the eye chart and unable see colors. The fovea and fine visual function can also be affected by retinal injuries occurring at some distance from the fovea. Many injuries, especially those caused by lasers, are surrounded by a zone of inflammation and swelling which, when it extends into the region of the fovea, can reduce foveal function. The actual degree of visual impairment will depend upon the location and extent of both injury and the inflammatory response. Generally, the closer the injury is to the fovea, the greater the chance of severe dysfunction.

The retinal periphery, all of the retinal area surrounding the fovea, is involved in a variety of functions. Because it has a high concentration of photoreceptor cells which operate during dim or dark conditions, night vision is one of its primary functions. During bright conditions the peripheral retina detects motion (peripheral vision). Unlike the fovea, however, the peripheral retina is unable to detect small or distant objects or to distinguish between fine shades of color. A laser injury restricted to this portion of the retina will have a minimal effect on normal visual function. Workers with isolated laser injuries in the retinal periphery may report having been dazzled at the time of exposure and may detect a dark spot (blind spot) in their peripheral vision; they should be able to perform all fine visual tasks normally. After a time, a worker will adapt to the presence of small- to medium sized blind spots. Even though the retina may be permanently damaged, the worker will eventually become unaware of it. Laser injuries which involve large portions of the peripheral retina may cause large defects in the individual's peripheral vision. These will always be a noticeable impairment and the worker will always be aware of these.

Maintenance and Support Systems

The maintenance system consists primarily of the choroid, a rich network of blood vessels on or behind the retina. If this network is injured by a laser beam, it bleeds and may lead to partial or complete, temporary or permanent blindness. The eyelids are the most relevant parts of the support system; they may be able to limit a laser exposure to 0.25 seconds, the duration of the blink reflex. The eyelids themselves may be burned by high energy infrared laser irradiation together with surrounding skin and the cornea.

ANSI Z136.1, Safe Use of Lasers, provides comprehensive information for evaluating potential hazards from a laser system. Three aspects of a laser's use will influence total hazard evaluation and the application of control measures.

These are:

1. The laser device's capability of injuring workers. This ability is measured in terms of the Maximum Permissible Exposures or MPE which is measured by the radiant exposure, H (J/cm2) or the irradiance (power density), E (W/cm2) for point sources.
2. The physical environment in which the laser is used (e.g enclosed laser system versus open lab bench). Laser beam exposure conditions are usually broken into three areas.
    a. In intrabeam viewing the target organ is directly exposed to a primary laser beam. This is the traditional worst case exposure condition and

suggests the first rule of laser safety: Never look directly in to any laser beam for any reason.

   b. In a specular reflection, the target organ is exposed to a mirror-like reflection of a primary laser beam from a smooth surface. In this type of reflection, the power being delivered to the target organ can approach that of an intrabeam exposure. Consequently exposure to specular reflections is usually as hazardous as intrabeam exposure.
   c. With diffuse reflections, the target organ is exposed to a laser beam being reflected from an uneven surface (i.e., surface has irregularities larger than the wavelength of the laser beam). As the beam is spread by the uneven surface, it rapidly increases in diameter and decreases the beam irradiance, reducing or eliminating the hazard for all but class 4 lasers.

3. The persons or populations who may be exposed (e.g., general public versus laser worker).

A practical means for both evaluation and control of laser radiation hazards is to first classify laser devices according to their relative hazards and then to specify approximate controls for each classification. The benefit from using a hazard classification system is that it usually precludes the need for laser measurements and reduces the need for calculations. Classification of lasers is usually the manufacturer's responsibility, but becomes the user's responsibility if any modifications are made. The laser hazard classification system (Table 3.1) has four classes. While the hazard depends upon a laser's output parameters and potential to cause injury, the classification system is based upon the amount of radiation accessible during normal use, not during service or maintenance. Each laser system class has associated safeguards which must be implemented to protect the worker from injury.

Chapter 3: Laser Hazard Classification System

Table 3.1: Laser Classification

Class	**Hazard Type**	**Parameter (P/A = Laser Power/ Pupil Area)**
Class I	No Hazard	P/A < 3 hr MPE
Class II	Visible Laser	P/A <.25 sec MPE
Class IIIa	Eye Hazard	P/A ≤ 5x Class I MPE P/A ≤ 5x Class II MPE

Class IIIb	Eye/Skin Hazard	$P/A \leq 0.5$ W for $t > 0.25$ sec $P/A \leq 10$ J/cm^2 for $t < 0.25$ sec
Class IV	Diffuse Reflection Eye Hazard Fire Hazard	$P/A \geq 0.5$ W for $t > 0.25$ Sec $P/A \geq 10$ J/cm^2 for $t < 0.25$ sec

Class I - Exempt Laser, No Hazard

Class I lasers are termed "No-Risk" or "Exempt" lasers because they are not capable of emitting hazardous laser radiation levels under any operating or viewing conditions. Continuous output power levels are < 0.39 μW. The exemption from hazard controls strictly applies to emitted laser radiation hazards and not to other potential hazards. Most lasers by themselves do not fall into the Class I category but when the laser is incorporated or imbedded into a consumer or office machine equipment (e.g., laser printers and CD players may have class IIIb or IV lasers) the resulting system may be Class I. If a Class I system contains a more dangerous laser, the access panel to the embedded laser must contain a warning to alert the user of the potentially hazardous laser radiation which will be encountered if the panel is removed.

Class II - Low Power, Low-Risk

Class II lasers, often termed "Low-Power" or "Low-Risk" laser systems, are visible lasers operating at power levels < 1 mW and are only hazardous if the viewer overcomes his or her blink reflex response to bright light and continuously stares into the source. The possibility of such an event is remote since it could just as readily occur as blinding oneself by forcing oneself to stare at the sun for more than 10 to 20 seconds. Because this hazard, although rare, is as real as eclipse blindness, Class II lasers must have a CAUTION label affixed to indicate that an individual should not purposefully stare into the laser. Precautions are required to prevent continuous staring into the direct beam. Momentary (< 0.25 sec) exposure occurring in an unintentional viewing situation is not considered hazardous. Examples of Class II lasers are code readers in food stores, laser tag guns, pointers and positioning lasers in medical applications. This class is further refined depending whether a laser is continuous-wave or pulsed:

- Visible, CW laser devices that can emit a power exceeding the limit for Class I for the maximum possible duration inherent to the design of the laser or laser system, but not exceeding 1 mW.
- Visible repetitively pulsed laser devices that can emit a power exceeding the appropriate limit for the Class I for the maximum possible duration inherent to the design of the laser device but not exceeding the limit for a 0.25 second exposure.

Additionally, there is a Class IIa defined as a visible (400 nm to 700 nm) laser or laser system used exclusively in bar code scanning systems where the laser is not intended to be viewed and does not exceed the exposure limit for 1000 seconds of viewing time. These lasers are exempt from any control measures.

Class III - Moderate Power, Moderate-Risk

Class III, "Moderate-Risk" or "Medium Power" laser systems are those which are potentially hazardous for intrabeam viewing and even specular reflection (i.e., mirror like image) can cause injury within the natural aversion response time, i.e., faster than the blink reflex (0.25 sec). They are not capable of causing serious skin injury or hazardous diffuse reflections under normal use but they must have DANGER labels and safety precautions are required to prevent intrabeam viewing and to control specular reflections. Class III lasers are divided into two subclasses, Class IIIa and IIIb. Class IIIa is a visible laser or laser system with an output between 1 mW and 5 mW which is normally not hazardous for momentary viewing but which may cause eye injury if viewed with magnifying optics from within the beam. Class IIIb is a laser or laser system with an output between 5 mW and 500 mW. Class IIIb is further broken into four different frequency and energy regions:

- Infrared and ultraviolet laser devices. These emit a radiant power in excess of the Class I limit for the maximum possible duration inherent to the design to the laser device. Cannot emit an average radiant power of 0.5 W or greater for viewing times greater than 0.25 seconds, or a radiant exposure of 10 J/cm2 with an exposure time of less than 0.25 seconds.
- Visible CW or repetitive pulsed laser devices. These produce a radiant power in excess of the Class I assessable exposure limit for a 0.25 second exposure (1 mW for a CW laser). Cannot emit an average radiant power of 0.5 W or greater for viewing time limits greater than 0.25 seconds.
- Visible and near-infrared pulsed laser devices. These emit a radiance energy in excess of the Class I limit but cannot emit a radiant exposure that exceeds that required to produce a hazardous diffuse reaction.
- Near-infrared CW laser devices or repetitively pulsed laser devices. These emit a power in excess of the exposure limit for Class I for the maximum duration inherent in the design of the laser device. Cannot emit an average power of 0.5 W or greater for periods is excess of 0.25 seconds.

Class IV - high power, high-risk

Class IV, "High-Power" laser systems have average outputs of greater than 500 mW for CW or greater than 10 J/cm2 for a 0.25 second or less pulsed laser and pose a "high-risk" of injury and can cause combustion in flammable materials. This class includes pulsed visible and near IR lasers capable of producing hazardous diffuse reflections, fire, and skin hazards. Also, systems whose diffuse reflections may be eye hazards and direct exposure may cause serious skin burns. Class IV lasers usually require the most restrictive warning label and even more restrictive control measures (i.e. safety goggles, interlocks, warning signs, etc.). Class IV is broken into two frequency (i.e., wavelength) based subclasses:

- Ultraviolet (200 nm to 400 nm) and infrared (1.4 μm to 1000 μm) laser devices that emit an average power of 0.5 W or greater for periods greater than 0.25 seconds, or a radiant exposure of 10 J/cm2 within an exposure duration of 0.25 seconds or less.

- Visible (400 nm to 700 nm) and near-infrared (700 nm to 1400 nm) laser devices that emit an average power of 0.5 W or greater for periods greater than 0.25 seconds, or a radiant exposure in excess of that required to produce a hazardous diffuse reaction.

Chapter 4: Laser Effects

Table 4.1 summarizes laser biological effects. The primary laser danger is to the eye. This is the most common type of laser injury besides electrocution and these injuries may be permanent. The location and type of injury will depend on the type of laser (visible, infrared, ultraviolet) and the amount of energy (both total and deposition rate, J/sec) deposited in or on the eye. Figure 4.1 shows the interaction of various electromagnetic radiation frequencies/energies with the eye.

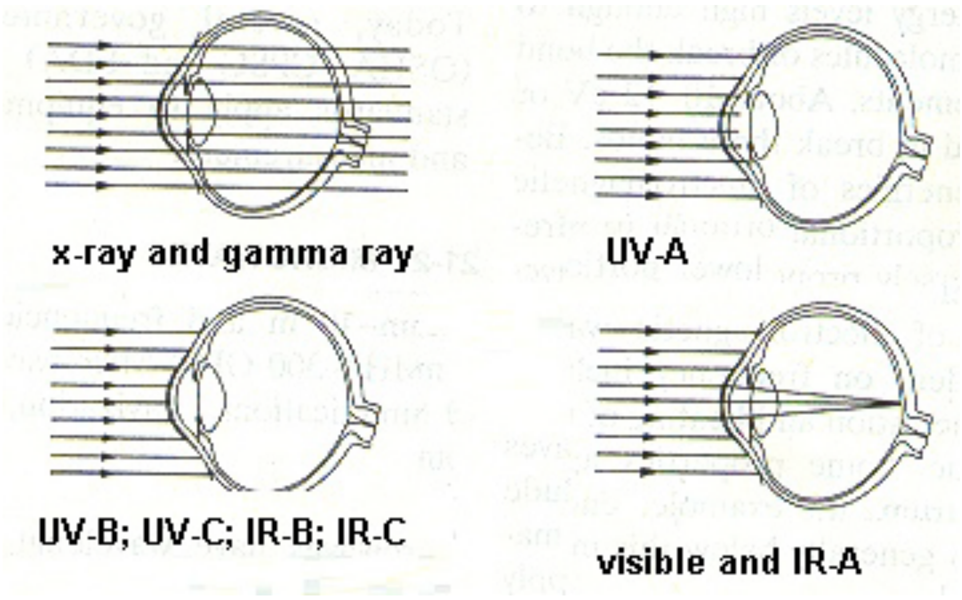

Figure 4.1: Electromagnetic Radiation and the Eye

Most higher energy x- and gamma rays pass completely through the eye with relatively little absorption. Absorption of short-ultraviolet (UV-B and UV-C) and far-infrared (IR-B and IR-C) radiation occurs principally at the cornea. Near ultraviolet (UV-A) radiation is primarily absorbed in the lens. Light is refracted at the cornea and lens and absorbed at the retina; near infrared (IR-A) radiation is also refracted and absorbed in the ocular media and at the retina.

The eye transmits more than merely visible light (400–700 nm), certain infrared frequencies (e.g., IR-A) are also transmitted and may cause retinal injury. For a person to receive an eye injury: (1) they must be looking with unprotected eye or optical sight, (2) the laser must be oriented so it passes through the sight or into the eye, and (3) central vision is affected only if the person is looking directly at or near the laser source. Even though it is possible to be injured by light entering through the "corner of the eye," it is unlikely that a single pulse will result in injury; however, if thousands of pulses are directed into an area, one or more persons might be injured.

Table 4.1: Potential Biological Laser Effects

Band	Wavelength (nm)	Eye	Skin
UV-C	200-280	Corneal burn	Erythema (sunburn), skin cancer
UV-B	280-315	Corneal burn	Accelerated skin aging, pigmentation
UV-A	315-400	Photochemical cataract	Pigmentation darkening, photosensitive reaction, skin burn
Visible	400-780	Photochemical and thermal retinal injury	Photosensitive reaction, skin burn
IR-A	780-1400	Cataract, retinal burn	Skin burn
IR-B	1400-3000	Corneal burn, aqueous flare, possibly cataract	Skin burn
IR-C	$3000\text{-}10^6$	Corneal burn	Skin burn

4.1 Retinal Effects

Light (400 – 760 nm) and near-infrared (IR-A: 760 – 1400 nm) is sharply focused onto the retina. When an object is viewed directly, the light forms an image in the fovea at the center of the macula. This central area, approximately 0.25 mm in diameter for humans, has the highest density of cone photoreceptors. The typical result of a retinal injury is a blind spot within the irradiated area. A blind spot due to a lesion in the peripheral retina may go unnoticed. However, if the blind spot is located in the fovea, which accounts for central vision, severe visual defects will result. Such a central blind spot would occur if an individual were looking directly at the laser source during the exposure. The size of the blind spot depends upon whether the injury was near-to or far-above the threshold irradiance, the angular extent of the source of radiation, and the extent of accommodation. The blind spot may be temporary or permanent.

A hemorrhagic lesion is a severe eye injury characterized by severe retinal burns with bleeding, immediate pain and immediate loss of vision. Such an injury requires a high intensity laser. The spreading hemorrhage will produce long lasting (months) vision degradation/loss and ultimately produces a permanent blind spot (blind spot in visual field) at the point of hemorrhage.

A thermal lesion requires less laser energy/intensity than is needed to produce a hemorrhagic lesion. However, it still produces a permanent blind spot

Flash blindness is a temporary degradation of visual activity resulting from a brief but intense exposure to visible radiation. It is similar to the effects of a flashbulb. In flash blindness, the blind spot is temporary and its size depends upon the length of exposure and location of focus on the retina. Scatter of the laser beam through the atmosphere or an off-axis exposure may increase the blind spot size and result in an increased obscurence of the field of vision. There is a threshold of laser energy to produce flash blindness, but the energy is less than that which causes a thermal lesion. Flash blindness is differentiated from glare by the fact that the afterimage (blind spot) moves with eye movement and the afterimage lasts for a short period of time (minutes) after the laser exposure and recovery times range from a few seconds to a few minutes.

Glare/Dazzle is an effect similar to flash blindness. Vision degradation occurs only during laser exposure and the glare stays in the same point in the visual field so one can move the eye to eliminate the effect.

In summary, retinal effects are due to visible and near IR laser exposure. Retinal lesions can occur even if there is no prolonged loss of vision (i.e., at periphery of vision field), however a retinal lesion is not always produced even when visual function disturbance has occurred (flash blindness, glare). If a retinal lesion is temporary, total visual recovery is seen within approximately three minutes.

4.2 Corneal Effects

The anterior structures of the eye are the cornea, conjunctiva, aqueous humor, iris and lens. The cornea is exposed directly to the environment except for the thin tear film layer. The corneal epithelium (i.e., the outermost living layer of the cornea), over which the tear layer flows, is completely renewed in a 48-hour period. The cornea, aqueous humor and lens are part of the optical pathway and, as such, are transparent to light. One of the more serious effects of corneal injury is a loss of transparency. At very short wavelengths in the ultraviolet and long wavelengths in the infrared, essentially all of the incident optical radiation is absorbed in the cornea. Because of rapid regrowth, injury to this tissue by short ultraviolet radiation seldom lasts more than one or two days unless deeper tissues of the cornea are also affected. Thus, surface epithelium injuries are rarely permanent.

Photokeratitis can be produced by high doses of UV (UV-B and UV-C: 180 - 400 nm) radiation to the cornea and conjunctiva that cause keratoconjunctivitis. This is a painful effect also known as snow blindness or welder's flash. It occurs because the UV energy causes damage to or destruction of the epithelial cells. Injury to the epithelium is extremely painful as there are many nerve fibers located among the cells in the epithelial layer; however, it is usually temporary because the corneal epithelial layer is completely replaced in a day or two. The reddening of the conjunctiva (conjunctivitis) is accompanied by lacrimation (heavy tear flow), photophobia (discomfort to light), blepharospasm (painful uncontrolled excessive blinking), and a sensation of "sand" in the eye. Corneal pain can be severe but recovery usually only takes one to two days.

Corneal opacities can occur when near-ultraviolet (UV-A: 315 – 400 nm) and far-infrared (IR-B and IR-C: 1.4 – 1000 µm) radiation damage the stroma causing an invasion of the entire cornea by blood vessels which turns the cornea milky. Because exposure is normally followed by a latent period lasting between 6 and 12 hours (varies with the exposure and wavelength), cause and effect may be difficult to pinpoint. Ordinary clear glass or plastic lenses or visors will protect the eye from far-infrared laser radiation such as that emitted from the CO2 laser.

Cataract formation is also possible for UV-C, UV-B, UV-A, visible, IR-A, and IR-B wavelengths. Near ultraviolet and near-infrared radiation (UV-A, IR-A, and possibly IR-B) are absorbed heavily in the lens of the eye. Damage to this structure is serious because the lens has a very long memory. An exposure from one day may result in effects which will not become evident for many years (e.g., glassblower's or steel puddler's cataract). New tissue is continually added around the outside of the lens, but the interior tissues remain in the lens for the lifetime of the individual. The lens has much the same sensitivity to ultraviolet as the cornea, however:

1. The cornea is such an efficient filter for UV-C that little if any reaches the lens except at levels where the cornea is also injured.
2. In the UV-A band, the cornea has substantial transmission while the lens has high absorption (due to a pigment which accumulates throughout life and which could become dense enough to turn the lens almost black).
3. UV-B appears to be effective in causing lenticular opacities, however, if the exposure is low, the opacity may last only for a few days and then disappear.
4. For infrared wavelengths greater than 1.4 **µ**m (IR-B and IR-C) the cornea and aqueous humor absorb essentially all of the incident radiation, and beyond 1.9 **µ**m the cornea is considered the sole absorber, however, absorption of energy may cause heating of the interior structures which could contribute to opacities in the crystalline lens (at least for short exposure times).
5. For IR-A irradiation, damage appears to be due to the breakdown of crystalline cells contributing to opacities.

4.3 Skin Injury

Because of the skin's great surface area, the probability of laser skin exposure is greater than the probability of laser eye exposure. However, despite the facts that injury thresholds to the skin and eye are comparable except in the retinal hazard region, laser injury to the skin is considered secondary to eye injury. Form far-infrared and UV (regions where optical radiation is not focused on the retina) skin injury thresholds are approximately the same as corneal injury thresholds. Threshold injuries resulting from short exposure to the skin from far-infrared and UV radiation are very superficial and may only involve changes to the outer, dead layer (i.e., the "horny layer") of skin cells. Skin injury requires high powered laser exposure in the spectrum from 180 nm to 1 mm depending upon the wavelength, dose rate, and total energy absorbed. Such a temporary injury to the skin may be painful if sufficiently severe, but eventually it will heal, often without any sign of the injury because it lacks deep tissue involvement. Although unlikely to occur, injury to large areas of skin are more serious as they may lead to serious loss of fluids, toxemia, and systemic infection.

Chapter 5: Laboratory Controls

Although accidents occur, laser systems are designed to be safe. The objective of safe design is to insure that the equipment controls, interlocks, beam enclosures, shutters, and filters are appropriate to the hazard potential of the systems and the experience level of personnel operating and servicing the equipment. The goal of restricting human access to hazardous levels of optical radiation (or live electric currents) is usually achieved by permanent interlocks which are designed to be failsafe or failure-proof. For example, extensive use is made of mechanical-electrical interlocks. In this instance, a lateral or rotary movement of a hinge or a latch activates the switch which is in the power circuit for the laser. If the contacts are activated, the system will not operate. Interlocks are designed to require intentional operation to inactivate or bypass the interlock. This design of interlocks is to insure that even partial opening of a panel to a point where hazardous radiation can be emitted from the opening results in shutdown. Additionally, positive-activated switches (e.g., "dead man" type) are often used to insure operator alertness and reduce the risk of accidental firing.

For certain applications laser projections are used. In such instances, it is often desirable to alter the output beam pattern of a hazardous laser so a relatively safe pattern results. Methods to accomplish this include the use of wide beams, unfocused beams or beam diffusers. A CW laser with an emergent beam diameter of 10 - 20 cm is 100-times less hazardous than a laser of the same power with a 2 mm beam diameter. An unfocused beam is safer because the biological effect depends upon the total power and the beam irradiance. A diffuser is used to spread the beam over a greater area and thus change the output from intrabeam viewing to an extended source. Generally, the actual classification of the laser would not change unless the output beam diameter were greater than 80 mm. In theory, a diffuser could change a Class IV laser into a Class I or II laser; however, in practice, diffusers are most economical in reducing the hazard classification approximately one class. The safety applied to indoor laser installations usually depends upon the class of the laser.

- Class I (exempt) laser systems do not require much control. The user may opt to post the area with a Low Power Laser sign. The laser should be labeled with the beam characteristics. Some Class IIIb or Class IV laser systems are embedded in closed devices (e.g., printers). For such systems, the manufacturer normally installs enclosure interlocks and service panels to prevent tampering and persons using the system must receive training on hazards and controls for that laser before being designated an authorized user.
- Class II (low power) lasers require a few more controls. This is the first instance when posting the area with a CAUTION sign becomes mandatory. Additionally, non-reflective tools are often used to reduce reflected light. Controls applied to the system include blocking the beam at the end of its useful path, controlling spectator access to the beam, and controlling the use of view ports and collecting optics.
- Class IIIa lasers are widespread (e.g., laser pointers, levelers, and gun scopes are Class IIIa) and potentially hazardous when using optics. Thus, posting of the area with either CAUTION or DANGER signs depends upon the irradiance. Personnel maintaining such systems or conducting research with unenclosed beams should be given a baseline eye exam. Other controls which may be necessary to prevent direct beam viewing and to control specular reflections are:
    - Establish alignment procedures that do not include eye exposure
    - Control fiber optic emissions
    - Establish a normal hazard zone for outdoor use
    - Consider eye protection if accidental intra-beam viewing is possible
- Class IIIb laser systems are potentially hazardous if the direct or specularly reflected beam is viewed by the unprotected eye, consequently eye protection may be required if accidental intra-beam viewing is possible. It is at this point that many of the suggested controls become mandatory. Besides posting the area with DANGER signs, other control measures include:
    - Laser operated only by authorized operators who are trained on the systems laser hazards
    - Baseline eye exam required for maintenance and research applications
    - Spectators must be under the direct supervision of the operator
    - Laser power controlled by a key-operated master switch
    - Beam stops mandatory
    - Laser area interlocks (for CW power levels greater than 15 mW)
- Class IV laser systems that are pulsed visible and IR-A lasers are hazardous to the eye for direct beam viewing, and from specular (and sometimes diffuse) reflections. Ultraviolet, infrared, and CW visible lasers present a potential fire and skin hazard. The safety precautions associated with these high-risk lasers generally consist of publishing and adhering to an operational safety procedure manual; using door interlocks to prevent

exposure to unauthorized or transient personnel entering the controlled area; the use of baffles to terminate the primary and secondary beams; and the wearing of protective eye wear or clothing by personnel within the interlocked facility.

  - Safety interlocks at the entrance of the laser facility shall be so constructed that unauthorized or transient personnel shall be denied access to the area while the laser is capable of emitting laser radiation at Class IV levels.
  - Laser electronic firing systems for pulsed lasers shall be so designed that accidental pulsing of a stored charge is avoided. Additionally, the firing circuit shall incorporate a fail-safe (e.g., dead man) system.
  - An alarm system including a muted sound and/or warning lights (visible through laser protective eye wear) and a countdown procedure should be used once the capacitor banks begin to charge.
  - Good ambient illumination is essential when eye protection is being worn. Light colored, diffuse surfaces assist in achieving this goal.
  - Operate high-energy/high-power lasers by remote control firing with television monitoring. This eliminates the need for personnel to be physically in the room with the laser. However, enclosing the laser, the laser beam, and the target in a light-tight box is a viable alternative.
  - Because the principal hazard associated with high-power CW far-infrared (e.g., CO2) lasers is fire, a sufficient thickness of earth, firebrick, or other fire-resistant materials should be provided as a backstop for the beam.
  - Reflections of far-infrared laser beams should be attenuated by enclosure of the beam and target area or by eye wear constructed of a material that is opaque to laser wavelengths longer than 3 **μ**m (e.g., Plexiglas). Remember, even dull metal surfaces may be highly specular at far-infrared laser wavelengths (e.g., CO2 - 10.6 **μ**m).

Warning signs and labels are used to alert workers. Placarding of potentially hazardous areas should be accomplished for Class IIIb and IV lasers. Appropriate warning labels shall be affixed permanently to all Class II, III, and IV lasers and laser systems. Class II and IIIa usually use CAUTION signs/labels while class IIIb and IV use DANGER signs/labels.

A laser operational safety procedure manual is a document used to describe both a systems potential hazards and controls implemented to reduce the risk of injury from the laser. It may detail specific administrative controls (e.g., signs, lights), engineering controls (e.g., interlocks, enclosures, grounding, ventilation), required personal protection (e.g., eye wear, clothing) and training (laser safety, chemical safety).

As a minimum, an operational safety procedure must be promulgated for:

- Class IV laser systems.
- Two or more Class III lasers with different operators and no barriers.

- Complex or nonconforming interlock systems or warning devices.
- Modifications of commercial lasers which have decreased safety.
- Class II, III, or IV laser systems used outdoors or off-site.
- Beams of Class II, III, or IV laser which must be viewed directly or with collecting optics near beam.

Chapter 6: Laser Protective Eye Wear

Laser protective eye wear should be selected on the basis of protecting the eye against the maximum exposure anticipated while still allowing the greatest amount of light to enter the eye for the purpose of seeing. Protective eye wear is not the most desirable method of providing safety. The use of engineering controls (door interlocks, optical pathway enclosure, design of laser system to emit Class I levels only, etc.) are more reliable safeguards for total protection. Currently, there is no approved eye wear for the new ultra fast pulsed lasers.

Additionally, laser protective eye wear may create additional hazards from reduced visibility, it may be forgotten when required to be worn, or the wrong frequency eye wear may be selected. The primary usefulness of laser eye protection is in the testing of and training with laser devices (e.g., RDTE - research, development, testing and evaluation). Proper training of laser operators should preclude the need for laser eye protection. Emphasis should also be placed on the need not to aim a laser at other persons or at specular surfaces. The object of laser eye protectors is to filter out the laser wavelengths while transmitting as much of the visible light as possible. Because many laser systems emit more than one wavelength, each wavelength must be considered. When selecting eye wear, considering only the wavelength corresponding to the greatest output power is not always adequate. For example, a helium-neon laser may emit 100 mW at 632.8 nm and only 10 mW at 1150 nm, but safety goggles which absorb the 632.8 nm wavelength may absorb little at the 1150 nm wavelength.

The optical density (OD) is the parameter used for specifying the attenuation afforded by a given thickness of any transmitting medium. Optical density (OD) is used to describe the percent transmission by the equation: I/I_0 x 100 = %T 100 x 10^{-A}, where %T is percent transmitted, I_0 is the incident beam power and I is the transmitted beam power. Thus, a filter which attenuates a beam by a factor of 1000 (e.g., 1 x 10^3 and %T = 0.1) has an OD of 3 and goggles with a transmission of 0.000001% (e.g., 0.00000001 or 1 x 10^{-8}) has an OD of 8.0. The optical density of two highly absorbing filters, when stacked, is essentially the sum of two individual optical densities. The required optical density (OD_{req}) is determined by the maximum laser beam intensity to which the individual could be exposed. Not all laser applications will require laser protective eye wear. Some of the factors to consider when reviewing the need for type of laser eye wear are:

- Determine the wavelength(s) of the laser and the maximum viewing duration anticipated. This allows one to determine the exposure limit (protection standard) for the wavelength and viewing duration and also can distinguish between eye protection designed to protect against unintentional exposure (on the order of 0.25 seconds) and eye protection designed to protect against situations where intentional viewing of much greater duration is anticipated.

- Determine the maximum incident beam intensity. If the entire beam may enter the pupil of the eye, either through the use of optical instruments to focus the emergent beam or when the beam diameter is less than 7 mm, divide the laser output power/energy by the maximum area of the pupil (0.4 cm2). Otherwise the emergent beam radiant exposure (i.e., irradiance) is the maximum intensity. Compare the irradiance with the threshold of damage for the filter material to determine if it will provide protection against short-term, high irradiance, beam impact.
- Determine desired optical density (OD). The optimum OD is the minimum density required to attenuate the maximal radiant exposure/irradiance expected at the eye to the level of the protection standard.
- Review the available eye protection and select the design. Designs range from spectacle type to heavy-duty, coverall goggles. Some frames meet impact safety requirements. For crowded laboratory applications, it is recommended that filter surfaces be curved so that incident beams are reflected in a manner that reduces the beam irradiance rapidly with distance from the surface.

Not all protective eye wear is the same. The filters are designed to use selective spectral absorption by colored glass or plastic, or selective reflection from dielectric (or holographic) coatings on glass, or both. Colored glass absorbing filters are the most effective in resisting damage from wear and intense laser sources. Most absorbing filters are not case hardened to provide impact resistance, however, clear plastic sheets are generally placed behind the glass filter. Reflective coatings can be designed to selectively reflect a given wavelength while transmitting as much of the rest of the visible light as possible. Absorbing plastic filter materials have greater impact resistance, lighter weight, and are easy to mold into curved shapes; however, they are more readily scratched, quality control may be more difficult, and the organic dyes used as absorbers are more readily affected by heat and UV radiation and may saturate or bleach under q-switched laser irradiation. After purchase, eye protection should be checked periodically for integrity.

Chapter 7: Associated Laser System Hazards

Besides the risks from the laser energy, some laser installations may contain hazards from ancillary equipment used in the process. The following are potential associated laser system hazards.

- Electrical hazards. Most laser systems pose a potential for electrical shock (e.g., capacitor banks in pulse lasers, high-voltage DC or RF power supplies in CW lasers, etc.). While not usually present during laser operation, they are a risk during installation and maintenance. Insure high voltages are not exposed and capacitors are properly discharged. Water used as a cooling system on some lasers may increase the shock hazard.
- Chemical hazards. When a laser interacts with any material, energy is transmitted resulting in vibrational energy (heat). If the irradiance is high enough, molecular bonds are disrupted and small particles of the processed material are vaporized and separated. As they cool, they recondense forming fine solid particulate substances. Table 7.1 lists some Laser Generated Air Contaminants (LGAC) which may pose a hazard. Adequate ventilation is needed to control vaporized target materials; gasses from flowing gas lasers or laser reaction byproducts (e.g., bromine, chlorine, hydrogen cyanide, ozone, etc.); gases or vapors from cryogenic coolants; and vaporized biological target materials (from medical applications). Many dyes used as lasing media are toxic, carcinogenic, corrosive or pose a fire hazard. An MSDS should be available for any chemical handled in the laser laboratory. Cryogenic coolants (e.g., liquid nitrogen, helium, and oxygen) may cause skin and eye injury if misused.
- Collateral radiation hazards. Collateral radiation is radiation other than that associated with the primary laser beam. These include X-rays, UV, plasma and RF. Any power supply which requires more than 15 kV may be a source of x-rays.
- UV and visible radiation hazards. Laser discharge tubes and pumping lamps may generate UV and visible radiation at levels exceeding safe limits for the eye and skin. Flash lamps and CW laser discharge tubes may emit direct or reflected UV radiation which could be a potential hazard if quartz tubing is used.
- Fire hazards. Class IV lasers may cause fires in materials found in beam enclosures, barriers, stops and electrical wiring if they are exposed to high beam irradiance for more than a few seconds.
- Explosion hazards. High-pressure arc lamps, filament lamps, and capacitors may explode if they fail during operation. These should be enclosed in protective housings. Laser targets and some optical components may shatter if heat can not be dissipated quickly enough. Use adequate shielding when brittle material must be exposed to high intensity lasers. Radiation producing machines are regulated by Federal and State agencies. The Food and Drug Administration (FDA) regulates manufacturers of electronic systems capable of producing laser and high intensity light. The goal is to insure that manufactured systems are safe. However, it is possible that a laser lab may make changes either to the laser configuration or to the lasers use creating a potentially unsafe work place.

Table 7.1: Common Laser Generated Air Contaminants (LGAC)

Material	**LGAC**
Mild Steel	magnesium, silicon, chromium, nickel
Stainless Steel	chromium, nickel, other base metals
Wood	benzene, acrolein, alkenes, alcohols
Polycarbonate	benzene, PAHs, carbon oxide
Fabrics	formaldehyde, benzene, styrene, hydrogen cyanide
Formica	formaldehyde, hydrogen cyanide, methanol, furfural, furan, cyanomethal, acetate
Plexiglas	formaldehyde, methyl butadiene, methyl acrylate, limonene, methanol, phthalic acid, ester
Tissue	bacteria, viral strains, organic compounds, formaldehyde, benzene, hydrogen cyanide