Don't Turn a Blind Eye to Safety: Protecting Personnel from Harmful Lasers

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While lasers have many useful purposes for both commercial and military applications, they can also be hazardous if not operated safely. This paper discusses the safety precautions that must be taken to adequately protect personnel when operating and/or testing lasers in a free-space environment. First, a brief overview of lasers and associated terminology are introduced. Second, the properties of one of the two most common beam profiles, Gaussian, are discussed. An understanding of the beam profile is important in correctly identifying the safe operating environment for the laser. Exposure to laser energy can result in damage to the eye and skin. Therefore, the concepts of Optical Density, Nominal Ocular Hazard Distance and Skin Hazard Distance are discussed. These parameters help ensure that the correct Personal Protective Equipment (PPE) is used and help identify the hazard zone. Finally, recommendations for selecting the appropriate PPE are discussed. The concepts presented in this paper can be applied to any hazardous laser system.

Introduction

During the last few decades, lasers have become increasingly popular in scientific, medical, military and commercial applications. Lasers are used in many common products, including printers, DVD players, laser pointers and scanners. Similarly, lasers are extensively used in the medical field for hair removal, cancer diagnosis, imaging and various surgical procedures. There are multiple applications for lasers in military situations as well, include targeting, ranging and communications. While the list of uses for lasers is extensive, safety needs to be a vital part of the design and operation of all laser products. Laser-related hazards can have extreme consequences, from serious injury to death. Therefore, to protect individuals from the harmful effects of lasers, it is imperative that the proper Personal Protective Equipment (PPE) is used and the safe operating distance is understood. Laser-related injuries can be prevented by understanding and applying basic laser safety practices.

Laser Overview

A typical laser is comprised of three fundamental elements: the lasing medium, the excitation mechanism and the optical cavity. A basic laser system is shown in Figure 1.

The excitation mechanism is the energy source used to excite the lasing medium. Typical excitation mechanisms include electricity from a power supply, a flash lamp or the energy from another laser. The lasing

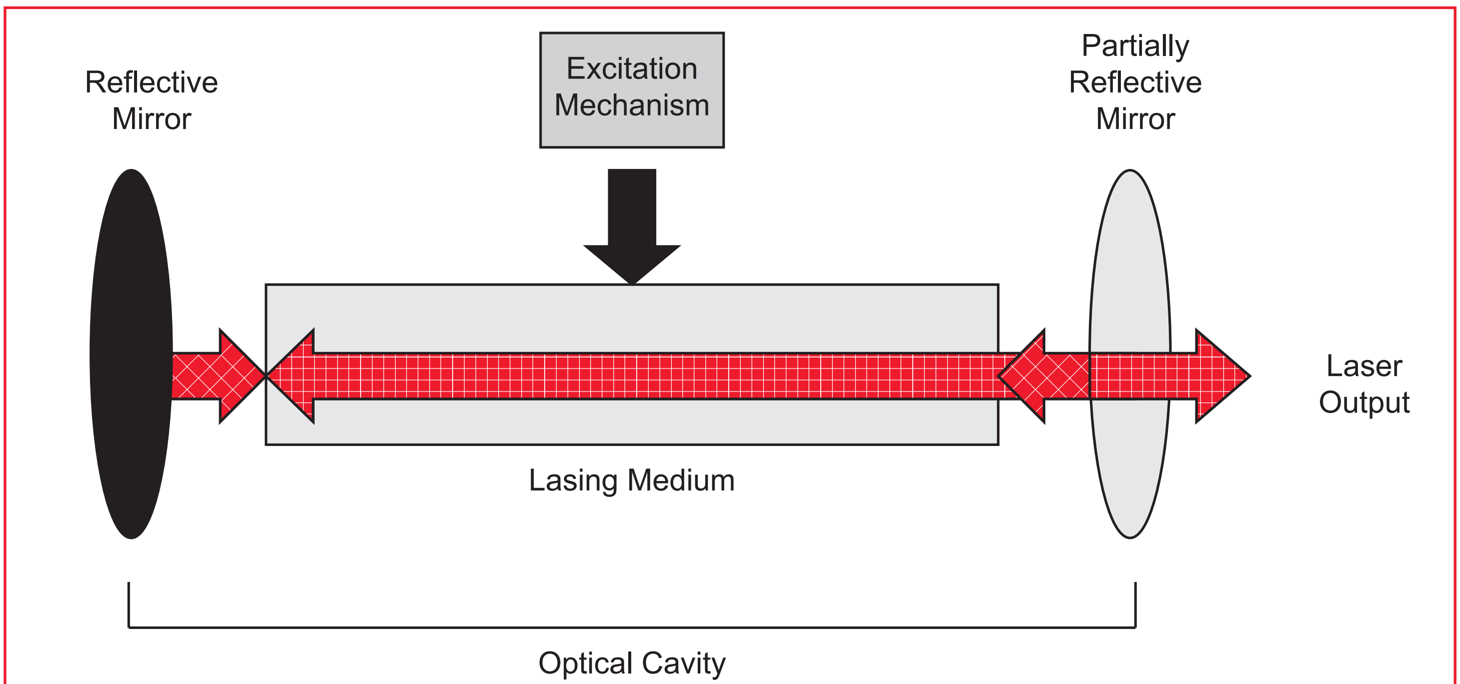

Figure 1 — Architecture of a Basic Laser.

medium can be a solid, liquid or gas that emits radiation when excited. The lasing medium is the major factor that determines the wavelength of the laser system. There are hundreds, if not thousands, of laser mediums, with some of the most common being carbon dioxide (CO2), helium-neon (HeNe), neodymium:yttrium aluminum garnet (Nd:YAG) and gallium arsenide (GaAs). The optical cavity consists of mirrors to act as the feedback mechanism for light amplification. The optical cavity usually consists of a mirror at each end of the lasing medium, which is used to reflect radiation from the lasing medium back into itself. As the radiation is reflected between the mirrors, it increases in strength, resulting in amplification of the energy from the excitation mechanism in the form of laser radiation. The output coupler is usually a partially transparent mirror at one end of the lasing medium, which allows some of the laser radiation to leave the lasing medium in order to produce the laser beam.

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Lasers operate based on the principle of stimulated emission. Electrons in the atoms of the lasing medium normally reside in a steady-state, low-energy level. When energy from the excitation mechanism is applied to the lasing medium, most of the electrons are raised to a higher energy level. This higher energy level is an unstable state for the electrons and they only stay in this state for a short period. The electrons then relax to a lower, relatively long-lived, metastable state. By pumping large amounts of energy into the lasing material, it is possible to obtain a population inversion where most of the electrons are in the metastable state. From the metastable state, electrons will spontaneously return to their low-energy state and, in doing so, will produce a photon. This photon can stimulate an atom in the metastable state to emit a photon of the same wavelength, phase and direction of propagation. If the photons travel parallel to the long axis of the optical cavity, they will continue to stimulate emissions of photons having the same wavelength, which combine coherently (in phase). When the beam strikes the reflective mirror in the optical cavity, the beam is reversed and continues to stimulate photon emission. When the beam reaches the partially reflecting mirror, a small portion of the coherent radiation is released while the rest is reflected back through the lasing medium to continue the process of stimulating photons. This process produces a continuous-wave laser output. Due to this process, the term "laser" originated as an acronym for "Light Amplification by Stimulated Emission of Radiation."

Depending on the application of the laser, it may be necessary to produce short, high-energy laser pulses. Using a technique called Q-switching, it is possible to generate extremely high-energy pulses when compared to continuous wave operation. Q-switching is achieved by placing a variable attenuator in the optical cavity.

Although ordinary light and lasers are both electromagnetic radiation, lasers have unique properties in that they are monochromatic, coherent and directional. Monochromatic means that the laser light consists of essentially one wavelength. In contrast, a typical light bulb emits light constituted of various wavelengths. Also, the light output from a laser is highly directional. Unlike a typical light bulb, which radiates in an omni-directional manner, laser energy diverges very slowly and is concentrated in a narrow cone that propagates in a single direction. Finally, radiation from a laser is coherent, meaning that the waves of the laser radiation are in phase with each other. In contrast, light waves from a light bulb are a mixture of frequencies and wavelengths, and are not in phase with one another.

Laser Classes

The ANSI Z136.1 standard has developed a laser hazard classification scheme based on the ability of the laser beam to cause biological damage to the eye or skin [Ref. 1]. There are four ANSI laser classes, as outlined here:

- **Class 1** lasers encompass both visible and invisible lasers, and are incapable of producing damaging laser radiation levels. By definition, Class 1 lasers do not produce accessible radiation levels in excess of the Class 1 Accessible Emission Limit (AEL). Class 1 lasers are exempt from laser safety controls. ANSI Z136.1 has a subcategory designated 1M for those lasers that meet the Class 1 definition for unaided viewing, but exceed the Class 1 AEL for aided (e.g., telescopic) viewing, but do not exceed the Class 3B AEL.
- **Class 2** lasers emit in the visible portion of the spectrum and are not hazardous for momentary viewing due to the human aversion response (e.g., blinking, head turning). Continuous viewing of Class 2 lasers may be hazardous. Class 2 lasers are limited to 1

mW for continuous wave output. For pulsed lasers, Class 2 lasers exceed the Class 1 AEL for the maximum duration inherent in the design or intended use, but do not exceed the Class 1 AEL for a 0.25 second exposure. Similar to Class 1M, ANSI Z136.1 has a subcategory designated 2M for those lasers that meet the Class 2 definition for unaided viewing, but exceed the Class 2 AEL for aided viewing, but do not exceed the Class 3B AEL.

- **Class 3** lasers are divided into two sub-classes. Class 3R lasers have an accessible output between 1 and 5 times the Class 1 AEL for invisible lasers or less than 5 times the Class 2 AEL for visible lasers. These lasers are generally considered safe with restricted beam viewing. Class 3b lasers have an accessible output greater than Class 3R, but less than Class 4. These lasers are potentially hazardous if viewed by the unprotected eye. Care is required to prevent intrabeam viewing and to control specular reflections.
- **Class 4** lasers are those capable of producing hazardous diffuse reflections, as well as fire and skin hazards. Class 4 lasers emit accessible laser radiation that exceeds the Class 3B AEL. These lasers require extensive laser safety controls and procedures to ensure safe operation.

Laser Effects on the Human Body

Laser radiation poses two concerns for the human body: damage to the eye and skin burns. The exact effect on the human body is dependent on various parameters, including wavelength, power and exposure duration.

As the eye is often far more vulnerable to injury than the skin is from visible and near-infrared laser radiation, it is considered the organ most important to protect from all wavelengths of laser radiation. The increased hazard to the eye from visible and near-infrared laser radiation is a consequence of the eye's imaging process. Parallel rays of visible light from a distant object, or from a laser at any distance, can be imaged on the retina in a very small area. The focusing effect of the cornea and lens of the eye will concentrate these rays by a factor of approximately 100,000. Such a concentration of radiant power can cause the retina to be burned in much the same way that a piece of paper can be set ablaze when a magnifying glass focuses the rays of the sun [Ref. 2]. To protect the eye during laser operation, laser goggles are typically worn to attenuate the laser energy below the Maximum Permissible Energy (MPE) limits.

The shortest focal length of the eye's lens can be associated with the closest point that can be imaged onto the retina (the closest distance of accommodation); this is therefore referred to as the "near point." If the distance from the eye to the source is less than the near point of the eye, a blurred image will result. In laser safety, a reference near point viewing position is generally defined as 10 cm. While there might be people who have a near

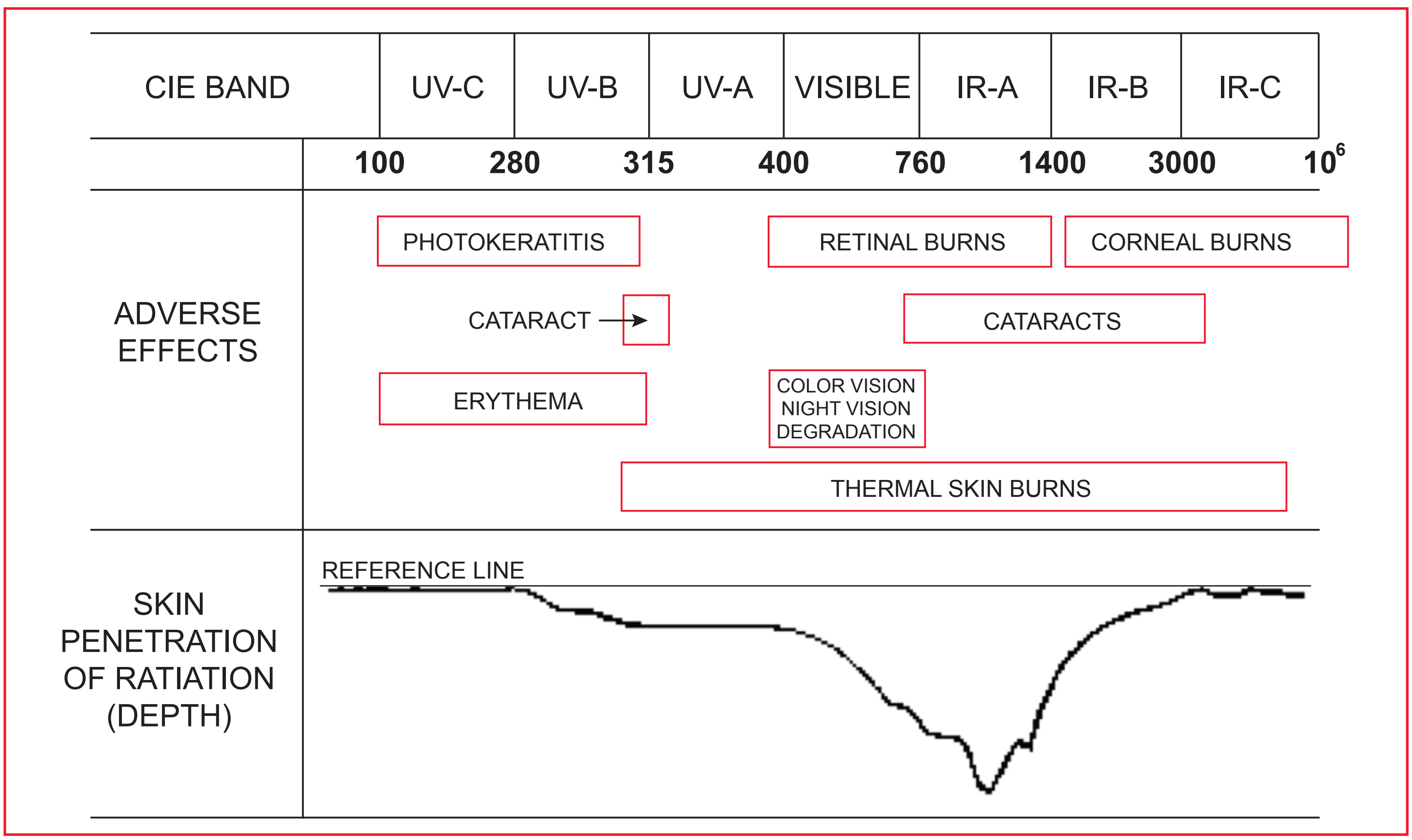

Figure 2 — Biological Effects of the Various Optical Bands [Ref. 4].

point less than 10 cm, such as myopes (nearsighted), the reference distance of 10 cm is still considered a sufficiently cautious (conservative) assumption for the closest viewing distance by the International Laser Safety Committee of the International Electrotechnical Commission (IEC) and the American National Standards Institute (ANSI) [Ref. 3].

Laser radiation can also have a damaging effect on skin. Skin effects are generally considered of secondary importance except in the case of high-power infrared lasers. However, with the increased use of lasers emitting in the ultraviolet spectral region, skin effects have assumed greater importance. Erythema (sunburn), skin cancer and accelerated skin aging are produced by UV-B radiation. Increased pigmentation and erythema result from exposure to UV-A and UV-C radiation. Photosensitization has resulted from the skin being exposed to light from 310 to 700 nm. Lasers emitting radiation in the visible and infrared regions produce effects that vary from a mild reddening to blisters and charring. These conditions are usually repairable or reversible. However, depigmentation, ulceration and scarring of the skin, as well as damage to underlying organs, may occur from extremely high-powered lasers [Ref. 4]. Figure 2 illustrates the optical bands and their associated biological effects.

Laser Beam Characteristics

The damaging effects of a laser are directly related to the amount of energy per unit area the laser can produce. For continuous wave lasers, the energy per unit area is referred to as irradiance and is measured in watts per centimeter squared (W/cm^2). For pulsed lasers, the surface density of the emitted energy is referred to as radiant exposure and is measured in joules per centimeter squared (J/cm^2). If the irradiance or radiant exposure exceeds the MPE limits, the laser will have harmful effects. The MPE is directly related to the wavelength of the laser and can be computed using Tables 5 through 5f in ANSI Z136.1-2014.

To accurately determine the eye and skin hazards with respect to a given laser, various characteristics of the laser beam need to be known and understood. The critical characteristics of a laser beam include the wavelength, output power (or energy per pulse for pulsed lasers), pulse repetition frequency (for pulsed laser), beam diameter, beam divergence, beam distribution and beam profile. Each of these parameters is described here:

- **Wavelength:** The distance (typically expressed in nm or µm) between successive crests of the wave of light from the laser
- **Output Power:**
    - o Continuous Wave Laser: The output power of the laser, expressed in watts (W)
    - o Pulsed Laser: Total energy in a single pulse, expressed in joules (J)
- **Pulse Repetition Frequency (PRF):** The number of pulses occurring per second, expressed in hertz (Hz)
- **Beam Diameter:** The distance between diametrically opposed points in that cross-section of a beam where the power or energy is 1/e (0.368) times that of the peak power or energy. Beam diameter is typically expressed in millimeters, centimeters or inches
- **Beam Waist:** The measure of the beam size at the point of its focus where the beam width is the smallest
- **Beam Divergence:** The increase in the diameter of the laser beam with distance from the beam waist, based on the full angle at the point where the irradiance (or radiant exposure for pulsed lasers) is 1/e times the maximum value. Beam divergence is expressed in radians or degrees
- **Beam Distribution:** The energy distribution of the laser beam. Typical distributions include Gaussian and Top Hat (also known as Flat Top). Figure 3 provides a graphical representation of a Gaussian beam distribution
- **Beam Shape:** The shape of the laser beam. Typical beam shapes include circular, elliptical or rectangular

It is worth noting that when safety calculations are being performed, the worst case — but credible — values for each parameter should be used. In some cases, this involves taking the maximum value (e.g., output power, pulse rate frequency) and in other cases, the minimum value (e.g., beam divergence and beam diameter). It is also important to ensure that the correct units of measure are used for each parameter when evaluating a formula.

1/e Point of a Laser Beam

Many of the lasers used today follow a Gaussian distribution, which means that they can be represented by Gaussian equations. These types of beams have a high irradiance in the center of the beam and begin to tail off towards zero along the edges, as shown in Figure 3. Based on this geometry, the laser beam can be represented at various energy levels, with a corresponding beam diameter and beam divergence. Therefore, it is imperative that the correct beam diameter and divergence be used in laser safety calculations to obtain accurate results.

Laser manufacturers frequently specify beam diameter and beam divergence at various points along the Gaussian distribution. Common points include

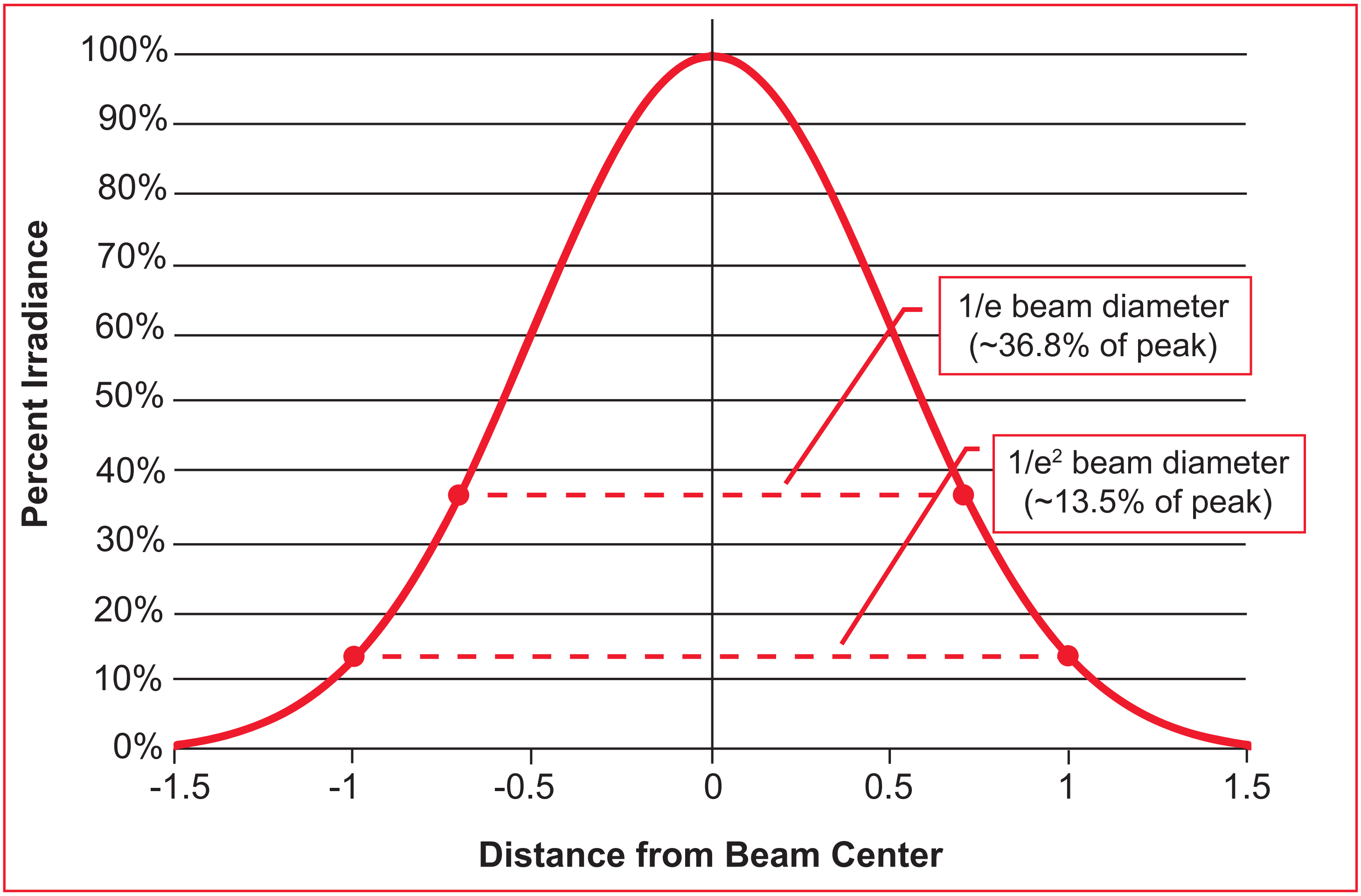

Figure 3 – Gaussian Beam Distribution

the 90 percent point, $1/e^2$, 50 percent point and 1/e. However, for all laser safety calculations, the 1/e point must be used. Although the 1/e criterion may appear to be a rather arbitrary definition of beam diameter, its usefulness in describing the parameters of Gaussian beams is illustrated as follows. If the total power in the beam is divided by the area defined by the 1/e diameter, then the resultant value, which has the units of power per unit area, is equal to the peak (on-axis) value of the beam irradiance. It thus defines the maximum or, from the safety perspective, the worst-case value [Ref. 3].

If the beam diameter is provided at power points other than 1/e, it can be converted to the 1/e points using Equation 1, where d is the beam diameter at the specified power point and E_d/E_o represents the ratio of the irradiance at the specified diameter d and the on-axis irradiance. If converting from $1/e^2$ to 1/e, E_d/E_o would equal $1/e^2$ (0.135); converting from the 90 percent point to 1/e, E_d/E_o would be set to 0.1.

$$d_{1/e} = \frac{d}{\sqrt{-\ln\left(E_d/E_0\right)}} \qquad (1)$$

Similar to the beam diameter, beam divergence can also be specified at a power point other than 1/e. Beam divergence can also be converted to the 1/e point using Equation 1.

Optical Density

As mentioned earlier, laser energy in excess of the MPE is hazardous to the human eye. When a laser emits laser energy in excess of the MPE, provisions must be taken to protect the eye. One of the procedural means to protect the eye is the use of laser goggles. The lenses of laser goggles contain a coating designed to attenuate the laser energy at a specified wavelength or group of wavelengths. The amount of attenuation provided by the laser goggles is expressed as the Optical Density (OD). The OD is defined as the negative logarithm (base 10) of the transmission where the higher the OD value, the greater the attenuation provided. In relation to the MPE, Equation 2 can be used to determine the requisite minimum OD to attenuate the laser beam below the MPE.

$$OD = \log_{10}\left(\frac{E_{MMD}}{MPE}\right) \qquad (2)$$

Table 1 – Example Specification for Laser Goggles.

Wavelength	OD
190-400 nm	5+
525 - 532 nm	3+
750 - 820 nm	7+

E_{MMD} is the irradiance at the minimum measurement distance (10 cm) through the measurement aperture (e.g., 0.7 cm for the size of a dilated pupil) and the MPE is calculated based on Tables 5 through 5f in ANSI Z136.1-2014. Once the OD is computed, it can be compared against the specifications for laser goggles to determine if they provide adequate attenuation. In addition to the OD, it is equally important to verify that the laser goggles are specified to cover the wavelength of the laser. Table 1 shows an example of how a pair of laser goggles may be specified. This information is usually written directly on the goggles.

Based on the laser goggles described in Table 1, for a laser operating at a wavelength of 1064 nm, these goggles would offer no protection. However, for a laser operating at a wavelength of 800 nm, the laser goggles would provide an OD of at least 7. If, for example, laser calculations showed that the requisite OD for an 800 nm laser is 7.4, these goggles would be inadequate since they are only guaranteed to provide a minimum OD of 7.

If magnifying optics are used, the irradiance — or radiant exposure for pulsed lasers — in Equation 2 must be multiplied by the effective gain. The effective gain can be computed using Equation 3.

$$Gain_{eff} = Transmittance \times \frac{\min(D_c^2, D_L^2)}{D_f^2} \tag{3}$$

$$\text{where } D_c = min(D_c, P \times D_f)$$

D_c is the diameter of the collecting aperture, D_0 is the diameter of the entrance aperture of the magnifying optics, P is the magnification of the magnifying optics, D_f is the diameter of the limiting aperture, and D_L is the diameter at the measurement distance (determined using Table 9 in ANSI Z136.1-2014). The diameter of the limiting aperture (D_f) is based on wavelength and exposure duration as defined in Table 8a in ANSI Z136.1-2014. Figure 4 identifies the key parameters related to magnifying optics.

In some cases, it is useful to know what the OD is, assuming that all of the laser energy is focused into the eye. This value is helpful when magnifying optics are used to focus the beam in a manner in which all of the laser energy could enter the eye. To compute the OD for total exposure, use Equation 2, but instead of using E_0 in the numerator, use the total power (or energy per pulse) of the laser beam divided by the area of the measurement aperture:

$$OD = \log_{10}\left(\frac{Total\ Power / Area\ of\ Measurement\ Aperture}{MPE}\right) \tag{4}$$

The measurement aperture is used to determine the effective power or energy that is compared with the AEL. The measurement aperture is wavelength dependent and can be determined using Table 9 in ANSI Z136.1-2014.

Nominal Ocular Hazard Distance

Another important safety parameter is the Nominal Ocular Hazard Distance (NOHD). The NOHD represents the distance from the laser before the laser energy falls below the MPE. In other words, laser output is considered hazardous within the NOHD, and is below the MPE outside of the NOHD. One of the primary

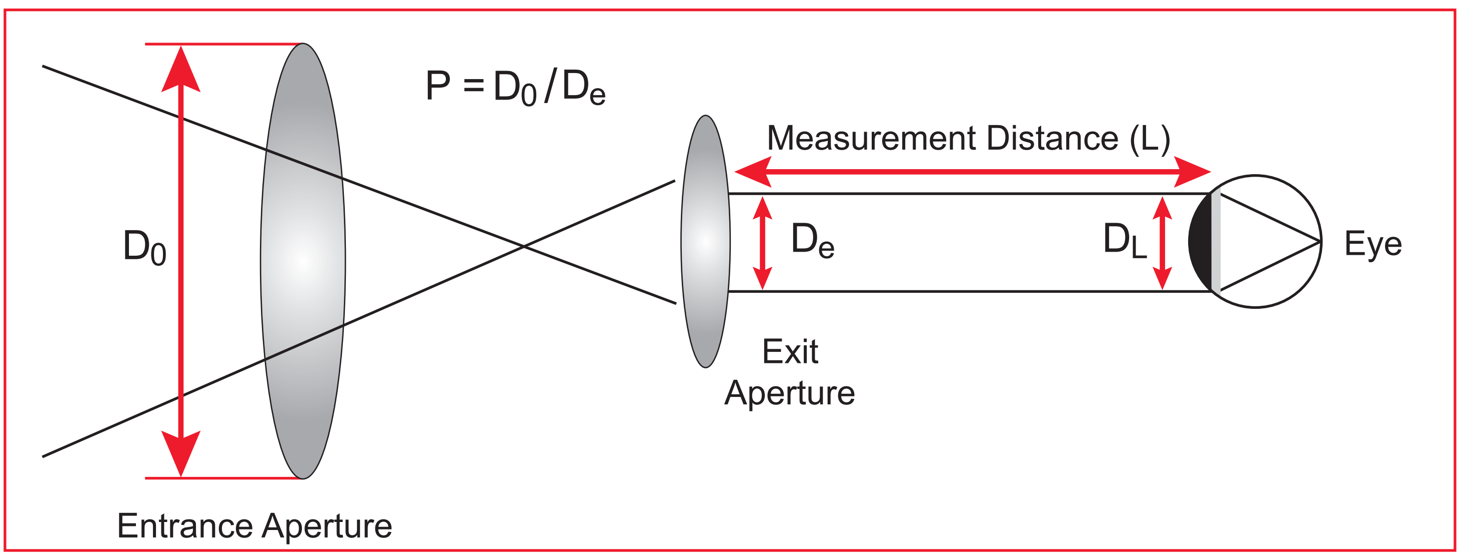

Figure 4 – Key Parameters with Magnifying Optics.

drivers for the NOHD is the divergence of the laser beam. The tighter the divergence of the laser beam, the longer the NOHD. In contrast, if the laser beam diverges quickly, the NOHD will be shorter. The NOHD (in centimeters) can be calculated using Equation 5.

$$NOHD = \frac{1}{Ø_{1/e}} \sqrt{\frac{-D_f^2}{ln\left(1 - \frac{AEL}{P \bullet e^{-\mu \bullet NOHD}}\right)} - D_{1/e}^2} \tag{5}$$

Where ϕ is the divergence of the laser beam as measured at the 1/e point in radians, D_f is the diameter of the limiting aperture in centimeters, AEL is the Class 1 accessible emission limit in Watts (AEL = MPE x area of limiting aperture), P is the power in watts, μ is the atmospheric attenuation coefficient and D is the beam diameter as measured at the 1/e point in centimeters. For a worst-case analysis, the atmospheric attenuation can be neglected by setting μ=0 (simulating a vacuum environment). If a more realistic result is desired, μ can be set according to the environment in which the laser will operate (μ typically ranges from 10^{-4} cm^{-1} in thick fog to 10^{-7} cm^{-1} in air of very good visibility; for military computations, $5x10^{-7}$ cm^{-1} is typically used). Note, Equation 5 includes the term NOHD on both sides of the equation because NOHD cannot be isolated algebraically. This type of equation must be solved numerically. For a pulsed laser, P would be replaced by the energy which is measured in joules, and the AEL would be expressed as joules. Once the NOHD is determined, precautions should be taken to ensure that people are prohibited from being within the NOHD — or, if there is a need to be within the NOHD, that the appropriate precautions are taken (e.g., laser curtains and laser goggles).

If there is a possibility that magnifying optics could be used to view the laser beam, the NOHD must be computed using Equation 6.

$$NOHD = \frac{1}{Ø_{1/e}} \sqrt{\frac{-D_c^2}{ln\left(1 - \frac{AEL}{P \bullet \tau \bullet e^{-\mu \bullet NOHD}}\right)} - D_{1/e}^2} \tag{6}$$

where $D_c = min(D_0, P \times \min(D_e, D_f))$

To account for the amount of light collected by a viewing optic, a collecting aperture with diameter D_c is needed. D_C is the minimum of the entrance diameter of the optics (D_0) and the magnification (P) multiplied by the minimum of the limiting aperture diameter (D_f) and the exit aperture diameter (D_e). The diameter of the limiting aperture must be accounted for since, in some instances, the limiting aperture diameter will be less than the exit aperture of the optical device. In an ideal scenario, the optics would transmit 100 percent of the light entering the device. Since that is not the case in reality, the term τ represents the transmittance of the optics. For typical 7 x 50 mm binoculars, D_0 is 50 mm or 5 cm, P is 7, De is 7.14 mm (50 mm / 7), and D_f is based on Table 8a in ANSI Z136.1-2014 (e.g., for a visible laser, D_f would be 7 mm or 0.7 cm, representing the diameter of the pupil). In this case, D_c equals 4.9 cm.

Skin Hazard Distance

Until now, the focus of laser safety analyses has been on hazards to the eye. However, as previously discussed, laser energy can also be hazardous to skin. Similar to the value of knowing the NOHD in protecting the eyes, it is helpful to know the distances at which the laser poses a skin hazard — known as the Nominal Skin Hazard Distance (NSHD). The NSHD can be computed in a similar fashion using Equation 5 and Equation 6. In these equations, the value for the limiting aperture, D_f, is 0.35 cm for wavelengths between 180 nm to 100 µm and 1.1 cm for wavelengths between 100 µm and 1000 µm. For most applications, D_f will be 0.35 cm. The AEL can be determined using Tables 7 – 7c in ANSI Z136.1-2014. Recall that AEL is equal to MPE times the area of the limiting aperture.

Protection from Laser Radiation

The most effective means of controlling risk related to laser operation is to eliminate the hazard. The only way to achieve hazard elimination is to completely enclose the laser so that no laser radiation is emitted outside the enclosure. While this may be an effective way of eliminating the hazard, it may be impractical for many laser applications. When the hazard cannot be eliminated, it must be mitigated — first through engineering controls. Engineering controls are design features of the laser or separate

Table 2 —Potential Laser-Control Measures.

Engineering Controls	Administrative and Procedural Controls	Personal Protective Equipment
• Protective Housing • Safety Interlocks • Beam Stop or Attenuator • Beam Enclosures • Laser Emission Indicators • Key Control • Protective Barriers and Curtains • Viewing Windows	• Restricted Access • Standard Operating Procedures • Laser Safety Training • Warning labels and signs • Controlled Operation • Oversight of a Laser Safety Officer	• Laser goggles • Clothing • Gloves • Face Shields

devices to limit or reduce exposure to the laser beam. Engineering controls include things such as protective housings, interlocks and beam attenuators. If engineering controls alone cannot mitigate the hazard, administrative and procedural controls may be used. Administrative controls rely on procedures and information rather than built-in design features or separate devices. Administrative controls include training, standard operating procedures and warning signs. As the last line of defense, personal protective equipment (PPE) may be used. PPE are items worn by individuals within close proximity of the laser, including items such as laser goggles, protective clothing and gloves. Table 2 provides a list of some commonly used laser-control measures.

When PPE is necessary, care should be taken to ensure that it is adequate for the intended laser. Different lasers require different PPE, and it should not be assumed that what is sufficient for one laser is adequate for another. This is especially true for laser goggles. Laser goggles can be purchased in a variety of styles and some can even be worn over prescription glasses. Regardless of the style selected, the goggles must be rated for the wavelength of the laser, have an optical density greater than that required for the laser, provide adequate visible light transmission to provide a safe working environment and provide all-around protection near the eyes to ensure that laser energy cannot enter through the edges of the goggles.

Hazard Evaluation Examples

Although none of the equations related to laser safety parameters are overly complex, it is essential that they be applied correctly to prevent errors and ultimately prevent an unsafe environment. The two examples here demonstrate the derivation of the OD, NOHD and NSHD in a practical manner. Since the permutations of various laser parameters can be endless, it is impractical to provide examples that cover all types of lasers and conditions. Hence, these examples are meant only to bring general awareness to the area of laser safety.

Example 1

Calculate the unaided OD, NOHD and NSHD for the laser described in Table 3. The beam distribution is Gaussian and the beam shape is circular. Assume no atmospheric attenuation.

To determine the required OD for this laser, Equation 2 must be used. Table 3 provides the MPE, so the only parameter that must be computed is EMMD (the irradiance at the minimum measurement distance). Based on Table 9 in ANSI Z136.1-2014, the measurement distance for a laser with an 1100 nm wavelength is 10 cm.

The first thing to note is that both the beam diameter and beam divergence are specified at the $1/e^2$ points. For laser safety calculations, these must be converted to the $1/e$ points. Since this is a Gaussian beam,

Table 3 — Laser Safety Parameters for Example 1.

Wavelength	Pulse Mode	Power	Beam Diameter	Beam Divergence	MPE[1] (Eye)	MPE[1] (Skin)
1100 nm	Continuous Wave	6 Watts	2.8 cm @ $1/e^2$	550 μrad@ $1/e^2$	0.005 W/cm^2	1 W/cm^2

[1] The MPE was determined using Tables 5c and 6a in ANSI Z136.1-2014 for eye exposure and Tables 6a and 7b for skin exposure. Derivation of the MPE is left as an exercise for the reader.

Equation 1 may be used to convert both the beam diameter (Equation 7) and the beam divergence (Equation 8).

$$d_{1/e^2} = \frac{d}{\sqrt{-ln\,(E_d / E_0)}} = \frac{d}{\sqrt{-\ln\,(1/e^2)}} = \frac{2.8\ cm}{\sqrt{2}} = 1.98\ cm \tag{7}$$

$$\varnothing_{1/e} = \frac{\varnothing}{\sqrt{-ln\,(E_d / E_0)}} = \frac{\varnothing}{\sqrt{-\ln\,(1/e^2)}} = \frac{550\ \mu rad}{\sqrt{2}} = 388.91\ \mu rad \tag{8}$$

Now, E_{MMD} may be computed using Equation 9.

$$E_{MMD} = \frac{Total\ Power}{Area\ of\ Beam\ (at\ measurement\ distance)} \tag{9}$$

Since the laser beam is circular, the area of the beam is the area of a circle (πr^2), where r is the radius of the circle at the measurement distance of 10 cm (Equation 10) [2].

$$d_{10cm} = \sqrt{d_{1/e^2}^{\,2} + (\varnothing_{1/e} \bullet z)^2} = \sqrt{(1.98\ cm)^2 + (3.8891 \times 10^{-4}\ rad \bullet 10\ cm)^2} = 1.98\ cm \tag{10}$$

In this example, the beam diameter at the measurement distance of 10 cm is approximately the same as the exit diameter of the beam, since the beam divergence is really small (i.e., the slow divergence of the beam is practically negligible at a distance of 10 cm).

Plugging the values into Equation 9 yields (Equation 11):

$$E_{MMD} = \frac{6\ Watts}{\pi \left(\frac{1.98\ cm}{2} \right)^2} = 1.949\ W/cm^2 \tag{11}$$

Hence, the optical density required for unaided viewing may be found using Equation 12.

$$OD = \log_{10}\left(\frac{E_{MMD}}{MPE} \right) = \log_{10}\left(\frac{1.949\ W/cm^2}{0.005\ W/cm^2} \right) = 2.6 \tag{12}$$

Next, the NOHD may be computed using Equation 5. However, since the atmospheric attenuation is zero, Equation 5 may be simplified as shown in Equation 13.

$$NOHD = \frac{1}{\varnothing_{1/e}} \sqrt{\frac{-\,D_f^2}{ln\left(1 - \frac{AEL}{P}\right)} - D_{1/e^2}^{\,2}} \tag{13}$$

[2] This method applies to a diverging circular beam. For a converging beam, knowledge of the external beam waist is required.

$$NOHD = \frac{1}{388.91\ \mu rad}\sqrt{\frac{-(0.7\ cm)^2}{ln\left(1-\frac{0.005\frac{W}{cm^2}\times\pi\times\left(\frac{0.7\ cm}{2}\right)^2}{6\ Watts}\right.} - (1.98\ cm)^2} = \begin{matrix}100{,}370\ cm\\ or\\ 1{,}003.7\ m\end{matrix} \tag{14}$$

The diameter of the limiting aperture, D_f, is 0.7 cm, based on Table 8 in ANSI Z136.1-2014. The AEL is defined as the MPE times the area of the limiting aperture. Hence, the NOHD may be computed using Equation 14.

The Skin Hazard Distance is also computed using Equation 5. The only difference between the NSHD and the NOHD calculation is the diameter of the limiting aperture and the AEL. According to Table 8a in ANSI Z136.1-2014, the limiting aperture is 3.5 mm for an 1100 nm wavelength laser. Therefore, the NSHD may be computed using Equation 15.

$$NSHD = \frac{1}{388.91\ \mu rad}\sqrt{\frac{-(0.35\ cm)^2}{ln\left(1-\frac{1\ W/cm^2\times\pi\times\left(\frac{0.35\ cm}{2}\right)^2}{6\ Watts}\right)} - (1.98\ cm)^2} = \begin{matrix}4{,}918\ cm\\ or\\ 49.18\ m\end{matrix} \tag{15}$$

Example 2

Calculate the aided (7 x 50 mm binoculars with 70 percent transmission) OD and NOHD for the laser described in Table 3 in Example 1. The beam distribution is Gaussian and the beam shape is circular. Assume no atmospheric attenuation.

To compute the aided OD, the effective gain ($Gain_{eff}$) must be computed first using Equation 3. To use Equation 3, the diameter of the collecting aperture, D_c, must first be computed. D_0 is the entrance aperture of the binoculars, which is 5 cm; P is the power of the binoculars, which is 7; D_f is the diameter of the limiting aperture, which is 0.7 cm; and D_L is beam diameter at the measurement distance of 10 cm, which is 1.98 cm given in Equation 10. Now, effective gain may be computed using Equation 16 and Equation 17.

$$D_c = min(D_0, P \times D_f) = min(5\ cm, 7 \times 0.7\ cm) = 4.9\ cm \tag{16}$$

$$Gain_{eff} = Transmittance \times \frac{\min(D_c^2, D_L^2)}{D_f^2} = 0.7 \times \frac{\min((4.9\ cm)^2, (1.98\ cm)^2)}{(0.7\ cm)^2} = 5.6 \tag{17}$$

The OD may now be computed as shown in Equation 18.

$$OD = \log_{10}\left(\frac{E_{MMD} \times Gain_{eff}}{MPE}\right) = \log_{10}\left(\frac{1.949\ W/cm^2 \times 5.6}{0.005\ W/cm^2}\right) = 3.4 \tag{18}$$

Next, the NOHD may be computed using Equation 6. Since the assumption is that there is no atmospheric attenuation, Equation 6 may be simplified as shown in Equation 19.

$$NOHD = \frac{1}{\varnothing_{1/e}}\sqrt{\frac{-D_c^2}{ln\left(1-\frac{AEL}{P\bullet\tau}\right)} - D_{1/e}^2} \tag{19}$$

Plugging the values into Equation 19 yields an NOHD of 5,886.43 meters, as shown in Equation 20.

$$NOHD = \frac{1}{388.91\ \mu rad}\sqrt{\frac{-(4.9\ cm)^2}{ln\left(1-\frac{0.005\ \frac{W}{cm^2}\ \text{x}\ \pi\ \text{x}\ \left(\frac{0.7\ cm}{2}\right)^2}{6\ Watts\ \text{x}\ 70\%}\right)}-(1.98\ cm)^2} = \begin{matrix} 588543\ cm \\ or \\ 5{,}885.43\ m \end{matrix} \tag{20}$$

Laser Calculation Software

Although most of the math related to laser safety involves basic algebra, it can become confusing, especially if calculations are performed infrequently. Also, hand calculations are prone to human error and may lead to inaccurate answers. Therefore, it is recommended that laser software based on ANSI Z136.1 (or an equivalent standard) be used for all laser safety calculations. Three popular laser software tools are:

- Laser Hazard Evaluator by the Laser Institute of America
- EASY HAZ™ Laser Hazard Analysis Software by Kentek Corporation
- Laser Hazard Analysis Software (LHAZ) by the Air Force Research Laboratory

While laser safety software may make calculations much easier, a cognizant laser safety officer, or other safety professional, should validate the results prior to implementing safety mitigations.

About the Author

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