15 Laser Safety

Laser, is an acronym for Light Amplification by Stimulated Emission of Radiation. Laser light is a form of electromagnetic radiation, but this radiation is usually not ionizing radiation (Figure 15-1). Because lasers are used in a great variety of applications throughout campus and laser light may cause injury if improperly used, this radiation safety manual provides a basic discussion of laser safety.

In medicine, physicians use the heating action of laser beams in microsurgery procedures to remove body tissue (e.g., OB/GYN, surgery, dermatology, etc.). The beam burns away the unhealthy tissue with little damage to the surrounding area. Additionally, lasers seal off blood vessels severed during the surgery, thus reducing the amount of bleeding. Ophthalmologists use lasers in both photodisruption and photocoagulation procedures to affix damaged retinas back to the eye's support system. Lasers are also used by laboratories in such applications as flow cytometry and cell separation. Industrial and engineering applications include the use of lasers to cut, drill, weld, guide and measure with high accuracy. In cutting applications, the laser light is focused to a point of 0.0025 mm, producing extreme heat (10,000 °F) that can cut through and melt extremely hard materials. Lasers are also used for alignment, leveling and surveying in construction and medical applications. In communications a laser can transmit voice messages as well as radio and TV signals via fiber optics. The benefit is a dramatically increased capacity as well as reduced interference.

Most of the lasers which are potentially hazardous are found in either single-use type dedicated rooms or in enclosed cabinets. There are no control on purchasing lasers so laboratory-type lasers can be purchased by anyone. Preventing accidental overexposures in this setting requires a system of administrative controls based on identifying the hazard and alerting the public and engineering controls to prevent access to the energized laser beam.

15.1 Characteristics and Components

Laser light has several features that are significantly different from an incandescent white light source. These characteristics include:

- 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 (i.e., 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 (i.e., one color) and coherent (i.e., in phase). White light is a jumble of colored light waves, each color is a different wavelength (or frequency). If all the wavelengths or colors except one were filtered out, the remaining light would be monochromatic. White light is propagated in all directions and is a jumble of phases because of reflection and scattering. If light waves are all parallel to one another, they are said to be coherent (i.e., the waves travel in a definite phase relationship with one another). In the case of laser light, the wave crests and the troughs coincide and the beam is coherent in both time and space, thus these waves reinforce one another.

- Laser beams can be continuous (CW - continuous wave) or pulsed. Pulsed lasers are switched on and off rapidly and may appear to be continuously emitting a beam of light.

- Not all lasers emit visible light. Some lasers produce infrared (IR) or ultraviolet (UV) light. Although this light cannot be seen, it is still capable of producing injuries.

Regardless of the application and the characteristics of a particular laser, most laser systems have three basic components (Figure 15-2) in common:

- Pumping system or energy source, can be a flash lamp, microwaves, chemical reaction, another laser, etc.
- Lasing medium may be a gas, liquid, solid, semiconductor, electron beam, etc.
- Resonant cavity which amplifies the energy of the light to a higher intensity.

Lenses, mirrors, shutters, absorbers, 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 can 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" state. If the orbital electron gives off this excitation 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 excited 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. This stimulated emission results in the amplification of the first wave. If the two waves strike other excited atoms, a large coherent beam can be built up. But if these waves strike unexcited atoms, the energy is absorbed and the amplification is lost. In the normal state of matter on 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.

15.1.a Ruby Lasers
To understand laser light production, consider the ruby laser (Figure 15-2 and 15-3). Ruby is composed of aluminum oxide with chromium impurities. The chromium atoms absorb blue light and become excited. They then drop first to a metastable level and finally to the ground (unexcited) state, giving off red light.

To "excite" atoms, lasers employ a pumping system. The ruby laser is made by placing a ruby rod within a spiral-shaped xenon flash lamp which provides the energy to excite the chromium electrons (other types of pumping systems include: optical, electron collision, and chemical reaction). Light from the flash lamp enters the ruby and excites most of the chromium atoms, many of these excited atoms quickly fall to the metastable level. Some atoms then emit red light and return to the ground state. The red light waves can then strike other excited chromium atoms, stimulating them to emit more red light.

A resonant optical cavity is formed by placing mirrors, one of which is 100% reflecting and the other only 50% reflecting, at each end of the lasing material (i.e., ruby rod). Lasers are constructed so the beam normally passes through the lasing material many times, exciting atoms and amplifying the number of emitted photons at each passage. When the photons arrive at the partially reflecting mirror, a portion is reflected back into the cavity and the rest emerges as the laser beam.

When most of the chromium atoms are back in the ground state, they absorb light, and the lasing action stops. The duration of the flash of red light from a ruby laser is very short, lasting only about 300 microseconds (i.e., 0.0003 seconds), but it can be very intense (i.e., some early lasers produced flashes of 10,000 watts). In continuous-wave lasers, such as the helium-neon laser, electrons emit light by jumping to a lower excited state, forming a new atomic population that does not absorb laser light, rather than to the ground state.

15.1.b Helium-Neon Lasers
One of the most common lasers found on campus is the helium-neon (HeNe) 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 HeNe 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. 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 helium atoms and excite some of them to metastable states from which their subsequent decay is restricted to processes which don't 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 lose their energy in several steps; one such step 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 currently do not have that ability). The metastable helium 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 diffraction and scattering (Figure 15-3).

The mirrors create a long optical path length which is needed for sufficient amplification, by stimulated emission of radiation, to occur. If this amplification exceeds energy losses 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.

15.1.c X-ray Lasers
In the mid 1980s a new method of generating x-rays was developed; the x-ray laser. These lasers focus the light produced by a conventional laser onto a thin metal wire, intensely heating it to produce a hot plasma, or ionized gas. The atoms of this gas are highly excited and emit x-ray photons, or packets of (nonvisible) light. These photons, in turn, strike other excited atoms, stimulating them to emit more x-rays. This cascading effect produces an intense beam of x-rays.

15.2 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.

15.2.a Radiation Characteristics
The pulse duration is the duration (i.e., ms, µs, or ns) 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 doesn't 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, \( \lambda \), is the distance between two peaks of a periodic wave. It is the inverse of the frequency, \( \nu \), the number of waves per second, and is related to the energy (i.e., the shorter the wavelength, the greater the energy; \( E = h \nu = hc/\lambda \)). Table 15-1 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.

Lasers are characterized by their output. The output of a CW laser is 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). Pulsed laser peak power 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) range. Pulsed laser output is 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).
15.2.b Components of the Eye

From the laser effects viewpoint, the eye (Figure 15-4) is composed of several subsystems: light transmission and focusing, light absorption and transduction, and maintenance and support systems.

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 make up 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 and narrowing (constricting) the pupil during 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 0.050 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 strong enough 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 to 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 (i.e., all of the retinal area surrounding the fovea) is involved in a variety of functions. Night vision is one of the primary functions of the retinal periphery because it has a high concentration of photoreceptor cells which operate during dim or dark conditions. 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 (scotoma) 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 scotomas. Even though the retina may be permanently damaged, the worker will eventually become aware 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 eye's 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.
15.3 Laser Hazard Classification

ANSI Standard Z136.1-1993, Safe Use of Lasers, provides comprehensive information for evaluating potential hazards from a laser system. Three aspects of a laser's use will influence the total hazard evaluation and the application of control measures. These include:

- The laser device's capability of injuring workers is measured in terms of the Maximum Permissible Exposure or MPE, which is measured by the radiant exposure, \( H \) (J/cm²) or the irradiance (power density), \( E \) (W/cm²) for point sources and the J/cm²/sr or W/cm²/sr (sr - steradian is a measure of solid angle, there are \( 4\pi \) steradians about a point in space) for extended sources (in 1993, ANSI removed use of extended source MPEs).
- 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 down into three areas:
  - 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 into any laser beam for any reason.
  - 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.
  - 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.
- The persons/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 15-2) 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.

### Table 15-2. Laser Classification

<table>
<thead>
<tr>
<th>Class</th>
<th>Type Hazard</th>
<th>Parameter(^1)</th>
<th>Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>No Hazard</td>
<td>P/A &lt; 8 hr MPE</td>
<td>Not required</td>
</tr>
<tr>
<td>II</td>
<td>Visible Laser</td>
<td>P/A &lt; ¼ sec MPE</td>
<td>Recommended</td>
</tr>
</tbody>
</table>
| IIIa  | Eye Hazard  | P/A ≤ 5 x Class 1 MPE  
                   P/A ≤ 5 x Class 2 MPE | Recommended |
| IIIb  | Eye / Skin Hazard | ≤ 0.5 W for t > ¼ sec  
                   ≤ 10 J/cm² for t < ¼ sec | Required |
| IV    | Diffuse Reflection Eye Hazard, Fire Hazard  
                   | ≥ 0.5 W for t > ¼ sec  
                   ≥ 10 J/cm² for t < ¼ sec | Required |

\(^1\)P/A = Laser Power / Pupil Area

15.3.a 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 \( \mu \)W. 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 printer and CD player may have class IIIb or IV lasers) the resulting system may be Class I. If a Class I system contains a more dangerous laser (Class IIIb or IV), 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. Preferably, interlocks should be provided on any removable part or panel which allows access to the enclosed laser.
15.3.b 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 (CW) or pulsed:

- Visible (400 nm to 700 nm), 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 (400 nm to 700 nm), repetitively pulsed laser devices that can emit a power exceeding the appropriate limit for 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.

15.3.c 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 the 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 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 (1.4 µm to 1000 µm) and ultraviolet (200 nm to 400 nm) laser devices (Table 15-1). Emit a radiant power in excess of the Class I limit for the maximum possible duration inherent to the design of 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 within an exposure time of 0.25 seconds or less.
- Visible (400 nm to 700 nm) CW or repetitive pulsed laser devices. 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 (400 nm to 1400 nm) pulsed laser devices. Emit a radiant energy in excess of the Class I limit but cannot emit a radiant exposure that exceeds that required to produce a hazardous diffuse reflection.
- Near-infrared (700 nm to 1400 nm) CW laser devices or repetitively pulsed laser devices. Emit 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 in excess of 0.25 seconds.

15.3.d Class IV - high power, high-risk

Class IV, "High-Power" laser systems have average outputs of > 500 mW for CW or > 10 J/cm² for a 0.25 second pulsed laser 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.). The Class IV systems are 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 (Table 15-1) 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 reflection.

15.4 Laser Effects

Table 15-3 summarizes laser biological effects. The primary laser danger is to the eye. This is the most common type of laser injury 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 on or on the eye.

Figure 15-5 shows the interaction of various electromagnetic radiation frequencies/energies with the eye.

High 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.

As can be seen in Figure 15-6, 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.

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 or scotoma within the irradiated area. A scotoma due to a lesion in the peripheral retina may go unnoticed. However, if the scotoma is located in the fovea, which accounts for central vision, severe visual defects will result. Such a central scotoma would occur if an individual were looking directly at the laser source during the exposure. The size of the scotoma 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 scotoma 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 scotoma (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 scotoma.

- **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 scotoma 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 scotoma size and result in an increased obscurance 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 (scotoma) 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.

### Corneal Effects

The anterior structures of the eye (cf. 15.2.b.1) 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 epithelial 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 damages the stroma causing an invasion of the entire cornea by blood vessels which turns the cornea milky. Because exposure is usually followed by a 6- to 12-hour latent period depending on 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 µm (IR-B and IR-C) the cornea and aqueous humor absorb essentially all of the incident radiation, and beyond 1.9 µm 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.

**Skin Injury**

Thermal effects are the major cause of tissue damage by lasers. Energy from the laser is absorbed by the tissue in the form of heat, which can cause localized, intense heating of sensitive tissues. The amount of thermal damage that can be caused to tissue varies depending on the thermal sensitivity of the type of tissue. Thermal effects can range from erythema (reddening of the skin) to burning of the tissue.

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 (Figure 15-7) except in the retinal hazard region, laser injury to the skin is considered secondary to eye injury. For 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.

**Accident Data Review**

Although the UW does not have a history of laser injuries, nationwide there is a relatively large database of incidents. One of the first reported injury occurred to a university student in 1964. While using a pulsed 20 joule, 41 msc ruby laser, he received a permanent macular burn of the right eye during a laser adjustment. In this instance, the student (wearing no laser protective eyewear) leaned over the laser from the side to adjust the Brewster window and the laser flash lamp unexpectedly fired, initiating a laser pulse. No retinal scotoma was observed 6 weeks following the exposure, but the vision was reduced to 20/200. While progress has been made in laser safety, the type of incidents occurring are still similar. Thus the university incident where a student was using a Ti-Sapphire laser (0.001 joules/pulse at 200 psec/pulse at 1 kHz). A chemistry department graduate student, while not wearing laser protective eyewear, was aligning optics on a chirped pulse Ti-Sapphire laser. The beam back scatter from the rear side of the system (estimated at about 1% of the total) caused a retinal lesion with initial hemorrhage and permanent blind spot in the central vision. As a first measure in protecting yourself, you should be aware of the type and magnitude of incidents. The three potential hazards from lasers are to the eye, to the skin, and non-beam injuries. A study of 330 incidents over the period 1964 - 1996 was undertaken with the following results (Tables 15-4 and 15-5).
Eye Injury
Eye injury is by far the most commonly reported laser related incident, being involved in slightly over 73% or 241 of the 330 recorded incidents. Of these incidents, over 91% involved some change of which 68% were permanent. Alignment activity is obviously the period of increased risk when working with lasers as indicated by the fact that 35.7% of the incidents occurred during alignment. The type of laser being used during 75.5% of these injuries were one of five: Nd:YAG, argon, dye, ruby, and HeNe.

Another fact of note is that not using laser eyewear appears to be a main cause of these injuries. Regular prescription glasses may provide some protection from UV and far infrared (IR-B, IR-C), but provides no protection for near infrared (IR-A) and visible lasers. Of the 220 cases reporting injury, laser protective eyewear was not being used or was not available in 209 cases (95%). Laser safety equipment failure is normally not a factor. Of the 11 eye injury cases using eyewear, 7 were due to improper choice or fit and only 4 were due to eyewear failure. This indicates a possible need for more appropriate information on limitations of eyewear and increased education regarding the proper use and selection of laser protective eyewear.

Skin Injury
Skin injuries are normally considered to be less important simply because the results of the injury are normally less disastrous than eye injury. The fact that 46 of the reported 330 incidents were skin related implies that they continue to occur and are clearly a problem in both industrial and medical environments.

Non-Beam Related Injury
Ancillary hazards (see 15.8) such as fire, electrical, equipment failure, laser generated air contaminants (LGAC) represent only 43 of the reported 330 incidents. Generally speaking, many laser sites containing a Class IV laser have, at some time, experienced some incident involving one or more non-beam type incident. The most dramatic of the non-beam incidents are electrical shock (5 deaths, 8 severe shock), fire and fumes and embolism (3 deaths). Although many of the non-beam events may be of a nature that they don’t become official laser incidents, they are commonly reported as industrial hygiene problems. Thus, it is important to note that these incidents do occur and they may be a significant hazard. For example, laser cutting of plastics can release highly toxic gaseous byproducts that can, in some instances, be life threatening. Similarly, live viruses have been reportedly detected in the smoke during laser surgery and the smoke may be mutagenic.

15.5 Laboratory Controls
Although accidents / incidents occur, laser systems are designed to be safe. The objective of safe design is to insure that the equipment controls (i.e., the "bells and whistles"), 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 fail-safe 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., "deadman" 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" operator.

**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 following 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 wearing of protective eyewear 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., deadman) system.

An alarm system including a muted sound and/or warning lights (visible through laser protective eyewear) 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 eyewear constructed of a material that is opaque to laser wavelengths longer than 3 µm (e.g., Plexiglas). Remember, even dull metal surfaces may be highly specular at far-infrared laser wavelengths (e.g., CO₂ - 10.6 µm).

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. Examples of such warning signs are seen in Figure 15-9 and appropriate templates are displayed in Figure 15-10 and 15-11 at the end of the chapter.

A laser operational safety procedure manual is a document used to describe both a system’s potential hazards and controls implemented to reduce the risk of injury from the laser. It may detail specific points-of-contact (e.g., safety officer, maintenance and repair), administrative controls (e.g., signs, lights), engineering controls (e.g., interlocks, enclosures, grounding, ventilation), required personal protection (e.g., eyewear, clothing), operational procedures (e.g., initial preparation, target area preparation, shutdown procedures, etc.), emergency response 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.

Figure 15-9. Laser Warning Signs
15.6 Laser Protective Eyewear

Laser protective eyewear 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 eyewear 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 eyewear for the new ultra fast pulsed lasers. Additionally, laser protective eyewear may create additional hazards from reduced visibility, it may be forgotten when required to be worn, or the wrong frequency eyewear 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 eyewear, 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 beam transmission using the equation \( \text{OD} = \log_{10} (I_0/I) \), where \( I_0 \) 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., \( 1 \times 10^3 \)) has an OD of 3 and goggles with a transmission of 0.000001% (e.g., 0.000 000 01 or \( 1 \times 10^{-8} \)) 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 \( \text{OD}_{req} \) is determined by the maximum laser beam intensity to which an individual could be exposed, or \( \text{OD}_{req} = (EL/H_0) \), where \( EL \) is the exposure limit (i.e., protection standard) and \( H_0 \) is the maximum exposure in the beam.

Not all laser applications will require laser protective eyewear. Some of the factors to consider when reviewing the need for type of laser eyewear 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 cm\(^2\)). 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. The optimum OD is the minimum optical density required to attenuate the maximal radiant exposure/irradiance expected at the eye to the level of the protection standard. Use \( \text{OD}_{req} \) from above where the expected radiant exposure/irradiance is \( H_0 \) and the protection standard is \( EL \).

- 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 eyewear 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. Never store laser safety eyewear with other eyewear.

15.7 Laser Dyes

Laser dyes are complex fluorescent organic compounds which, when in solution with certain solvents, form a lasing medium for dye lasers. Certain dyes are highly toxic or carcinogenic. Most of these dyes come in a solid powder form which must be dissolved in solvents prior to use in the laser system. Since these dyes frequently need to be changed, special care must be taken when handling these dyes since improper use of dyes or solvents may present a range of hazards for the laser researcher.

15.7.a Laser Dye Hazards

Although little is known about them, many organic laser dyes are believed to be toxic and/or mutagenic. Because they are solid powders, they can easily become airborne and possibly inhaled and/or ingested. When mixed with certain solvents (e.g., DMSO), they can be absorbed through unprotected skin. Direct contact with dyes and with dye/solvent solutions should always be avoided. The use of DMSO as a solvent for cyanide dyes should be discontinued, if possible. Preparation of dye solutions should be conducted in a fume hood and personal protective equipment (gloves, lab coats, etc.) should be worn. Contact the Laser Safety Officer at 2-9608 if you want additional information on laser dye toxicity.

A wide variety of solvents are used to dissolve laser dyes. Some of these (e.g., alcohols) are highly flammable and must be kept away from ignition sources. Fires and explosions resulting from improper grounding or overheated bearings in dye pumps are not uncommon in laser laboratories. Dye pumps should be inspected, maintained, and tested on a regular basis to avoid these problems. Additionally, dye lasers should never be left running unattended. Some of the solvents used with laser dyes may also be skin irritants, narcotics, or toxics. You should refer to the Material Safety Data Sheet (MSDS) which is supplied by the solvent manufacturer for additional information on health effects.

### Table 15-6. Common Dye Solvents

<table>
<thead>
<tr>
<th>Chemical Substance</th>
<th>Exposure Limits(^2) (ppm)</th>
<th>LD50(^1) (mg/kg)</th>
<th>Glove*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzonitrile</td>
<td>500</td>
<td>B, PVA</td>
<td></td>
</tr>
<tr>
<td>Benzyl alcohol</td>
<td>3,100</td>
<td>B', V</td>
<td></td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>10 / 75</td>
<td>400 - 1600</td>
<td>PVA, V</td>
</tr>
<tr>
<td>Chloroform</td>
<td>10 / 50</td>
<td>1060 - 2000</td>
<td>PVA, V</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>300</td>
<td>6000 - 30000</td>
<td>B', V, Ni</td>
</tr>
<tr>
<td>o-Dichlorobenzene</td>
<td>25 / 50</td>
<td>500</td>
<td>V(\dagger)</td>
</tr>
<tr>
<td>1,2-Dichloroethane</td>
<td>10 / 50</td>
<td>400</td>
<td>B', V</td>
</tr>
<tr>
<td>Dichloromethane</td>
<td>50 / 25</td>
<td>2,000</td>
<td>V(\dagger), PVA</td>
</tr>
<tr>
<td>Dimethylformamide</td>
<td>10</td>
<td>2,800</td>
<td>B, Ne(\dagger)</td>
</tr>
<tr>
<td>Dimethyl sulfoxide (DMSO)</td>
<td></td>
<td>19,700</td>
<td>B, Ne, V(\dagger)</td>
</tr>
<tr>
<td>1,4-Dioxane</td>
<td>25 / 100</td>
<td>4,200</td>
<td>B, PVA</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1,000</td>
<td>10,000</td>
<td>Ni, Ne(\dagger)</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>100 mg/m3</td>
<td>8,500</td>
<td>Ni, Ne, PVC(\dagger), Nr</td>
</tr>
<tr>
<td>Ethylene glycol phenyl ether</td>
<td></td>
<td>1,260</td>
<td>B, Ni</td>
</tr>
<tr>
<td>Glycerin Mist</td>
<td>10 / 15 mg/m3</td>
<td>12,600</td>
<td></td>
</tr>
<tr>
<td>Hexafluoropropoxypropanol</td>
<td></td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>200</td>
<td>5,600</td>
<td>Ne(\dagger)</td>
</tr>
<tr>
<td>N-Methyl-2-pyrrolidone (NMP)</td>
<td></td>
<td>4,200</td>
<td>Nr(\dagger)</td>
</tr>
<tr>
<td>Propylene carbonate</td>
<td></td>
<td>29,000</td>
<td>B, Ni</td>
</tr>
<tr>
<td>Tetrahyrofuran</td>
<td>200</td>
<td>3,000</td>
<td>PVA(\dagger)</td>
</tr>
<tr>
<td>Tetrahydrothiopheneoxide</td>
<td></td>
<td>3,500</td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td>50 / 200</td>
<td>5,000</td>
<td>PVA, V</td>
</tr>
<tr>
<td>1,1,1-Trdichloroethane</td>
<td>350</td>
<td>10,000</td>
<td>PVA, V</td>
</tr>
<tr>
<td>Tetrachloroethylene</td>
<td>10 / 25</td>
<td>460</td>
<td>Ni, V</td>
</tr>
<tr>
<td>Trifluoroethanol</td>
<td></td>
<td>2,000</td>
<td>Nr(\dagger), Ne(\dagger), Pe</td>
</tr>
</tbody>
</table>

\(^1\)Exposure limits are those cited in 1996 ACGIH Threshold Limit Values (TLV) booklet and current federal-OSHA PEL stds.

\(^2\)LD50 values based on oral administration to rats.


\(\dagger\)indicates permeation breakthrough time of less than 8 hours for glove-solvent combination.
15.7.b Laser Dye Handling, Storage and Disposal
Powdered laser dyes should never be handled where the airborne dust could be breathed. Dyes must be mixed only in a properly functioning fume hood. The proper protective equipment (safety glasses, chemical gloves, and lab coat) should always be used by the person handling the dye. The gloves being used should be resistant to the solvent being handled (see Table 16-7). Mixing of dyes and solvents should be done carefully to avoid spilling. Any spills or leaks should be cleaned up immediately with an individual wearing the proper personal protective equipment. Avoid breathing vapors from the solvent being used. Clearly identify and mark containers used for mixed dye/solvent solutions. Practice good hygiene and wash your hands thoroughly after handling dyes.

Limit the amount of mixed dye/solvent being stored in the laboratory. Once mixed, the dye/solvent should be stored in sealed Nalgene or other unbreakable plastic containers until ready to use. Be aware of any solvent incompatibility. Be sure to check transfer lines and pump connections for continuity prior to each use with the dye/solvent. All pumps and dye reservoirs must be placed in trays with sufficient capacity to contain all of the dye/solvent should it leak. This double containment method should prevent dye stains on floors and other surfaces.

Dyes and dye/solvent solutions are considered hazardous wastes and must be disposed of properly. Contact the Safety Dept., 2-8769 for disposal guidance or http://www.fpm.wisc.edu/chemsafety/oshmm.htm to schedule a disposal pickup.

15.8 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 of target materials are disrupted and small particles of the material (e.g., plastics, composites, metals and tissues) are vaporized which may produce toxic and noxious airborne contaminants. As they cool, they recondense forming fine solid particulate substances. Table 15-7 lists some of the 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 by products (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 (see Chapter 16) 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, RF excited components like plasma tubes and Q-switches. Any power supply which requires more than 15 kV may be a source of x-rays (cf. 10.1).

**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.

<table>
<thead>
<tr>
<th>Material</th>
<th>LGAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>mild steel</td>
<td>magnesium, silicon, chromium, nickel</td>
</tr>
<tr>
<td>stainless steel</td>
<td>chromium, nickel, other base metals</td>
</tr>
<tr>
<td>wood</td>
<td>benzene, acrolein, alkenes, alcohols</td>
</tr>
<tr>
<td>polycarbonate</td>
<td>benzene, PAHs, carbon oxide</td>
</tr>
<tr>
<td>fabrics</td>
<td>formaldehyde, benzene, styrene, hydrogen cyanide</td>
</tr>
<tr>
<td>formica</td>
<td>formaldehyde, hydrogen cyanide, methanol, furfural, furan, cyanomethyl, acetate</td>
</tr>
<tr>
<td>plexiglas</td>
<td>formaldehyde, methyl butadiene, methyl acrylate, limonene, methanol, phthalic acid, ester</td>
</tr>
<tr>
<td>acrylic</td>
<td>formaldehyde, limonene, styrene, chloromethane, acrolein, methyl esters</td>
</tr>
<tr>
<td>tissue</td>
<td>bacteria, viral strains, organic compounds, formaldehyde, benzene, hydrogen cyanide</td>
</tr>
</tbody>
</table>
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.

Compressed and toxic gases. Many hazardous gases are used in laser applications, including chlorine, fluorine, hydrogen chloride, and hydrogen fluoride. The use of mixtures with inert gases, rather than the pure gases is generally preferred. Hazardous gases should be stored in appropriately exhausted enclosures, with the gases permanently piped to the laser using the recommended metal tubing and fittings. An inert gas purge system and distinctive coloring of the pipes and fittings is also prudent. Compressed gas cylinders should be secured from tipping. Other typical safety problems that arise when using compressed gases are:

✓ working with freestanding cylinders not isolated from personnel
✓ regulator disconnects, releasing contents to atmosphere
✓ no removable shutoff valve or provisions for purging gas before disconnect or reconnect
✓ labeled hazardous gas cylinders not maintained in appropriate exhausted enclosures
✓ gases of different categories (toxics, corrosives, flammable, oxidizers, inerts, high pressure and cryogenics) not stored separately

Cryogenic Fluids. Cryogenic fluids are used in cooling systems of certain lasers and can create hazardous situations. As these materials evaporate, they can create oxygen deficient atmospheres and an asphyxiation hazard by replacing the oxygen in the air. Adequate ventilation must be provided. Cryogenic fluids are potentially explosive when ice collects in valves and connectors that are not specifically designed for use with cryogenic fluids. Condensation of oxygen in liquid nitrogen presents a serious explosion hazard if the liquid oxygen comes in contact with any organic material. While the quantities of liquid nitrogen that may be used are usually small, protective clothing and face shields must be used to prevent freeze burns to the skin and eyes.

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 laser’s use creating a potentially unsafe work place.

15.9 Laser Safety Audits

As noted in section 15.5, most laser systems are designed to be safe. They are manufactured with equipment controls, interlocks, beam enclosures, shutters, filters, etc. appropriate to the system’s potential hazard. However, because things continually change at a university it is a good practice to have a laser audit program to:

✓ Identify, assess, and mitigate laser beam hazards and laser-related non-beam hazards.
✓ Ensure compliance with the lab’s written Laser Safety Program.
✓ Update the laser inventory.
✓ Update the laser user list.
✓ Educate users in on-the-job laser safety
✓ Build rapport with the laser user(s).

The frequency of these laser audits varies depending on the nature of the laser hazard, the requirements prescribed in the operational safety procedure manual, available auditing resources, etc. However, the audits should be frequent enough to address changes in the configuration and/or the laser system use, but not so frequently that it adversely impacts the operation of the laser user.

The audit should be conducted by a qualified laser safety individual. While laser users may be qualified to conduct self-audits, official audits should be conducted by a Safety Department representative. However, the audit should not be a contentious event and the auditor should strive to build rapport with the laser user(s). Factors to consider in building this rapport include:

✓ Make an appointment to perform the initial laser facility visit.
✓ Provide the laser user with a copy of the laser safety program document prior to the initial visit.
✓ Initially emphasize the service component of this audit rather than the regulatory/enforcement component.
By conducting an on-site audit, crucial information on each laser system, application and use environment can be ascertained. Some preliminary information to review includes the laser technical criteria (wavelength, output, beam diameter, etc.) laser user data (training dates and disposition of eye exams, if required). Review the diagram of the laser facility noting the beam path, equipment locations, doorways, etc. Properly document the initial visit and provide the laser users with a copy designating what items need correction and what actions are required. As part of the audit, perform appropriate follow-up to assure initial compliance.

15.9.a Auditing Laser Beam Hazards
Although audits may be conducted at anytime, it is usually easier (and safer) to perform audits with the laser not energized. For this reason, official audits are conducted by appointment. Items checked during the audit:

- Determine the locations of all exposed optics and the beam path. In many cases the laser user can assist you in this process.
- Examine the walls of the facility in the beam plane for burn marks or other artifacts to determine if the laser beams have left the optical table (or other area of use). Look behind beam stops to see if they are being left out of position when you are not there.
- Determine if the beam(s) are at eye level when the user is sitting or standing. Examine the optical table for items such as unused optics, tools, etc. which might present a specular reflection hazard.
- Verify that beam enclosures, beam tubes, fibers, collimators, etc. are in position, secured and properly used.
- Consider if the beam is being manipulated in some way which affects the hazard (focusing, enlarging beam diameter, pulse manipulation, filtration, pumping, etc.).
- Examine the laser use environment for compatibility with the beam characteristics (cardboard beam stops, uncovered windows, etc.).
- Check all interlocks, switches, and shutters to assure they are operating properly.
- Examine laser safety eyewear to determine whether it is appropriate for the laser hazards, is scratched or has melt marks on-the lens. If skin protection is required, make sure it is adequate.
- Check postings, labeling, warning lights, etc. to assure they meet compliance.
- Examine the standard operating procedures for safety considerations.
- Determine if training, eye exams, etc. requirements have been met by the laser user(s).

15.9.b Auditing Non-Beam Hazards
The laser may not be the only potential safety hazard in a facility. While conducting the audit of the laser system, it is both cost effective and prudent to check for other, non-laser potential hazards.

- Examine the room for obvious physical hazards (cords, obstructions, etc.).
- Examine the room for fire and explosion hazards (solvent storage issues, blocked fire extinguishers, poorly maintained dye pumps, etc.).
- Determine if toxic laser media (halogen gases, laser dyes, etc.) are being used and if proper controls / precautions are being utilized. Determine if laser generated air contaminants (LGAC) are a concern in the laser application.
- Verify that engineering controls (dye mixing hoods, LGAC ventilators, etc.) are maintained and working.
- Survey the area for electrical hazards, concentrating on lasers and laser power supplies. Assure optical tables are grounded (especially if cooling water is being used).
- If compressed or cryogenic gases are being used, verify that appropriate controls/procedures are being utilized.
- Determine if there are collateral radiation hazards associated with laser power supplies or excitation sources.
- Review the non-laser safety procedures used in the laser facility. Concentrate on the used of personal protective equipment (PPE) and emergency procedures.

15.9.c Post Audit Actions
With all audits, it is good practice to meet with the laser user(s) before leaving the facility to inform them of the preliminary results of the audit. This should include not only problems found and corrections needed, but also good points of their safety program. Because proper documentation of audits is essential, use a formal check-off type survey form to insure consistency. An example of such a form can be found in Appendix C. All items of noncompliance should be clearly identified in the documentation sent to the laser user and all required actions
should be clearly identified (along with a required time of completion) in the documentation sent to the laser user. Insure that all pertinent individuals are copied on audit reports.

**15.9.d Operational Safety Tips**
The laser user can prevent laser accidents. Sixty percent of laser accidents in research settings occur during the alignment process. If individuals suspect they have received a laser hit, they should contact University Health Services and the laser safety officer. Unfortunately, experience has demonstrated that most laser injuries go unreported for 24 - 48 hours by the injured person. This is a critical time for treatment of the injury. Post-accident investigations often reveal that laser-associated accidents result from unsafe practices. Some of the causes of preventable laser accidents are:

- Not wearing protective eyewear during alignment procedures
- Not wearing protective eyewear in the laser control area
- Misaligned optics and upwardly directed beams
- Improper methods of handling high voltage
- Available eye protection not used
- Intentional exposure of unprotected personnel
- Lack of protection from nonbeam hazards (see Section 15.8)
- Failure to follow procedure
- Bypassing interlocks, door and/or laser housing
- Insertion of reflective materials into beam paths
- Lack of preplanning
- Turning on power supply accidentally
- Operating unfamiliar equipment
- Wearing the wrong eyewear

To reduce the risk of accidents, incorporate into the lab's laser operational safety procedure a few additional safety tips to be followed especially when performing laser alignment:

- No unauthorized personnel will be in the room or area.
- Locate controls so that the operator is not exposed to beam hazards.
- Laser protective eyewear will be worn. If you can see the beam through your laser eyewear, you are not fully protected.
- Make sure warning / indicator lights can be seen through protective filters.
- All laser users should be trained and familiar with their equipment.
- The individual who moves or places an optical component on an optical table is responsible for identifying and terminating each and every stray beam coming from that component.
- Terminate beams or reflections with fire-resistant beam stops. Anodized aluminum or aluminum painted black (which is not necessarily fire-resistant) can work well for this purpose.
- Use surfaces that minimize specular reflections.
- To reduce accidental reflections, watches and reflective jewelry should be taken off before any alignment activities begin. Don't wear neckties around Class 4 open beam lasers.
- Enclose as much of the beam as possible
- Beam blocks must be secured.
- Don't direct the beam toward doors or windows.
- When the beam is directed out of the horizontal plane, it must be clearly marked.
- A solid stray beam shield must be mounted above the area to prevent accidental exposure to the laser beam.
- All laser users must receive an orientation to the laser use area by an authorized laser user of that area.
- The lowest possible / practical power must be used during alignments.
- When possible, a course alignment should be performed with a HeNe alignment laser.
- Have beam paths at a safe height, below eye level when standing or sitting, not at a level that tempts one to bend down and look at the beam. If necessary, place a step platform around the optical table. Close and cover your eyes when stooping down around the beam (i.e., when you will pass by the beam at eye level).

**15.10 Review Questions** - Fill-in or select the correct response
1. Three basic components laser systems have in common are: __________, __________, and __________.
2. All lasers emit visible light. true / false
3. The frequency of the helium-neon laser is __________. This is in the __________ spectral band.
4. The wavelength of the laser light is related to the energy of the laser beam. true / false
5. The cornea transmits most laser wavelengths except for UV and far-IR wavelengths, which at high energies may burn it. true / false
6. The retina is particularly sensitive to __________ and __________ laser beams.
7. The closer a laser injury is to the fovea, the greater the chance of severe dysfunction. true / false
8. The laser hazard classification system has __________ classes.
9. Class _____ are termed “low-risk” laser systems, and class _____ are termed “high-risk” laser systems.
10. Class II laser systems must have a __________ label affixed.
11. Class IIIb and class IV laser systems must have a __________ label affixed.
12. The primary biological hazard from lasers is to the __________.
13. A blind spot in the visual field is a __________.
14. Laser eye injuries can be permanent or temporary. true / false
15. Some laser light that cannot be seen is still capable of producing injury. true / false
16. The probability of laser skin injury is greater / less than the probability of laser eye injury.
17. The goal of restricting human access to hazardous levels of optical radiation is usually accomplished by permanent __________ which are designed to be fail-safe.
18. __________ and __________ should be used to alert workers of potential hazards from class II, III, and IV lasers.
19. Class IV UV, IR, and CW visible lasers present a potential fire and skin hazard. true / false
20. Protective eyewear should be checked periodically for integrity. true / false

15.11 References
Laser Institute of America, Oft-ignored Air Contaminants Crucial Issue for Industry, Health Care, LIA Today, July, 1999
Rockwell, R. J. Jr., Laser Incidents: A review of Recent Events, presented at Advanced Concepts in Laser Safety

Figure 15-10. Class 2 and 3a Warning Sign
Figure 15-11. Class 3b and 4 Warning Sign
LASER AUDIT

Auditor's Name: ________________________________ Date of Audit: ________________
Location of Laser System: ________________________________
Name of Laser User: ________________________________ Contact during Audit: ________________________________

Laser system Information
Laser Type: ________________________________ Laser Class: _______ Laser Make: ________________________________
Laser Model: ________________________________ Laser Serial Number: ________________________________
Wavelength: _______ nm Output (max/used): ________________________________ W or J (circle one)
Beam Diameter at Aperture: ________________ mm Beam Divergence: ________________ mrad
Pulse duration: ________________ sec Pulse Frequency: ________________ Hz
Laser is Q-Switched / Mode locked: Y or N (circle one)
Laser is: active or inactive (circle one)

Laser Posting, Labeling and Security Measures
Entrances properly posted: Y N Comments: ________________________________
Room security adequate: Y N Comments: ________________________________
Door interlock system: Y N NA Comments: ________________________________
Laser status indicator outside room: Y N NA Comments: ________________________________
Laser class label in place: Y N Comments: ________________________________
Laser hazard label in place: Y N Comments: ________________________________
Laser aperture label in place: Y N Comments: ________________________________

Laser Unit Safety Controls
Protective housing in place: Y N Comments: ________________________________
Interlock on housing: Y N NA Comments: ________________________________
Interlock on housing functioning: Y N Comments: ________________________________
Beam shutter present: Y N Comments: ________________________________
Beam shutter functioning: Y N Comments: ________________________________
Key operation: Y N Comments: ________________________________
Laser activation indicator on console: Y N Comments: ________________________________
Beam power meter: Y N Comments: ________________________________
Emergency shutoff available: Y N Comments: ________________________________

Laser Configuration Diagram Attached

Additional Comments:
Date of Audit: ____________________

**Engineering Safety Controls**

- Laser secured to table: Y N  Comments: ________________________________
- Laser optics secured to prevent stray beams: Y N  Comments: ________________________________
- Laser at eye level: Y N  Comments: ________________________________
- Beam is enclosed: Y N  Comments: ________________________________
- Beam barriers in place: Y N  Comments: ________________________________
- Beam stops in place: Y N  Comments: ________________________________
- Remote viewing of beam: Y N  Comments: ________________________________
- Beam condensed or enlarged: Y N  Comments: ________________________________
- Beam focused: Y N  Comments: ________________________________
- Beam intensity reduced through filtration: Y N  Comments: ________________________________
- Fiber optics used: Y N  Comments: ________________________________
- Windows in room covered: Y N NA  Comments: ________________________________
- Reflective materials kept out of beam path: Y N  Comments: ________________________________
- Beam management documented: Y N  Comments: ________________________________
- Physical evidence of stray beams: Y N  Comments: ________________________________
- Class 4 diffuse reflection hazard: Y N NA  Comments: ________________________________

**Administrative Safety Controls**

- Authorization up-to-date: Y N  Comments: ________________________________
- Authorization posted: Y N  Comments: ________________________________
- SOP up-to-date: Y N  Comments: ________________________________
- SOP posted: Y N  Comments: ________________________________
- Emergency contact list posted: Y N  Comments: ________________________________
- Laser safety guidelines posted: Y N  Comments: ________________________________
- Laser safety policy manual available: Y N  Comments: ________________________________

**Other Laser Safety Measures**

- Eye exam requirement met: Y N  Comments: ________________________________
- Proper laser eye protection available: Y N NA  Comments: ________________________________
- Proper skin protection available: Y N NA  Comments: ________________________________
- All users have met training requirement: Y N  Comments: ________________________________

**Non Beam Hazards**

- Toxic laser media in use: Y N  Comments: ________________________________
- Fume hood for dye mixing: Y N NA  Comments: ________________________________
- Cryogens in use: Y N  Comments: ________________________________
- Compressed gases in use: Y N  Comments: ________________________________
- High voltage power hazard: Y N  Comments: ________________________________
- Optical tables properly grounded: Y N  Comments: ________________________________
- Collateral radiation hazard: Y N  Comments: ________________________________
- Explosion hazard: Y N  Comments: ________________________________
- Fire hazard: Y N  Comments: ________________________________
- LGAC production: Y N  Comments: ________________________________