LIGHT

Introduction to Optics and Photonics

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PHOTON
and
PHOTON2

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People sometimes take misguided approaches to the safe use of lasers. For example, when bar code scanners were first introduced in checkout lanes at a local supermarket, several clerks began to stand as far from the laser scanner as their arms would permit. When asked about this odd behavior, one cashier replied, "The manager told us to be careful of the radiation, and it's aimed right at us!" At the other end of the safe-use spectrum is the video instructor who flashed a laser pointer toward the camera and stated "It's just a light." The safe use of lasers does not require fear, but rather caution, knowledge of the properties of laser light, and some common sense.

Chapter 1

LASER SAFETY OVERVIEW

1.1 WHY LEARN ABOUT LASER SAFETY?

The availability of a large variety of affordable lasers has made the laser a common tool in industry, medicine, research and education. You will no doubt use lasers or see laser demonstrations if you are enrolled in an optics course. Whether you are working with lasers in a school laboratory, using lasers on the job, or listening to music on a CD player, you should be aware of how lasers differ from other light sources and how these differences translate into rules for safe usage of lasers.

The safe handling and use of lasers depends on many factors: the wavelength (or color) of the light, the power (or power density, called *irradiance*), the viewing conditions, and whether the laser is continuously on (called *continuous wave,* or *cw)* or pulsed. We will discuss the basic concepts of laser safety in this chapter, and throughout one important idea prevails: *treat every laser with respect and care.*

Many state, federal and international laser safety standards exist, but the one most often quoted in the United States is the American National Standards Institute's (ANSI) Z136 series of laser safety standards. The parent document, *ANSI Z136.1*, provides complete information on laser classifications, hazards and controls, and is designed to be a reference for users of all types of lasers. Other documents in the series are numbered sequentially (for example, Z136.2, Z136.3) and cover specific uses of lasers in areas such as health care, education, telecommunications and outdoor light shows. The documents are available from the Laser Institute of America at its web site www.laserinstitute.org.

The International Electrotechnical Commission (IEC) has also created a series of laser safety regulations covering all aspects of laser use and laser product labeling. Like the ANSI standards used in the United States, these international regulations are constantly being updated to reflect current research on laser hazards and new types of lasers. ANSI and IEC work together in an effort to harmonize regulations worldwide, a necessity in a global economy.

American manufacturers of lasers and laser systems must comply with regulations of the Center for Devices and Radiological Health (CDRH) of the Food and Drug Administration (FDA). Among the product safety standards is a requirement that each laser must bear a label indicating the laser hazard classification and information on the beam power and wavelength. Since 2001, the CDRH has allowed American laser manufacturers to conform to the IEC regulations, which reduces the burden of having to show compliance with two different sets of rules. It does add confusion, however, since the ANSI and CDRH classification are not quite the same, as we will see.

1.2 CHARACTERISTICS OF LASER LIGHT

The video instructor in the introductory paragraph was correct that a laser produces light. (We are including ultraviolet, visible and infrared radiation in this broad definition of light.) However, laser light has some very unique characteristics that distinguish it from ordinary light sources. After all, you might be burned by touching a 60 watt light bulb, but a 60 watt laser can cut metal! The light from most lasers is usually described as:

monochromatic Lasers emit a single wavelength (color) or narrow band of wavelengths.

coherent The light produced by a laser consists of waves that are "in step." (Coherence will be further explored in Chapter 6.)

highly directional Most laser beams do not spread much as they propagate. We say they are "collimated" and, as a result, beam energy is concentrated in a small area.

In Chapter 9, we will further explore the properties of laser light.

1.3 LASER HAZARDS

As a result of the unique characteristics of laser light, laser users need to be aware of specific hazards associated with lasers. These hazards are often grouped into three main categories: eye hazards, skin hazards and secondary hazards. We will concentrate on eye hazards and eye safety, because the loss of vision is a life-altering occurrence. It should be noted, however, that electrical hazards can be the most lethal hazards associated with laser operation.

Eye Hazards

The human eye is designed to focus visible light onto the light-sensitive retina, forming an image that is eventually interpreted by the brain. Since near infrared (IR) light also passes through the cornea and lens, it focuses on the retina as well. However, near IR light does not have sufficient energy to stimulate the retinal sensors to produce a signal. That is, we can't see near IR light, but it is still being focused on the retina and may damage retinal tissue.

Figure 1.1 illustrates the focusing process in the eye for rays that enter nearly parallel to the optical axis of the eye. (A more detailed diagram is found in Chapter 8.) This is the situation when an object is located far from the eye. In the same way, collimated laser light focuses to a very tiny spot on the retina. A rule of thumb is that the light entering the eye from a collimated laser beam is concentrated by a factor of about 100,000 times when it strikes the retina because the area of the focal spot on the retina is approximately 1/100,000 of the pupil area. That means a 0.10 W/cm^2 laser beam would result in a 1000 W/cm^2 exposure to the retina!

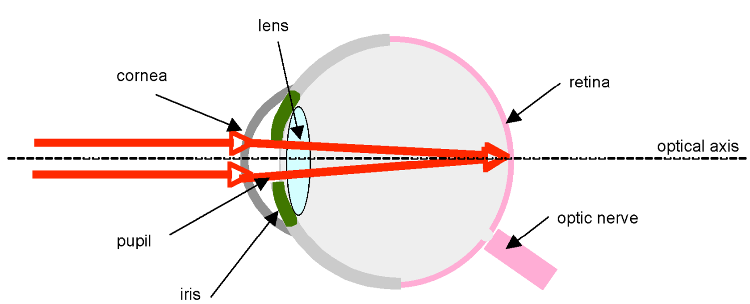


Figure 1.1 - Focusing effects of the human eye.

Wavelength Dependence

When light strikes a material, it may be reflected, transmitted, scattered or absorbed. To some extent, all of these processes occur. You are familiar with these behaviors of light from everyday experience. Visible light is reflected by a shiny surface, transmitted by a clear pane of glass, scattered by fog, and absorbed by a piece of black cloth.

Damage occurs when radiation is absorbed by tissue. Whether radiation is absorbed or harmlessly passes through depends on the type of material and the wavelength. It is clear that hazardous effects to various structures of the eye depend on the wavelength of the laser radiation and the type of tissue exposed. As shown in Table 1.1:

Mid and far infrared (so-called IR-B and IR-C) and mid and far ultraviolet (UV-B and C) wavelengths are absorbed by the cornea and may damage corneal tissue.

Near ultraviolet (UV-A) wavelengths pass through the cornea and are absorbed by the lens. This can cause lens clouding (cataracts).

Visible and near infrared (IR-A) wavelengths pass through the cornea and lens and are focused on the retina. This portion of the spectrum is called the "retinal hazard region."

Certain specific wavelengths in the IR-A and IR-B regions are also absorbed by the lens, which may cause damage.

UV-C	UV-B	UV-A	VISIBLE	IR-A	IR-B	IR-C
100 nm-280 nm	280 nm-315 nm	315 nm-400 nm	400 nm-700 nm	700 nm-1400 nm	1400 nm-3000 nm	3000 nm-1 mm
Cornea	Cornea	Lens	Retina	Retina	Cornea	Cornea

Table 1.1 Laser spectral regions (approximate wavelengths) and eye damage.

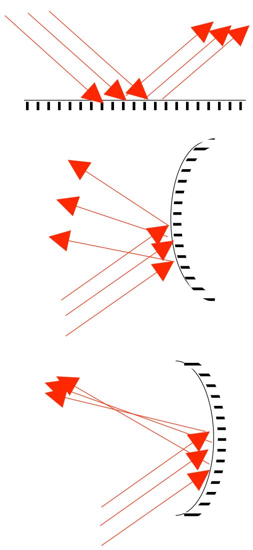


Figure 1.2 - Specular reflections from flat, convex and concave surfaces.

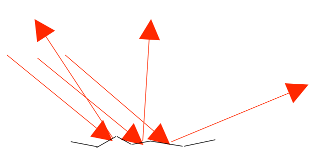


Figure 1.3 - Diffuse reflection from a rough surface.

Viewing conditions

The damage caused to your eye by exposure to laser light depends on the amount of light energy absorbed. The most hazardous viewing condition is *intrabeam* viewing, that is, looking directly into the beam. Note that looking at a beam from the side is normally not hazardous. Despite what you may have seen in science fiction movies, a beam of light is not visible at right angles to the direction of propagation unless there is something to scatter the light out of the beam and into your eyes. For example, to see the beam of a laser pointer there must be dust or fog in the room.

Reflected beams may or may not be harmful to look at, depending on the laser power, the laser wavelength, the curvature of the reflector surface, and whether the reflection is specular or diffuse. Specular reflections are mirror-like reflections from shiny objects, and they can return close to 100% of the incident light. Flat reflective surfaces will not change a fixed beam diameter, only the direction of propagation. Convex surfaces will cause beam spreading and concave surfaces will make the beam converge (Figure 1.2).

As Figure 1.3 shows, diffuse reflections result when irregularities in the surface scatter light in all directions. Whether a reflection is specular or diffuse depends upon the wavelength of incident radiation as well as on the smoothness of the surface. Specular reflection requires that the surface roughness must be less than the wavelength of the incident light. Thus, a surface that diffusely reflects 500 nm visible light might cause specular reflection of 10.6 µm wavelength radiation from a carbon dioxide (CO_2) laser.

Skin Hazards

Although skin injuries are not as life-altering eye injuries, skin damage may occur with high power lasers. Exposure to high levels of optical radiation may cause skin burns. This *thermal damage* is the result of extreme heating of the skin and is a particular danger when medium and high power infrared lasers are being aligned. Accelerated skin aging and the increased risk of cancer may result from exposure to ultraviolet wavelengths. This is called *photochemical damage* and it is similar to a sunburn. Protective clothing such as gloves and flame-retardant laboratory coats may be required for some laser applications.

Secondary Hazards

Some of the most life threatening hazards are not due to the laser beam, but are the result of associated equipment or byproducts of laser processes. These hazards include:

Electrical Hazards Electric shock is potentially the most lethal hazard associated with laser use. Electrical hazards most often result from inappropriate electrical installation, grounding or handling of the high voltage associated with many lasers. The power supply for a common helium neon laser includes capacitors that hold an electrical charge long after the laser is shut off. While not ordinarily lethal, the shock resulting from grabbing the exposed connector is certainly painful.

Fire and Explosion Hazards High-pressure arc lamps, filament lamps and associated optics can shatter or explode. High power lasers used for cutting may also present fire hazards, particularly if used in enclosures or near flammable materials.

Other Associated Hazards Operation of a laser system may involve the use of compressed gases, toxic dyes or cryogenic (extremely cold) liquids. Dangerous fumes may be generated when the laser is used for material processing, requiring engineered ventilation systems. So-called *laser generated air contaminants* result from the interaction of high-energy laser radiation, assist gases used in material processing, and the material itself. In addition to molten and evaporated materials liberated from the processed surface, new noxious and toxic compounds may be formed in some processes including metal oxide fumes, cyanide and formaldehyde. When lasers are used in a medical setting, particles of biological origin such as bacteria may be released into the air.

1.4 LASER HAZARD CLASSIFICATIONS

How can a laser user know the level of danger associated with a given laser? Laser hazard classifications provide a simplified method to make users aware of the potential hazards associated with radiation produced by a laser. The classifications are the result of research and experience with sunlight and manmade sources of light, as well as laser emissions. Until recently, different laser classification schemes were used in North America and in Europe. In order to assist manufacturers operating in both markets, CDRH (USA) agreed to accept the IEC (European) standards, known as IEC 60825-1. Although the ANSI classifications are being revised and will most likely adopt the IEC classifications, for now both IEC and ANSI laser hazard classifications are in effect.

CDRH, IEC and ANSI have in common four major laser hazard classifications based mainly on the laser emission wavelength and power, although they differ in the sub-classifications. (In fact, one set of standards uses Roman numerals instead of Arabic numbers, to add to the confusion!) In this chapter we present a brief and simplified description of hazard classifications. For more detail and the most recent information, you should consult the latest ANSI Z136.1 standard. In what follows, the sub-classifications with an IEC notation are not part of the ANSI classification scheme for laser users, but may be seen on laser equipment.

Class 1 lasers are of such low power that they cannot cause injury to the human eye or skin. Few lasers are Class 1, however the class also includes more powerful lasers located in enclosures that limit or prohibit access to the laser radiation. For example, Class 1 lasers include laser printers, DVD players and even high-powered laser cutting systems that do not allow access to the beam while in operation. These so-called *embedded* laser systems are considered Class 1 as long as the enclosure is intact.

Class 1M is a new (IEC) classification for lasers that are normally safe for eyes and skin, but may cause injury to the eyes if the output is concentrated using optics. For example, a highly divergent beam might be considered *eye safe* unless it is focused with a lens.

Class 2 lasers must emit visible radiation. They have output power higher than that of a Class 1 laser but less than 1 mW. This upper limit is important because the definition of Class 2 assumes that a person will blink or turn away from a brilliant source of light within one quarter of a second, before the eye is harmed. This is called the *human aversion reaction time,* or *blink reflex*, and it is based on many years of medical research with human subjects. Class 2 lasers will not injure the eye when viewed for 0.25 seconds or less.

However, like many conventional light sources, they may cause injury if stared at for a longer time.

Class 2M is a new (IEC) classification for lasers that produce visible output with power less than one milliwatt. The eye is protected by the aversion reaction to bright light, unless the beam in concentrated by optics such as a telescope.

Class 3A lasers normally will not cause injury when briefly viewed with the unaided eye. Nonetheless, users should use caution and avoid viewing the beam directly. For visible lasers, the output power levels range from 1 mW to 5 mW. Many laser pointers are Class 3A. The IEC **Class 3R** classification is similar to Class 3A.

Class 3B includes laser systems with constant power output (cw lasers) from 5 mW to 500 mW. Repetitively pulsed laser systems with beam energy between 30-150 millijoules per pulse for visible and infrared light or greater than 125 millijoules per pulse for other wavelengths are also included in Class 3B. The average power for the pulsed lasers must be less than 500 mW. Class 3B lasers can produce eye injury when viewed without eye protection and could have dangerous specular reflections. Eye protection is required when using Class 3B lasers.

All laser systems that exceed Class 3B limits are considered **Class 4**. Viewing *either* the specular or diffuse reflections of the beam can be dangerous. Class 4 lasers can also present a skin or fire hazard, and both eye and skin protection are required when operating them. Commercially available Class 4 systems are often completely contained in an enclosure so that the overall system is rated Class 1. Interlocks and other controls prevent the operation of the laser when the enclosure is opened.

1.5 IRRADIANCE AND MAXIMUM PERMISSIBLE EXPOSURE (MPE)

How is protective equipment chosen for a particular laser application? In addition to the laser wavelength, the power density or *irradiance* must be considered. Irradiance is a central concept in the discussion of laser hazards and laser classification. It is defined as the power per unit area, and is often (but not always) given the symbol E or E_e. The standard (SI) unit of irradiance is W/m^2, but it is often more conveniently expressed in W/cm^2.

$$E = \frac{P}{A} \tag{1.1}$$

IRRADIANCE

In Equation 1.1, A is the area illuminated by light incident with power P. Note that the letter E is also used to represent energy as well as electric field strength. It is usually clear from the context and always clear from the units which quantity is being considered.

EXAMPLE 1.1

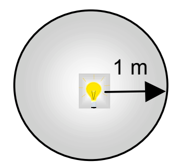
Compare the irradiance from a 60 W light bulb at a distance of 1 meter from the bulb to that of a 5 mW laser pointer which makes a 4 mm diameter spot one meter from the laser.

Solution:

The light from the bulb spreads out in all directions, so the total power (60 Watts) passes through the surface of a sphere 1 meter in radius. (Of course, much of the radiation from an ordinary light bulb is infrared—heat—and not visible light!)

$$A = 4\pi\, r^2 = 4\pi\ (100\text{ cm})^2 = 126000\text{ cm}^2$$

$$E = \frac{P}{A} = \frac{60\text{ W}}{126000\text{ cm}^2} = 0.00048\,\frac{\text{W}}{\text{cm}^2}$$

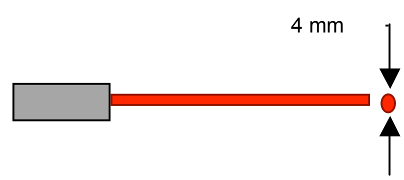


The irradiance of the light bulb is 0.00048 W/cm^2 one meter away from the bulb.

The laser beam makes a spot with a 4 mm diameter. The power (5 mW) is concentrated onto a 2 mm (= 0.2 cm) radius circle.

$$A = \pi\, r^2 = \pi(0.2\text{cm})^2 = 0.126\text{ cm}^2$$

$$E = \frac{P}{A} = \frac{0.005\text{ W}}{0.126\text{ cm}^2} = 0.040\,\frac{\text{W}}{\text{cm}^2}$$



The irradiance of the laser is 0.040 W/cm^2, more than 80 times that of the light bulb (when the total radiation of the light bulb -60 watts- is considered). Also note that the irradiance of the laser changes slowly as you move away from the laser because the beam does not spread very much as it propagates. The irradiance of the bulb drops as 1/r^2 where r is the distance from the bulb. Can you explain why? (The dependence of irradiance on distance for a point source radiator will be explored in Chapter 2.)

Maximum permissible exposure (MPE) is defined in *ANSI Z-136.1* as "the level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin." The MPE is not a distinct line between safe and hazardous exposures, but rather an exposure level that should be safe for repeated exposures. MPE is usually expressed as the allowable irradiance (in W/cm^2) at a particular wavelength for a given exposure time (in seconds). MPE tables exist for both eye and skin exposure, and it can also be calculated from formulas provided in the ANSI standard. Table 1.2 gives the maximum permissible exposure for the eye for a variety of lasers calculated from the formulas given in ANSI Z-136.

Laser Type	**Wavelength (nm)**	**MPE (average power density—mW/cm^2)**		
		Exposure time in seconds		
		0.25 s	10 s	600 s
HeCd	325	—	100	1.67
Argon	488	2.5	1.0	0.0167
Argon	514	2.5	1.0	0.0167
HeNe	633	2.5	1.0	0.283
Nd:YAG	1064	—	5.1	202
CO_2	10600	—	100	100

Table 1.2 MPE calculated for selected cw lasers and exposure times.

Note that for visible radiation (400-700 nm), the MPE is shown for 0.25 seconds, the human aversion response time. For infrared lasers, the blink reflex does not provide protection since the light is invisible. However, research shows that normal eye movements will redirect the eye from the beam within 10 seconds, so MPE is calculated for 10 seconds for infrared lasers. The remaining time period in the chart, 600 seconds (or 10 minutes), is assumed to be an average amount of time to perform a beam alignment. This is more important for beams that are not visible, since a technician would presumably get out of the way in less than 10 minutes if blinded by a visible laser beam.

EXAMPLE 1.2

Does the beam from a 3 mW laser pointer (650 nm) exceed the MPE for 0.25 seconds if it enters a 7 mm diameter fully dilated pupil?

Solution

To calculate irradiance at the pupil, use Equation 1.1 and the area of the pupil ($A = \pi r^2$). Note that the pupil radius is 0.35 cm.

$$\text{Irradiance} = \frac{3\ \text{mWatt}}{\pi (0.35\ \text{cm})^2} = 7.8x10^{-3}\ \frac{\text{watts}}{\text{cm}^2}$$

The MPE for a laser operating at 650 nm is 2.5 x 10^{-3} W/cm^2 (using the closest wavelength value from Table 1.2). The MPE is exceeded by more than three times.

As the MPE table indicates, the biological effects of laser radiation depend on both the wavelength of the laser and exposure duration. For example, the maximum permissible exposure for lasers producing visible light is generally less than for ultraviolet or infrared for the wavelengths shown. Also, looking at any one laser reveals that MPE decreases as exposure time increases. Although all the lasers listed here are assumed to be operating at constant output power (cw), MPE can also be calculated for pulsed lasers.

1.6 CHOOSING LASER SAFETY EYEWEAR (LSE)

Protective eyewear in the form of goggles, spectacles, wraps and shields provides the principal protection for the eyes. Some form of laser safety eyewear must be worn at all times during operation of Class 3B and Class 4 lasers.

The main considerations when choosing laser safety eyewear are the operating wavelength and power. Eyewear is available for specific lasers or wavelengths (such as helium-neon safety goggles) or designed for a broader spectrum of wavelengths and laser types. Most laser safety eyewear is expensive, often costing several hundred dollars per pair. Eyewear for carbon dioxide lasers is the exception, available for under $50 per pair from many suppliers. (It should be noted that designer sunglasses can also cost well more than $200 per pair!) Laser eyewear should be treated with care to avoid scratches or other damage that can change the optical properties and make the eyewear susceptible to laser damage.

Comfort and the effect on color vision are also important when choosing laser safety eyewear. If the LSE is uncomfortable or prevents the wearer from seeing, for example, color traces on monitoring equipment, users may not want to wear it. It is also important not to "overprescribe" LSE. If the eyewear makes it impossible to see the beam, alignment will be difficult. Accidents occur when a technician removes the safety eyewear to complete an alignment and is injured by the beam.

Figure 1.4 - Laser protection eyewear is available in many styles, including goggles to be worn over prescription glasses. The absorbing dye is chosen to block wavelengths of interest. (Photo courtesy Kentek Corp. www.kentek.com)

Calculating Optical Density for LSE

The lens of the eyewear is a filter/absorber designed to reduce light transmission of a specific wavelength or band of wavelengths. The absorption capability of the lens material is described by the *optical density* (*OD*). If E_o is the irradiance incident on an absorbing material and E_T is the irradiance transmitted through the material, the transmitted irradiance is related to the *OD* by an exponential function

$$E_T = E_o 10^{-OD} \quad (1.2)$$

The transmittance (T) of light through an absorber is defined as the ratio of E_T / E_0. We can rewrite Equation 1.2 in a form used commonly with optical filters

$$T = \frac{E_T}{E_o} = 10^{-OD} \quad (1.3)$$

Transmittance

Thus, an *OD* of 1 means the filter has reduced the irradiance of the beam to $1/10^1 = 1/10$ of its original irradiance and *OD* of 5 means the filter has reduced the irradiance of the beam to $1/10^5 = 1/100{,}000$ of its original irradiance. The required *OD* for laser safety eyewear is the minimum *OD* necessary to reduce the beam to a non-hazardous level. Optical density for a given wavelength is usually labeled on the temple of the goggles or on the filter itself. Often, laser safety eyewear is labeled with the *OD* for several wavelength ranges.

To calculate the *OD* required for a particular laser, we need to know the incident radiation on the front surface of the LSE, E_0. The irradiance transmitted by the LSE cannot exceed the maximum permissible exposure (MPE). If we replace E_T in Equation 1.2 with MPE, we get

$$10^{-OD} = \frac{E_o}{MPE}$$

or, equivalently

$$\mathrm{MPE} = \mathrm{E_o} 10^{-OD}$$

Solving the last expression for *OD* gives a useful equation for calculating required *OD* for laser safety eyewear

$$OD = \log_{10}\left(\frac{E_o}{MPE}\right) \quad (1.4)$$

OD for LSE

EXAMPLE 1.3

A 50 Watt Nd:YAG laser (cw at 1.064 μm) is projected onto a fully dilated pupil of 7-mm diameter. The eye is exposed for 10 seconds. Calculate the minimum *OD* of a laser safety goggle needed to protect the eye from damage.

Solution:

From Table 1-2, the MPE for a Nd:YAG laser for a 10 s exposure is 5.1 x 10^{-3} W/cm^2.

The irradiance at the pupil is calculated from Equation 1.1. The power is 50 watts and the pupil is a circle of radius 0.35 cm.

$$E_o = \frac{P}{A} = \frac{50 \text{ watts}}{\pi\left(0.35 \text{ cm}\right)^2} = \frac{50 \text{ watts}}{0.38 \text{ cm}^2} = 132 \ \frac{\text{watts}}{\text{cm}^2}$$

Use Equation 1.4 to determine the required *OD*

$$OD = \log_{10}\left(\frac{132 \dfrac{\text{W}}{\text{cm}^2}}{5.1\text{x}10^{-3} \dfrac{\text{W}}{\text{cm}^2}}\right) = 4.4$$

The optical density for the LSE must be at least 4.4.

In practice, the *OD* may be determined from a calculation similar to that in the example, or by consulting the laser or eyewear manufacturer. Many suppliers of laser safety equipment have online calculators to assist in the selection of laser safety eyewear.

1.7 LASER SAFETY CONTROLS

To ensure safe use of lasers, *administrative controls* and *engineering controls* are required. Warning signs and labels, standard operating procedures, personal protective equipment and laser safety training are examples of administrative controls. Engineering controls are designed into lasers and laser systems to prevent accidental exposure of eyes or skin. Shutters, interlocks, delayed emission and remote firing are examples of engineering controls incorporated into laser system design.

ANSI Z136.1 states that any facility operating Class 3B and Class 4 lasers must have designated a person to serve as Laser Safety Officer (LSO). The job of the LSO is to ensure that laser safety procedures are in place and followed during laser operation and maintenance. Courses are available to train LSOs and help them remain current with ANSI standards.

Among the administrative controls required by the ANSI laser safety standards are warning signs and labels for lasers and for work areas where lasers are in use. The most common signs used for lasers and laser systems are the CAUTION sign (for Class 2 and some Class 3A lasers) and the DANGER sign (used with higher power Class 3A and all Class 3B and 4 lasers). The sign dimensions, colors, and lettering size are all specified by ANSI standards. The IEC also has a specific format for warning signs, which differs from ANSI's, and may be seen on some laser equipment.

Figure 1.5 Laser Warning Signs (from the Laser Institute of America, www.laserinstitute.org.) Class 3 and 4 signs indicate if the beam is visible or invisible.

In some applications, laser beams must be in the open. In these cases, the LSO must define an area of potentially hazardous laser radiation called the *nominal hazard zone* (NHZ). The NHZ is defined as the space within which the level of direct, scattered or reflected laser radiation exceeds the MPE. This area must be clearly marked and appropriate controls must be in place to exclude casual visitors.

1.8 PRACTICAL RULES FOR USING LASERS

Since many school laboratories use only low power Class 2 and 3A lasers, the following guidelines are sufficient for many classrooms. Labs with higher power Class 3B lasers and Class 4 lasers need to be evaluated and monitored by a trained Laser Safety Officer.

Do not look into a laser beam. Do not look at specular reflections from mirrors or other shiny surfaces and do not stare at diffuse reflections. Remember that some lasers produce invisible beams, so it is important to be aware of the beam's location. If you are working with optical fiber, never look into the end of the fiber unless you know for sure that it is not connected to a laser source.

Only trained and qualified personnel should work with lasers. Lasers are not toys, and should not be used by casual visitors or friends visiting the laser lab.

Keep room lights on if possible. Bright room lights will cause the pupil to close, minimizing the light that enters your eye.

Remove watches, rings and other shiny objects. Before turning on a laser, remove any jewelry or other items that could cause specular reflection. Remember that lenses and other components that are primarily designed for transmitting light can also reflect light.

Use beam blocks. Opaque blocks should be used to stop and absorb the beam at the end of its useful path.

Do not bend down below beam height. If you sit down in a lab where lasers are in use, be sure that the chair is high enough that your head is above beam height. If you drop something, use a beam block to stop the laser beam before bending down to pick up the object.

Wear laser safety eyewear. If eyewear is provided, wear it. Eyewear is required for Class 3B and higher lasers.

Report any accidents immediately. If there is exposure to the eye, an ophthalmologist should be consulted.

For additional information on the safe use of lasers, consult one of the references at the end of this chapter. In addition, many research universities have laser safety information on their websites.

REFERENCES

Laser Institute of America, "ANSI Z136.1 (2000) Safe Use of Lasers ," Orlando, Florida.

WEB SITES

1. Laser safety industry society
   www.laserinstitute.org (Laser Institute of America)
2. Companies dealing with laser safety
   www.kentek.com (Kentek Corporation)
   www.rli.com (Rockwell Laser Industries)
3. Many universities have laser safety web sites. Two of these are:
   www.safetyoffice.uwaterloo.ca (University of Waterloo laser safety manual. Click on the "training" link.)
   www.lbl.gov/ehs/pub3000/CH16.html (Lawrence Berkeley Laboratory laser training manual)

REVIEW QUESTIONS AND PROBLEMS

QUESTIONS

1. Explain the importance of:
   a) Maximum Permissible Exposure and
   b) Nominal Hazard Zone.
2. What are the two ways that skin might be affected by laser exposure?
3. What is the most lethal hazard associated with the laser?
4. Which is more hazardous, intrabeam beam viewing from a curved surface or flat surface mirror? Does it matter whether the curvature is concave or convex? Why?
5. What wavelengths pose the greatest danger for retinal exposure?
6. What is the "human aversion response" time and how long is it?
7. To which classification would each of the following lasers/laser systems belong?
   a. A completely enclosed system (e.g., DVD player, laser printer, laser engraver)
   b. Most inexpensive red laser pointers
   c. Lasers used for cutting, welding or other material processing
   d. A 50 mW argon laser
   e. Low power lab HeNe laser (1 mW or less)
8. What is the difference between Class 3A and Class3B lasers? What controls apply to each?

LEVEL I PROBLEMS

9. Find the power of a laser if the irradiance is 1500 W/cm^2 and all the laser's output power is focused on a circular spot with a 16 µm diameter. (3.02 mW)
10. What OD would be required for laser protective eyewear if the worst case exposure is 100 times the MPE? 1000 times?

LEVEL II PROBLEMS

11. What is the minimum *OD* for laser protective eyewear if an Argon laser with power of 75 W is projected onto a partially dilated pupil with a diameterof 5mm and is exposed for .25 seconds. (*OD*>5.2)
12. Consider a pupil opening 5 mm (0.5 cm) in diameter. What is the maximum HeNe power allowed for a 0.25 second exposure? (By exposure, we mean looking directly into the beam, intrabeam viewing, or directly viewing a specular reflection of the beam.) Use the MPE chart.
13. Two students are playing around with a laser pointer (670 nm wavelength) on a dark night. Because of the darkness, the students' pupils are dilated to 7 mm (0.7 cm) diameter. Calculate the highest power diode laser allowed for a 7 mm diameter pupil to be protected by the blink reflex (0.25 seconds). Compare this power to the usual laser pointer, which is around 5 mWatts. (Highest Power = .962 mW, about 20% of the typical 5mW laser pointer)

INTERNET RESEARCH PROJECTS

14. Your company has been hired to perform its first laser light show in a large sports stadium. You are using a 5 Watt argon laser, with wavelengths from 450 nm to 530 nm. What control measures should you have in place for your employees? What control measures should you have in place to protect your audience?

15. The XYZ Company has purchased a 4 kW CO2 laser to use with an existing robot in the manufacture of precision widgets. The laser will produce pulses of IR to produce precise holes in the steel widgets. You have been hired to oversee the installation of the laser. What engineering and administrative control measures would you take to protect the employees of XYZ?