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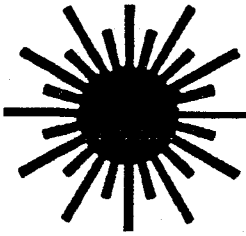

LASER SAFETY

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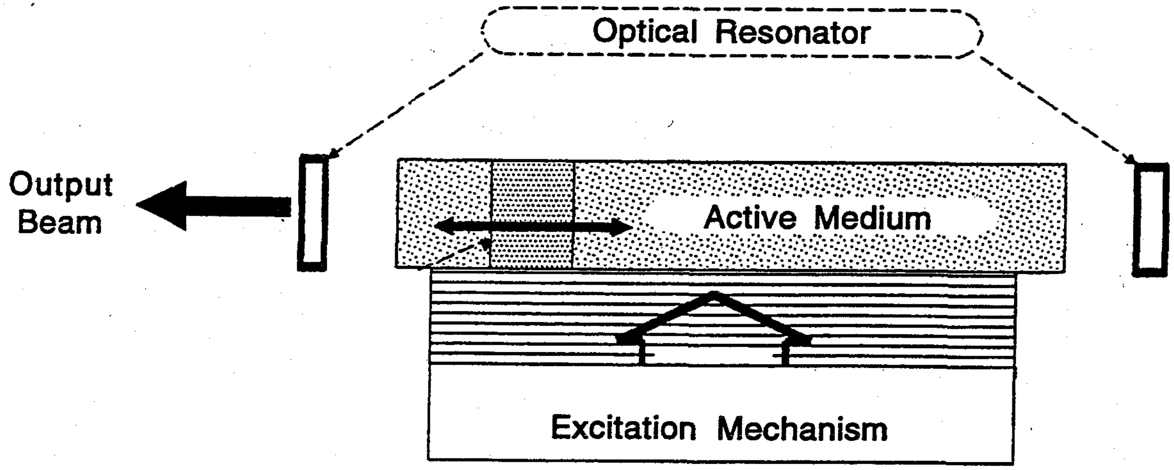
TABLE OF CONTENTS

MODULE 1.0

LASERS
and
LASER SYSTEMS



RII Education

LASERS AND LASER SYSTEMS

The development of modern lasers is the result of nearly 300 years of research on the nature of light and matter. Today, lasers are used in industry, communications, medicine, art and entertainment, commerce, the military, and research. In this module, you will learn about the fundamental physical principles of laser light and about some of the major laser applications.

- Classical Concepts of Light
- Fundamentals of Laser Physics
- Laser Applications

Table of Contents

LASERS AND LASER SYSTEMS

CLASSICAL CONCEPTS OF LIGHT

SECTION OBJECTIVES

- Distinguish between the wave and particle theories of light
- Describe the principle components of a wave
- Calculate the wavelength/frequency of electromagnetic energy
- Sketch the electromagnetic spectrum

HISTORICAL BACKGROUND

In the 17th century, Sir Isaac Newton and the Dutch physicist Christian Huygens proposed conflicting theories of the nature of light. Newton proposed the particle or "corpuscular" theory, which held that light was composed of streams of particles. Huygens favored the wave theory of light.

Both theories explain certain characteristics of light, but neither presents a complete view. For example, the wave theory explains diffraction, straight line propagation, interference, refraction, and polarization. On the other hand, the particle description of light offers a better explanation of the photoelectric effect, photon emission and absorption, exposure of film, and photon-electron interactions. However, the corpuscular theory is unable to explain why a light source does not lose mass as it emits light – a phenomenon easily explained by the wave theory.

A century after the debate over the nature of light had begun, Thomas Young performed his now famous double-slit experiment on the interference of light. This experiment demonstrated conclusively that light traveled as a wave and Young was actually able to measure the wavelength of light. In the mid-1880s, the Scottish physicist James Clerk Maxwell combined the empirical laws of electricity and magnetism into the theory of electromagnetism – a theory that predicts that light propagates as an electromagnetic wave. Maxwell derived a set of equations (Maxwell's equations) that predicted mathematically that "light" was comprised of oscillating electric and magnetic force fields. The equations suggested that light propagates from a source at some oscillating frequency and at a fixed velocity that was a universal constant.

But which theory is correct? Today, we know that both views of light are correct. Sometimes light behaves as a wave; at other times it behaves as if it were composed of particles. Neils Bohr suggested that this apparent contradiction results from our limitations as observers, and that scientists must strive to develop a mathematical description that offers the greatest generality, simplicity, elegance, and predictive power.

WAVE THEORY

Light energy propagates as a wave of electromagnetic energy (Figure 1), and like all other waves is characterized by its amplitude (h), wavelength (λ), frequency (υ), and period (τ). Amplitude is defined as one half of the distance between the wave crest and trough. Wavelength, is defined as the length of one period of the wave; the frequency is the number of waves that pass a point

Example

Calculate the frequency of light with a wavelength of 0.5 μm.

Solution

Wavelength (λ) and frequency (υ) are related by

$$c=\lambda\upsilon$$

Substituting for λ, and c in the equation and solving for μ, we obtain

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

$$\upsilon = \frac{3x10^8}{0.5x10^{-6}}$$

$$\upsilon = 6x10^{14} \text{ Hz}$$

in one second; and the period is the time it takes for one wave to pass a point. The speed of light (c), which is equal to 3 x 10^8 m/sec, is related to the wavelength and frequency by:

$$c=\lambda\upsilon \qquad (1)$$

The equations governing the propagation of electromagnetic waves can be derived from Maxwell's equations (1864). Accordingly, the variation in the electric (E(x,t)) and magnetic (B(x,t)) field vectors for electromagnetic waves (monochromatic, plane-polarized) traveling along the x-axis are given by:

$$E(x,t) = E_0\cos(kx - \omega t) \qquad (2)$$
$$B(x,t) = B_0\cos(kx - \omega t) \qquad (3)$$

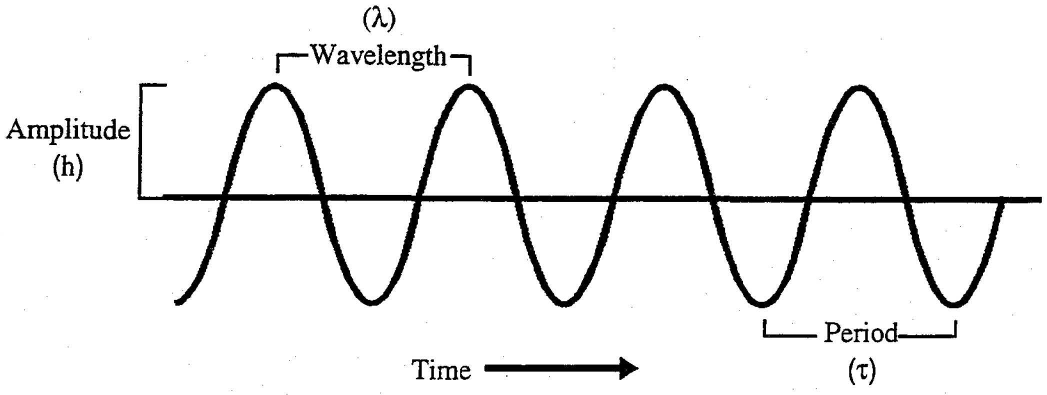


Figure 1. The Wave Nature of Light

SKILL REVIEW
1

Calculate the wavelength of a radio wave whose frequency is 1000 kilocycles (10^6 cycles/sec.)

Calculate here:

where (x) refers to the horizontal displacement along x-axis and (t) represents the time. In this equation, the wave number (k) is equal to $2\pi/\lambda$, and the angular velocity (ω) is equal to $2\pi\upsilon$.

At this point we have described how electromagnetic energy propagates as waves, but we have yet to explain the source of such radiation. Electromagnetic waves may be produced in one of three ways. They may be produced by accelerated charges; from molecular, atomic, or nuclear transitions; and from nuclear reactions.

ELECTROMAGNETIC SPECTRUM

Light is an electromagnetic wave. Radio waves, X rays, infrared radiation, and gamma rays are also electromagnetic waves. Electromagnetic waves differ only in wavelength (frequency). The different types of electromagnetic waves form the electromagnetic spectrum, which is shown in Figure 2. At the low end of the spectrum are radio waves, which have long wavelengths. At the upper end of the spectrum are the X rays and gamma rays, which have very short wavelengths.

In general, the view of electromagnetic energy as a wave is most useful in explaining the properties of long-wavelength (low-energy) radiation such as radio, radar, and microwaves. However, a particle view of electromagnetic energy is more productive in explaining the properties of short-wavelength (high energy) electromagnetic radiation such as X rays and gamma rays.

Although all types of electromagnetic radiation are fundamentally the same, the physical,

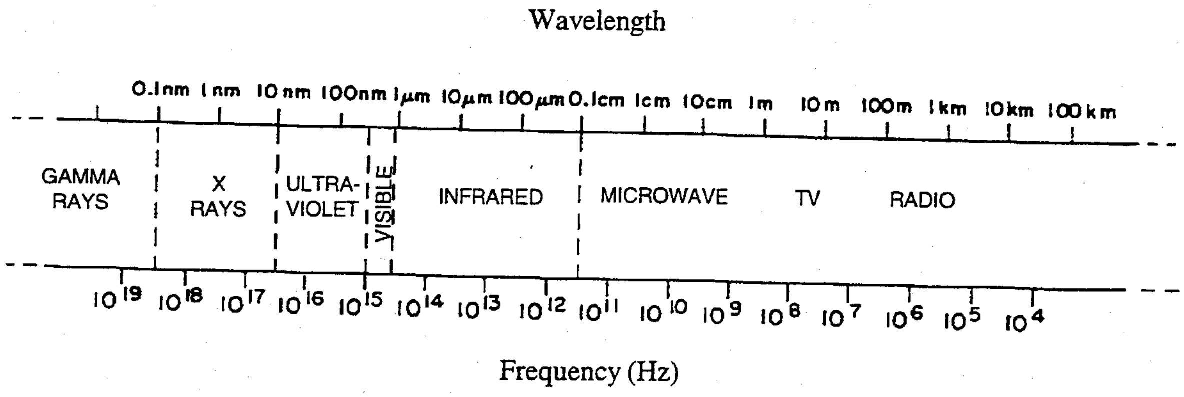


Figure 2. The Electromagnetic Spectrum

chemical, and biological properties of electromagnetic radiation vary enormously with the wavelength. Therefore, the safety precautions, methods of detection, and techniques needed to produce certain types of radiation also differ depending upon the wavelength.

ULTRAVIOLET CATASTROPHE

By the end of the 19th century, Maxwell's theories of the wave nature of light were being challenged by new studies in blackbody radiation. A blackbody is an idealized system that is considered to be a perfect emitter (or absorber) of electromagnetic radiation.

The events of this era are a fascinating detective story in science. Following the discovery of the electron, scientists pondered how a radiating atom could be "stable". It was thought that the electrons in an atom were constantly moving. It was argued that this motion would cause radiation to be emitted (what we now call bremsstrahlung or "breaking radiation"). As a result, the scientists concluded that the energy radiated by an atom would result in a decrease in the kinetic energy of the electrons, causing them to slow down. Thus, they incorrectly surmised that all of the electrons would eventually collapse into the nucleus; a condition contrary to reality. Certainly, this was not what was meant by a stable state! Based upon such

Example

Calculate the energy of one photon emitted by a helium-neon laser ($\lambda = 0.633\ \mu m$).

Solution

Substituting for wavelength (λ) and (c) and solving for frequency (υ) in equation (1), we obtain

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

$$\upsilon = \frac{3 \times 10^{8}}{0.633 \times 10^{-6}}$$

$$\upsilon = 4.74 \times 10^{14}\ \text{hz}$$

The equation for the energy of a photon is given by

$$E = h\upsilon$$

Substituting for (h) and (υ) in the equation, we obtain

$$E = (6.63 \times 10^{-34}) \times (4.74 \times 10^{14})$$

$$E = 3.14 \times 10^{-19}\ J$$

a conceptual dilemma, the structure of atoms could not then be completely explained. New theories were needed.

In the late 1890s, in an effort to unravel the mystery, Sir James Jeans, following a suggestion made by Lord Rayleigh, was able to mathematically predict a portion of the spectral shape of a blackbody emitter, using the classical theory of equipartition of energy. His approach, however, erroneously predicted that the emission spectra would increase at shorter wavelengths. This was contrary to what had been measured from an ideal blackbody radiator shown in Figure 3. This contradiction, was called Jeans' Paradox or the "ultraviolet catastrophe," introduced a true turning point in the history of physics.

The classical theories of Maxwell could not correctly predict the structure of atoms, the different energy states of atoms and how excited atoms emitted or absorbed radiation. A new, radical approach was needed to explain the reality of atomic structure.

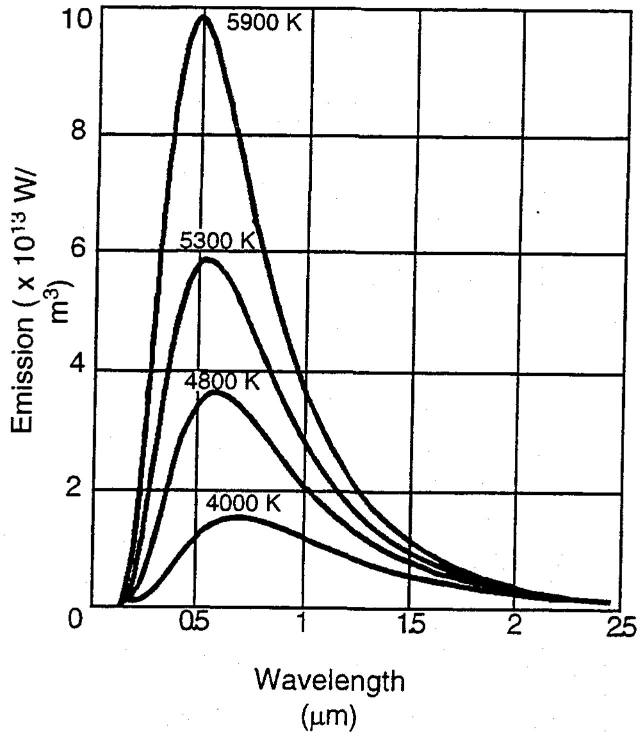


Figure 3. Black Body Radiator

QUANTUM THEORY

It was in late October, 1900 at a meeting of the Berlin Physical Society that German Physicist Max Plank presented an extraordinary solution for Jeans' Paradox – a solution that originated the science that is today called quantum physics. Plank's proposal would unleash a conceptual bombshell that eventually led to a totally new understanding of the physical universe.

In order to have his formula agree with experimental data, Plank was forced to make the following unprecedented assumption: that the internal energy of an emitting source (resonator) must have its internal energy divided in discrete quantities (**quanta**) that were proportional to the resonator frequency. Moreover, each quanta would be an integer multiple of what Plank would call the "energy element." This element was the product of a constant (*h*) and frequency (υ) of the resonator.

This infinitesimal bit of energy was later to be called a quanta or **photon**. Thus, one quanta has a discrete energy value. It was also later shown to have a momentum equivalence but no mass. The amount of energy per photon (E) is given by:

$$E = h\upsilon \qquad (4)$$

where Plank's constant h=6.63 x 10^{-34} Joule-seconds and υ is the radiation frequency (expressed in Hertz or cycles/seconds).

Plank's treatment of the radiation field itself was purely classical, with no suggestion that the radiation field itself could be similarly quantized. Although his work went unheralded for several years, it was eventually recognized that his concept was a fundamental statement and that the value of the proportionality constant *h* (which Plank first thought to be a mathematical convenience) was a universal constant of the greatest importance.

SKILL REVIEW
2

Calculate the energy of a photon from a CO_2 laser with a wavelength of 10.6 μm.

Calculate here:

It was, in fact, work by Einstein in the early 1900s that would firmly predict that the energy divisions of a simple atomic resonator can only take on values of multiples of $h\upsilon$ and that during radiation absorption and emission processes the resonator energy changes only in steps of $h\upsilon$ and that, in fact, the entire radiation field itself is quantized. All of these factors laid the foundation for the prediction by Einstein in 1917 of the process that is fundamental to laser operation: stimulated emission.

THE BOHR MODEL OF ATOMS

In 1913, Niels Bohr, a Danish physicist, developed a mathematical theory of atomic spectra to explain the fact that atoms emit or absorb only certain characteristic frequencies of light.

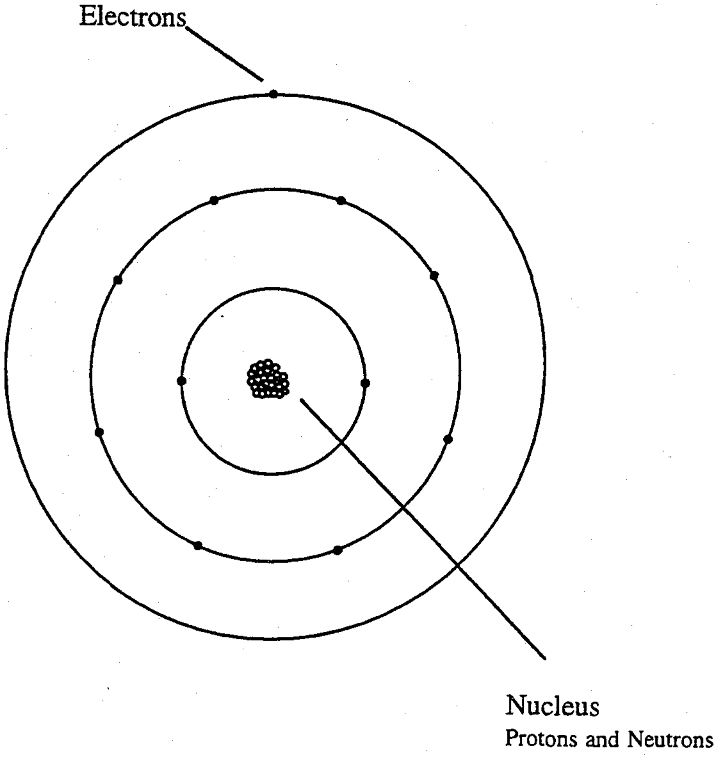


Figure 4. The Bohr Model of the Atom

The Bohr model of the atom (Figure 4) assumed that:

1. Electrons move about the nucleus in fixed paths called orbits
2. Electrons in orbitals closer to the nucleus have less energy than those farther from the nucleus
3. Electrons can only occupy certain discrete quantized orbits or states
4. Electrons gain or lose fixed amounts of energy (quanta) when they jump from one orbit to another, emitting or absorbing a photon of radiant energy according to Planck's equation.

According to the Bohr model, the structure of atoms and molecules can be represented by energy level diagrams as will be discussed in the next section. As an atom is excited (absorbs energy), the electrons jump to higher orbits, which are called **energy states**. The more complex the atomic structure, the larger the number of available energy states and the more complex the energy transitions.

CHARACTERISTICS OF LIGHT

In an ordinary light bulb, a metal filament is heated, which causes electrons to jump to higher orbits. When the electrons return to lower energy levels, light is given off. Such light consists of many different wavelengths and the light travels in all directions. The light appears white because it consists of a combination of all visible wavelengths, or colors, as well as invisible light in the ultraviolet and infrared regions. This fact can be demonstrated by passing ordinary white light through a prism. Figure 5 shows how a prism separates the white light into a continuous spectrum according to wavelength.

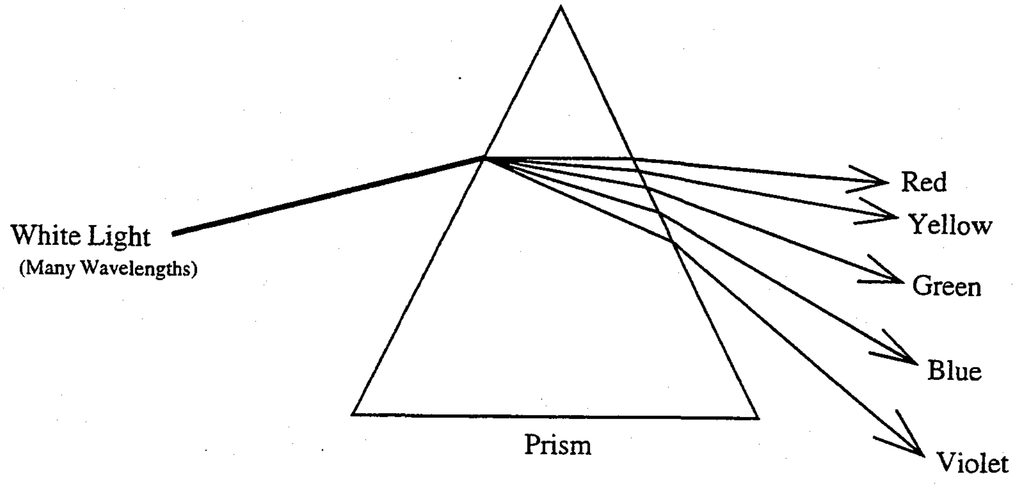


Figure 5. The Visible Spectrum

FUNDAMENTALS OF LASER PHYSICS

SECTION OBJECTIVES

- *Compare* and *contrast* laser light with ordinary light
- *Describe* three components that are common to all lasers
- *Explain* the relationship between stimulated emission, population inversion, and pumping in producing laser light
- *Differentiate* among 2-, 3- and 4-level lasers

CONCEPTS OF LASER OPERATION

The term **laser** is an acronym for Light Amplification by Stimulated Emission of Radiation. Stimulated emission will be discussed in detail in following sections. Lasers are devices that produce a very special kind of light. Unlike ordinary light, laser light is only one wavelength (**monochromatic**), travels in one direction (**directional**), and is in phase (**coherent**). These characteristics are what give laser radiation its intensity and ability to travel great distances without spreading out as compared to ordinary light.

Although the theory upon which laser devices are built dates back to Einstein's work in 1917, the practical difficulties in constructing such devices were overcome only since the mid-1950s. The first person to develop such a device was Charles H. Townes at Columbia University. Townes worked with microwaves, which have much longer wavelengths than light. He called his device a **maser**, which is an acronym for Microwave Amplification by Stimulated Emission of Radiation. The first laser, a ruby laser, was first operated by Theodore Maiman on May 16, 1960. Since that time many hundreds of different types of lasers have been built.

LASER COMPONENTS

Lasers differ in output power, wavelength, and beam characteristics. Some lasers use solid crystals, others use gas, some are electronic diodes, and still others use liquid dyes. Yet, there are three basic components that are common to all lasers (Figure 6). These components are an **active medium**, an **excitation mechanism**, and an **optical cavity**.

The active medium is a collection of atoms, molecules, or ions that can absorb energy from an outside source and re-emit the energy in the form of laser light. The medium is usually in the form of a rod, a tube, or a rectangular solid. The medium can be a solid crystal material such as ruby, Nd:YAG, or Nd-doped glass; a liquid dye such as rhodamine; a gas such as HeNe or CO_2; or a transistor-type material such as GaAs and GaAlAs. This material determines many of the output characteristics of the laser light, such as wavelength.

In order to produce a laser beam, external energy must be added to the active medium by some excitation mechanism. The excitation mechanism causes electrons to jump to higher energy levels. If the electrons are then somehow stimulated to drop back to a lower energy level, the

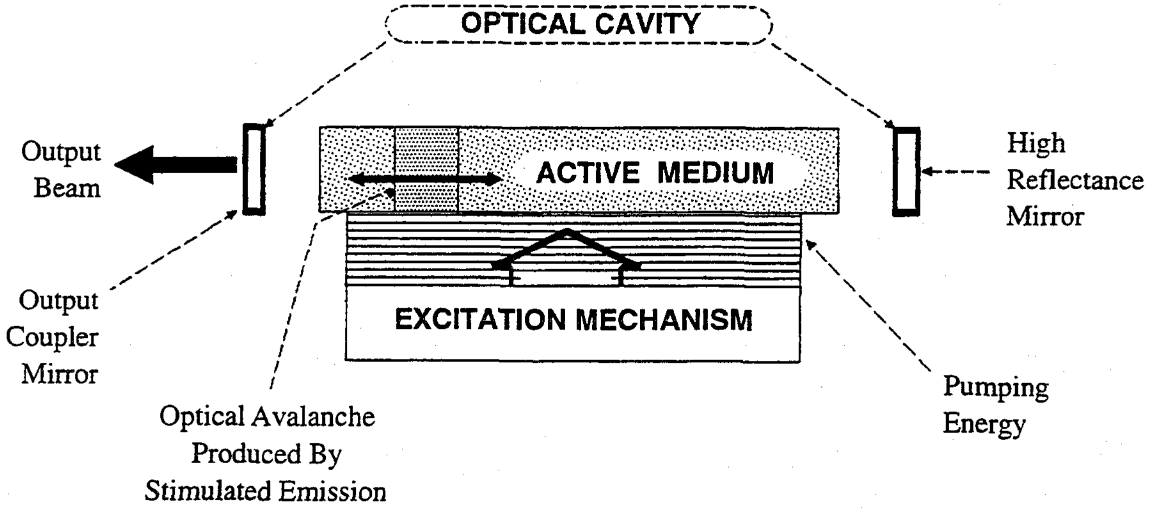


Figure 6. Components Common to All Lasers

energy difference between the two levels is released in the form of monochromatic light, which is emitted from the material.

It takes more than an active medium and an excitation mechanism to produce laser light. Such a system could produce light, but it would be emitted in all directions and would behave like ordinary monochromatic light. In order to produce a laser beam, an optical cavity is needed to amplify and to direct the output energy. The optical cavity consists of two mirrors placed at opposite ends of the active medium. The mirrors reflect laser light back and forth through the medium. On each pass through the medium, the intensity of the laser light is amplified. One mirror reflects essentially 100 percent of the light hitting it, while the other mirror, called the **output coupler**, reflects only part of the light, transmitting the remainder. In this way some of the laser light is emitted from the laser.

Sometimes the output coupler is blocked from the inside by a special material that can be "switched" from a transparent state to an opaque state. This special material enables the laser to be turned on and off so that it can produce pulses instead of continuous output. Outside a laser, other optical devices, such as additional mirrors and lenses, are used to direct the light and to condition it for specific applications.

STIMULATED and SPONTANEOUS EMISSION

We have described in very general terms how a laser operates. Now we will explain at a more detailed level the atomic transitions that are involved in this process. As mentioned previously, an electron can be excited to higher energy level by absorbing a photon (**absorption**). Electrons, however, do not remain indefinitely at these higher energy states and tend to fall back to a lower energy level (state) by spontaneously emitting a photon. This process is called **spontaneous emission.**

A common example of spontaneous emission occurs in phosphor materials. When the atoms of the phosphor are excited by an external light source such as the sun or a light bulb, electrons jump to higher energy states. The electrons then spontaneously drop back to lower energy levels. As the electrons that were excited to higher energy states spontaneously drop to lower energy states, photons of visible light are emitted. It is this process that causes a phosphor to glow in the dark. The larger the number of different frequencies of light emitted, the more the glow will appear as white light.

In 1917 Albert Einstein proposed that an excited electron could be stimulated to jump to a lower energy level by interacting with a photon of energy emitted by a neighboring excited electron. *The released photon would be identical in frequency, energy, direction, and phase with the triggering photon.* Furthermore, the triggering photon would continue unchanged by the interaction. These two photons could then in turn trigger other excited electrons to emit identical photons. This type of emission is called **stimulated emission**. Because the photons are identical, the light would be amplified, which is the basis for the acronym Light Amplification by Stimulated Emission of Radiation.

POPULATION INVERSION

Stimulated emission occurs naturally, but because electrons normally exist in nature at the lowest energy levels, the effect is very small and is indistinguishable from ordinary spontaneous emission. However, if a device could be built that causes more electrons to be in the higher energy levels, then such a device could produce a light beam in which nearly all of the light has the same wavelength and is highly directional (**collimated**). The condition in which more atoms are in the excited than in the lower energy level is called **population inversion**.

One excitation mechanism that can produce a population inversion is **optical pumping**. Optical pumping involves illuminating an active medium with a high-energy optical source, such as a flashlamp or another laser, to excite the atoms or molecules. If a broadband light source is used, only those photons with a frequency that corresponds to specific energy states of the atom will be absorbed. The remaining wavelengths are lost and usually cause unwanted heating. Optical pumping is most commonly used with solid state and dye lasers.

A second excitation mechanism is **electrical pumping**. Electrical pumping involves an electrical discharge that excites atoms as a result of collisions with electrons and/or molecules. Electrical pumping can only be used with laser materials that conduct electricity without destroying laser action. Electrical pumping is most commonly used with gas lasers and semiconductor lasers.

SKILL REVIEW
3

What are the three components that are found in all lasers?

Answer here:

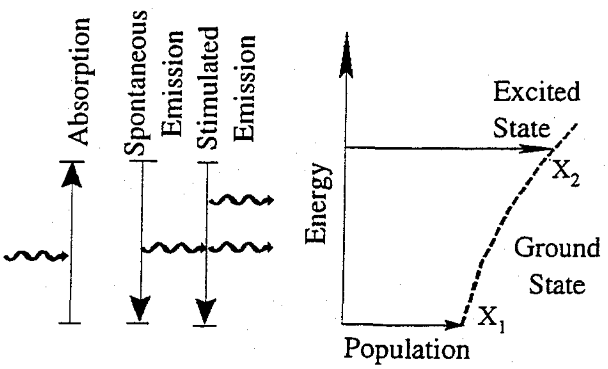
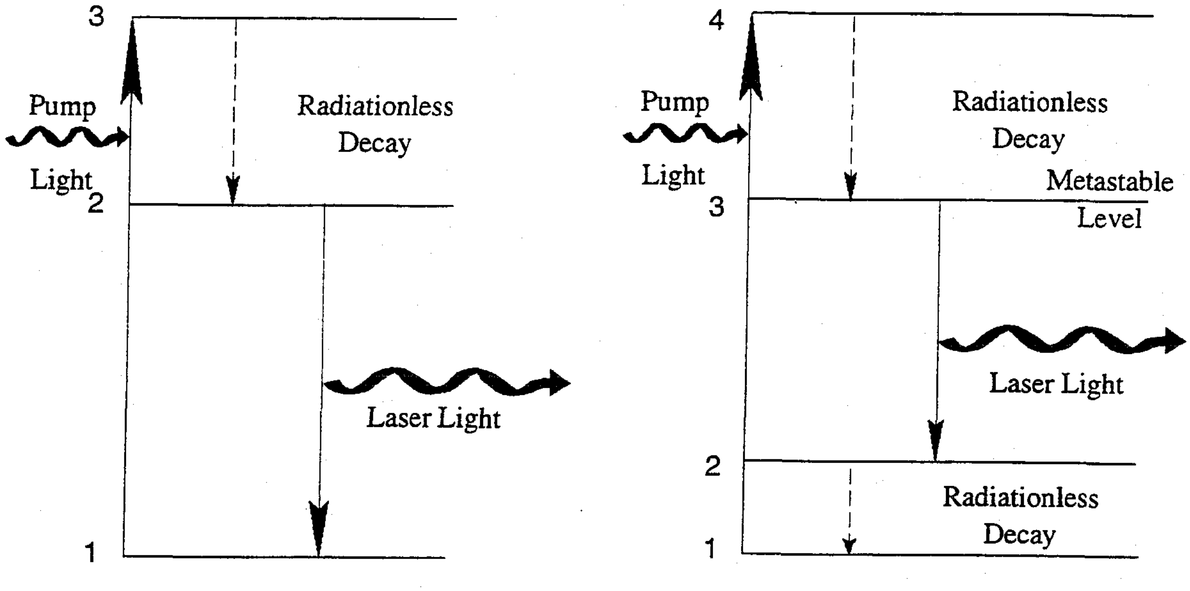


Figure 7. Laser Energy-Level Diagram for a 2-Level Laser System



THREE-LEVEL SYSTEM FOUR-LEVEL SYSTEM

Figure 8. Laser Energy-Level Diagrams for 3-and 4-Level Systems

A third pumping mechanism is **chemical pumping**. Chemical pumping uses the binding energy released in chemical reactions to produce population inversions. Although chemically pumped lasers can produce very high power, chemical pumping is not commonly used. However, chemically pumped lasers have been investigated for potential military applications.

SKILL REVIEW
4

Name the three methods used to establish a population inversion.

Name here:

TWO-LEVEL LASERS

A two-level laser uses only two energy levels – the ground state and the upper level. The disadvantage of a two-level laser (Figure 7) is that the ground state is also the lower energy level. Consequently, the majority of the electrons must be raised to higher energy levels to produce a population inversion. Such a laser requires a large excitation energy. Furthermore, the population inversion is difficult to maintain. As a result, most of today's laser systems involve three or four energy levels (Figure 8).

THREE- AND FOUR-LEVEL LASERS

In a three-level laser, electrons at the ground state are excited to a higher energy level. The electrons then quickly fall from the higher energy level to a longer-lived upper energy level, called a **metastable energy level**. The lifetime of an electron in the metastable energy level is on the order of one thousand times longer than in the upper energy level. As a result a population inversion is formed between the metastable energy level and the ground state. Since the ground state is also the lower energy level in a three-level laser, the population inversion is difficult to maintain. For this reason, three-level lasers often operate in a pulsed mode. A ruby laser is an example of a three-level laser.

Most lasers involve four energy levels. As Figure 8 shows, in a four-level laser the electrons are excited to a very short-lived higher energy level from which they quickly fall to a metastable upper energy level. The population inversion is then formed between the metastable level and a lower energy level that is not the ground state. One advantage of a four-level laser system is that fewer electrons must be raised to the metastable level to produce a population inversion. A second advantage of a four-level system is that it maintains a population inversion more easily than can a three-level system. When the electrons in the lower energy level of a four-level laser have shorter life times than electrons in the metastable level, the population inversion tends to maintain itself much more easily because electrons are lost to the pathway of the lower level. It is for this reason that some four-level lasers are capable of producing a continuous beam, which is also called **continuous wave** (CW). The Nd:YAG laser is an example of a four-level laser.

In actual lasers, the energy level transitions are more complex. Instead of a single metastable layer, electrons may be excited to multiple levels. Similarly, there may be more than one lower level. As a result many lasers emit at multiple wavelengths. For example, the helium-neon laser is well known for emitting red light. However, the helium-neon laser can also emit at the green, yellow, orange, and infrared wavelengths.

Another complicating factor in actual lasers is the role of different types of atoms and molecules in the active medium. One type may absorb the excitation energy and then transfer the energy to another type of atom or molecule. For example, in the helium-neon laser, the helium captures the excitation energy and then transfers the energy by a collisional process to the neon atoms, causing the population inversion within the energy levels of the neon gas.

Wavelengths of the More Common Laser Types

Laser Type	Media	Wavelength(s) (µm)
Excimer Gas Lasers		
Argon Fluoride	(UV)	0.193
Xenon Chloride	(UV)	0.308
Xenon Fluoride	(UV)	0.351
Gas Lasers		
Argon	(Blue)	0.488
	(Green)	0.514
Krypton	(Blue)	0.476
	(Green)	0.528
	(Yellow)	0.568
	(Red)	0.647
Xenon		0.535
Helium Neon	(Red)	0.633
Hydrogen Fluoride	(NIR)	2.700
Carbon Dioxide	(FIR)	10.600
MetalVapor Lasers		
Copper Vapor	(Green)	0.510
	(Yellow)	0.570
Gold Vapor	(Red)	0.627
Solid State Lasers		
Nd:YAG	(NIR)	1.064
Doubled-Nd:YAG	(Green)	0.532
Erbium: Glass	(IR)	1.540
Erbium:YAG	(IR)	2.94
Holmiun:YLF		2.060
Holmium:YAG		2.100
Chromium-Sapphire	(Red)	0.6943
Titanium-Sapphire	(NIR)	0.840-1.100
Dye Lasers		
Rhodamine 6G Dye (tunable)		0.570-0.650
Coumarin C-30	(Green)	0.504
Semiconductor Lasers		
GaAs	(NIR)	0.840
GaAlAs	(VIS/NIR)	0.670-0.830

Code:	UV:	Ultraviolet	(0.200-0.400 µm)
	VIS:	Visible	(0.400-0.700 µm)
	NIR:	Near Infrared	(0.700-1.400 µm)
	FIR:	Far Infrared	(1.400-30.00 µm)

LASER APPLICATIONS

SECTION OBJECTIVES

- *Name* major categories of laser use and identify the type of laser appropriate for each of these applications
- *Describe* four industrial and four medical laser applications
- *Summarize* the advantages and disadvantages associated with laser communications
- *List* three commercial laser products
- *Describe* three military and three research laser applications

CATEGORIES OF LASER USE

The earliest lasers created quite a sensation. Everybody wanted one and no laboratory was complete without a laser. Lasers were used to "zap" everything from cell cultures to razor blades. In fact, so many holes were burned in razor blades that during these early years, laser power was unofficially measured in *Gillettes*.

Initially, the laser was just a fascinating novelty when it was introduced in the 1960s. The problems which lasers could help to solve had yet to be discovered. This situation, however, quickly changed and within 20 years the sales of lasers reached one billion dollars. Today lasers are used in industry, medicine, research, art and entertainment, education, and military applications. Some of the principle categories of laser use are listed in Table 1. Table 2 lists some common types of lasers.

LASERS IN INDUSTRY

Industry uses lasers to cut, weld, drill, mark, and solder materials. Other industrial laser applications include the manufacture of integrated chips, precise surveying, alignment, and communications.

Lasers offer many advantages, which are described in the following sections, but they do have some shortcomings. Lasers are expensive – a laser drill can cost between fifty thousand and five hundred thousand dollars. Personnel must be trained to operate lasers, and laser safety programs must be developed to ensure that lasers are operated safely. Despite their shortcomings, lasers offer so many advantages that they have become an integral part of industry.

Materials Working

Lasers offer several advantages for materials processing. One advantage is that, because only the laser beam touches the material, a laser tool never becomes "dull." Unlike ordinary machine tools, laser beams do not break or slip, and seldom need to be replaced. Another advantage is that lasers cut with virtually no damage to surrounding surfaces. This property makes lasers especially useful in working with materials such as glass, which fractures easily, and with soft materials like rubber, which tends to be ripped by ordinary drills. A third advantage of lasers is the extreme precision with which they can cut and drill. Lasers are capable of cutting very precise, small holes. It

TABLE 1

MAJOR CATEGORIES OF LASER USERS

COMMERCE	INDUSTRY	MEDICINE	MILITARY	RESEARCH
Copiers	Alignment	Cellular research	Navigation	Interferometry
Displays	Annealing	Dentistry	Ranging	Plasma diagnostics
Fiber optics	Cutting/drilling	Surgery	Simulation	Scanning microscope
Holography	Dynamic balancing	Diagnostics	Weapons	Spectroscopy
Printing	Metrology	Ophthalmology	Guidance	Velocimetry
Reading/Scanning	Nondestructive testing			
Recording	Sealing			
Video-discs	Soldering/welding			

TABLE 2

LASER APPLICATIONS

LASER MEDIA	WAVELENGTH (µm)	APPLICATION
Ruby	0.6943	Satellite ranging, medical, drilling holes
Neodymium-YAG	1.06	Metal processing, welding, eye surgery, military weapons and ranging
Carbon dioxide	10.6	High-power metal treatments, surgery
Argon Ion gas	0.488 - 0.514 0.351 & 0.363	Eye surgery, cell counters, diagnostics, photoetching, light shows
HeliumNeon	0.6328	UPC checkout systems, alignment, construction, videodiscs
Gallium arsenide diode	0.840	Communications, infrared beacons in array formats, laser printers, CD players
Krypton Ion gas	0.4762 & 0.5280	Light shows, holography, diagnostics
Dye lasers, such as Rhodamine 6-G	Tunable: 0.570-0.650	Spectroscopy, IC circuit etching, photochemical reactions

might seem peculiar at first, but lasers do not cut large holes very well. Because the energy required to cut a hole increases with the square of the radius, the energy needed to drill a 10 mm hole is 100 times the energy needed to drill a 1 mm hole.

Materials Marking

Lasers are also widely used in industry for material marking. Laser marking involves removing (ablating) the surface layer of a material or changing the color of the surface by heating. Laser marking has many advantages over conventional methods of marking. Virtually all materials can be laser-marked with permanent high quality marks without contacting, mechanically distorting, or contaminating the material; and the marks can be made with high speed, low cost, and low maintenance.

Laser marking is used for pharmaceuticals, foods, cosmetics, and automobiles. The use of laser marking is rapidly expanding. For example, the annual U.S. sales of laser marking systems ranges from 25 million and 30 million dollars in the late 1980s. More than 50 companies in the United States manufacture marking systems. The carbon dioxide and neodymium-YAG lasers are commonly used to thermal etch product codes, manufacturer identification, date of manufacture, and real time production line identification such as batch number and production staff.

Semiconductor Processing

Semiconductor processing applications include lithography, selective annealing, thin-film removal (resistor trimming), link-making and link-blowing on memory chips, vapor deposition, metal planarization, doping, hole drilling, surface inspection, etching, aligning, and photomask and screen generation, among others. Lasers operating in the ultraviolet and short wave visible spectra (0.300-0.550 μm) are being used for various photoetching processes in the manufacture of multilayer integrated circuits. This includes systems such as the nitrogen, helium-cadmium, argon ion, copper vapor, as well as excimer lasers such as argon-fluoride, krypton-chloride, krypton-fluoride, xenon-chloride, and xenon-fluoride.

Alignment and Control

Alignment and control applications include surveying, construction alignment, and tool alignment. Lasers are used in agriculture and construction to precisely level fields. Low power (<10 mW) CW lasers, such as the helium-neon and gallium arsenide diode lasers, are used in a variety of precision alignment and machine control applications. Lasers, for example, are used in the logging industry to align saw blades so that the maximum amount of lumber is obtained.

Lasers are also used in quality control. For example, lasers are used to precisely control wire size. Typically, the wire is passed through a scanning line of laser light so that the shadow of the wire falls upon a photodetector. The photodetector electronically converts the size of the shadow into a feedback signal that controls the rate at which the wire is drawn, which in turn controls the size of the wire.

Lasers are used to detect imperfections in products that must be manufactured to precise specifications. For example, tolerances on lenses and hypodermic needles can be measured with lasers. By reflecting laser light off these surfaces and measuring the amount of light scatter, such items can be inspected and sorted at high speed. In the textile industry, people have been replaced by lasers for inspecting fabrics. Traditionally, such a task was tedious, very time consuming, and expensive. Lasers can do the same task around the clock; and the laser can inspect more than 10 feet of cloth per second.

Lasers are also used for counting. Lasers count the number of newspapers printed. Laser gyroscopes count the number of rotations very accurately. Such lasers are used in aircraft and missiles to determine course and position. Lasers can also count the amount of pollutants in the air. Since different atoms and molecules absorb en-

SKILL REVIEW
5

What are two advantages and two disadvantages of industrial lasers?

Answer here:

ergy at different wavelengths, laser spectroscopes can be used to determine the concentration of pollutants such as sulfur dioxide and ozone.

LASERS IN COMMUNICATIONS

A laser signal can simultaneously carry more than a billion conversations. Lasers can be used to link spacecraft, satellites, aircraft, surface vessels, and submarines. Compared to radio frequency systems, laser communications systems offer small size and weight, and high information capacity. Also, because lasers are highly directional, they provide a secure means to transmit information through the atmosphere, and it is nearly impossible to jam a laser transmission. For these reasons, laser communications have become an essential part of military communication systems.

However, atmospheric laser transmission has certain disadvantages that make it less suitable for commercial communication systems. One shortcoming is attenuation and distortion of a laser beam as it passes through the atmosphere. A second disadvantage is that only low-power beams can be transmitted for safety reasons. A third limitation is that laser communication is limited by line-of-sight applications, although the use of satellites can minimize this problem.

The communications industry has circumvented these problems through the use of fiber optics. An **optical fiber** consists of a central core, which has a high index of refraction, surrounded by an outer layer, which has a much lower index of refraction. Light travels through the optical fiber by internally reflecting off the walls.

As light travels through an optical fiber, there are some losses. Consequently, a long-distance fiber optic communication system must have repeaters placed at intervals along the cable path. Repeaters amplify and retransmit the optical signals, compensating for the losses within the fiber. Fiberoptics communications are extremely clear since they are not affected by electromagnetic noise – even the electromagnetic burst caused by a high-altitude, nuclear explosion. One telephone company advertises the clarity of its fiber optic communication system as a major selling point.

Present long-distance, optical fiber communications systems use low-frequency, near-infrared semiconductor diode lasers as the light source. It is predicted that the market for these diodes will reach $1 billion in the 1990s. However, the uses for fiber optics are not limited to communications, which could become the *singularly largest* application area of all laser uses. Fiber optics are being used in the automobile industry where noise from electrical circuits can damage microprocessors. Fiber optics are used in the Stealth bomber to reduce electromagnetic emissions and because fiber optics are immune to strong electromagnetic fields, which could be caused by jamming or nuclear explosions. Also, fiber optics are used to conduct a laser beam down the arm of a robot to a target material.

LASERS IN MEDICINE

The medical use of lasers has become widely accepted. It is predicted that lasers will be used in virtually every hospital in the United States for surgery and for ophthalmology.

Surgery

Lasers provide the least invasive surgical procedure. Lasers, which are used in 16 fields of medicine, may eventually be used in 10 to 40 percent of the 11.5 million surgical procedures performed each year in the United States.

Lasers are used in treating certain cardiovascular diseases. One of the most promising areas is in treating coronary-arterial blockage which can cause heart attacks. In this procedure, laser light is used to blast apart the fatty material blocking the artery with minimal damage to the cell wall. Lasers are equally successful in removing lesions, tumors, and malignant cells from the digestive tract.

Lasers have replaced the scalpel in many dermatological applications. For example, lasers are used to remove disfiguring "port wine" stains on the head or neck. These stains are caused by blood vessels which have grown near the surface of the skin. The procedure is quick and relatively painless, and there is usually little or no scarring if done correctly. Lasers are also used to treat other kinds of skin lesions and cancers; lasers have even been used to remove tatoos.

Ophthalmology

Nd:YAG lasers are used to remove "secondary cataracts" that sometimes form after cataract surgery. Argon lasers are routinely used to treat retinal diseases, retinal tears, and glaucoma. The latter therapy has greatly expanded the number of ophthalmologists who are routinely using lasers as part of their daily treatments. Many ophthalmologists believe that one cannot conduct a successful medical practice for eye diseases today without access to a laser either at the hospital or at the physician's private office.

Cancer Treatment

Lasers offer a new method for treating certain types of cancer. For example, one type of cancer can be treated by injecting the patient with a dye that is absorbed in the tumor. Using a laser with the proper wavelength, the laser energy is also selectively absorbed by the tumor. A photochemical reaction then kills the tumor without damaging surrounding healthy tissue. This approach, called Photo Dynamic Therapy (PDT) provides a highly specific therapy over chemical or radiation treatments.

Diagnostic Applications

Diagnostic applications include DNA sequencing, cell separation, cell sorting (cytometry), AIDS detection, and cancer detection. Laser holograms are used as diagnostic aids to produce three-dimensional representation of body organs such as the brain, liver, and breast to detect the presence of tumors.

Cervical cancer is a common problem in women that responds best if treated early. For this reason, pap smears are done annually. A pap smear consists of performing a biopsy on cells from the cervix. The tests are time consuming and sometimes indeterminate. Laser diagnosis of pap smears is simpler and more reliable.

The economic implications of the successful implementation of laser-based therapeutic procedures are highly significant. For example, corneal sculpting alone is estimated to have a potential market of $6 billion per year for the replacement of eye glasses.

The combining of diagnostic and therapeutic functions in individual laser systems is particularly promising for the medical systems of the future. For example, in laser angioplasty, lasers can potentially be used to identify the material that is to be vaporized, to vaporize it and to monitor the progress of the vaporization – all in one combined process.

SKILL REVIEW
6

Can you think of a possibile reason why lasers are not now in use in all hospitals?

Answer here:

LASERS IN ART AND ENTERTAINMENT

Laser light, with its brilliance and spectral purity, is an ideal tool for artists, lighting designers, and kinetic light sculptures. Some laser artists have placed laser kinetic sculptures in private collections, as well as in galleries and museums.

The use of laser light as an entertainment media traces it origins to small planetarium shows in the 1970s. Today, laser entertainment is a big business. Laser light shows have become integral parts of symphonies, rock concerts, ballets, discotheque lighting, fashion shows, and sports "half-time" shows. Lasers are used to project graphic displays on buildings and even the side of the Grand Coulee Dam. Laser billboards are predicted in the next decade.

The laser projection systems used by artists and laser entertainment companies are, in fact, a marriage of highly sophisticated assemblies of laser and electro-optic equipment with computers. Such systems use either argon or krypton-ion gas lasers, helium-neon lasers, or in rare cases, a tunable dye laser. Laser emission levels for most indoor projection effects are often less than 250 mW. Outdoor laser light shows generally require at least 5 W, and it is not uncommon that powers up to 20 W are used. Furthermore, outdoor light shows usually require a number of lasers to produce the desired effects.

LASERS IN COMMERCE

Lasers, once the play toys of researchers, have become everyday components of commercial products. Lasers are now being used in a wide variety of applications that involve both the recording and playback of information. Examples include high speed, non-impact laser printers, product-code scanning systems, and laser videodiscs. Sales of just three laser-based products – optical memories, laser printers, and bar code scanners – account for 12 billion dollars per year.

Laser printers

Laser printers are being adopted widely, with annual sales of $3 billion in 1988, an increase of 28% over the previous year. Japan presently holds an 85% share of world production of low-end laser printers. The module you are reading, for example, was mastered using a laser printer.

Laser scanners

Laser scanners are capable of digitizing virtually any image. Present scanning speeds are approaching 10 megapixels per second. These scanners have led to the development of new filing systems based on optical data storage. These systems completely replace paper copy and yet produce high quality paper output on demand. Laser scanners are revolutionizing the print media. With the laser scanners, images can be loaded into a computer and then edited. Even inexpensive minicomputers can be used to produce professional-looking documents.

One of the more important commercial uses of laser scanners is to read bar codes. Nearly every supermarket uses laser scanners to read the Universal Product Code (UPC), which is now imprinted on all items. A low-power helium-neon laser is scanned across the code pattern. The reflected beam is computer processed to identify the scanned product.

Laser scanners are now widely used in inventory control by all types of businesses. Even the United States Postal Service uses laser scanner systems to monitor and control the flow of mail sacks in the large bulk mail facilities across the country.

Optical character readers are another type of laser scanner that read typed text from a page. Optical readers enable you to enter typed information directly into a computer without having to type it in. Optical readers cannot be used for hand written information, but scientists continue to work on this problem.

Optical Disks

Optical disks are used to store enormous amounts of information onto a small surface. For example, the Compact Disk Read-Only Memory (CD-ROM) format can store 4.8 billion bits of data on a 12 cm diameter disk.

Home videodiscs were introduced to the American market in the 1970s – and they were an immediate flop with consumers. The disk contains microscopic digital encodings that can be scanned and decoded with a low-power, helium-neon laser. Unlike VCRs, videodiscs could not be used to record programs and so they never really caught on.

Although the videodisc market did not succeed in the home market, it did find commercial applications. As an example, videodiscs are used for information display throughout the Disney EPCOT Center in Orlando, Florida. One specially recorded disk feeds hundreds of color video terminals throughout the park to generate high quality video reproduction. Videodiscs are also used in educational, financial, and medical libraries. Other users include the Federal Government education, and major industries. A new generation of optical disks that have the capability to both read and write data promise to further expand the market for these devices.

Videodiscs were quickly followed by the introduction of compact disc players – those wonderful machines that provide concert-quality sound reproduction. Compact disc players use small, inexpensive diode lasers to read optical disks.

The world market for CD-ROM drives for 1989 was estimated at 179,200 drives, valued at 108 million dollars. The world market is expected to rise to 691,600 drives in 1993, valued at 200 million to 400 million dollars.

Lasers are also being used in special, high-speed copy machines. In these devices, the laser is intensity-modulated and scanned across the copy machine drum so as to write the information onto the drum. Copies can be made at high speeds.

The newest optical devices are optical computers. Optical computers use fiber optics. They may or may not require laser light. Optical computers promise speed and power not possible with ordinary electronic computers. The possibilities are endless and tomorrow's optical computers may make today's super computers seem as slow and antiquated as the first XT computers, which used the 8086 computer chips.

LASERS IN THE MILITARY

When lasers first appeared, science fiction writers immediately envisioned futuristic weapons that could blast a plane out of the sky or sink the largest battle ship. Alas, lasers could not do these things and were relegated to what appeared to be mundane tasks such as determining range.

All at once the American public was introduced to "Star Wars." The military hoped to use lasers to shoot down attacking missiles before they could reach their targets. Although *missile drones*, Sidewinder air-to-air missiles, and antiship missiles were shot in tests, opponents scoffed that the effort was simply another example of frivolous military expenditures. Critics argued that such systems were prohibitively expensive and that they would most likely not even work.

Then in January 1991, the world witnessed the allied war against Iraq. Television viewers saw first hand how laser-guided missiles could strike their targets with deadly precision. The Patriot missile system was observed to engage more than twenty SCUD missiles, knocking them from the sky. All at once people began to comprehend the power and accuracy of these new weapons.

The research on lasers weapons is continuing. It is likely that laser antipersonnel weapons will be developed, as well as laser weapons that can destroy enemy optical targeting devices. Research will continue on "Star Wars" missile weapons. It is not unlikely that antimissile laser weapons will be developed within the next decade.

LASERS IN RESEARCH

Lasers are used in virtually every field of research: physics, chemistry, materials science, electronics, biology and medicine. The monochromatic beam of the laser provides an ideal tool for many spectroscopic and other analytical chemical applications because most molecules have specific absorption, transmission and fluorescence spectra.

Laser systems are used to detect pollutants in air and water, to determine the chemical composition of unknown substances and to measure concentrations of chemicals to accuracies in parts per billion. One laser system, LIDAR (Light Detection and Ranging), can be operated in the field to detect atmospheric pollution. As laser light passes through various concentrations of particles in the atmosphere, it is scattered in many directions. By analyzing the spectra of the scattered radiation, it is possible to determine the presence and concentration of many atmospheric pollutants.

Laser radiation is also used to produce certain chemical reactions that would otherwise not occur. For example, excimer lasers operating in the 0.193-0.351 µm range have been used to produce vinyl chloride monomers. There are several groups examining the possibility of laser assisted catalysis. However, there are no industrial applications known at this time.

Lasers are being used in nuclear fusion research. In this research, lasers are used to focus a trillion watts of laser light onto a tiny pellet containing a mixture of two hydrogen isotopes: deuterium and tritium. Irradiation of the pellet causes the isotopes to be heated to nearly 100 million degrees and to be forced together. Under the proper conditions, a fusion reaction, like that which occurs in the sun, can be produced. If such a reaction could be sustained, this process could be supply a nearly limitless source of electrical power. At the present time, fusion has been initiated, but the energy required to produce the reaction has been greater than the energy output. Most experts project at least another decade of research will be needed before the break-even point is reached and another decade before pilot electrical plants will be constructed.

CHAPTER REVIEW

SUMMARY

1. Sir Issac Newton and Christian Huygens first proposed the particle and wave theories of light in the 17th century.

2. Max Planck first introduced the concepts of the quantum theory in 1900.

3. A photon has a discrete energy and momentum like an electron or proton, but no mass.

4. Albert Einstein first predicted the process of stimulated Emission in 1917.

5. Theodore Maiman operated the first laser device in 1960.

6. All lasers have three basic components: an active medium, excitation mechanism and an optical cavity.

7. Most lasers are made from materials which involve four energy levels in the light generation process.

8. Laser light is monochromatic, directional and coherent.

9. Today, we know that light is a transverse electromagnetic wave, but that it has properties of waves (e.g. interference) and particles (momentum).

10. Lasers are used in industry, communications, medicine, art and entertainment, commerce, the *military and research.*

KEY TERMS Define each term

absorption
active medium
chemical pumping
coherent
collimated
continuous wave
directional
electrical pumping
energy state
excitation mechanism
LASER
metastable energy level
monochromatic
optical cavity
optical fiber
optical pumping
output coupler
photons
population inversion
quanta
spontaneous emission
stimulated emission

FOR FURTHER READING

Coherent, Inc. Staff. (1980). McGraw-Hill Book Company. *Lasers: Operation, Equipment, Application and Design.* Gives concise explanations, supported by detailed drawings and close-up photographs, of how you can use the laser on your job.

Encyclopedia of Lasers and Optical Technology. (1991). Academic Press. This work will bring readers up to date with the latest advances in lasers and optics.

Gamow, G. (1961). *Biography of Physics.* New York: Harper & Row. A thoroughly enjoyable and well written book that combines the history of modern physics with a general discussion of the basic physical laws.

Gibilisco, S. (1989). *Understanding lasers.* Blue Ridge Summit, PA: TAB BOOKS. The author presents a general description for the reader on the nature of laser light and goes on to describe some of the current uses for lasers

Goldman, Leon. (1981). Springer-Verlag. *The Biomedical Laser: Technology and Clinical Applications.* The emphasis of this book is on the practical, rather than the esoteric, is dictated not only by the short history of biomedical laser use, but by the extent of the community to which this information will appeal.

Johnson, J. (1981). *Lasers: A Look Inside.* Raintree Publishers. Discusses the development of the first modern laser, the parts of a laser and how they work, and applications of lasers in medicine and technology.

Readings from Scientific American. (1969). W. H. Feeman and Company. *Lasers and Light.* Collection of articles from various issues of Scientific American.

REVIEW QUESTIONS

1. The particle theory of light provides a better explanation of ____ than the wave theory.

   a. reflection
   b. photoemission
   c. diffraction
   d. polarization

2. The frequency of a Nd:YAG laser is ____ Hz.

   a. 5.31 x 10^{10}
   b. 1.73 x 10^{12}
   c. 1.06 x 10^{13}
   d. 2.83 x 10^{14}

3. Calculate the energy of a photon from a Nd:YAG laser.

4. Calculate the time for a HeNe laser beam to make a round trip to the moon (Earth-moon distance 3.84 x 10^8 m).

5. Order each of the following terms by wavelength (longest to shortest).

   a. X rays
   b. infrared
   c. ultraviolet
   d. visible light

6. How is laser light different from ordinary light?

7. Sketch the <u>three</u> principle parts common to all lasers. Use bottom half of page 28.

8. Why do you think that laser light does not ordinarily occur naturally?

9. Explain why 3-level lasers are usually pulsed, but 4-level lasers can be CW.

10. Explain why certain lasers emit at multiple wavelengths.

11. List two ways in which a laser differs from an ordinary drill, relative to its ability to drill a hole.

12. Describe <u>four</u> major industrial laser applications.

13. Why do telephone companies use optical fibers rather than free-air transmission?

14. Explain why outdoor laser shows could be hazardous if proper safety guidelines were not followed?

15. Describe <u>three</u> commercial, military, and research uses for lasers.

SKILL REVIEW ANSWERS

1. 300 m (984 ft)
2. 1.88×10^{-20} Joules
3. active medium, excitation mechanism, optical cavity or resonator
4. optical, electrical, chemical pumping
5. Advantages: does not touch the material being worked, never dulls, never breaks, never slips, does not damage surrounding material, cuts precise small holes, drills good holes in brittle and soft materials

   Disadvantages: expense, heat effected zone near cut, limited material thickness
6. cost

Answer Review Question #7 here.

CHAPTER REVIEW ANSWERS

1. b

2. 2.83×10^{14} Hz

3. 1.88×10^{-19} Joules

4. 2.56 sec

5. infrared, visible, ultraviolet, X ray

6. Laser light is monochromatic, directional, coherent

7. See Figure 6

8. Population inversions required for stimulated emissions require the proper excitation energy; an active medium with a totally reflecting and partially reflecting mirror is needed. These conditions are not likely to be met in nature.

9. It requires less excitation energy to maintain a population inversion for a four-level laser compared to a three-level laser.

10. Such lasers have complex energy transitions with multiple metastable levels and lower levels.

11. A laser beam never "gets dull", never touches the material, never breaks

12. Materials working, materials marking, semiconductor processing, alignment and control

13. Attenuation, distortion, line-of-sight transmission, no EM interference

14. Outdoor shows require more powerful lasers and can be directed long distances without much power loss.

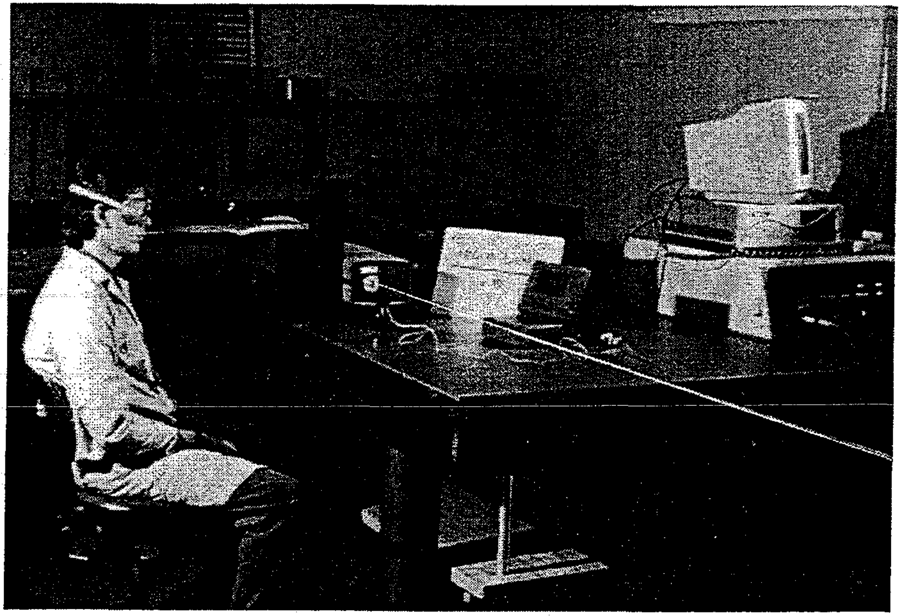
15. *Commercial*: laser printers, laser scanners, optical disks (videodiscs, CD players, copy machines, optical computers;

    Military: laser ranging, laser-guided weapons, antimissile weapons, antipersonnel weapons, anti-optical weapons;

    Research: spectroscopy, chemical reactions, nuclear fusion.

MINI MODULE: BEAM PROP

PROPERTIES OF LASER BEAMS



Education

PROPERTIES OF LASER BEAMS

A review of the basic laser characteristics of direct and reflected beams

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POINT SOURCE EMISSION

The emission from most lasers can be considered as emanating from a "virtual point source" located within or behind the laser device. A "virtual point source" is one which really doesn't exist, but the properties of the emitted beam are such that there appears to be a point source at this position. The geometry necessary to locate the virtual point source is shown in Figure 1.

The distance of the virtual point source behind the front mirror of the laser can be related to the size of the beam at the mirror (X) and the laser beam divergence (ϕ) by equation (1):

$$L = \frac{X}{2\tan(\phi/2)} \qquad (1)$$

where L = distance from front laser mirror to the virtual point source.
X = beam diameter at mirror.
ϕ = beam divergence of laser (full angle)

For small beam divergences, one can make the approximation that:

$$\tan(\phi/2) \approx \phi/2$$

where ϕ is expressed in radians.

Thus, equation (1) becomes:

$$L = \frac{X}{\phi}$$

For a typical He-Ne laser, $\phi = 1.0$ mrad and $X = 2$ mm. Hence:

$$L = \frac{2.0 \times 10^{-3}}{1.0 \times 10^{-3}} = 2 \text{ meters}$$

Thus, the virtual point source appears to be located two meters behind the exit mirror.

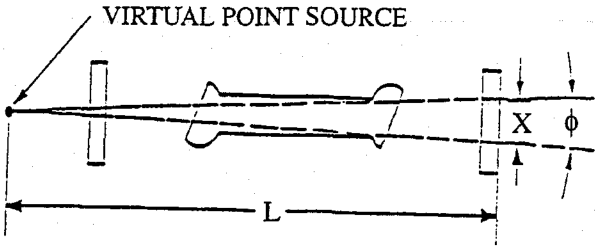


Figure 1
Virtual Point Source

GAUSSIAN DISTRIBUTION OF THE BEAM

The distribution of energy in a laser beam is not uniform. If one were to measure the irradiance point by point across the center of the output aperture, the peak intensity is in the center of the beam and approaches zero as one moves towards the edges. This distribution is maintained as the beam propagates through space subject to thermal broadening and/or distortion produced by atmospheric effects.

The intensity profile of an ideal laser beam (TEM_{oo} mode) is defined by a Gaussian (bell-shaped) distribution as shown in Figure 2. The decrease in intensity at the edges of the beam is the result of diffraction effects produced at the beam aperture edges. Such a Gaussian spatial intensity distribution can be expressed by:

$$I(R) = I_o \exp(-2R^2/W^2) \qquad (2)$$

where R is the radius and W is a constant which defines the mean radius and is commonly referred to as the "spot size." At this point the intensity has fallen to $1/e^2$ of the peak intensity at the center of distribution.

Important points on the beam distribution are the 1/e and $1/e^2$ intensity points as these are used as standard reference points to define the laser beam diameter and divergence parameters. *(Note: the "e" is the natural number associated with the natural logarithm and is equal to 2.7183).*

Note that the beam divergence would be larger when measured at the $1/e^2$ point than if measured at the 1/e point.

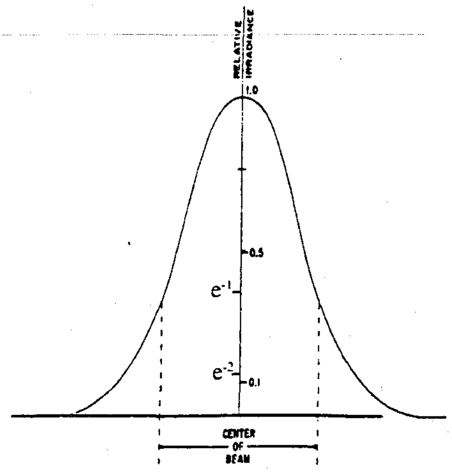


Figure 2
Gaussian Beam Distribution

In the ANSI-Z-136 standard "For the Safe Use of Lasers", the output aperture (a), and the beam divergence, (ϕ), are defined relative to the 1/e points. Because such safety hazard calculations are sensitive to the beam size and/or divergence criteria, conversions from $1/e^2$ points to 1/e power points are sometimes required in hazard computations. The beam diameters at the two criteria points are related by the following:

$$d_{e^{-2}} = (1.414) \times d_{e^{-1}} \tag{3}$$

Many manufactures specifications use the $1/e^2$ points to define beam divergence. In this case, $1/e^2 = 0.1353$, or the total power (energy) is:

$$100\% - (0.1353 \times 100\%) = 86.47\%$$

or approximately 86% of the total energy/ power falls within the $1/e^2$ aperture.

The 1/e point defines the beam diameter (a) where the intensity is reduced by the factor $1/2.7183 = 0.3679$; thus the 1/e intensity is:

$$100\% - (0.3679 \times 100\%) = 63.21\%$$

or approximately 63% of the energy (or power) is contained within the an aperture of diameter "a".

MODE STRUCTURE

Departure from the Gaussian distribution can result when independent oscillation occurs within the laser resonator at higher TEM order modes. For example, gas lasers may be designed to support oscillation in many different transverse modes. Mode selection may often be accomplished by slight adjustment of the mirror alignments. With this technique, one can observe the different complex intensity distributions of each mode. This is shown in Figure 3. The lowest order TEM_{00} mode with the nearly Gaussian intensity distribution has the lowest cavity losses and hence will generally be the dominant mode of oscillation.

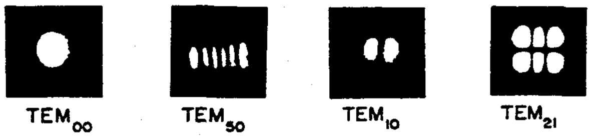


Figure 3
TEM Mode Variations

Optically pumped solid-state lasers - such as the "long pulse" Nd:YAG (pulse length 0.5 - 3 milliseconds) - usually display a randomly varying spatial mode output. Thermal gradients in the laser crystal caused by nonuniform absorption of the pump light give rise to lens effects within the laser media which change during the pumping cycle. The result is a sporadic switching of modes during the laser pulse. The time average of the output beam distribution is generally bell-shaped and is dependent upon the optical purity of the laser media, the pumping scheme, and the level at which the system is operated above lasing threshold.

Some pumping schemes produce pronounced "hot spots" in the intensity distributions. For long range transmission, atmospheric effects can also produce intensity variations over localized regions of the beam which vary by a factor of at least ten. Such non-uniformities in the distribution make it difficult at times to specify the diameter of the beam. As a result, an average value of beam radius is chosen. Typically, this is often (1) the half-power point; (2) the 1/e power point; or (3) the $1/e^2$ power point. A common laboratory practice is to measure the diameter using one of these criteria on a densitometer recording obtained from a photographic negative of the output beam distribution.

BEAM DIVERGENCE

Beam divergence is a very important laser parameter and is typically expressed in units of milliradians (10^{-3} r). Figure 4A illustrates the radian unit for a plane angle (ϕ). The symmetry of the laser beam allows the geometry to be reduced to the two dimensions of a plane. The angle (ϕ), (expressed in radians) can be related to the angle (expressed in degrees) by noting that if (ϕ) is 360 (degrees), the arc length, s, becomes the circumference of a circle; where ($s = 2\pi R$); therefore,

$$\phi = s/R \text{ radians} \qquad (4)$$

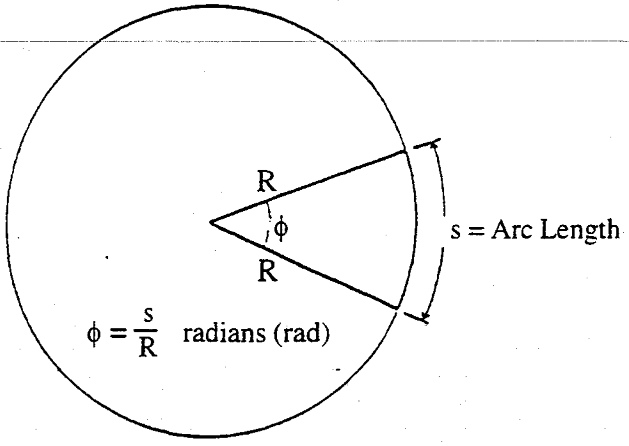


Figure 4A
Radian Unit of Plane Angular Measure

Substituting the value for a full circle:

$$\phi_c = [2\pi R]/R = 2\pi \text{ radians} = 360 \text{ degrees}$$

Therefore:

$$1 \text{ degree} = \pi/180 \text{ radians}$$

or:

$$1 \text{ radian} = 180/\pi = 57.3 \text{ degrees}$$

The minimum laser beam divergence, called the diffraction limited beam divergence, is related by the Equation:

$$\phi_{diff} = \frac{4\lambda}{\pi \omega_o} \qquad (5)$$

where: λ = laser wavelength
ω_o = minimum beam waist

Thus, the diffraction limited beam divergence for a typical helium neon laser ($\lambda = 0.633$ µm and $\omega_o = 1.1$ mm) can be computed:

$$\phi_{diff} = \frac{4 \times 0.633 \times 10^{-6}}{\pi \times 1.1 \times 10^{-3}}$$

$$= 0.73 \times 10^{-3} \text{ radians}$$

$$= 0.73 \text{ mrad}$$

Thus, the lower limit for this specific HeNe laser is of the magnitude of 0.73 milliradians. Most commercial helium neon lasers will have beam divergences ranging from 0.5 to 2 mrad.

The concept of beam spread can be expanded into three dimensions by introducing the solid angle of Figure 4B. The solid angle (Ω), is expressed in units of steradians (sr) and is determined by using the area (A) cut out of a surface of a sphere divided by the square of the distance (R^2) from the center of the sphere to the surface element. That is:

$$\Omega = A/R^2 \qquad (6)$$

For a sphere, the solid angle may be opened up to include the entire surface area ($A_s = 4\pi R^2$), therefore:

$$\Omega = A_s/R^2 = 4\pi R^2/R^2 = 4\pi \text{ sr}$$

and the hemisphere has 2π sr. Note that the emission from a typical laser will be confined in a solid angle of to less than 10^{-6} sr!

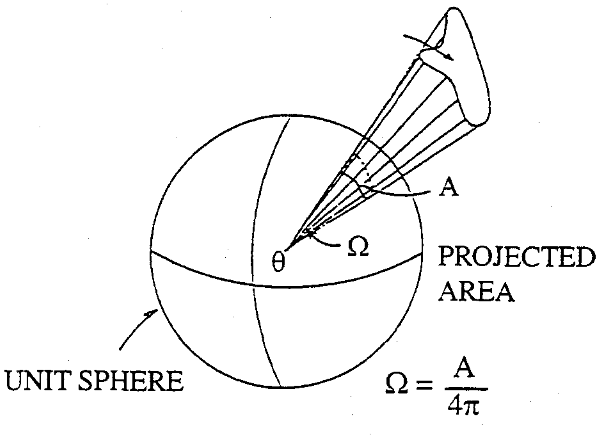


Figure 4B
Steradian Unit of Solid Angular Measure

UNITS OF ENERGY AND POWER

In many applications, the most important laser beam characteristic is the enormous intensity of the beam. Intensity is related to the beam power the cross sectional area and the manner in which the beam spreads from one point in space to the next.

The two most important radiometric units are energy and power. Basic definitions apply for each but for our purposes, let us conjecture that energy is related in some way to the heat generated in a target when a laser beam is absorbed. Energy is now expressed in units called Joules; named after the English scientist James P. Joule who lived in the late 1800's.

In fact it was J.P. Joule who first showed by experiment that, whenever a specific quantity of mechanical energy was converted into heat, the same quantity of heat was always developed. Thus the equivalence of heat and mechanical work as two forms of energy was first recognized. Heat energy has been traditionally expressed in units of the calorie which is roughly defined as the amount of heat energy needed to raise one gram of water one degree Centigrade (actually defined from 14.5 to 15.5 °C).

Light is also a form of energy and, as such, obeys the same energy equivalency laws and can share the same systems of units as mechanical or thermal energy. For example, since one joule is equivalent to approximately one-fourth of a calorie, one can state that if a four-joule laser pulse is totally absorbed in water, the temperature of one gram of the water will increase by approximately one degree Centigrade.

Power is the rate at which the energy is produced or delivered. It is measured in units of a joule per second which is equivalent to one watt. This is named in honor of James Watt whose steam engine was the predecessor of today's more powerful gasoline or Jet engines. For the purpose of rating such engines, the quantity for describing power was expanded (actually at Watt's suggestion) to that of "horsepower" where one horsepower is the equivalent of 746 watts.

Power, by definition, is the time-rate at which work is done; specifically, it is the rate at which energy is used of produced. Energy relates the ability to do work. As with other forms of energy (eg, chemical, mechanical, electrical), electromagnetic energy (light energy) is a conserved quantity.

Energy is often assigned the symbol Q and power the symbol Φ. Time is given the symbol t. Strictly speaking, since power may be delivered in any random way, it is a function of time and the energy delivered over some time increment and is mathematically the time integral (incremental addition) of all values of the product of a given power function Φ(t) and a time increment dt over a given range of time (usually over the limits: t=0 to t=τ). The relationship between energy, power, and time is defined by the integral equation:

$$Q = \int_{o}^{\tau} \Phi(t)\, dt \qquad (7)$$

Where the quantities are expressed in radiometric units as follows:

Q = Energy expressed in joules
$\Phi(t)$ = Power expressed in watts
dt = Time increment expressed in seconds
τ = Pulse duration in seconds

Thus:

Energy = Power x Time
1 joule ≅ 1 watt x 1 second

Note that a specific laser beam energy can be delivered in many ways to a target. For example, an identical quantity of energy can be delivered from a laser either at high-power for a short time period or at low power for long time period. For energy dependent processes, such as ultraviolet photobiological effects, both of the these delivery rates could provide the same energy to the target and, hence, identical biological results.

IRRADIANCE AND RADIANT EXPOSURE

The concentration of the laser power and/or energy is also important when considering the effects a beam may produce on biological targets. Irradiance (sometimes incorrectly called power density) is the term used to describe the concentration of laser power incident upon a particular area. The term Radiant Exposure is the term related to energy per unit area. Values for both irradiance and radiant exposure are determined for specific beam geometries and/or distributions. In both cases an estimate of beam size (area) is needed. A cw laser is usually rated in average power (watts) while a pulsed laser is normally rated according to the total energy (joules) per pulse.

The intensity of the laser is usually expressed by the irradiance (E) which is defined as power per unit area of the beam. This is determined by dividing the average value of beam power (Φ) by the average value of the beam cross- sectional area (A). The irradiance units are expressed in watts per square centimeter for cw beams. For pulsed lasers the intensity is expressed by the radiant exposure (H) which is defined as the energy (Q) per unit area (A). The radiant exposure is expressed in joules per square centimeter for laser pulses.

It should be noted here that both the intrabeam eye and skin Maximum Permissible Exposures (MPE's) in the ANSI Z-136.1 (1986) Standard are expressed in terms of either an irradiance or radiant exposure.

For cw sources, the irradiance (E_s) and is expressed as the power per unit area. The area is usually expressed in cm^2. Since the beam area is considered circular, with the area given by the area of a circle: $A = \pi D^2/4$. Irradiance is expressed in units of watts/cm^2; or:

$$E_s = \frac{\Phi}{A} = \frac{4 \times \Phi}{\pi \times D^2} \quad (\mathrm{W/cm^2}) \qquad (8)$$

Similarly, for pulsed sources, Radiant Exposure is expressed as energy per unit area and is expressed in units of joules/cm^2; or:

$$H_o = \frac{Q_p}{A} = \frac{4 \times Q_p}{\pi \times D^2} \quad (\text{J/cm}^2) \qquad (9)$$

In order to determine the peak power of pulsed laser, it is necessary to know the pulse shape and duration.

PULSED - VERSUS - CONTINUOUS WAVE LASERS

Continuous wave (cw) lasers, by definition, produce a continuous, steady power. The power from pulsed lasers vary with respect to time. A sample laser pulse is depicted in Figure 5.

Pulse characteristic of a typical Q-switch laser pulse. Note that the pulse width is defined at half-power points. The energy contained in the pulse is represented by the shaded area under the $\Phi=\Phi(t)$ power curve. In this case, the peak power is given as 7 megawatts in a pulse of width of 10 nanoseconds. The total pulse energy is: $Qp = (7 \times 10^6) \times (10 \times 10^{-9}) = 7$ mj.

The duration of the pulse time is defined by the increment shown in the figure which has been designated at the "half-power points". Also shown is an important designation for a single pulse which is the instantaneous power maximum or the so-called peak power. Even some physically small laser devices (such as Q-switched lasers) are capable of extremely high peak power values well over hundreds megawatts. Note in Figure 5 that a laser pulse can be approximated by the shape of a triangle. Recall that the area of a triangle is the product of one-half the base width multiplied by the magnitude of the height.

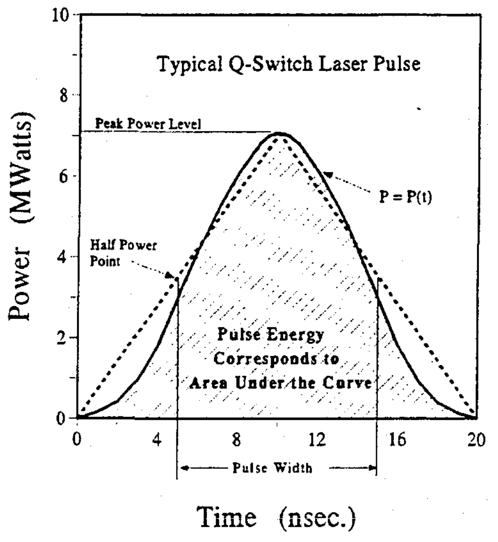


Figure 5
Typical Laser Pulse

Thus, since the time has been selected at half power points and the power represents the height, the result of the multiplication yields:

Area of triangle = Height x One-half base

or:

Energy = Peak Power x pulse length
Joules = Watts x Seconds

Thus, the area under the power-time curve is equivalent to the amount of energy delivered during the pulse.

In pulsed laser operation, an instantaneous peak irradiace in excess of 100,000 W/cm^2 is quite easily generated in an unfocused Q-switched Nd:YAG laser pulse. If this output were contained within a typical beam divergence of 2 mr and focused by only moderate power optics, the peak irradiance at the focal plane would be increased at least one-hundred fold.

Lasers with very short pulses produce high peak-power values with a small amount of energy. When a laser is able to emit repetitive pulses at a rapid rate, additional quantities must be taken into account. Frequency of pulsing or Pulse Repetition Frequency (PRF) (pulses per second) is specified as-well-as the time interval between pulses or pulse repetition time (PRT). This time increment includes both the "on-time" as-well-as the off-time between pulses. ***The ratio of the on-time to the PRT is called the duty cycle.*** This reflects the fraction of time that the beam is actually operating.

When a laser is repetitively pulsed, the total amount of energy delivered (Q_T) accumulates with each pulse. The accumulated energy divided by the corresponding total-on-time (T_{tot}) gives the average power (Φ_{av}) of such a pulse train. Thus, one can express:

Total Energy = Average Power x Total-on-time

$$Q_T = \Phi_{av} \times T_{tot} \qquad (10)$$

The peak power (Φ_{peak}) may be closely approximated by assuming a triangular pulse shape and dividing the energy per pulse (Q_p) by the pulse duration measured at the half-power points.

That is:

$$\Phi_{peak} = \frac{Q_p}{T} \qquad (11)$$

where:

Q_p = Pulse Energy (joules)
T = Pulse Duration (Seconds)

For example, a 100 mJ laser pulse of 20 ns will have a peak power of:

$$\Phi\text{peak} = 100 \text{ mJ/20ns} = (100 \times 10^{-3})/(20 \times 10^{-9})$$

$$= 5 \times 10^{6} \text{ watts} = 5.0 \text{ MW}$$

If the beam is focused to a 1 μm (10^{-4} cm) spot, the peak irradiance (E_p) at the focal plane will be:

$$Ep = \frac{\text{Power}}{\text{Area}} = \frac{\Phi}{A} = \frac{4\Phi}{\pi D^2} \qquad (12)$$

$$Ep = \frac{4 \times 5 \times 10^{6}}{\pi (10^{-4})^2} = 6.4 \times 10^{14} \text{ watts/cm}^2$$

If this same 100 mJ laser was pulsed at a 20 Hz pulse rate, the average power of the pulse train would be:

$$\Phi_{av} = Q_p \times (\text{PRF}) \qquad (13)$$

where PRF is the Pulse-Repetition-Frequency (cycles or pulses per second), thus:

$$\Phi_{av} = 100 \text{ mJ} \times 20 \text{ Hz}$$

$$= 2000 \times 10^{-3} \text{ J/sec or watts}$$

$$= 2.0 \text{ watts}$$

This average power is an important factor for high PRF lasers when determining the laser classification and maximum permissible exposure levels.

The average power from such a repetitively pulsed laser can be considered to be a "cw" equivalent power.

FOCUSED LASER BEAMS

The beam from an ideal laser, i.e., a laser which emits a coherent wave, can be considered as a diffraction-limited beam. In this case, divergence of the beam is limited to the effects of diffraction at the beam edges. The emission from such a laser will display a far-field diffraction pattern at a distance $D = \pi a^2/\lambda$, where a is the diameter of the emergent laser radiation.

Thus the TEM_{00} beam from a typical helium-neon laser will display a 0.5-1.0 mr beam spread at a distance of 1.0-5.0 meters from the laser. The focusing geometry is shown in Figure 6.

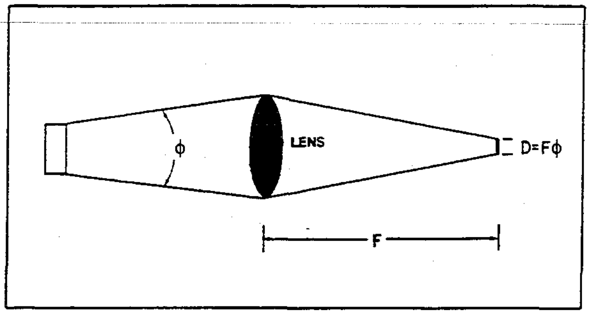


Figure 6
Geometry of a focused laser beam

Due to the high degree of coherence of a laser beam, it is theoretically possible to focus the beam to the diffraction limit of the wavelength of light. Typically, however, the laser will have a finite beam spread and can be expressed by the simple equations of geometrical optics.

The spot diameter (d) is given by the simple equation:

$$d = f\,\phi \qquad (14)$$

where:

d = spot diameter
f = focal length of lens
ϕ = laser beam divergence (radians)

As an example, one can calculate the spot size of a beam focused on the human retina. For this case, consider a "typical" Helium Neon laser where: $\phi = 1.0$ mrad and assume that the effective focal length (f) of the human eye is 1.7 cm. Thus:

$$\begin{aligned} d &= f\,\phi \\ &= (1.7 \text{ cm}) \times (1.0 \times 10^{-3}) \\ &= 17 \times 10^{-4} \text{ cm} = 17 \times 10^{-6} \text{ m} = 17\ \mu\text{m} \end{aligned}$$

To give some idea of how small this focused spot is, consider that 17 micrometers is approximately the size of two or three human blood cells stacked end-to-end.

Now using the equation for the area of a circle, the focused beam area can be calculated:

$$\begin{aligned} A &= \frac{\pi d^2}{4} \qquad (15) \\ &= \pi \times (17 \times 10^{-4})2]/4 \\ &= 2.27 \times 10^{-6} \text{ cm}^2 \end{aligned}$$

The irradiance of a 1 mw He-Ne laser beam focused by the lens of the eye into the retina (assuming no reflection or transmission losses) will be:

$$\begin{aligned} E_R &= \frac{\Phi}{A} \qquad (16) \\ &= \frac{1 \times 10^{-3}}{2.27 \times 10^{-6}} \text{ W/cm}^2 \\ &= 440 \text{ W/cm}^2 \end{aligned}$$

As the spot diameter approaches the wavelength of light, the spot becomes diffraction-limited. For example, the beam from a highly coherent single transverse mode (TEM_{00}) gas laser will produce a diffraction limited Gaussian-shaped intensity pattern when focused.

This distribution may be described mathematically by Eq. (3) where it is considered that the focused beam energy will be contained in a spot diameter as defined at the e^{-2} power point given by the following relationship:

$$d_{TEM_{00}} = \frac{4 f \lambda}{\pi \omega_o} = \frac{1.27 f \lambda}{\omega_o} \qquad (17)$$

where:

λ = Wavelength of light
ω_o = Minimum beam waist at lens
f = Focal length of lens

Thus, using the earlier example of a typical helium neon laser ($\lambda = 0.633\ \mu$m and $\omega_o = 1.1$ mm) focused by a 100 mm focal length lens, we have:

$$d_{TEM_{00}} = \frac{4 \times (100 \times 10^{-3}) \times (0.633 \times 10^{-6})}{\pi \times 1.1 \times 10^{-3}}$$

$$= 73.3 \times 10^{-6} \text{ meters} \approx 73\ \mu m$$

If the focusing lens used is on a microscope, the focal length $f \approx 1.0$ mm, and the spot size approaches 0.73 μm. Thus the smallest possible spot size of a focused laser beam will approach the dimensions the wavelength of light which is being focused.

Now, combining Eqs. (14) and (15) yield an expression for the area of the focused spot:

$$A = \frac{\pi(f\phi)^2}{4} \qquad (18)$$

If this is substituted into Eq. (16), the expression for the focused beam irradiance at the focal plane of the lens is shown to be dependent on laser and optics parameters:

$$E_R = \frac{4\,\Phi}{\pi\,(f\phi)^2} \quad W/cm^2 \qquad (19)$$

Thus, the irradiance (power per unit area) of a focused laser beam will vary inversely with the square of the focal length of the lens and inversely with the square of the beam divergence angle. Hence, these two factors have dramatic effect on the magnitude of the irradiance at the focal plane of the lens.

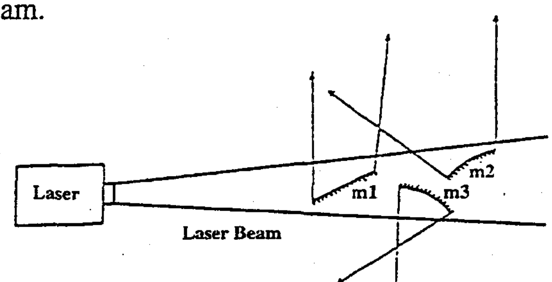
Consequently, either a reduction in the focal length of the lens used to focus the beam of a reduction in the beam spread by a factor of ten will produce a one-hundred fold increase in irradiance at the focal plane of the lens. Simultaneous reduction of both by a factor of ten would increase the irradiance at the focal plane by a factor of 10^4.

Typical beam divergence values for gas lasers (CO_2, helium-neon, argon, etc.) will be about one mr. Solid-state Nd:YAG lasers generally have a higher beam spread (1-30 milliradian), due primarily to the high beam divergence associated with the random multimode operation of such devices.

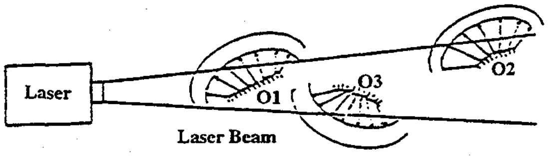
REFLECTED LASER RADIATION

When the laser beam illuminates material objects, a portion of the beam will be reflected. The reflected laser energy is redirected and, thereby, may create additional sources of potential hazard to observers away from the primary laser beam.

Laser light reflected from material objects is said to be either specular or diffuse. The type of reflected light is dependent upon the reflector surface. Figure 7 illustrates the important difference between the two types of reflectors. Specular reflectors may change the direction, intensity, and beam divergence (Figure 6a) of the laser beam; however, the quality of the wave-front remains the same. Mirrors, glass and highly glossy or smooth, polished surfaces produce specular reflections. A high quality mirror (such as used in laser equipment) will produce minimal changes in the intensity and divergence characteristics of the beam.



(a) Specular Reflectors



(b) Diffuse Reflectors

Figure 7
Specular and Diffuse Reflections

For comparative purposes, consider that when a person stares at a standard 100 watt frosted light bulb, a diffuse light source is viewed with a radiance of about 40 x 10^{-3} W/cm^2·sr. Viewing the diffuse reflection of a 1.0 mW laser directed on a wall 10 meter away can be shown to be nearly 50 times less "bright" than directly viewing a 100 watt light bulb (which should tell you something about long-term staring at 100 watt light bulbs)!

However, comparison of the irradiance at the wall 10 meters away yields a different result: the irradiance on the wall produced by the 100 watt light bulb 10 meters away can be shown to be nearly 8.0 mW/cm^2. A typical 1 mW HeNe laser can produce an irradiance of more than 2,500 mW/cm^2, or nearly 330 times greater!

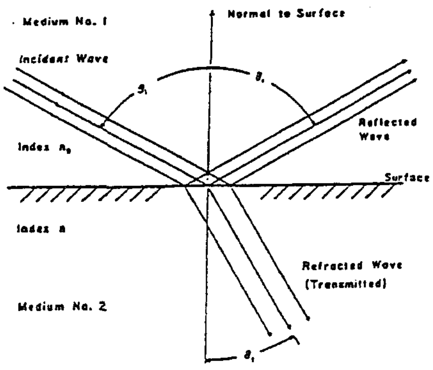


Figure 8
External reflection and refraction at a boundary

Figure 8 illustrates the geometry of reflection and refraction at a boundary, given a light wave and a typical, flat specular reflector such as plate glass. The law of reflection states that the angle incidence is equal to the angle of reflection, that is: $\theta = \theta_r$. For a mirror, all of the light is reflected. For other media, such as glass, only part of the light is reflected while part is transmitted, refracted, or absorbed.

Most rough or matte-like surfaces are considered to be diffuse reflectors. The beam is reflected/scattered rather uniformly in all directions by the rough surface. Such reflectors are called diffuse or Lambertian. To a nearby observer, a diffuse reflector appears to be an extended source, where light is uniformly emitted into a hemisphere from ***each point*** over the illuminated surface area.

The degree to which a surface resembles a diffuse reflector depends upon its apparent roughness ***at the illuminating wavelength***. For the visible spectrum and the near-infrared, the surface will be rather smooth; however, as the wavelength becomes longer (going further into the infrared), these visually "rough surfaces" may behave as specular reflectors. That is, if the size of the surface roughness is less than the wavelength of the source, it tends to appear smooth.

Given a transparent medium, such as glass or water, and ignoring small absorption/scattering losses at the surface and in the medium, the total energy is conserved, that is

$$T + R = 1 \tag{20}$$

where T is the portion transmitted and R is the portion reflected. Reflection will occur at a surface formed by the boundary between two media with different indices of refraction.

The index of refraction is an important optical parameter and is most simply related to the speed of light in medium (v_{medium}), that is:

$$\begin{aligned} n &= \frac{\text{speed of light in vacuum}}{\text{speed of light in the medium}} \\ &= \frac{c}{v_{medium}} \end{aligned} \tag{21}$$

where c is the speed of light in the vacuum of free space and n is the index of refraction. The index of refraction is always greater than or equal to unity ($n \geq 1.0$) and is only unity (1.0) in free space; however, the index of refraction of air is so close to unity (1.0) that in the first approximation it is normally set equal to unity (1.0). The index of refraction is a function of the wavelength of light [$n = n(\lambda)$] and that fact is best illustrated by using a prism to cause dispersion of white light or sunlight into a rainbow-like spectrum of its component colors. For yellow light, the index of refraction of water is 1.65.

Figure 9 illustrates the case where n_o is less than n, as would be the case if the wave was incident from the air on to a piece of glass. The angle of refraction, θt, is related to the angle of incidence by Snell's Law, which is expressed by:

$$n_o \sin \theta_i = n \sin \theta_t \qquad (22)$$

If medium #1 is air, then $n_o = 1.0$ and Snell's Law can be written as

$$\sin \theta i = n \sin \theta t$$

Thus:

$$\theta t = \arcsin [(\sin \theta_i)/n]$$

When a laser beam strikes a first surface mirror, there is essentially 100% reflection, however, when it strikes water or glass, the amount reflected varies significantly with the angle of incidence. When the beam is normal to the surface ($\theta_i = \theta$), the reflected energy is at a minimum (for glass, of the order of 4% to 6%). As the angle of incidence is increased, the percentage reflected increases. As θ_i approaches, 90°, and the beam is just grazing the surface, the reflection approaches 100%. This is illustrated in Figure 9 for plate glass.

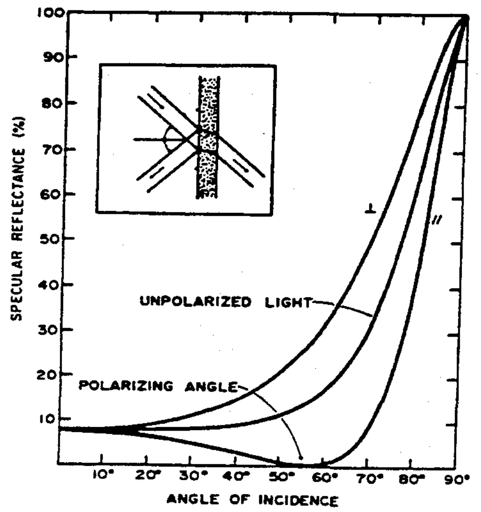


Figure 9
Percent of Reflected Polarized Light For Glass
(n = 1.5)

RADIANCE AND INTEGRATED RADIANCE

There are two major viewing conditions where the beam is considered to be a so-called point source. The first is the case called intrabeam viewing (looking down the laser barrel) and the second is the case of viewing a diffuse reflection of a beam at sufficient distance away that the point of reflection on the diffusing surface is so small that one has difficulty resolving the boundaries with the human eye. In both cases, the beam appears to be emitted from a point source and the irradiance will obey an inverse square law relationship with regard to distance from the source. These represent, perhaps, the two most common "viewing conditions" (however unwise) of a laser beam.

There is, however, another important "viewing" scenario. This is the situation where the laser beam emulates a so-called extended source; a scenario that can produce much larger images on the retina. One common example would be the diffuse reflection of a moderately sized beam when viewed at close distance. In this case it becomes useful to describe the "brightness" of the reflection as though the diffuser itself were the source.

When the source serves as an extended source, the "emission from the source" (eg.: the total reflected light) can be described by the accumulated irradiance emitted from each increment of the surface into a cone of so-called "solid angle". This gives rise to radiometric units (often called brightness) that are defined as source radiance (for cw lasers) or, for pulsed sources, the integrated radiance.

Radiance and integrated radiance are very special quantities in that they uniquely describe the emission characteristics. These are so-called "conserved" quantities (such as energy and momentum) and, as such, nothing can be done optically to increase the radiance of a source.

The unit of solid angle is defined such that all space about a point source (i.e., the source of light) will encompass 4π sr. as discussed earlier.

The radiance (L) is an expression of the power (Φ) per unit area (A) of the source - per unit of solid angle (Ω). Integrated radiance (L_p) is expressed in terms of the pulse energy (Q_p) per unit area (A) of the source - per unit of solid angle (Ω); that is:

$$L = \frac{\Phi}{A \times \Omega} \ (\mathrm{W/cm^2 \cdot sr}) \qquad (23)$$

and:

$$L_p = \frac{Q_p}{A \times \Omega} \ (\mathrm{J/cm^2 \cdot sr}) \qquad (24)$$

The solid angle (Ω) is defined as the unit of area projected normal to the source area divided by the square of the dis- tance from the unit area to the source (see Fig. 4B).

The unique factor about the radiance from a diffuse reflector is that as long as the viewer is within the extended source distance, the radiance is a constant value <u>independent</u> of viewing distance. The same holds for integrated radiance of pulsed emission sources.

To quantitate the total radiance of a diffuser, one must determine the total back reflected light from <u>each part</u> of the extended source. The result of this complicated mathematical integration yields a rather simple relationship which combines the surface reflectivity (σ) of the diffuser and irradiance (E_s) level <u>incident upon</u> the surface, that is given by the formula:

$$L = \frac{\sigma E_s}{\pi} = \frac{\sigma \times 4 \times \Phi}{(\pi \times D_L)^2} \ \mathrm{W/cm^2 \cdot sr} \qquad (25)$$

For example, assume that 0.5 watt argon laser is diffusely reflected from a 80% reflector from a 5mm beam diameter on the diffuser. The source radiance will be:

$$L = \frac{(0.8) \times 4 \times 0.5}{[(3.14) \times (0.5)]^2} = 0.65 \ \mathrm{W/cm^2 \cdot sr}$$

Note that 0.65 $\mathrm{W/cm^2 \cdot sr}$ is about 16 times larger than the radiance emitted by a 100 watt light bulb. It is also over 300 times above the extended source MPE given in the ANSI Z-136 standard. One would conclude that this diffuse reflection is hazardous!

INVERSE SQUARE LAW FOR DIFFUSE REFLECTIONS

In practice, most non-glossy surfaces which are slightly rough act as a diffusing surface to an incident laser beam at wavelengths in the visible or near-infrared spectral regions. Figure 10 illustrates the viewing geometry of such a diffuse reflection of a laser beam.

In effect, such a rough surface acts as a plane of infinitesimal scattering sites which reflect the beam in a radially symmetric manner.

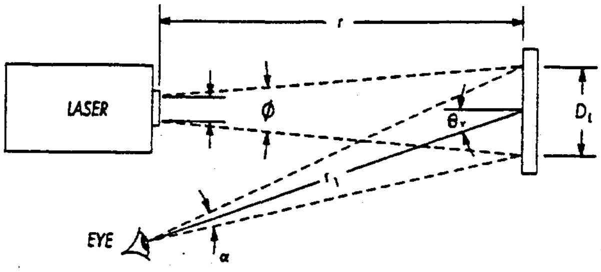


Figure 10
Representation of Diffuse Reflection
of a Laser Beam

The reflected radiant intensity (power per unit solid angle), denoted by the symbol: $I(\Theta)$, is dependent upon the cosine of the angle (Θ) measured from the normal to the surface.
That is:

$$I(\Theta) = I_o \cos \Theta \qquad (26)$$

where:

$I(\Theta)$ = Radiant intensity occurring at an angle θ from normal (W/sr)
I_o = Radiant intensity (W/sr) reflected along the normal to the surface
θ = Angle measured from normal to the surface.

This relationship is known as Lambert's Law, and a surface which behaves in this manner is often referred to as a Lambertian Surface. This surface defines an ideal diffuse reflector.

It should be stressed that "rough" surfaces do not act as diffuse reflectors at all wavelengths. For example, brushed aluminum (which may partially diffuse for visible laser radiation) is a good specular reflector for far-infra- red radiation as emitted from a CO_2 laser. Hence, caution must be exercised when assuming that diffuse reflections result from "rough" surfaces for all laser types.

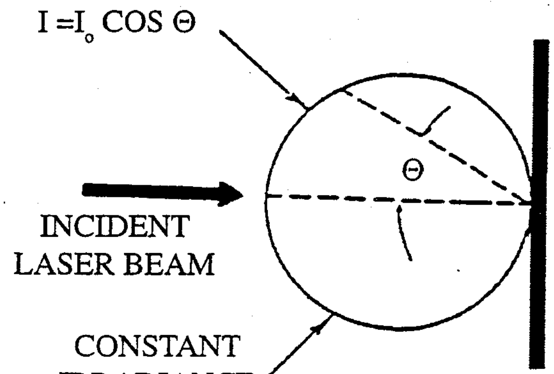


Figure 11
Ideal Diffuse Reflector

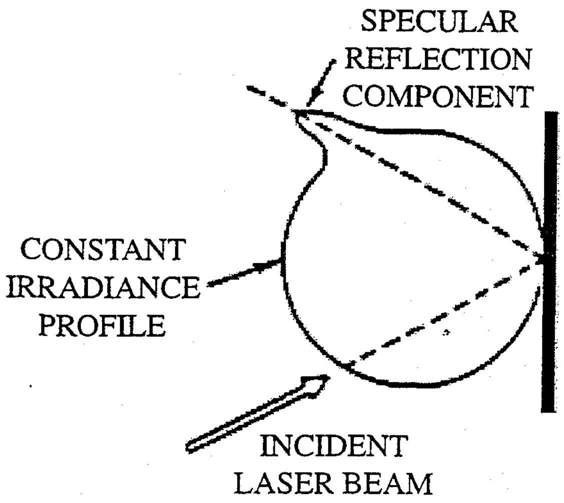


Figure 12
Typical Skewed Diffuse Reflection

Additionally, most slightly "rough" surfaces may still have some properties that allow a small component to specular reflection. This may occur with just a few-percent of the incident radiation specularly reflected and the remainder diffusely reflected. This behavior is generally the rule, and not the exception, for most common surfaces. As a result, the reflected radiation is not exactly radially symmetric, but has a skew in its irradiance profile that corresponds to the direction of the specularly reflected component (See Fig. 12).

Given a diffuse reflector and an observer at a distance greater than r_{1max}, one may use the inverse square-law range equations for a diffusely reflecting point source ($r_1 >> D_L$) to calculate the exposure at a distance r1. These equations are given:

$$E = \frac{\sigma \Theta \cos \Theta_v}{\pi r_1^2} \quad (W/cm^2) \qquad (27)$$

$$H = \frac{\sigma Q \cos \Theta_v}{\pi r_1^2} \quad (J/cm^2) \qquad (28)$$

where σ is the reflectivity coefficient of the surface at a particular wavelength and Θ or Q is the total power or energy of the laser. Therefore, solving for the distance r_1 and setting E=MPE, the safe range: $r_{1\text{"safe"}}$ is given by:

$$r_{1\text{"safe"}} = \left[\frac{\sigma \Phi \cos \Theta_v}{\pi(MPE)}\right]^{0.5} \qquad (29)$$

At that distance where the source can be considered a point source, the point source MPE values are used. Assuming a Q-switched Nd:YAG laser, with a pulse rate of 10 Hz. and the pulse train lasting 10 seconds, the ANSI Z-136.1 standard (see Table 5 in the standard) indicates that the MPE is:

$$MPE = 5 \times 10^{-6} \ J/cm^2$$

for a Q-switched single pulse. Since this is a multiple pulse laser (10 Hz) one must apply the multiple pulse correction factor ($C_E=N^{-(1/4)}$). This is determined by the number of pulses (N=PRFxT) where we assume a 10 second "on time":

$$C_E = N^{-(1/4)} = (10x10)^{-(1/4)} = 0.316 \text{ thus:}$$
$$MPE = C_E \text{ x } MPE$$
$$MPE = 0.316 \text{ x } 5 \text{ x } 10\text{-}6 \text{ J/cm}^2$$
$$= 1.58 \text{ x } 10^{-6} \text{ J/cm}^2$$

Solving for $r_{1\text{"safe"}}$, one has for the case where Θ_v = 90 degrees and Q_p = 500 mJ.

$$r_{1\text{"safe"}} = \left[\frac{\sigma \Phi \cos \Theta_v}{\pi(MPE)}\right]^{0.5}$$

where:

$$r_{1\text{"safe"}} = \left[\frac{1.0 \text{ x } 500\text{x}10^{-3} \text{ x } 1.0}{\pi(1.58\text{x}10^{-6})}\right]^{0.5}$$

thus:

$$r_{1\text{"safe"}} = 317 \text{ cm}$$

The results of the hazards analysis are:

1) There is a diffuse reflection hazard, for this laser, and
2) Unprotected personnel must be more than 3.17 meters from the diffuse reflector.

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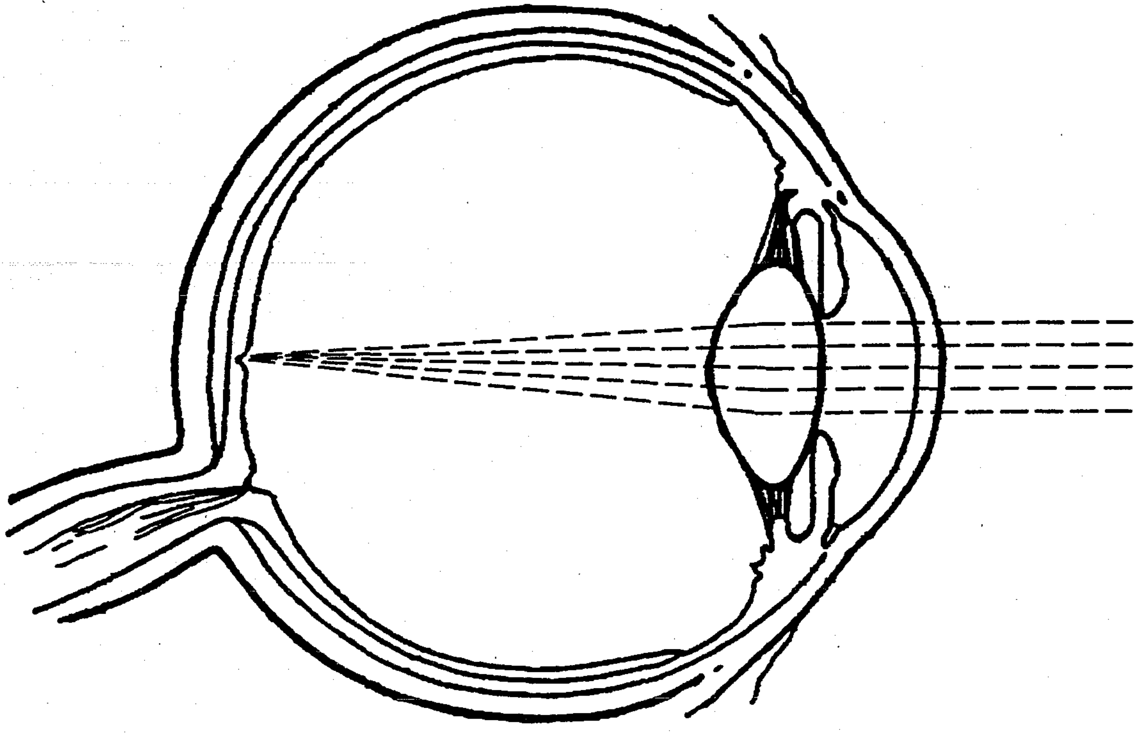
MODULE 5.0

BIOEFFECTS of LASERS



Education

BIOEFFECTS OF LASERS

Lasers offer many health advantages in the field of medicine. Laser surgery provides a dry, highly sterile operating field that reduces the likelihood of infection. Furthermore, laser incisions are highly localized, which minimize tissue swelling and scarring, and promote healing.

Medical and industrial lasers, however, do emit intense electromagnetic radiation that has the potential for causing irreparable skin or eye damage. There are a variety of mechanisms by which the absorbed laser radiation can cause injury. These mechanisms include thermal, photochemical, acoustic-shock, and carcinogenic effects. This module explains the biological effects of exposure to laser radiation. The module also describes other laser-related hazards and actual laser accidents.

- The Skin and Internal Organs
- The Eye
- Laser Accidents

Table of Contents

BIOEFFECTS OF LASERS

THE SKIN AND INTERNAL ORGANS

SECTION OBJECTIVES

- *Distinguish* between the effects of exposure to different UV wavelengths
- *Identify* the factors related to thermal skin damage
- *Describe* the health effects associated with acute exposure to laser radiation
- *Explain* why, under normal circumstances, the internal organs are not at risk from laser radiation

CHARACTERISTICS OF SKIN

Skin characteristics can be analyzed with a visual color classification and general description of the surface qualities. For example, some physical skin characteristics which can affect the reflectance, absorption and scattering of laser energy are the smoothness of the tissue surface; differences in density; and differences in hydration and circulation. These and other factors related to the vascular dynamics of the area should be included in any evaluation.

Absorption in the skin relates to such pigments in tissue as melanin, melanoid, iron, carotene, hemoglobin, oxyhemoglobin, and reduced hemoglobin. Absorption processes depend not only upon the specific absorption in the tissues which contain pigment, but also upon the absorption produced by multiple internal reflections. Skin is a diffuse medium; pigments within the skin abosorb at specific spectral bands. This creates a scattering action caused by the structural inhomogeneities of the skin. The total radiation reflected from tissues in the 0.300 - 1.000 μm spectral range is a combination of the surface reflections and radiation backscattered from the dermal layers.

Tissues are certainly not an ideal optical medium. They are not homogeneous and each of the components has distinct absorbing and scattering characteristics. The melanin in the skin, fatty tissues, muscle, cartilage and blood filled capillaries all contribute to the total absorption.

In the visible light spectrum (0.400 - 0.700 μm), absorption does not follow a simple exponential relationship. For most of the human body, the surface structure of the skin, which contains the melanin pigment layers, is highly specialized as shown in Figure 1. For this reason, the absorption near the surface should be greater than for layers below the surface.

In the near infrared region (1.000 - 2.200 μm), an exponential law provides a reasonably accurate description of absorption as a function of skin thickness. The absorption due to scattering and pigments, as well as other skin constituents, can be thought of as being combined into a single absorption event.

LASER SKIN DAMAGE

Historically, because the eye is so much more susceptible to damage from laser radiation, skin damage has been much less emphasized. However, repeated, or even a single, exposure to certain laser wavelengths can cause skin damage of varying degrees. Furthermore, the proliferation of high-power laser systems, particularly in the ultraviolet spectral region,

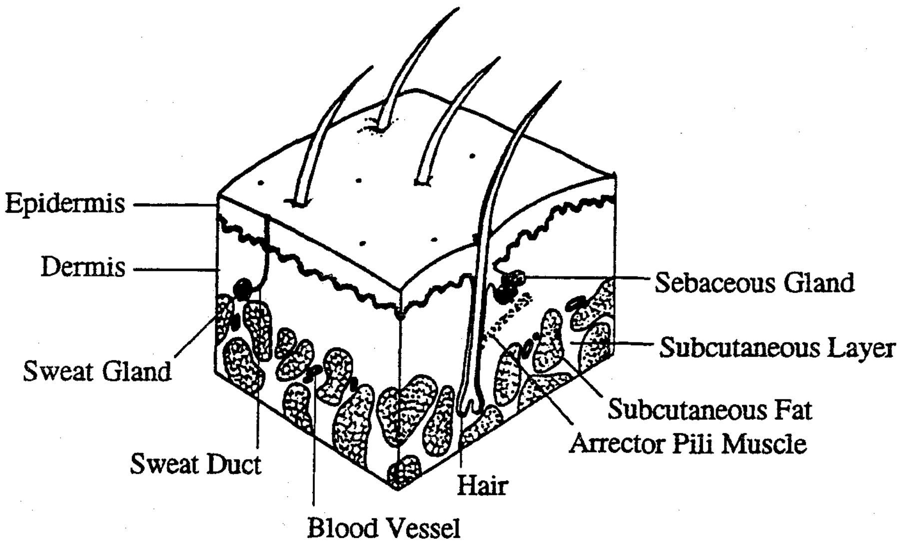


Figure 1. Cross section of the layers and structures of human skin

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has increased the likelihood that personnel using these lasers may have skin exposed to dangerous levels of radiation.

Quantitation of the photobiological effects of laser energy must be based upon the total of absorbed energy. The ideal situation is to attempt to relate observed effects to the amount of radiant energy absorbed at specific depths below the skin surface. To be sure, this is a complex problem. However, some degree of quantitation of absorption values can certainly lend insight to the understanding of the biological effects of lasers.

Thermal effects are the principal cause of tissue damage. Thermal damage occurs when the absorbed laser radiation causes the skin temperature to increase. The elevated skin temperature, in turn, causes the tissue proteins to be denatured. Direct thermal skin damage is most often caused by exposure to laser radiation in the near-UV to the far-IR band (0.315-10^3 μm) for exposure times which are typically greater than 10 microseconds.

The reaction produced in living tissue by a CW laser exposure is essentially nonspecific. This reaction most closely resembles the tissue destruction produced by a deep electrical burn.

Tissue damage can also be caused by ***photochemical*** effects. Photochemical damage is caused by exposure to ultraviolet radiation (0.200-0.400 μm) for any exposure time. It is of note that photochemical effects are also produced in the retinal tissues by low level exposures of shortwave ***visible*** radiation (0.4-0.55 μm) for exposures lasting for 10 seconds or more.

A third skin-damage mechanism is ***acoustic shock***. Thermally induced acoustic-shock waves can cause skin damage for extremely brief exposures on the order of a microsecond or less. Such are generally produced by Q-switched lasers.

Skin damage also depends on structural inhomogeneities in the skin. The inhomogeneities can cause internal scattering of laser radiation. As a result there will be multiple internal reflections in addition to absorption and transmission of the incident laser beam.

As shown in Figure 3, almost 99 percent of the radiation penetrating the skin will be absorbed in the outer 4 mm of tissue. This applies for most

TABLE 1

ABSORPTION COEFFICIENTS OF HUMAN SKIN

WAVELENGTH (μm)	COEFFICIENT (cm^{-1})	WAVELENGTH (μm)	COEFFICIENT (cm^{-1})
0.3	290	2.3	35
0.4	150	2.4	45
0.5	60	2.5	50
0.6	30	2.6	75
0.7	21	2.7	800
0.8	17	2.8	7000
0.9	15	2.9	12700
1.0	11	3.0	11700
1.1	10.6	3.1	8000
1.2	11	3.2	3000
1.3	13	3.3	1200
1.4	26	3.4	700
1.5	28.5	3.5	400
1.6	22	3.6	200
1.7	21	3.7	200
1.8	22	4.0	110
1.9	70	4.5	120
2.0	50	5.5	300
2.1	35	6.0	1000
2.2	30	10.6	1000

* The data in Table 1 was derived from the coefficients reported for human tissues in the range from 0.4-1.8 μm and the coefficients reported for water in the range from 1.8-15 μm.

of the common laser sources operating in the 0.3-1.0 μm wavelength range.

For wavelengths greater than 0.4 μm, skin damage essentially consists of a thermal coagulation necrosis. This type of injury, which can be produced by many optical radiation sources will often depend on local absorption sites

The degree of thermal tissue effects depends upon the following factors:

1) Absorption and scattering of the beam in tissues at the various laser wavelengths
2) Irradiance or radiant exposure of the laser beam incident upon the tissues
3) Duration of the exposure and pulse repetition characteristics, if applicable
4) Extent of the local vascular flow
5) Size of the area irradiated

The absorption of light in tissues can be approximated by using Lambert's Law which is described by an exponential relationship such as depicted in Equation 1 and Figure 3.
This is written:

$$I = I_0 \exp(-a\,L) \qquad (1)$$

where: I_0=Intensity incident on surface (W/

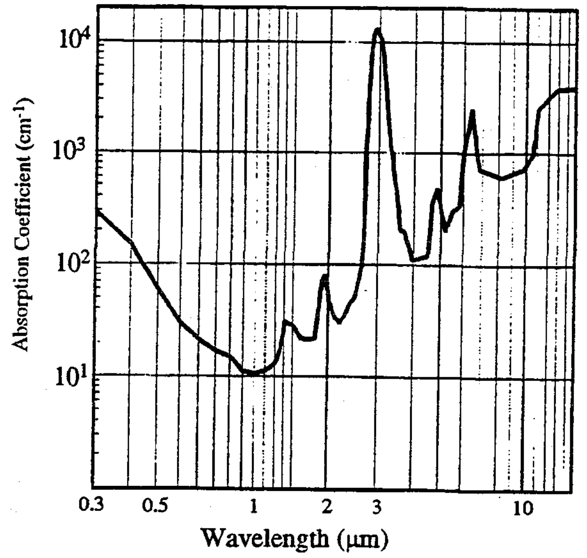

Figure 2. Absorption Coefficients for Human Tissue

cm^2), I=Intensity transmitted through to a given tissue thickness (W/cm^2), L=Thickness required to absorb the light to a given level (cm). a=Linear absorption coefficient of the tissue at the laser wavelength (cm^{-1}).

Values for the absorption coefficient are shown in Figure 2 and are also listed in Table 1. For example, one can compute the depth at which 99% of the beam will be absorbed for a Nd:YAG laser at the 1.06 μm wavelength. This is expressed:

$$I=(1.00 - 0.99)\ I_o = I_o \exp(-a\ L)$$

Thus:

$$L = -(1/a) \times \ln(0.01)$$

Approximating the absorption coefficient in tissues at 1.06 μm (see Figure 2) to be a=11 cm^{-1}, then:

$$\begin{aligned} L &= -(1/11) \times \ln(0.01) \\ &= -(0.091) \times (-4.6) = 0.42 \text{ cm} \\ &= 4.2\text{mm} \end{aligned}$$

This is graphically shown by the exponential representation of tissue transmission for the Nd:YAG laser given in Figure 3.

Wavelength Dependance in Tissue Absorption

As detailed in Table 2, UV-C radiation is absorbed in the outer dead layers of the epidermis called the stratum corneum. UV-A radiation causes pigment-darkening, but excessive exposure will cause erythema (sunburn). Of the three types of UV radiation, UV-B radiation poses the most serious health risk. The table summarizes the biological effects of exposure to laser radiation at various wavelengths. As shown, UV-B radiation can cause sunburn, skin cancer, accelerated skin aging, and increased pigmentation. UV-B can also cause cancer by direct action on DNA or by interacting with potential carcinogenic intracellular viruses.

The risk from exposure to laser radiation also depends upon other factors such as ***skin pigment***. People with more skin pigmentation skin are at slightly increased risk from exposure to laser radiation at certain wavelengths because the larger pigmentation can more readily absorb radiation.

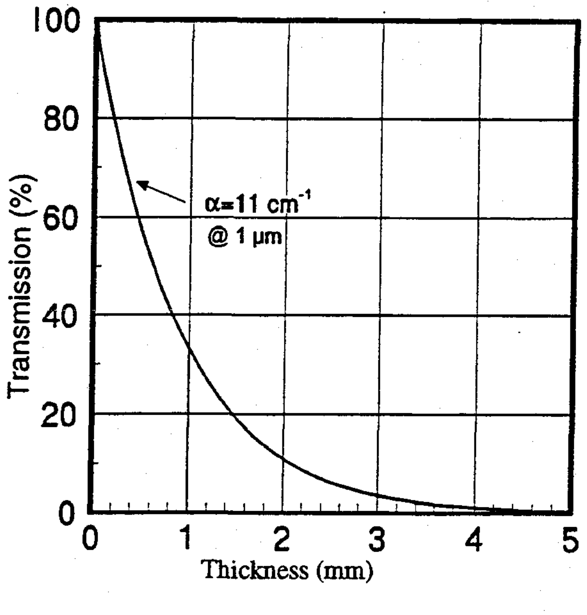

Figure 3. Absorption of 1 μm Laser Radiation in Skin Tissue

TABLE 2

SUMMARY OF BASIC LASER BIOLOGICAL EFFECTS

WAVELENGTH BAND	EYE	SKIN
UV-C (0.200-0.280 µm)	{Photokeratitis}	Erythema (sunburn) Skin cancer
UV-B (0.280-0.315 µm)		Accelerated skin aging Increased Pigmentation
UV-A (0.315-0.400 µm)	Photochemical cataract	Pigment darkening Photosensitive reactions Skin burn
Visible (0.400-0.780 µm)	Photochemical and thermal retinal injury	Photosensitive reactions Skin burn
IR-A (0.780-1.40 µm)	Cataract retinal burn	Skin burn
IR-B (1.40-3.00 µm)	Corneal burn, aqueous flare, possibly cataract	Skin burn
IR-C (3.00-1000 µm)	Corneal burn only	Skin burn

A second risk factor is ***phototoxic*** and ***photosensitizing chemicals*** in the skin. Such chemicals may potentiate the effects of lasers operating in the visible and UV regions.

A third risk factor is the effect of ***chronic exposure*** to radiation. At the present time, the health risks associated with long-term exposure to laser radiation are still unclear. Some data suggests that the effects of the individual laser pulses are additive for a given exposure.

Studies on the simulating effect of very low level exposures of the ruby laser on hair growth, phagocytosis index, and wound healing suggest that chronic exposure to even very low levels of radiation may be of biologic significance.

The exposure levels required to produce minimal reactions in the human skin for six common laser types emitting in the visible and IR are summarized in Table 3 and Figure 4. The

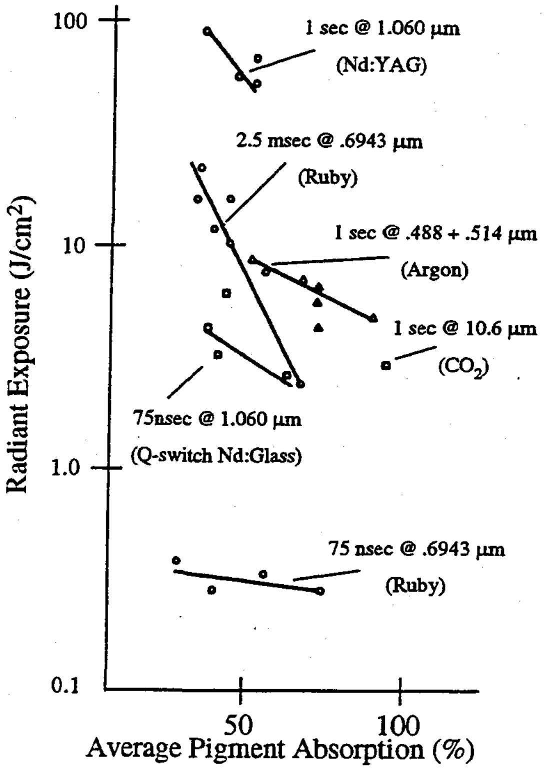

Figure 4. Minimum Reactive Dose Dependence on Skin Absorption

TABLE 2

MINIMAL REACTIVE DOSE LEVELS FOR SKIN DAMAGE

Laser	Wavelength µm	Radiant Exposure* (J/cm^2)	Exposure Time (sec)
Ruby	0.694	11-20 (unpigmented) 2.2-6.9 (pigmented)	2.5×10^{-3}
Ruby (Q-switched)	0.694	0.25-0.24	7.5×10^{-8}
Argon ion gas (CW)	0.514	4.0-8.2	1.0
CO_2 (CW)	10.600	2.8	1.0
Neodymium glass (long pulse)	1.060	2.5-5.7	7.5×10^{-8}
Neodymium-YAG (Q-switched)	1.064	46-78	1.0
Excimer (xenon chloride)	0.308	0.50	-

* At 50% probability levels for minimal tissue reaction, except for excimer which is minimal level for tissue ablation.

variations, or spread, in the data in the figure are directly related to the degree of absorption in the tissues.

The ***thermal reaction*** of skin layers to laser radiation is strongly dependent upon both the duration and the area of the exposure. The early work of Henriques and Moritz investigated the time-temperature response for tissue exposures of thermal insults up to 70°C.

The tissue/temperature destruction data, shown in Figure 5, indicate that the skin can withstand substantial temperature gradients for very short exposure times. The response appears to be logarithmic as the exposure times become shorter. For example, tissues can withstand a temperature change of up to 70°C for 1 second. However, a 21°C rise above body temperature will produce cell destruction for exposures longer than 10 seconds.

Tissue destruction caused by temperature changes results from the denaturation of cell protein, interference with basic cell metabolism, and secondary effects such as interference with the vascular blood supply. Under more extreme exposures, the skin may actually be burned,

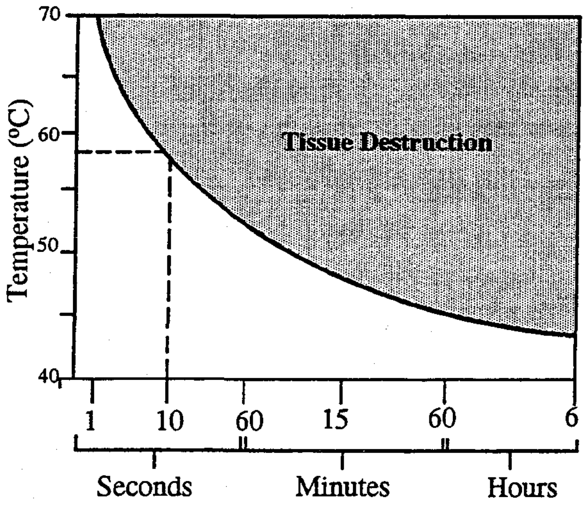

Figure 5. Tissue Destruction as a Function of Time and Temperature

During the ablation process a plume of gas phase material is produced which expands rapidly from the surface. The ablation appears to be performed without production of extensive thermal effects. While not known for certain, there appears to be a threshold for ablation in biological material which is on the order of about a few hundred mJ/cm^2. The mechanism of ablation is also uncertain but it has been postulated that direct "photochemical" bond disruption rather than thermal effects is the mechanism by which ablation occurs. The lack of clear thermal injury within the biological material points to minimal conduction of heat during the ablation process.

Since excimer lasers produce wavelengths in the region where mutagenic and carcinogenic effects have been reported from other optical (non-laser) sources, there is interest in knowing if these effects can occur in tissues radiated with these lasers.

In surgical type uses, much of the incident UV energy is deposited in material that is fragmented during the ablation process. This means less dose to cause a "sunburn" since the beam will be deposited over a large area. Most of the energy of the laser beam goes into the formation of the fragments, thus minimizing heating and subsequent thermal damage of the surrounding material. Getting an effect without heat rise is quite useful medically but occupationally it might suggest that irradiation of the skin might be accomplished without worker awareness.

Finally, we know little about human photochemistry effects at wavelengths less than 0.254 µm. However, it is reasonable to expect that at excimer laser wavelengths there does exist concerns about ***cytotoxicity and mutagenicity***. Reports from studies using 0.193 and 0.248 µm lasers have shown that 0.248 µm radiation is cytotoxic. In fact, it was shown to be almost equivalent to effects produced by germicidal lamps operating at 0.254 µm. Mutagenic potential of 0.248 µm was also higher than 0.193 µm in cell culture tests. More research work needs to be performed in these areas to fully explain the effects of high power UV laser sources.

SKILL REVIEW
2

Why would a skin exposure to a Nd:YAG laser be more painful than an exposure to a CO_2 laser of equivalent irradiance?

Answer here:

radiation. The wavelength also determines if the radiation can be focused by the eye (Figure 7). ***For these reasons the wavelength is the first and perhaps the most important factor in determining a laser's hazard potential.***

A second factor that must be considered in determining the hazard potential of a laser is the ***time of exposure***. This is manifest by the irradiance (W/cm^2) for a continuous wave (CW) laser or the radiant exposure (J/cm^2) for a pulsed laser. Injuries caused by exposure to CW lasers are due principally to thermal or photochemical mechanisms; injuries caused by exposure to pulsed laser radiation can be either thermal or, for shorter pulses, the result of acoustic-shock waves. In comparison to CW lasers, pulsed lasers require much less energy to cause eye damage. The shorter the pulse duration and the greater the repetition rate, the greater the hazard posed by a short pulsed laser.

Since the irradiance or radiant exposure is a function of the beam size, decreasing the beam diameter may increase the risk of causing tissue damage. It should be noted, however, that the retinal damage threshold level for large sized retinal exposures is *significantly lower* than the threshold level for point source exposures.

A third factor that determines the degree of impairment is the location of the exposure in the eye. The fovea (the central 2° of the visual field) is the region of the retina which is most sensitive to visual detail. Destruction of the macula, which is less than 1-mm in diameter, renders an individual legally blind. With the macula destroyed, an individual could not discern the "large E" on the Snellen chart, which means that visual acuity is reduced to 10-200, or worse.

A laser exposure that lasts only an infinitesimal fraction of a second can destroy the macula, causing blindness. A macular burn would most probably result if an individual viewed a laser beam directly or via a specular reflection under conditions where the eye resolved the laser source directly onto the macula.

On the other hand, a similar injury in the periphery of the retina will often result in little loss of vision function. The remainder of the retina, the parafovea to the peripheral retina, is increasingly less sensitive to light. However, laser-induced lesions at any location on the retina will usually cause irreversible vision loss, and such lesions are difficult to medically treat. A peripheral burn might occur through an accidental exposure in which the eye was not directly viewing the beam and was focused on something else.

A fourth hazard factor is ***image size***. Larger image sizes—typically 100 µm or greater—for exposure times greater than 10 seconds *do not* dissipate heat as rapidly as smaller image sizes. Consequently, the retinal irradiance required to produce a minimal burn on the retina will be about 10-100 times lower for larger image sizes than for point-source image sizes (20 µm). It is for this reason that different safety exposure criteria are needed for point-source and extended-source lasers.

Exposure to Visible and Infrared (IR)

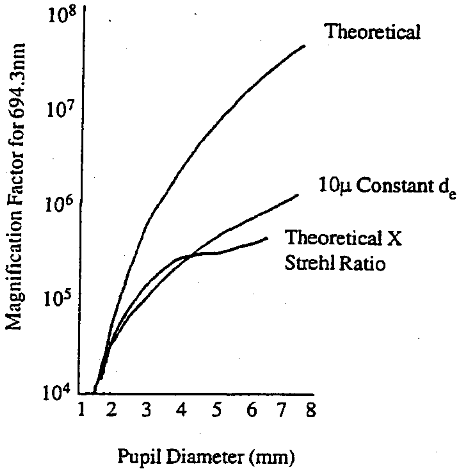

Figure 10. The Relationship Between Pupil Size and Optical Gain for a Point Source as Viewed by a Normal Eye

SKILL REVIEW
4

Which wavelengths are transmitted to the retina?

Answer here:

Wavelengths.

The optical wavelengths between 0.4 µm and 1.4 µm, may be transmitted and focused by the lens of the eye. At these wavelengths, the magnification factor on the retina can be as much as 10^5 to 10^7 for pupil diameters between 2 mm and 7 mm as shown in Figure 10. The theoretical curve (top curve) shown in the figure is derived using the Airy disk formula for peak retinal irradiance. The middle curve shows the optical gain for a constant retinal image diameter of 10 µm. The bottom curve, which is believed to be the best estimate of actual optical gain, was derived by multiplying the theoretical values by the Strehl ratios (I_{max}/I_{avg}). The Strehl ratio may be somewhat high due to uncertainties in measuring low levels of forward scatter.

If the diameter of a laser beam is larger than the pupil diameter, diffraction of the beam occurs at the edge of the iris. If the beam is smaller than the pupil, spherical aberrations and forward scattering cause the point image to spread. As Figure 9 shows, the transmittance of the ocular media is greatest for wavelengths between 0.4 µm and 1.4 µm. In this range of wavelengths, most of the laser energy is absorbed by the retina. In the visible and IR-A portions of the spectrum, the cornea, lens, and ocular media are largely transparent.

Only about 5 percent of the light received by the eye is actually used for vision; the remainder being absorbed in the pigment granules in the pigment epithelium layer of the retina and the choroid layer under the rods and cones. At these wavelengths laser radiation is focused by the eye to an extremely small spot size on the retina. The focusing effect can cause retinal burns for even modest corneal exposure levels. At higher exposure levels, more severe burns are produced. Higher exposure levels can also cause craters in the retina and hemorrhage within the eye. Figure 11a shows small retinal burns just above the damage threshold caused by a Q-switched laser.

Although IR-A radiation is invisible to the human eye, it is still focused by the lens. This makes exposure to IR-A lasers especially hazardous. Even a fairly low-power Nd:YAG laser operating in a pulsed mode can cause permanent eye damage. Exposure to IR-A radiation (0.7-1.4 µm) can result in cataracts and retinal burns. Exposure to IR-B radiation (1.4-3.0 µm) can cause damage to both the lens and cornea. IR-C (3.0 µm-1 mm) is absorbed by water in the ocular media, and can cause the ocular media to become opaque.

Exposure to Ultraviolet (UV) Wavelengths

UV radiation is absorbed by the outer layers of the eye. Excessive short-term exposure of the eye to UV-B (0.280-0.315 µm) or UV-C (0.200-0.280 µm) radiation can produce photokeratitis, which results from damage to the outer epidermal cell layer of the cornea. This injury is characterized by photophobia, eye redness and tearing, discharge from the mucous membrane that lines the inner surface of the eyelid (conjunctiva), corneal-surface cell-layer splitting (exfoliation) and stromal haze.

LASER ACCIDENTS

SECTION OBJECTIVES

- *Identify* five common causes of laser accidents
- *Relate* case studies of laser injuries to common causes of laser accidents

LASER ACCIDENT CAUSES

Laser accidents result because of a variety of causes. In nearly all cases, however, the accidents could be avoided by proper safety training that ensures individuals follow established laser safety procedures. Exposure to laser radiation is not the only laser-related hazard. Other potential hazards include electrical shock from the laser power supply, exposure to flammable or toxic chemicals, and noise-related injuries associated with laser operation.

Beam Alignment

The most common cause of accidents is accidental eye exposure during beam alignment. This observation is explained by the fact that alignment generally requires the eye as part of the process. For example, in CO_2 laser surgery, the alignment beam, usually from a HeNe laser, and the CO_2 beam must follow the exact same optical path so they coincide at the target spot. The alignment process requires that a few test burns be made to ensure that the two beams are coaxial. It is during these kinds of alignment procedures that laser accidents often occur.

Misaligned Optics

The second most common cause of laser accidents results from misaligned optics. In laser operations where precision is crucial, misalignment of the lasers can result in patient injury. A case history of such an accident is described in the Laser Accident section.

Lack of Eye Protection

The third most common cause of accidents is the failure to wear *available* eye protection. Many accidents have involved individuals who had eye protection within reach but who failed to use it. All accidents of this nature are avoidable, if the proper safety procedures are followed. For example, in an operating room, or in any other medical environment where lasers are in use, eye protection should be a procedural requirement. If the eyewear must be in place before the system can be operated, such accidents would not occur.

Malfunctioning Equipment

Accidents have also occurred because equipment malfunctioned, or because nontrained personnel attempted to adjust or do maintenance to a high voltage laser system. For instance, shutter timers have failed on ophthalmic lasers giving exposure to patients longer than expected, resulting in retinal injury. Proper maintenance of the shutter system may have prevented the injury. Unless specifically trained, personnel should never get involved with any kind of repair or service on high-voltage equipment. Only appropriately trained personnel should ever access the high voltage sections of a laser system.

Lack of Training

A number of laser accidents have been caused by individuals operating unfamiliar equipment. Such accidents might occur if a surgeon who is trained with a certain manufacturer's laser, attempts to use another manufacturer's laser, assuming that the two pieces of equipment will behave in the same way. Unfortunately, there are major differences in specific laser devices that result in the delivery to the target site at significantly different irradiance levels at what appears to be identical conditions in the two laser devices. It is really not total beam power that is important but, it is the power per unit area (irradiance). Irradiance can be dependent on many factors: laser design, beam divergence, focusing laws, beam distribution (mode) and delivery system.

Some manufacturers provide a chart indicating that at a particular total power level, with a certain lens on the system, a known irradiance level is delivered at the target site.

A 100 watt laser, defocused to cover a square mile area, will produce a power per unit area of about 5.6×10^{-7} W/cm^2. One wouldn't even be aware of an all day exposure to the beam. But, the same 100 watt laser, focused to a very small point, can do surgery. The difference between the two is the beam size, which effects the concentration or irradiance.

There have been a number of accident cases, particularly in the medical environment, where lasers were used in an unfamiliar situation. The expected reaction was not obtained and, at an "identical setting," a more severe reaction was produced.

Ancillary hazards, particularly laser generated smoke, also presents a hazard and requires protection. Laser Generated Air Contaminates (LGAC) can be released into the environment whenever laser irradiance is high enough to vaporize the target material.

LASER ACCIDENTS: CASE STUDIES

In this section, some case studies of laser accidents are described.

Case Study 1

A patient underwent a laser stapedectomy to correct a partial hearing loss in the left ear, using a 4.5 mm McGee prosthesis. The CO_2 articulator missed its intended target on the incus bone by approximately 2.5 mm, which resulted in a less than adequate implant location. As a result, the patient's hearing loss was not improved to the degree expected, and there was very low probability of further improvement through additional surgery.

The investigation of the laser and micromanipulator revealed that the upper lens of the micromanipulator jerked horizontally when adjustments in the beam diameter selector were attempted. Also, it was documented that the CO_2 laser was approximately 2 mm off center of the cross-hair.

The investigators concluded that the principal contributing factors in this accident were equipment design, equipment maintenance, and modifications to the design by the manufacturer.

Case Study 2

A person was partially blinded by a reflection from what was called a relatively weak Nd:YAG The exposure in the eye was approximately 6 mJ. However, 6 mJ in a 10 nsec exposure time creates enormous peak power—approximately a thousand times greater than the limit allowed into the eye. Although the laser was thought to be relatively weak, in fact it was many orders of magnitude above the accepted safe exposure limit.

As a result of the exposure, a vitreous hemorrhage was produced and the person went into shock. Fortunately, the hemorrhage did not produce a foveal lesion, and eventually some vision did return.

The accident was due to the fact that although eye protection, was available, it was not being used. This incident could have been avoided if a laser safety program had developed a safety awareness so that people wore protective eyewear.

Case Study 3

An attending nurse was temporarily blinded by a reflected beam from a retinal photocoagulator when the beam was reflected from a piece of the equipment. The nurse did not suffer any long-term loss of vision.

The likelihood of the accident occurring could have been eliminated by requiring the use of protective eyewear. Additionally, the use of coated optics could also reduce the potential hazard. Coated optics have thin dielectric coatings, called antireflection coatings, that are specifically designed so that if a beam strikes the coating, it will be almost completely transmitted and not reflected back.

Case Study 4

The 24 year old male laser technician was aligning the top spire argon laser entertainment setup. He had just completed the alignment and, thinking he was finished, closed the system up. Laser operation began again. He recalled that he was not sure about the alignment on the galvonometer mirrors. He returned to the laser and opened the cover. He defeated the interlocks to allow the laser to operate. He was not wearing the available laser eyewear and did not turn the laser power down (as was the instruction) during the alignment. He also did not turn-off the computer, as was the instruction. He reportedly did not remember that the system was operational with the computer operating. The system went into burst mode and the 20 W beam scanned onto his face. He sustained a right eye exposure and a very severe retinal burn. He was taken to an opthamologist who confirmed a retinal lesion. Reportedly, he now has only 2-3% vision in that part of the eye following the exposure. He reports a "black spot" in his central vision field. It is unclear whether this was a foveal lesion. He has returned to his laser technician job.

Case Study 5

A visiting professor from China lost part of the sight in his left eye after he removed his safety goggles during a laser test. The professor was in the research lab of a university. He was working on an experiment with a crystal he had grown. He had removed his goggles so he could see better and the laser reflected into his eye, burning the retina.

Case Study 6

A laser used for cloud level indication at a celestial observatory was undergoing alignment by the operator. The unit uses a Q-switched ruby laser with the beam directed up toward the dome. The operator had no recollection of any single event when it happened. He did comment that a days work at such high altitude makes one forgetful - and that he often uses oxygen while writing a report near the end of the day. After two weeks of poor vision, the operator went to a physician who noted a circular lesion with leakage and a retinal scar. From description of the dark spot, the lesion is off the fovea. The operator suspects beam "leakage" around the eyewear used. Upon inspection of the eyewear, it was determined that one pair had an over stretched head strap, the other had "open" spots around the face at the side. The operator reports he is experiencing increasing pain and decreasing visual acuity after three weeks, apparently due to increased swelling. He has difficulty reading and it is apparently getting worse.

Case Study 7

A construction worker using a 5 mW HeNe laser (the second day it was on the construction site) received the beam in the eye while reaching over to pick up a shovel. The laser was used in aligning sewer pipe. While doing this, he received a fast "scan" across his glasses while turning his head and "saw the bright red light."

The laser beam power was labeled at 5mW, Class 3a. The beam diameter out of the laser is about 3/8 inch (approx 9.5 mm - hence: area =

0.0709 cm^2; hence emergent beam irradiance was 70.5 mW/cm^2 and the required OD would be: 0.71.

That night, after exposure, his eyes felt dry and he couldn't read the TV guide. He went to a laser experienced ophthalmologist who confirmed peripheral retinal burn.

Case Study 8

A male technician received several reflected laser pulses from an XeCl excimer laser (λ = .308 µm). The laser was operating in a pulsed mode at approximately 1 pulse per second. The technician had removed a portion of the protective housing that covered a beam splitter and was watching for an abnormal electrical discharge inside the laser chamber. About 15 mJ per pulse was reflecting off the beam splitter and produced four distinct burns on his neck. As this wavelength, no heat was detected and the burns were not evident until several hours after the exposure. The burn spots were similar to severe, localized sun burn but required nearly three weeks to heal. Eye protection was being used.

SKILL REVIEW
5

List five common causes of laser accidents:

List causes here:

CHAPTER REVIEW

SUMMARY

1. Skin and eye damage are the principle health hazards related to exposure to laser radiation.

2. Laser injuries can be caused by thermal, photochemical, acoustic- shock, and carcinogenic effects

3. The degree of thermal tissue damage depends upon wavelength, skin type, irradiance, exposure time, pulse characteristics, vascular flow, and exposure area.

4. Exposure to UV-B radiation poses the most serious health hazard for the skin; exposure to visible and IR radiation poses the most serious eye hazard.

5. Laser-radiation injuries are limited to the outer layers of the skin and to the eye.

6. The sclera, choroid, and the retina are the three major layers of the eye.

8. Damage to the fovea can cause blindness.

9. Visible and IR wavelengths are focused on the retina, which magnifies the intensity so that retinal burns can occur at a small laser power.

10. UV radiation is absorbed by the outer layers of the eye. Damage can include corneal injury, cataracts, and photophobia.

11. Visible light can cause lesions by thermal and photochemical mechanisms, depending on the specific laser wavelength.

12. The most common causes of laser accidents are misaligned optics, lack of eye protection, malfunctioning equipment, lack of training, and not following procedure during beam alignment.

KEY TERMS Define each term

aqueous humor
aqueous chamber
choroid
cone
cornea
erythema
fovea
iris
lens
macula lutea
optic nerve
photokeratitis
photophobia
pupil
retina
rods
sclera
stratum corneum
vitreous humor

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REVIEW QUESTIONS

1. Laser injury mechanisms include all of the following except
   a. thermal
   b. photochemical
   c. corrosive
   d. acoustic-shock

2. Sunburn is caused by exposure to
   a. UV
   b. visible
   c. IR
   d. X-rays

3. Which of the following is the most serious laser injury?
   a. skin lesion
   b. foveal burn
   c. cataract
   d. corneal damage

4. Which of the following would not be involved in an injury from exposure to a CW CO_2 laser?
   a. skin pigment
   b. irradiance
   c. exposure area
   d. vascular flow

5. Argon laser energy is absorbed by the eye in which of the following:
   a. cornea
   b. pupil
   c. pigment epithelium
   d. sclera

6. Distinguish between the effects of exposure to different UV wavelengths.

7. For most common laser sources, most of the laser energy is absorbed in skin:
   a. in the outer 40 mm of tissue
   b. in the first 4 mm of tissue
   c. in the outer 4 cm of tissue.
   d. in only pigmented areas
   e. none of the above

8. Describe the damage hazards from exposure to visible and IR-A laser radiation.

9. At what wavelength will tissues have the largest absorption coefficient?
   a. 10.6 µm
   b. 2.95 µm
   c. 2.1 µm
   d. 1.06 µm
   e. 0.488 µm

10. Most laser accidents could be avoided by
   a. Using protective glasses
   b. Laser safety training
   c. Proper laser maintenance techniques
   d. All of the above

SKILL REVIEW ANSWERS

1. 46 mm

2. The Nd:YAG has greater depth penetration which causes direct heating of nerve endings in the skin. The CO_2 laser is absorbed in the outer 50-100 mm of tissue and the heat must conduct to the nerves.

3. See Figure 5 for eye labels.

4. 0.4-1.4 μm

5. Alignment, optic misalignment, no eye protection, equipment malfunction, no training.

CHAPTER REVIEW ANSWERS

1. c

2. a

3. b

4. a

5. c

6. UV: photochemical cataracts, skin burn, pigment darkening, photosensitive reactions; UV-B photokeratitis, increased pigmentation, accelerated skin aging. UV-C: Erythema, skin cancer, photokeratitis.

7. b

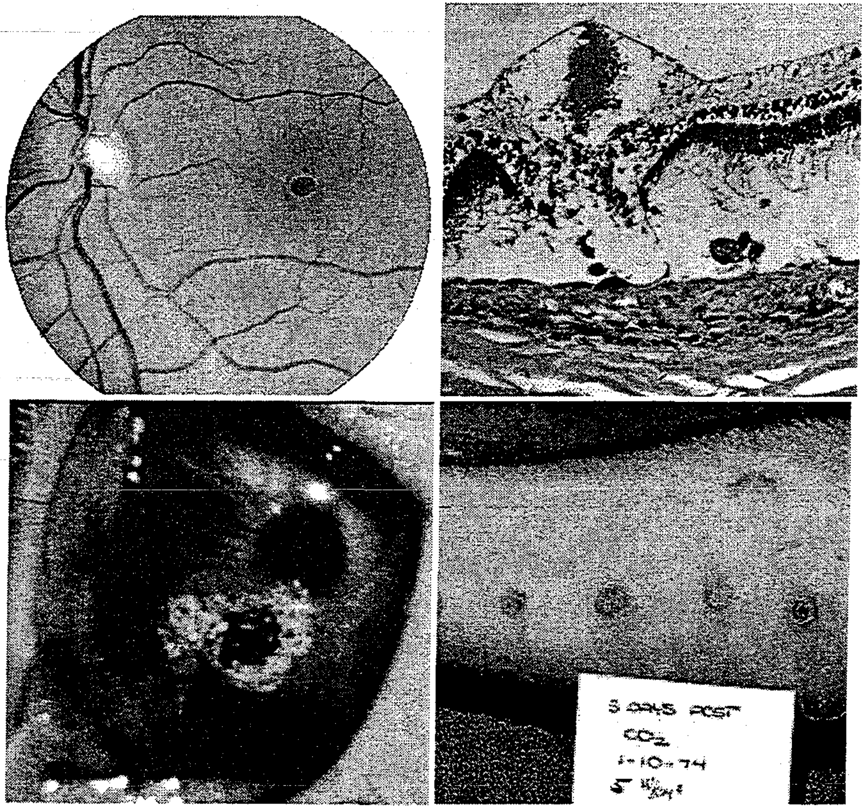
8. Exposure to visible and IR-A: retinal burns except for low-level exposures (near threshold) in the 0.400-0.550 μm (blue-green) spectrum where photochemical effects produce damage when the exposure exceeds 10 seconds.

9. b

10. d

MINI MODULE: ACCIDENTS

LASER ACCIDENTS
AND EYE INJURY



Education

LASER ACCIDENTS

SECTION OBJECTIVES

- *Detail* methods of recording laser accident data
- *Identify* eight common causes of laser accidents
- *Review* international scope of laser accident cases
- *Relate* case studies of laser injuries to common causes of laser

LASER ACCIDENT AND INJURY

OVERVIEW

As the laser industry expands and matures, laser users continue to experience many types of serious accidents at what seems to be an alarmingly increasing rate. These events are described by one of the following basic exposure scenarios:

- The accidental exposure of the eye resulting in either temporary or often permanant vision function loss.
- The accidental exposure of skin resulting in burns and or photochemically based skin effects.
- Ignition of fires in both facility and personnel natures.
- High voltage exposures are often lethal.
- Injury to patients during medical therapy caused by unknowledgeable use, equipment failure, severe fires and gas embolism.
- Inhalation of LGAC's and/or viewing laser generated plasmas.
- Ocular exposures to pilots at flashblinding levels causing persistent after images and/or vision degradation.

This section provides a summary of the types and causes of laser related accidents and eye injury. It can be generally stated that as the laser industry expands and matures, laser users are experiencing, perhaps even at an alarmingly increasing rate, the following conditions of risk:

- Hazardous eye and skin exposures.
- Fires of a personnel and facility nature.
- Inhalation of hazardous gases and/or particulates.
- high voltage shocks...etc.

All of these unfortunate events will be defined in this section as a laser associated incident.

RECORDING ACCIDENT DATA

Collecting information on such laser accidents is, at best, a difficult task. The first effort to collect laser accident data, which emphasized mainly eye exposure cases, was a part of the voluntary ***Radiation Incidents Registry*** (RIR). This database was maintained by the Food & Drug Administration (FDA) from the early1960's within the federal agency called ***The Bureau of Radiological Health*** or BRH. Note that this agency was renamed in 1983 and is now called ***The Center for Devices and Radiological Health*** or CDRH, the agency that regulates the manufacture of laser products.

Device Experience Network

Then, in the early 1980's, specificactivityon the ***Laser Incidents Registry*** (LIR) laser incident data collection seemed to cease for several years. This continued until about the mid-1980's when the FDA's ***Device Experience Network*** (DEN) was initiated. It should be stressed, however, that the DEN is the new FDA system for reporting problems associated with medical devices only and, hence, does not generally reflect problems with laser equipment in nonmedical areas. DEN reports include reports under the ***Product Reporting Program*** (PRP) in a voluntary manner similar to the earlier RIR as-well-as the legally mandated reports required of manufacturers under the ***Medical Device Reporting Regulation*** (MDR).

ACCIDENT ANALYSIS

Early evaluations of laser accident data suggested that laser accidents generally fall into one or more of the following major categories(1,2).

- Unanticipated exposure during alignment.
- Available eye protection not used.
- Equipment malfunction.
- Improper methods of handling high voltage.
- Intentional exposure of unprotected personnel.
- Operators unfamiliar with laser equipment.
- Lack of protection for ancillary hazards.
- Improper restoration of equipment following service.

Other Laser Accident Analysis

There have been limited efforts to record laser accident dataon an ongoing basis. One such program has been the ***Rockwell Laser Accident Database (RADB)***; maintained by Rockwell Laser Industries. This database includes a collection of laser accident information gained from a number of different sources.

Except for the RADB, there have been limited other long-term efforts, either within or without of official government compliance activities, with the mission to record and analyze accidents. Such efforts are especially helpful in learning how and under what conditions laser accidents occur and how they may be prevented.

Only in a few isolated cases, such as one well documented laser eye protection failure of July, 1985 at Lawrence Livermore Laboratory(3), has the U.S. Federal Government made the effort to fully analyze and document the laser accident cause and suggest avenues of prevention. It is of note that in this case, it was a Department of Energy (DOE) review activity because the laboratory where the accident occurred was a major DOE contractor.

Medical Post-Accident Therapy

One major concern relative to all accidental laser retinal injuries has been the question regarding the value (or lack thereof) of medical therapy following the exposure event. For the victims of accidental retinal burns, the question of whether therapy can assist in reducing the damaging effects is of major importance.

A recent detailed follow up on laser injury patients by Gabel, et. al. concluded that medical therapy (such as the use of steroids or drugs) has been found ineffective for treatment of such accident victims(4). It should be noted, however, that this report was limited to a sample of only six cases. The report did indicate, however, that for laser accident cases with subhyaloidal hemorrhage, the use of a laser may be considered in the therapy for the ***control of the bleeding***.

ANALYSIS OF INCIDENTS

A recent increase of laser case study reports has occurred following the advent of the ***Medical Device Regulations of the Food, Drug and Cosmetic Act*** (21 CFR 803). This law mandates that medical device manufacturers are required to report to the FDA when they receive information that reasonably suggests that their equipment may have caused or contributed to a death or serious injury or has malfunctioned in a way that would result in death or serious injury if it were to recur.

Are Accidents Reported?

Drawing upon the ***Device Experience Network*** (DEN) data of the U.S. FDA, Bauman(5) has suggested, that only a very limited percentage of the laser accidents that do occur actually get reported. The reasons cited centered upon behavior of the laser users.

For example, users tend to report accidents to the manufacturer more reliably ***only when their device is still under a warranty or service contract.*** Also, only those manufacturers that provide aggressive technical service and support are likely to learn about a reportable accident.

The International Scope of Laser Accidents

The concept that reported incidents represent only a fraction of the occurrence rate has also been supported by authors outside of the USA. For example, Bandle and Holyoak recently concluded in their analysis of laser accidents(6): "The total number of accidents remains small, perhaps 100 or 200 if the estimated figure quoted for the USA(7) is extended to all the developed nations of the world. However, accident statistics traditionally demonstrate a marked underestimate of the real figure due mainly to non-reporting and to incorrect classification of the cause of injury. If we allow for the need to introduce a further factor for the number of incidents or near misses which do not result in any significant injury, and therefore go unreported, ***one might suppose a figure for total incidents of several thousands over the last 20 years to be nearer the truth.***"

In addition, a recent report by Haifeng(8), et. al., from the People's Republic of China, based upon analysis of 29 ocular eye injury cases over the period 1976-1986 indicated that nearly 90% occurred during periods when laser workers were adjusting lasers or measuring parameters while 10% of the exposures occurred in bystanders. Most of their reported injuries (63%) occurred following exposure by the invisible beam from Q-switched Nd:YAG lasers operating at 1.064 μm.

In addition, they reported that most injury occurred in the macula-fovea implying that a condition of intrabeam viewing existed during the accident. This fact suggests the concept that the users were ill informed regarding potential laser hazards. Such Nd:YAG laser lesions are seldom detected unless an obvious decrease in visual acuity occurs after the exposure.

They supported this notion when they stated that: ***"Some persons concerned did not fully recognize the dangers of lasers, so they even looked directly at the beam."***

The authors concluded that: "Most injury occurred in the macula-fovea, and afterwards visual function declined severely. Hence, protective measures must be increased, especially among persons operating Q-switched lasers of the 1064nm wavelength, the beam of which is invisible and can markedly affect the fundus."

RLI LASER ACCIDENT DATABASE

Over the past decade, in lieu of an official all inclusive government laser incident data base, an attempt has been made by Rockwell to independently collect laser accident data and, where the exposure information was provided, deduce some understanding of the conditions of the incident and, if possible, correction methods that may prevent such incidents in the future.

The data analysis attempts to record the key factors involved in each incident and, where possible, to deduce an understanding of the conditions of the reported incident.

It is of note that information on many of the more recent incidents was usually obtained by direct communication between the author and the accident victim and/or employer. In many cases, those involved were often inquiring of information regarding a possible therapy action for serious eye function loss and/or recommendations for medical referral.

It is of note that there still does not appear to be any medical therapy that can provide any significant long term assistance to those who have received retinal damage from laser exposure although corticosteriods, anti-prostaglandins and antioxidant vitamins are being used by some[36].

TERM OF INCIDENT DATA

The number of incidents that have been recorded over the laser decade are shown in Table 1. Over this period, 272 events have been reported which averages to 8.8 reported incidents per year over this period. The number of events in the first decade (1964-1973) was 26 incidents (2.6/year). This increased to 96 incidents in the second ten-year period (9.6/year) and more recently to 150 recorded incidents in the third period (13.6/year). The data clearly suggests that the number of laser related incidents is increasing. If one compares the number of incidents of the last decade to the number of incidents in the previous decade, it indicates an increase of nearly 49% over that period.

Table 1
Number of Laser Incidents Per Year
Period 1964-1994

Period	No. Yrs	No Incidents Recorded	Average Per Year
'64 - '73	10	26	2.6
'74 - '83	10	96	9.6
'84 - '94	11	150	13.6
avg.	31	272	8.8

SKILL REVIEW
1

List five common causes of laser accidents:

List causes here:

Collecting information on such laser accidents is, at best, a difficult task. It should be mentioned that in gathering this data the author found a significant reluctance for individuals to release accident information. For obvious medical/legal reasons, most of the sources would release information only in a manner that would not identify the source.

ACCIDENT DATA SUMMARY

The summary of the types of accidents are provided in Table 2 below. This shows the general division into the three major areas: (1) Eye injury, (2) Skin injury, and (3) Non Beam related events, such as fire, electrical, equipment failure, laser generated air contaminants (LGAC's) and special conditions (eg: embolism, other..). A summary is also given in Figure 1. A review of the data suggests the following general key factors:

Eye injury

Is by far the most commonly reported laser related incident and was involved in slightly over 73% of all of the incidents recorded. Over 90% of the eye-injury cases recorded some function loss of which 77% were permanent.

A typical case (RLI#152) is as follows: An untrained summer research assistant was doing alignment on his first day at work using a 150 mW argon/dye laser operating at 530 nm. The laser was "slung" in a laser holder located under optical bench and the beam was directed upwards through a beam channel in the optical bench. The student chose to stand on top of the table and look downward while attempting to align a beam bender mirror. No protective eyewear was used. The beam bender mirror slipped and the beam was directed into his eye causing an immediate retinal burn on the edge of the macula.

The following example (RLI#260) provides a major argument supporting "real" laser safety policies and practices and why these should be a significant part of all laser programs. A research assistant received exposure in both eyes while working unsupervised in the lab. She was in the lab reportedly having an argument with her boyfriend (who was not authorized to be there in the first place). The assistant was not wearing laser protective eyewear although it was available. She claimed that the professor never wore the eyewear and that it was just a "paper policy".

Following the event, the student sued the university for $39 million and reportedly settled for $1 million out-of-court. She claimed the protective eyewear and laser safety policy was only "on paper" and was not practiced. She also ignored the policy that NO guests were allowed and that she also required supervision to operate the laser. None-the-less she collected on her claim.

Such a settlement clearly indicates that the courts tend to favor the injured party. Obviously laser safety programs that are viewed only as "paper policies" can ultimately be very expensive. It is evident that those in policy making roles must "practice what they preach".

Alignment

Such activity is clearly a time of heightened risk when working with lasers. The data summary indicates that 37.2% of the cases reported eye incidents during alignment procedures.

A typical case of an alignment injury is given in the following (RLI#255): During optics alignment involving a 30 mJ pulsed Nd:YAG laser (10 Hz) on a target using a prism, the beam exceeded the prism's critical angle and struck the scientist in the eye resulting in a permanent retinal burn. Unfortunately, no protective eyewear was worn at the time. An ophthalmologist was consulted and confirmed retinal burns. Blurry vision resulted especially when reading.

In a similar incident (RLI#263) involving an 10 Watt argon laser being used in a large laser light-show installation. During an alignment process, the technician received a 60 mW intrabeam exposure from the laser's Brewster window into the left eye. Two permanent retinal (non-foveal) lesions were produced. Laser protective eyewear was available, but was not over the technician's eyes at the time since the goggles apparently fogged easily and were annoying to use. A blind spot has persisted in the area of the lesion.

Eye injury laser types

It seems significant that only five different laser types: Nd:YAG, Argon, Dye, Ruby and HeNe were involved in 90 % of the severe eye injuries.

For example, one of the more unusual eye injuries (RLI#166) occurred in a laser technician working on a 1.0 J pulsed Q-switched ruby laser mounted atop a forklift. The technician did alignment while perched on the forklift. He suspicioned that the eyewear was the problem because of a poor head strap causing light to "leak" at the sides. Claimed that he could "see" flashing during alignment including flashlamp light.

Exposure caused blurry vision, retinal swelling and retinal fluid leakage. With time, his vision was getting worse. Installation is in a observatory at an 10,000 feet altitude.

The breakdown for all laser related incidents is given in Table 3 as follows:

Table 3
Most Common Lasers Producing Laser Related Incidents

Laser Type	No.	Percentage
Nd:YAG	81	29.7
Argon	56	20.5
CO2	35	12.8
Dye	27	9.9
HeNe	19	7.0
Ruby	17	6.2
Unspecific	15	5.5
Do. YAG/Ruby	10	3.7
Other (HeCd,Cu..)	10	3.7
Diode	2	1.1
	272	100

Equipment failures

These are becoming a more important factor in eye injuries. Note in Table 2 that 14 of the 180 eye injury incidents can be attributed to equipment failure (7.8%).

For example (RLI#35): a field service engineer was working on an argon laser photo-coagulator. During the inspection, the engineer "looked down" the tube bore when the laser "accidentally" fired. The person received an intrabeam ocular exposure causing a permanent retinal lesion. Physician felt functional loss might be partially reversible.

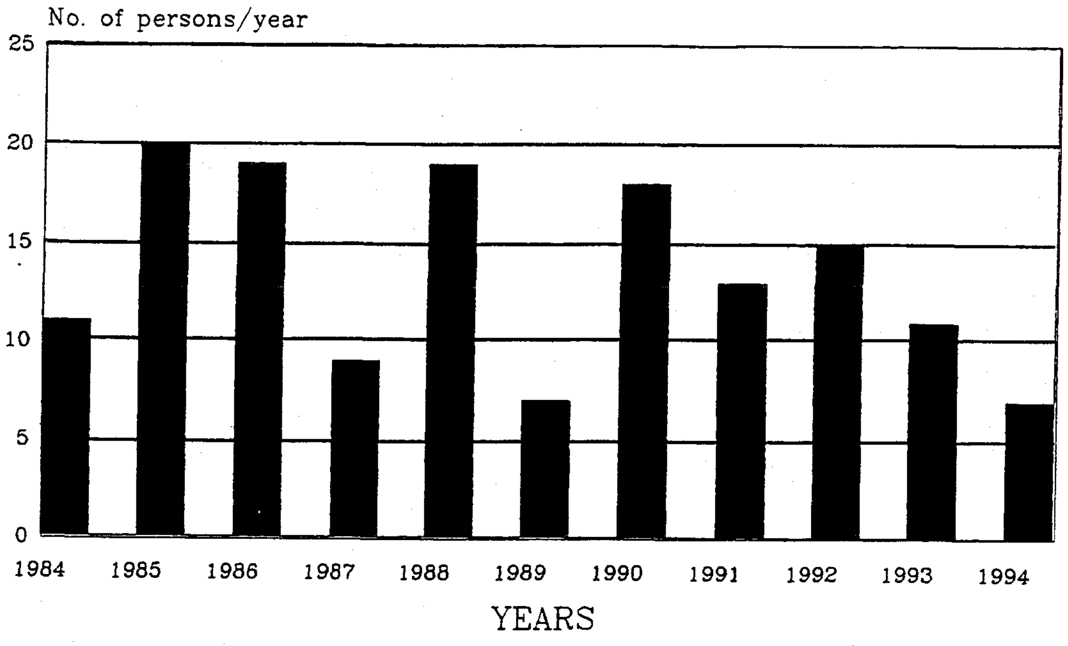
Laser light violations of airspace

Two recent events have brought attention to a new concern of laser exposures. Numerous amusement facilities throughout the country have contracted laser lightshow companies to stage out-of-doors beam displays and sky scans on a nightly basis. These activities have become a concern to the Federal Aviation Administration (FAA) and aircraft pilots since some of these beams enter the airspace where take-off and landings occur, especially near major airports. Two recent events reinforce this concern. The first one (RLI#262) occurred in late 1993 at the airport in Las Vegas, Nevada. A Southwest airlines flight was taking off when the beam from a 12 W argon laser emanating from the Las Vegas Rio Hotel was viewed by both the pilot and first officer. While flying at 500 feet, they were exposed through the right side window of plane. The exposure caused a 5-10 sec. immediate total vision loss and 5-10 minute vision reduction in the First Officer. While vision recovered in both pilots, there was great concern that this event could, under different circumstances, put not only the pilot, but crew and passengers at life-threatening risk.

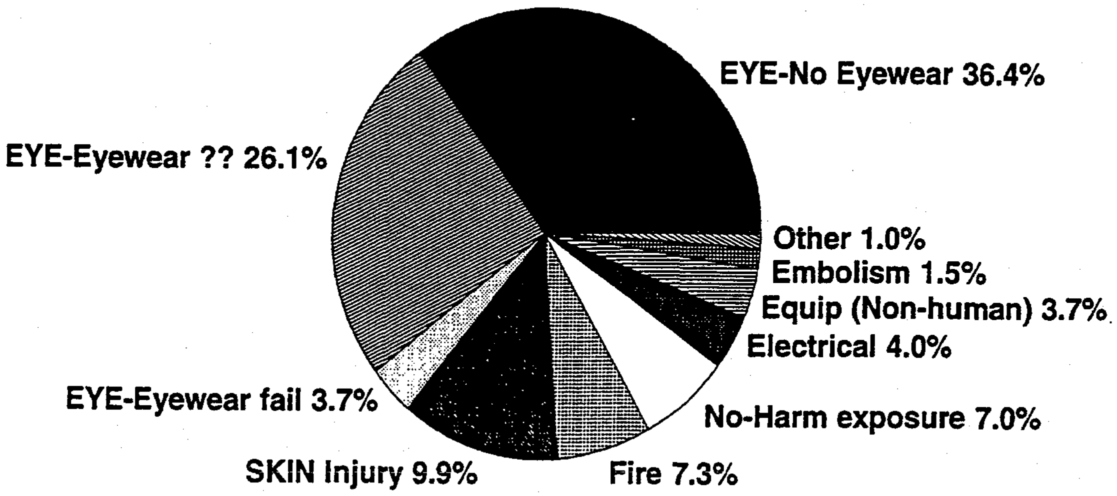
A second, very similar event was recorded (RLI#261) in mid June, 1994 in Biloxi, Mississippi. In this case a 15 W argon laser beam coming from the Palace Casino was intercepted during landing of an US Air Force C-130. Two 15 W beams were delivered via 100 µm fiber into the airspace. The flight engineer reportedly sustained a vision loss of 60 seconds following a 3-5 sec. exposure @3.5 miles from the casino while flying at 700 feet altitude. The laser company claimed that the beam block mechanism had been altered thus the safety shut-off system didn't work. The FAA suspended operation of the lightshow.

Both of these events raised major concerns by the FAA and various pilot groups. For example, a special Laser Safety Hazards Committee was formed by the G-10 Aerospace Behavioral Engineering Technology Committee of the SAE. This group's mission is to establish criteria and make specific recommendations to the FAA relative to the lasershow problem. At this writing new criteria are being developed for the FAA requirements for outdoor laser demonstrations (Order 7400.2D, Part

LASER ACCIDENT SUMMARY
Incidents Reported: 1984-1994

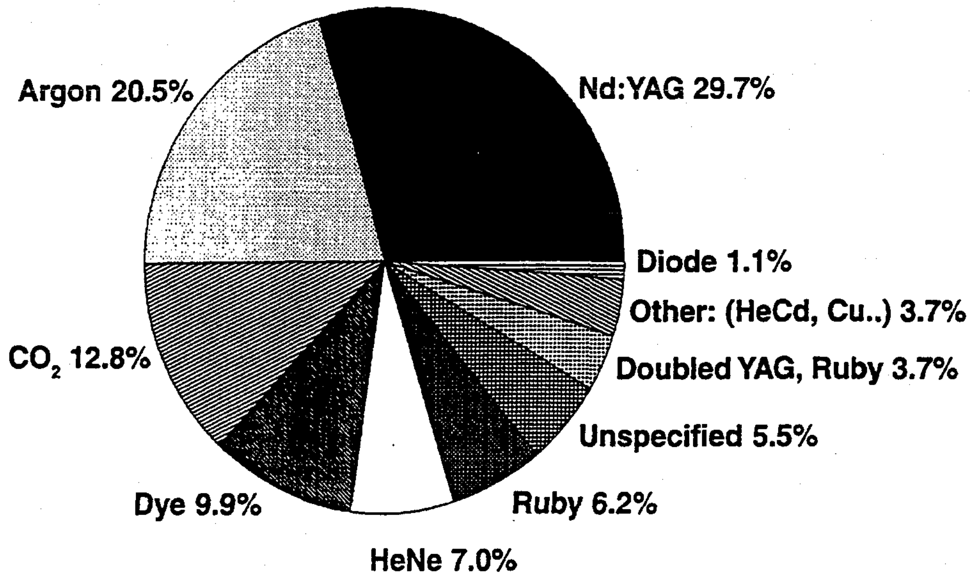


LASER ACCIDENT SUMMARY
Summary of 272 incidents: 1964 - 1994

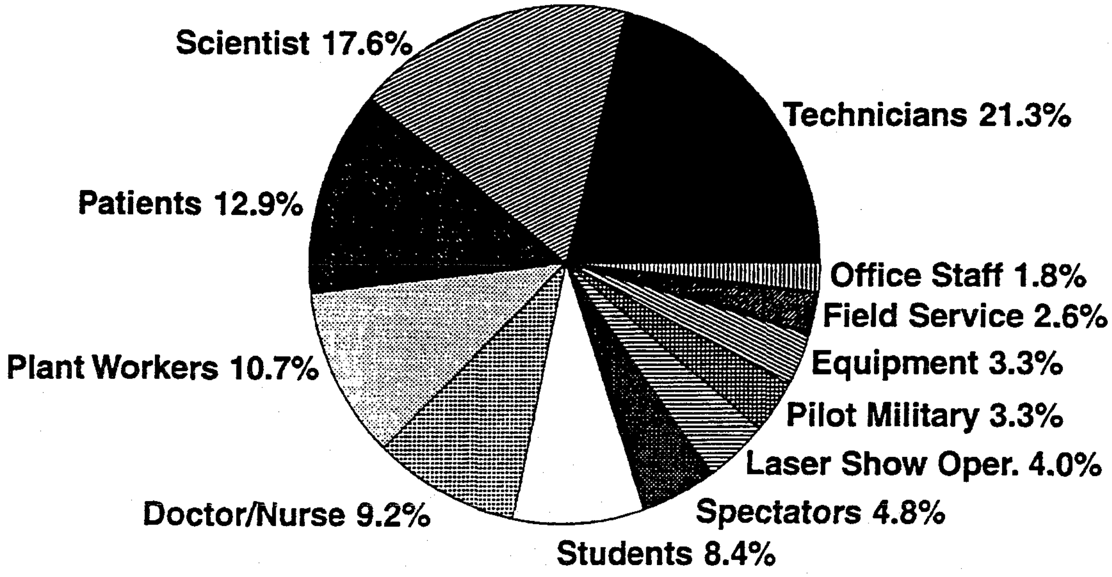


Laser Incidents by Major Category

LASER ACCIDENT SUMMARY
Breakdown of 272 events by type of laser



LASER ACCIDENT SUMMARY
Breakdown of 272 events by occupation



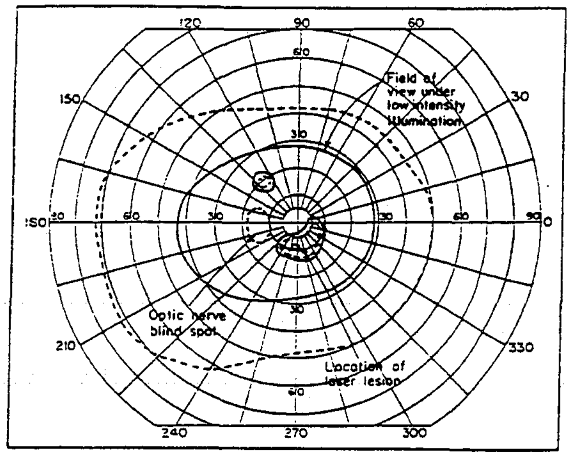


Figure 1

Eye damage caused by laser pulse is shown in this "field of view" diagram (dotted lines are high-intensity illumination; solid lines are low-intensity illumination)Outer circles show field of view; the two small regions inside the field of view are *blind spots* produced by the laser pulse . The blind spots are larger than the lesion and occupy a larger area under low illumination.

8, Chapter 34) which will limit exposures within flight zones. New exposure limits are being considered which are based more on a flashblindness criteria rather than retinal damage levels (MPE's).

Laser protective exuipment

Injury resulting from various laser protective eyewear failures recorded in the data accounted for 5.5% of the injuries and can be divided into three general categories:

Eyewear Failure

Beam penetration or "burn through". A classic example of this occurred (RLI#82) in a research laboratory when a scientist viewed into a chamber looking for a reaction being caused by a ND:YAG laser. He looked directly "into" the beam for approximately 30 seconds after which the plastic eyewear "burned through" and the beam produced a retinal burn in the right eye.

Improper Eyewear Choice

Poorly chosen (incorrect spectral band). An example of this is described in the case (RLI#169) where a technician received an intrabeam exposure from a 0.8 μJ Raman shifted, frequency doubled Nd:YAG laser (532 nm). The Raman upshifted line from a methane gas cell, produced an emission at 770 nm the near-infrared spectrum. The protective eyewear the technician had chosen provided protection at 532 nm but not for the upshifted NIR line and produced a retinal burn.

Improper Eyewear Fit

Poor fit allows hazardous exposure. An example of this can be seen (RLI#52) in the case of a production worker using a Nd:YAG laser. During an alignment of the laser through an opening in the top, his eyewear "slid up" as he leaned over. The beam reflection from a target paper went into eye causing a bright afterimage lasting 20 minutes which led to a permanent central retinal burn.

These type of incidents strongly suggests a need for information and education regarding the limitations regarding the safety equipment used with lasers.

Skin injuries

Most commonly produced by the CO_2 laser. Specifically, this laser type produced 56% of the skin burns reported. The Nd:YAG laser was second with 14.7% of the cases. Neither of these results are surprising.

A typical skin injury case is given in the following (RLI#130) example where a laser manufacturer technician was working on a 1000 Watt CO2 laser when he inadvertently opened the shutter to the laser when his hand was in the region of the focused beam. The beam penetrated the back of his hand and caused massive reaction with significant swelling. The technician did not loose hand or fingers but has a continued loss of feeling

Table 2
Laser Accident Summary
Total Incidents: 272

EYE INJURY RECORDED	Totals	Alignment	University Laboratory	Bystander	Other	University Laboratory
No Eyewear Used:	99	40	10	5	33	5
		11	11*	—	—	—
		51	21	5	33	5
Eyewear Use Unspecified:	71	9	4	6	50	6
	—	2		2	—	2
	170	62	25	13	83	13
Eyewear Malfunction:						
- Eyewear Failure	4	1	1		2	
- Improper Choice	4	2	1		1	
- Improper Fit	2	2	—		—	
	10	5	2		3	
Total Eye Injuries:	180	67	27	13	86	13
No Eye Injury Recorded:	15	3 (1)	2*	4	11	4
Total Eye Incidents:	199	70	29	17	97	17
SKIN INJURY						
Injury Reported:	27(1)	4	1	2	20	2
NON-BEAM INJURY:						
Fire	20		1	1	18	1
Electrical						
- Shock	6	1	2		3	
- Death	5	1	1		2	
	11	2			5	
Embolism						
- Non lethal:	1				1	
- Death:	3				3	
Equip. Failure						
- No injury	10				10	
Other (Misc.)	1				1	
	73	6	6	3	58	3
TOTAL INCIDENTS:	272	70	33	17	155	17

* Indicates incidents shared in two groups

(1) 7 fire/skin combinations NOT included in Skin Injury Total

in the hand. It took one-year for manipulation to be nearly restored after much physical therapy.

As the type of lasers in the workplace expand, so do the possible hazards. The following is a report (RLI#185) of a severe skin exposure from an ultraviolet spectrum Xenon Chloride Excimer laser operating at 308 nm. In this case the technician was doing work on the Class I laser when the enclosure was opened near the preionization discharge. Unfocused beam reflections from beamsplitter exposed the technician's neck area. Nothing was felt at the time. Several hours later, four "burns" (probably photochemical in origin) appeared on his neck. These areas healed very slowly.

What is surprising about the skin burn data is that so few episodes are reported. It should be stressed that as the power levels increase in the typical industrial laser into the 1-5 KW range and above, skin burns will no longer become "trivial" episodes as was demonstrated in the CO2 laser case described above.

Fires

Three laser types are involved in most all of the laser produced fires. The CO2 was the most commonly involved laser with 50% of the cases. Second place was evenly occupied by two laser types: the ND:YAG and a group of various dye lasers at 20% for each.

Note that the dyes in many dye lasers are very flammable. In one case (RLI#148) the lab worker experienced ignition of the methanol solvent used in a dye laser. The flames reportedly "went to ceiling". Fortunately no human injury occurred in that case. In another similar case at a major laboratory (RLI#221): a professor was working with several graduate students in a lab when a small explosion and fire occurred in a laser dye (dioxane) mixture pump. A class BC extinguisher used. The fire was apparently caused by arcing in the pump motor which ignited the flammable air/ dioxane mixture.

Electrical skock

Serious shock and/or death occurring while improperly handling high voltage in the laser power supplies and associated equipment has become a major concern with laser equipment. Such problems account for 3.9% of the incidents in this survey and suggests strongly that high voltage safety training is essential for those whose job requires high voltage access. Such staff must be trained in handling high voltage and treating those having been exposed.

A serious electrical shock from a laser can be demonstrated (RLI#267) by the case where, during the set up of a 20 W argon laser for a laser show, the technician reached to the rear of the power supply and unknowingly grabbed a high voltage wire with frayed insulation. Upon touching the wire, an electrical pathway went from his hand to his shoulder which was touching the laser cabinet producing a third degree burn on his fingers in contact with 300 VDC.

A more serious event (RLI#74) occurred with a laser company installer who was electrocuted while installing a copper vapor laser. A interlocked protective panel had been manually bypassed during the installation to make adjustments. This was a unique case wherein the serviceman did not instantly expire after the electric shock, but actually sat down and conversed with those in the room stating that he had done a very "dumb" thing. Then, after several minutes, as is common with severe electrical shock, he expired. A person experienced in CPR was unable to bring him back.

LGAC's

Ancillary hazards such as fire and laser generated air contaminants (LGAC's) is one of the hazard areas where incident reports represent only a small fraction of the actual occurrences. The experience of the author has been that almost every laser site containing a Class IV laser has, at some time, experienced some "incident" involving one or more of the so-called non-beam laser hazards. These are usually of such a nature that they don't become an official statistic.

What is important in including ancillary accidents in a survey such as this is to warn laser users that they do occur and that they can, in some instances, 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 virus have been reportedly detected in the smoke during laser surgery and the smoke has been suspicioned to be mutagenic[34]. This suggests the absolute need for smoke evacuation during surgical cases.

However, due to the difficulty of obtaining laser accident information, it suggests areas of emphasis that should be placed in the control measures utilized and training provided.

OCCUPATION ANALYSIS

The breakdown of the laser incidents by occupation is given in Table 4. Note that the combined group of scientists, technicians, laser plant workers, students, laser show operators and field service engineers make up nearly 65% of those involved. This would be considered as the highest risk group of laser occupations and are the group that routinely would be involved in the adjustments and alignment of higher power, Class IIIB and Class IV laser systems. It is also of note (see Table 2) that those involved with lasers working at universities or major laboratories account for over 12% of the recorded incidents.

Notable also is the medical grouping of Doctors/ Nurses and Patients. It is, perhaps, difficult to believe that the "Patients" grouping is the third largest at 12.9%. The introduction of new laser technology has had a definite "learning curve"in the medical field. For example, there have been numerous cases where errors during usage led to fires. In one recent case (RLI#256) a frequency doubled Nd:YAG laser (532 nm) was being used in vocal cord surgery. During surgery the anesthesia was incorrectly applied at a 100% oxygen level. During the surgery a fire internal to the patient occurred and the patient sustained severe internal burns. The patient did survive this case but in other, similar cases, there have been patient deaths. Clearly, anesthesia techniques with lasers require special procedures.

Another of the more severe medical cases (RLI#95) is typical of several events where a Nd:YAG laser was used with the incorrect procedure for cooling a fiber tip during inter uterine surgery. In this case, nitrogen was incorrectly used to cool the tip and led to death of patient by gas embolism. It is important to note that these type of cases have ceased occurring recently in response to much improved information regarding the hazards associated with improper fiber tip cooling methods.

Table 4
Occupations of Persons Involved in Incidents

Occupation	No.	Percentage
Technicians	58	21.3
Scientists	48	17.6
Patients	35	12.9
Plant Workers	29	10.7
Doctor/Nurse	25	9.2
Students	23	8.4
Spectators	13	4.8
Laser Show Operators	11	4.0
Pilot/Military	9	3.3
Equipment	9	3.3
Field Service	7	2.6
Office Staff	5	1.8
	272	100

NEED FOR TRAINING

Laser accidents result because of a variety of causes. In nearly all cases, however, the accidents could be avoided by proper safety training that ensures individuals follow established laser safety procedures. A number of laser accidents have been caused by individuals operating unfamiliar equipment. For example, such accidents might occur in the medical field when an operator has been trained with a certain manufacturer's laser, attempts to use another manufacturer's laser, assuming that the two pieces of equipment will behave in the same way. Unfortunately, there are major differences in specific laser devices that result in the delivery to the target site at significantly different irradiance levels at what appears to be identical conditions in the two laser devices.

In short, there is simply no good substitute for knowledgeable operators. Training is the keystone to safe laser use!

LASER ACCIDENT REPORTING

Included with this summary is a Laser Accident Report form that can be used to record information on laser incidents. Readers that have experienced a laser incident or have personal knowledge of an incident are encouraged to complete the form and send it to the author for inclusion in the accident data base. Any event where undesired exposure or involvement with non-beam hazards (electrical, LGAC's, plasma light, dyes...etc.) is appropriate.

FURTHER ANALYSIS

A further analysis was done on laser accident information now included in a computerized data base. As of this writing, data was available on 250 cases. An analysis was done on these cases relative to the type of laser involved and the type of incident reported. The conclusions are shown in *Fig. 1* and 2. The data is included in Appendix A.

LASER ACCIDENT CAUSES

Laser accidents result because of a variety of causes. In nearly all cases, however, the accidents could be avoided by proper safety training that ensures individuals follow established laser safety procedures. Exposure to laser radiation is not the only laser-related hazard. Other potential hazards include electrical shock from the laser power supply, exposure to flammable or toxic chemicals, and noise-related injuries associated with laser operation.

Beam Alignment

The most common cause of accidents is accidental eye exposure during beam alignment. This observation is explained by the fact that alignment generally requires the eye as part of the process. For example, in CO_2 laser surgery, the alignment beam, usually from a HeNe laser, and the CO_2 beam must follow the exact same optical path so they coincide at the target spot. The alignment process requires that a few test burns be made to ensure that the two beams are coaxial. It is during these kinds of alignment procedures that laser accidents often occur.

Misaligned Optics

The second most common cause of laser accidents results from misaligned optics. In laser operations where precision is crucial, misalignment of the lasers can result in patient injury. A case history of such an accident is described in the Laser Accident section.

Lack of Eye Protection

The third most common cause of accidents is the failure to wear *available* eye protection. Many accidents have involved individuals who had eye protection within reach but who failed to use it. All accidents of this nature are avoidable, if the proper safety procedures are followed. For example, in an operating room, or in any other medical environment where lasers are in use, eye protection should be a procedural requirement. If the eyewear must be in place before the system can be operated, such accidents would not occur.

Malfunctioning Equipment

Accidents have also occurred because equipment malfunctioned, or because nontrained personnel attempted to adjust or do maintenance to a high voltage laser system. For instance, shutter timers have failed on ophthalmic lasers giving exposure to patients longer than expected, resulting in retinal injury. Proper maintenance of the shutter system may have prevented the injury. Unless specifically trained, personnel should never get involved with any kind of repair or service on high-voltage equipment. Only appropriately trained personnel should ever access the high voltage sections of a laser system.

Lack of Training

A number of laser accidents have been caused by individuals operating unfamiliar equipment. Such accidents might occur if a surgeon who is trained with a certain manufacturer's laser, attempts to use another manufacturer's laser, assuming that the two pieces of equipment will behave in the same way. Unfortunately, there are major differences in specific laser devices that result in the delivery to the target site at significantly different irradiance levels at what appears to be identical conditions in the two laser devices. It is really not total beam power that is important but, it is the power per unit area (irradiance). Irradiance can be dependent on many factors: laser design, beam divergence, focusing laws, beam distribution (mode) and delivery system.

Some manufacturers provide a chart indicating that at a particular total power level, with a certain lens on the system, a known irradiance level is delivered at the target site.

A 100 watt laser, defocused to cover a square mile area, will produce a power per unit area of about 5.6×10^{-7} W/cm^2. One wouldn't even be aware of an all day exposure to the beam. But, the same 100 watt laser, focused to a very small point, can do surgery. The difference between the two is the beam size, which effects the concentration or irradiance.

There have been a number of accident cases, particularly in the medical environment, where lasers were used in an unfamiliar situation. The expected reaction was not obtained and, at an "identical setting," a more severe reaction was produced.

Ancillary hazards, particularly laser generated smoke, also presents a hazard and requires protection. Laser Generated Air Contaminates (LGAC) can be released into the environment whenever laser irradiance is high enough to vaporize the target material.

SUMMARY

The overall analysis reveals that laser accidents generally fall into one or more of the following major categories:

- Unanticipated eye exposure during alignment.
- Available eye protection is not often used.
- Equipment malfunction causes many unwanted exposures.
- Improper methods of handling high voltage lead to severe shock and even death.
- Protection for non-beam hazards is often lacking.
- Improper restoration of equipment following service frequently causes undesired hazards.
- Incorrect eyewear selection and/or eyewear failure are frequent causes of unwanted exposure.

Such statistical laser information as is provided in this review provides a starting point for more complete analysis into the types of hazards occurring in laser environments and suggests areas of emphasis that should be placed in the control measure selection and the training programs that are required.

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APPENDIX A: LASER ACCIDENT REPORT

Laser Incident Location

Date of Incident:	
Describe Site:	
City:	State:
Country:	

Laser Parameters

Laser Type:	Wavelength(s) (nm):
Divergence (mr):	Beam Diam. (mm):
Total Exposure Time (sec):	Energy/Power (W/J):
Pulse Time (sec)	Pulse Rate (Hz):
Scan Angle (r):	Scan Rate (Hz):
Laser Application:	

Accident Desciption Summary

Accident Subject:	Occupation:
Age(yrs):	Sex:
Major Problem Reported:	

Description of Accident

Permanent/Temporary Injury:

Eyewear Specifics

Eyewear Worn	☐	Available, Not Worn	☐
Incorrect Eyewear	☐	Eyewear Failure	☐
Other:			

Incident - Summary

Beam Hazards:	Eye	☐	Skin	☐
Non-Beam Hazards:	Electrical	☐	Fire	☐
	Embolism	☐		
Specifics:	Eyewear Failure	☐		
	Equipment Failure	☐		
	Alignment	☐		
	Bystander Injured	☐		
	University/Laboratory	☐		

Upon completion, forward information to:

RLI Laser Accident Database
c/o Rockwell Laser Industries
P.O. Box 43010
Cincinnati, Ohio 45243
Phone: 513-271-1568
Fax: 513-271-1598 E-Mail: Accident@rli.com

RLI LASER ACCIDENT DATABASE
Summary of All Laser Related Incidents

August 26, 1994

DATE	SITE	LASER TYPE	ACCIDENT SUBJECT	ACCIDENT SCENARIO
1994	Airspace @ laser show (NV)	Argon	Airforce Pilot	Pilot temporarily flashblinded
	Mobile Research Lab.	HeNe	Automobile	Electrical short causes automobile to burn
	Hospital	Dye	Physician	Ocular flashback when using incorect eyewear
	Livermore Berkeley Lab (CA)	Dye (?)	Research Scientist	A small (fine) defect in retina
	Berkleley Laboratory (CA)	Special Array*	Scientist	Parafoveal lesion in right eye.
	University (CA)	Nd:YAG	Professor	Retinal burn from stray beam
	Nat. Naval Med. Ctr. (MD)	Doubled Nd:YAG	Patient	Internal fire during vocal cord surgery
1993	University (CA)	Ti:Sapphire	Graduate Student	Minor injury to eye from specular reflection
	Bronson Hospital (MI)	Nd:YAG	Staff	Footpedal sticking - laser didn't turn off.
	Hospital O.R. (MI)	HGM Laserscapel*	Patient	Fiber malfunction caused undesired patient burn
	Aerospace Corporation (CA)	Nd:YAG + SHG	Research scientist	Foveal retinal burn.
	National Lab (CA)	HeNe	Floor tile repairer	Beam flashed into eyes
	Customer's Site	Argon	Field Service Tech.	Macular burn when shutter inadvertantly opened
	Airspace @ laser show (NV)	Argon ?	SW Airline Pilot	Pilot was temporarily flashblinded
	University (FL)	Nd:YAG	Associate Professor	Macular Damage of left Eye
	Dermatology Clinic (Canada)	Dye	Juvenile patient #2	Burns around eyelids; loss of facial hair
	Surgical OR	CO2	Patient	Fire ignited drapes; pedal accidentally pushed
	Dermatology Clinic (Canada)	Dye	Juvenile patient #1	Burns around eyelids; loss of facial hair
1992	Brown University (RI)	Nd:YAG	Research Assistant	Blurred spot in field of vision (one eye)
	Mt. Haleakala (HI)	Ruby	Technician	Blurry vision, retinal swelling & fluid leaks
	G.E. Corporate R&D (NY)	Nd:YAG	Safety Inspector	Accidental Burn of Coat Jacket Sleeve
	Hospital (MI)	Argon	Nurse	Broken fiber
	National Lab. (CA)	Nd:YAG	Scientist	Retinal burns in both eyes
	Operating Room (UK)	Nd:YAG	Nurse	Nurse hand burn; foot pedal accidentally pushed
	Motorola (AZ)	Diode	Lab technician	Temporary eye discomfort in left eye
	University (IL)	Nd:YAG	Student	Retinal burn off rear laser mirror
	Laboratory	Excimer	Technician	Photochemical burns on neck with Excimer laser
	Factory	Nd:YAG	Field Service Tech.	Non-fatal electric shock during servicing
	Derm. Clinic	Argon	Physician	Retinal burn caused by skin reflection
	Research (PA)	Nd:YAG	Technician	Retinal burn in central vision of right eye.
	Corporate R&D Lab (NY)	FD Nd:YAG+Dye	Research Scientist	Retinal burn of right eye.
	University (IL)	Nd:YAG	Student	Retinal burn off rear laser mirror
	Grand Coolee Dam (WA)	Argon	Light Show Operator	Temporary vision loss from flashback
1991	Laser sky scan (AZ)	Argon	Light Show Operator	Retinal burn
	Military	Nd:YAG	(Not indicated)	Near foveal burn of retina
	National Lab. (CA)	Nd:YAG	Student	Non-fatal electric Shock during troubleshooting
	Physics lab (NY)	Argon	Group of birds	Sky scan
	Univ. Physics lab (NJ)	HeNe	College student	Burning sensation after classroom demonstration
	Military	Nd:YAG	(Not Indicated)	Retinal burns from at least 4 pulses
	Surgi-Center (AZ)	CO2	Patient	Accidental skin burn during surgery
	Mercy Hospital (OH)	Nd:YAG	OR nurse	Foot pedal failure
	Mobile Med. Service (AZ)	Nd:YAG	Equipment	Irratic laser operation
	Hospital (AZ)	CO2	Physician	Doctor burned finger accidentally
	Factory (AZ)	Argon	Worker	Loss of vision
	Sea World Park (FL)	Argon	Light Show Operator	After images following diffuse viewing
	Hospital (AZ)	CO2	Patient	Unplanned exposure to patient
1990	Hospital (CO)	Doubled Nd:YAG	Technician	Retinal burn following equipment filter failure.
	Univ. Cen. Florida (FL)	Doubled Nd:YAG	Visiting Professor	Reflected beam caused vision loss
	G.E. Corporate R&D (NY)	HeNe	Engineer	Non damaging ocular exposure
	University (China)	Nd:YAG	Postgraduate Student	Macular lesion & hemorrhage
	Construction site (OH)	HeNe	Construction worker	Retinal lesion

DATE	SITE	LASER TYPE	ACCIDENT SUBJECT	ACCIDENT SCENARIO
1990	Epcot (FL)	Argon	Laser show audience	Non-injurious accidental audience exposure
	NY City Hospital (NY)	Nd:YAG	Patient	Death of patient by gas embolism
	Hotel (New Year's Eve) (FL)	Argon	Laser Technician	Non-lethal electrical shock
	Cincinnati Inc. (OH)	CO2	Technician	Severe hand burn when shutter accidently opened
	Hospital (AZ)	Unspecified	Physician	Eyewear failure claimed
	Hospital (AZ)	CO2	Patient	Superficial burn on patient
	Hospital (AZ)	Argon	Physician and patient	Broken fiber reportedly caused arm burn
	General Electric (OH)	Nd:YAG	Equipment	Explosions in fume exhaust filter
	Hospital (AZ)	Nd:YAG	Equipment	Safety shutter failure
	Outdoor campus rally (FL)	Argon	Light Show Operator	Multiple skin burns at finger tips
	Hospital (AZ)	CO2	Equipment	Fire
	Hospital (AZ)	Ar/Kr	Physician	Failure of safety shutter
	Hospital (AZ)	Nd:YAG	Equipment	Flashback from fiber
1989	Outdoor laser show (NC)	Argon	Light Show Operator	Retinal lesion in right eye
	Park Plaza Hospital (TX)	Nd:YAG	Physician	Eye exposed with incorrect eyewear - no effects.
	University (FL)	Nd:YAG	Chemistry Prof.	Retinal burn of left eye
	Laboratory	Dye/Nd:YAG	Research scientist	Retinal burn and vision loss
	Hospital (AZ)	SLT-CL100*	Nurse	Non injurious eye exposure
	National Lab. (CA)	Doubled Nd:YAG	Scientist	Beam exposure on right eye
	Hospital (AZ)	Unspecified	Physician and patient	Surgeon burned finger and patient accidentally
1988	Hospital (AZ)	Ar/Kr	Physician	Failure of safety shutter
	National Lab. (CA)	Dye	Professor	Explosion and fire
	Hospital	Nd:YAG	Patient	Death - gas embolism(?)
	Hospital (UK)	Argon	Registrar	Retinal damage from reflected beam
	Hospital	Nd:YAG	Technician	Temporary retinal damage
	Hospital (TX)	Argon	OR Nurse (#2)	Temporary afterimage
	Univ. Chemistry Lab (UK)	Dye	Postgraduate student	Viewed divergent reflected beam
	University (UK)	Argon	Student	Retinal burn from stray reflection
	Machine tool manf. (UK)	CO2	Engineer	Bad wiring causes third degree burns
	Research lab. (UK)	Ruby	Research scientist	Intrabeam retinal exposure
	University (UK)	Unspecified	Postgraduate student	Non hazardous diffuse reflection eye exposure
	Factory (UK)	CO2	Engineer	Reflected beam burned right hand
	Hospital	Argon	OR Nurse (#1)	Temporary afterimage
	Hospital	CO2	Patient	Endotracheal tube fire
	Epcot (FL)	Argon	Ligh show audience	Non-injurious audience area exposure from rain
	Xerox (CA)	Argon	Production Worker	Eye lesion
	Factory (MD)	CO2	Laser Repair Worker	Death by electrocution
	Epcot (FL)	Argon	Laser Technician	Severe skin burn
	Epcot (FL)	Argon	Light Show Operator	Non-foveal retinal lesions
1987	University	Dye/Nd:YAG	Scientist	Retinal lesion
	Operating room	CO2	Technician	Second degree burn on hand
	Rockwell Int. (CA)	Dye/Argon	Summer Research Aide	Lesion on the edge of macular
	Research lab (Japan)	Nd:YAG	Research Engineer	Accidental Macular burn of left eye
	University	Dye/Nd:YAG	Student	Near macular retinal lesion
	Hospital	Nd:YAG	Patient	Death by embolism
	Hospital	Unspecified	Patient	Endotracheal tube fire
	University	Argon	Student	Foveal lesion
	Factory	Diode (GaAs)	Engineer	Non-injurious eye exposure
1986	Hospital	CO2	Employee	Bystander burned on forehead during tests
	Texas St. Tech.Inst. (TX)	Nd:Glass	Technician	Death by electrocution
	National Lab. (CA)	Dye	Researcher	Retinal burn of right eye

DATE	SITE	LASER TYPE	ACCIDENT SUBJECT	ACCIDENT SCENARIO
1986	Laboratory (China)	HeCd	Patient	Retinal lesion
	Hospital	CO2	Field Service Tech.	Faulty shutter causes facial burns
	Laboratory (China)	Dye	Spectator	Retinal lesion
	Hospital	Argon	Ophthalmologist	Malfunction(?) flashback caused eye damage
	Hospital	Unspecified	Worker (bystander)	Stray beam caused burn to right eye
	Laboratory	Dye	Technician	Methanol coolant ignited
	Laboratory (France)	Nd:YAG	Technician	Retinal burn
	Optics Lab (France)	Nd:YAG	Technician	Two peripheral scotomas in right eye
	Hospital	Argon	Ophthalmologist	Malfunction(?) flashback causes vision blur
	Hospital	CO2	Equipment	Laser failure from improper gas connector fitting
	Manufacturer	Argon	Employee	Temporary eye discomfort from exposure
	Laboratory (China)	Ruby	Lab technician	Exposure to eye from uncollimated beam
	Laboratory (China)	Dye	Spectator	Retinal extramacular lesion
	Laboratory (China)	Argon	Spectator	Retinal lesion
	University	CO2	Graduate student	Shock and burns while cleaning tube condensate
	Hospital	Nd:YAG + fiber	Patient	Contact probe causes non-fatal embolism
1985	Factory	Nd:YAG	Graphic art worker #3	Chronic ocular effects
	Laboratory (China)	Ruby	Lab technician	Exposure to eye from uncollimated beam
	Epcot (FL)	Argon	Light Show Operator	Acccidental Audience Area Scanning
	Laser Manf.	CO2 (TEA)	Spectator	Burn to cornea
	Factory	Nd:YAG	Graphic art worker #2	Chronic ocular effects
	Factory	Nd:YAG	Graphic art worker #4	Chronic ocular effects
	Factory	CO2 (TEA)	Technician	Burns to cornea through open screw holes
	Factory	Nd:YAG	Graphic art worker #5	Chronic ocular effects
	Factory	Nd:YAG	Graphic art worker #1	Chronic ocular effects
	Hospital	Argon	Ophthalmologist	Malfunction caused backflash & temp. afterimage
	Hospital	Argon	Patient	Timer malfunction caused excessive exposure
	Laboratory (China)	Ruby	Lab technician	Exposure to eye from uncollimated beam
	Hospital	Unspecified	Patient	Timer malfunction caused patient retinal burn
	National Lab. (CA)	Nd:YAG	Research scientist	Retinal burn
	Hospital (UT)	Nd:YAG	Nurse	Nurse unconscious from shock from water leak
	University	Nd:YAG	Student	Non-injurious intrabeam eye exposure
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Hospital	Dye/Ar&Kr	Technician	Retinal burn in fovea
	Hospital	Nd:YAG	Patient	Laser induced fire burns patient
	Laboratory	Nd:YAG	Technician	Retinal lesion
1984	Bethesda Hosp. (OH)	CO2	Patient	Unwanted burn due to alignment failure
	Repair site	Nd:YAG	Field Service Tech.	Accidental retinal lesion/hemorrhage in right eye
	Factory	Unspecified	Workers	Dizziness caused by 10 Hz flashing
	Military base	Nd:YAG	Soldier	Multiple Retinal Lesions in Right Eye
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye from uncollimated beam
	Hospital	Argon	Physician	Tempory blindness
	Factory (MN)	CO2	Equipment	Internal equipment fire
	Epcot (FL)	Argon	Light Show Operator	Viewing hazardous diffuse reflections
	Laser Range	Unspecified	Bystander	Retinal burn in rangefinder operator
	Government facility	Nd:YAG	Technician	Non-lethal electric shock during alignment
1983	Univ. of Dayton (OH)	Cu vapor	Engineer	Death by electrocution
	Laboratory (IL)	Dye	Technician	Macular burn and foveal hole.
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	USAF Weapons Lab (NM)	Unspecified	Technician	Death by electrocution
	University (NY)	Dye	Graduate Student	Central vision loss

DATE	SITE	LASER TYPE	ACCIDENT SUBJECT	ACCIDENT SCENARIO
1983	Laser Range (Germany)	Ruby	Spectator	Retinal lesion
	Laboratory (NY)	Nd:YAG	Technician	Photokeratitis from flashlamp exposure
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye by mode locked laser
	Laboratory (NY)	FD Nd:YAG/Raman	Technician	Retinal burn
1982	G.M. Plant (IN)	CO2	Electrical Worker	Death by electrocution
	Laboratory (France)	Dye	Post Grad Student	Ocular scotoma in right eye
	Construction Site (MI)	HeNe	Survey Assistant	Temporary blurred vision
	Cigarette Plant (NC)	CO2	Production Worker	Laser causes production fire; laser burn on arm.
	Factory (Isreal)	Nd:YAG	Worker	Paramacular burn & vision loss
	Laboratory (Russia)	Ruby	Worker	Retinal burns in both eyes
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye from uncollimated beam
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Optics Lab (France)	Xenon	Technician	Grey spot retinal lesion
	National Lab. (NM)	Doubled Nd:YAG	Scientist	Blind spot (R)
	NASA Space Ctr. (MD)	Unspecified	Technician	Retinal lesion next to fovea
1981	Univ. Lab (USSR)	Ruby	Graduate student	Retinal burn; central scotoma
	Army base (CA)	Unspecified	Tank commander	Reduced left eye vision
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Hospital (WA)	Model 770 AMPL*	Patient	Third degree burn to upper lip
	Laboratory (Russia)	Nd:YAG	Scientific assistant	Retinal burn; central scotoma & hemorrhage
	Laboratory (Russia)	Ruby	Scientific assistant	Retinal burn; central scotoma
	Naval Research Labs (VA)	Dye	Chemist	Retinal burn and bleeding
	Laboratory (Russia)	Nd:YAG	Engineer	Retinal burn; central scotoma
	Clinic (MO)	HeNe (?)	Patient	Facial and wrist rashes; Cosmetics suspicioned
	Hospital (TX)	Model 770 AMPL*	Patient	Lip discoloration
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Hospital (NY)	CO2	Patient	Endotracheal tube fire
	Construction site (TX)	HeNe	Construction worker	Permanent visual impairment
	Clinic (KS)	HeNe (?)	Patient	Burn to left foot claimed
	Home (CA)	Argon	Pilot	Temporary blindness in helicopter pilot
	Home (OH)	HeNe	Security guard	Non damaging ocular exposure
	Factory (NY)	CO2	Plant Worker	Burns on wrist and forearm
	Factory (WI)	Model 1250/30*	Plant Worker	Retinal burn
	Laboratory (Germany)	Nd:YAG (?)	Worker	Retinal scar
	Laboratory (IL)	Dye/Argon	Physicist	Retinal burn
1980	Hospital (NE)	Argon (?)	Patient #5	Ocular hemorrhage
	Hospital (NE)	Argon (?)	Patient #6	Ocular hemorrhage
	Hospital (NE)	Argon (?)	Patient #7	Ocular hemorrhage
	Museum (NY)	HeNe	Spectator	Temporary sore eyes following laser show
	Laboratory (CA)	HeNe	Worker	Temporary photophobia
	Laser Show (AZ)	Unspecified	Spectator	Eye irritation following laser show
	Hospital (NE)	Argon (?)	Patient #4	Ocular hemorrhage
	Hospital (NE)	Argon (?)	Patient #1	Ocular hemorrhage
	Hospital (NE)	Argon (?)	Patient #3	Ocular hemorrhage
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Laser Manf. (CA)	CO2	Field Service Tech.	Minor burns to back skin from clothing ignition
	Museum (NY)	HeNe	Spectator	Temporary sore eyes following laser show
	Hospital (NE)	Argon (?)	Patient #2	Ocular hemorrhage
	XRE Corp. (MA)	HeNe	Technician	Retinal burn and vision loss
	Hospital (NE)	Argon (?)	Patient #8	Ocular hemorrhage
	Hospital (TX)	CO2	Patient	Endotracheal tube fire
	Hospital (OH)	Argon	Field Service Tech.	Accidental emission causes reversible eye burn

DATE	SITE	LASER TYPE	ACCIDENT SUBJECT	ACCIDENT SCENARIO
1980	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	University (NC)	Unspecified	Univ. student	Blurred vision following laser demonstration
	Army base (CA)	Unspecified	Electrical technician	Multiple retinal lesions
	Factory (FL)	Laser trimmer*	Engineer	Possible glare burn & spots when shutter failed
	Hospital (NY)	CO2	Physician	Hand burns caused by bent shutter blade
	Laboratory (France)	Dye/Nd:YAG	Teacher	Ocular scotoma produced by diffused beam.
	Hospital (NY)	CO2	Nurse	Hand burns caused by bent shutter blade
	Laboratory (CA)	Argon	Technician	Temporary pain and eye irritation
1979	Hospital (OR)	Argon (?)	Nurse	Temporary blindness
	Company Lab. (France)	CO2	Graduate student	No injury beam exposure.
	Factory (MA)	CO2	Manager	Heat on forehead from reflected beam
	University (CA)	Nd:YAG	Graduate student	Retinal burn and vision loss
	Hospital (France)	CO2	Patient	Endotracheal tube fire
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Laboratory (France)	Doubled Nd:YAG	Technician	Ocular scotoma
	Factory (CA)	Nd:YAG	Production Worker	Retinal burn
	Laboratory (CA)	Dye/Rhodamine	Technician	Scotoma and vision blur
	Hospital (CA)	Argon (?)	Physician	Flashback into eye from erratic safety shutter
	Facility (Australia)	HeCd	Worker	Loss of vision reported; cause in question
	Factory (CA)	Krypton	Laser Assembly Worker	Retinal burn
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
1978	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Ochsner Fnd. Hosp. (LA)	CO2	Patient	Endotracheal tube fire
	Laboratory (France)	Dye/Nd:YAG	Trainee Student	Ocular scotoma and hemorrhage.
	Laboratory (CA)	Argon	Electrical Worker	Left eye exposure - no permanent injury
	Laboratory (Russia)	Nd:YAG	Worker	Retinal burn; central scotoma & hemorrhage
	Laboratory (CA)	HeNe	Policeman	Temporary blurred vision from reflected beam
	Laboratory (Germany)	Dye	Lab technician	Retinal lesion after reflection from grid
	Factory (CA)	Argon	Production Worker	Retinal burn
1977	Laboratory (OH)	Holographic*	System operator(s)	Eye strain & color vision loss
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	ILS (FL)	Nd:YAG	Technician	Temporary vision loss
	Physics Lab (France)	Nd:YAG	Researcher	Perpheral macular lesion
	GTE Sylvania Lab (CA)	Nd:YAG	Researcher	Retinal burn/partial blindness
1976	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Laboratory (China)	Nd:YAG	Lab technician	Exposure to eye
	Laboratory (Germany)	Raman shifted	Lab technician	Retinal lesion resulted after optical alignment
1975	Laboratory (MD)	Ar/Kr	Physicist	Temporary after image
1974	Laboratory (France)	Nd:YAG	Research Scientist	Central scotoma lesion
	Laboratory (Germany)	Doubled Nd:YAG	Lab technician	Retinal lesion from paper reflection
1973	Laboratory (MI)	HeNe	Laser Service Tech.	Possible retinal lesion when mirror fell off
	Research (France)	Nd:YAG	Engineer	Foveal scotoma with scar & hemorrhage
	Laboratory (CA)	Doubled Ruby	Engineer	Retinal burns
	Laboratory (France)	Argon	Engineer	Central scotoma following unexpected exposure
1972	Laboratory (CA)	HeNe	Technician	Temporary vision loss
	Laboratory (NM)	Nd:YAG	Researcher	Retinal swelling (no permanent burn)
	Laboratory (Germany)	Dye	Lab technician	Retinal lesion

DATE	SITE	LASER TYPE	ACCIDENT SUBJECT	ACCIDENT SCENARIO
1971	Laboratory (CA)	Argon	Production Worker	Retinal burn
	Laboratory (CA)	CO2	Engineer	Eye & face burns
	Laboratory (Holland)	Ruby	Lab technician	Central foveal lesion
	Laboratory (CA)	HeNe	Research worker	Retinal lesion reportedly when beam block failed
	Laboratory (CA)	Argon	Physicist	Vision loss
1970	Laboratory (Germany)	Dye	Lab technician	Retinal lesion from glass reflection
1969	Laboratory (CO)	Unspecified	Physicist	Retinal burn
1968	Laboratory (CT)	Argon	Scientist	Eye damage
1966	Laboratory (CT)	CO2	Engineer	Thumb burn while holding materials in beam
	University (CA)	Ruby	Scientist @Univ.	Retinal burn
	Univ. Physics Lab.	Ruby	Scientist	Retinal burn from reflection off bottle
1965	Laboratory (NM)	HeNe	Physicist	Retinal burn (L)
	Bethesda Nav.Med. (MD)	Ruby	Lab technician	Retinal burn from reflected beam
	Laboratory (CO)	Gas (?)	Physicist	Retinal burns detected 1 month after laser work
	University (MA)	CO2	Technician	Skin burn on hand during experiment
	Laboratory (PA)	Ruby	Physicist #1	Retinal lesion
	Laboratory (PA)	Ruby	Physicist #2	Retinal lesion
1964	Laboratory (France)	Ruby	Electrical Worker	Faulty shutter causes central vision loss
	University (OR)	Ruby	College student	Macular burn of right eye
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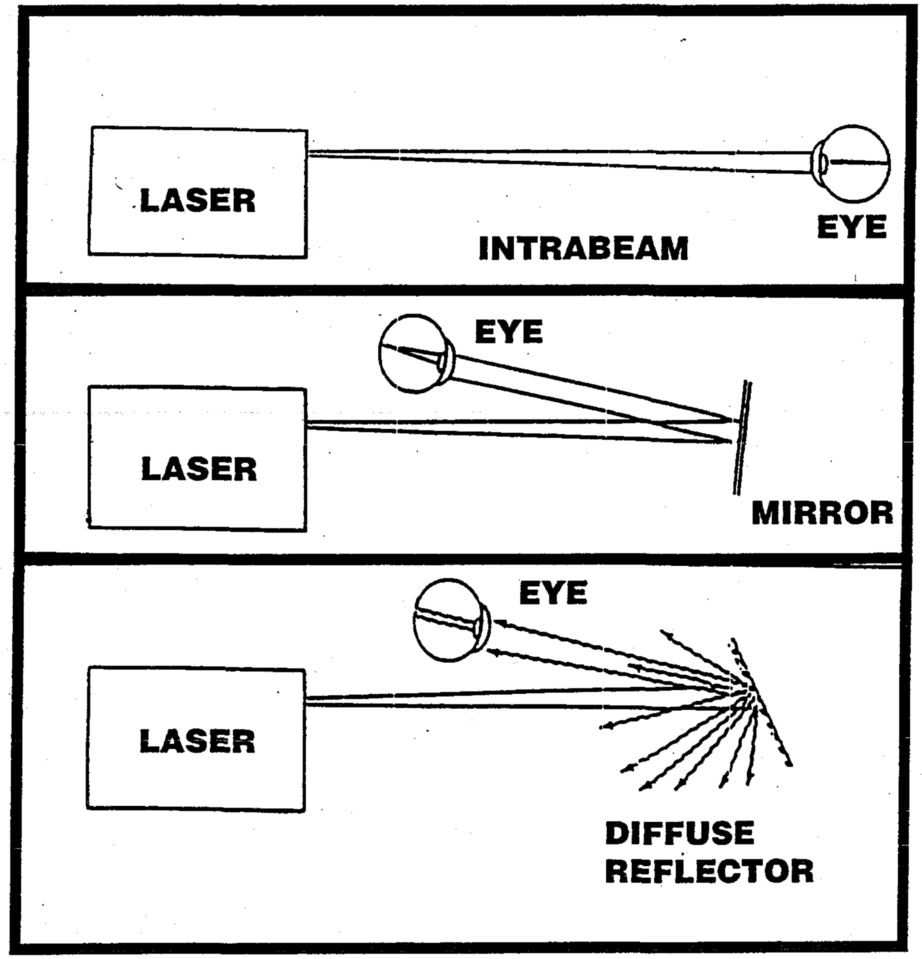
Count:		272		

MODULE 6.0

LASER HAZARD ANALYSIS



Education

LASER HAZARD ANALYSIS

Implementing Laser Hazard Analysis with the ANSI Z-136.1 Standard "For The Safe Use of Lasers"

HAZARD EVALUATION FACTORS

The first requirement in applying the ANSI Z-136 standard is to effect a hazard evaluation This evaluation should include three key factors:

- The laser's capability of injuring personnel
- The environment in which the laser is used
- The personnel who use or may be exposed

In some cases this can involve a detailed analytical evaluation which includes computation of factors such as:

- Maximum Permissible Exposures (MPE's)
- Accessible Emission Limits (AEL's)
- Nominal Hazard Zones (NHZ's)
- Filter Optical Density (OD) values

The ANSI Z-136 standard advises that ***"Only personnel trained in laser safety or optical engineering or physics are suited to perform the detailed hazard evaluation computations or the classification determinations of a laser or laser system."*** Consequently, it is stressed that an LSO who may not possess such qualifications to perform such analytical analysis may choose to delegate (effect) these responsibilities.

LASER PARAMETERS FOR HAZARD ANALYSIS

In order to accomplish the hazard analysis, the Laser Safety Officer (LSO) will need specific analytical information on the laser's operational output characteristic. Knowing the laser type is simply not sufficient information. The LSO must determine a number of factors relating the operational characteristics of each laser. This includes items such as:

- The wavelength(s) of the laser emission
- Exposure time (t), pulse duration (τ) and/or pulse repetition frequency (PRF) as applicable
- The output operational mode: pulsed/cw repetitive-pulse
  - ☒ continuous wave (CW) (e.g.: $\tau \geq 0.25$ s)
  - ☒ pulsed (e.g.: $\tau_p < 0.25$ s @ PRF< 1 Hz.)
  - ☒ repetitive-pulsed (e.g.: $\tau_p < 0.25$ s @ PRF $\geq$ 1 Hz.)
- Maximum anticipated exposure (T_{max})
- Output beam characteristics:
  - ☒ average beam power (Φ) expressed in Watts, or
  - ☒ pulse energy (Q) expressed in Joules
  - ☒ pulse repetition rate (PRF) expressed in Hertz (Hz), or
  - ☒ scan rate expressed in scans per second
- Beam geometry and optics
  - ☒ beam shape (circular, ellipse, rectangular)
  - ☒ circular emergent beam diameter (a) expressed in cm
  - ☒ elliptical major (b) or minor (c) axis expressed in cm
  - ☒ rectangular width (b_1) or height (c_1) expressed in cm
  - ☒ beam divergence (ϕ) expressed in milliradians (mr)
  - ☒ lens focal length usually expressed in mm
  - ☒ beam diameter incident on lens expressed in mm
  - ☒ focal length of lens expressed in mm
  - ☒ fiber optic numerical aperture (NA)

All of these factors can be useful in conducting a laser hazard analysis as will be outlined in the following.

The Laser Beam Diameter

The beam spread (divergence) of a typical laser beam is constantly changing in the region close to the laser generally called the "near field". The near-field is commonly as the distance (D_{nf}) which is defined by the ratio of laser aperture area and the laser wavelength:

$$D_{nf} \leq \frac{\text{Area of aperture}}{\text{Wavelength}}$$

For example, assume an argon laser with a beam diameter of 2 mm exiting the laser. The circular area of this beam aperture is:

$$\begin{aligned} A &= [\pi \cdot d^2]/4 = \pi \cdot [(0.002)^2]/4 \\ &= [(3.14) \cdot (4 x 10^{-6})]/4 = 3.14 \text{ x } 10^{-6} \text{ m}^2 \end{aligned}$$

Assuming the argon laser operates at a wavelength of 0.488 μm, the near field distance can be computed:

$$D_{nf} \leq \frac{3.14 \text{ x } 10^{-6} \text{ m}^2}{0.488 \text{ x } 10^{-6} \text{ m}} = 6.44 \text{ meters}$$

The diameter of a circular laser beam expands in size as it propagates from the laser. The beam follows a hyperbolic path in space; not the straight line pathway as usually *depicted*. In this case the laser beam path is often approximated by a linear equation: $D_L = a + r \cdot \phi$ to express beam diameter (D_L) as a function of the emergent beam size (a) and the beam divergence angle (ϕ) and the distance (r). This equation is only valid when $a << r \cdot \phi$; which does not apply in the near field region.

On order to more accurately compute beam size in the near (or far) field, the following more comprehensive hyperbolic formula for beam diameter (D_L) is used:

$$D_L = (a^2 + r^2 \cdot \phi^2)^{1/2} \qquad \text{(cm)}$$

where:

a = Emergent beam diameter (cm).
r = Range (distance) from laser (cm).
ϕ = Laser beam divergence (rad.)

For example, compute the beam diameter at a range of 10 meters for a dye laser operating at wavelength of 0.504 μm, where the beam divergence is 1.5 mrad and the emergent beam diameter is 3 mm. Then, substituting into the equation above:

$$\begin{aligned} D_L &= [(0.3)^2 + (10 x 10^2)^2 \cdot (1.5 x 10^{-3})^2]^{1/2} \\ &= [(0.09) + (1 x 10^6) \cdot (2.25 x 10^{-6})]^{1/2} \\ &= [(0.09) + (2.25)]^{1/2} \\ &= 1.53 \text{ cm} \end{aligned}$$

Note that when the beam waist is located in front of the laser exit port (as is sometimes the case), the above relationship may be modified by substituting the diameter of the beam waist (ω_o) for the term a, and $r - r_o$ for the term r (where ro is the distance to the beam waist). Thus the beam diameter equation for out-of-cavity beam waist conditions becomes:

$$D_L = [\omega_o{}^2 + (r - r_o)^2 \cdot \phi^2]^{1/2}$$

Using such values of beam spot diameter, the laser range equation can then compute a closer estimate of irradiance or radiant exposure at a given distance from the laser. A simple linear equation cannot simply be modified to allow for the possibility of an external waist.

Biological Mechanisms

From the data available, certain knowledge has been gathered on the mechanisms involved when injury occurs. This is the case whether the injury site is the retina, cornea or other ocular or tissue structure.

In general, as shown in Figure 1, there are three basic exposure conditions for exposures that can cause damage to the retina and/or cornea.

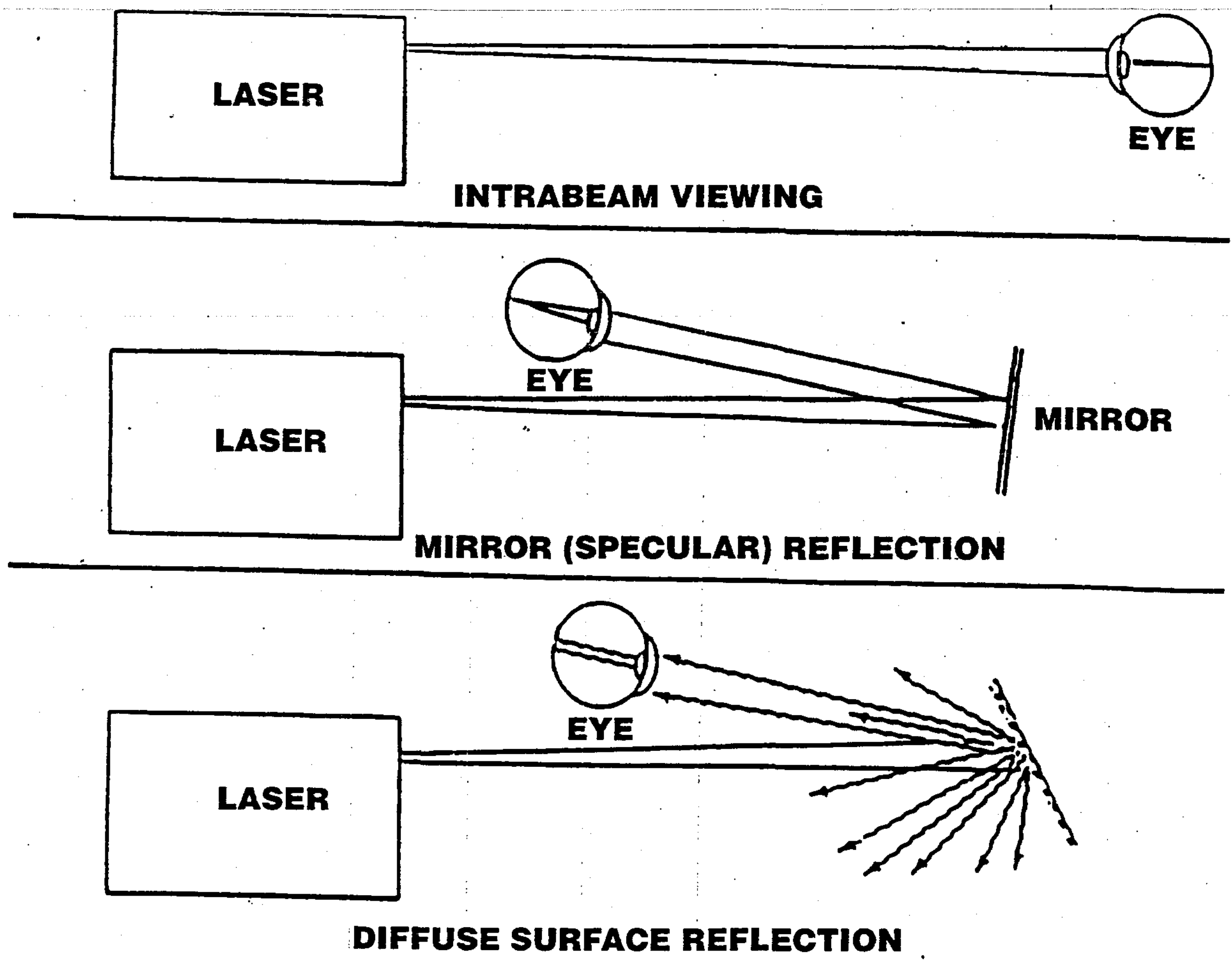


Figure 1
Conditions of ocular exposure to direct or reflected laser beams

These are referred to as:

- Intrabeam Exposure (point source viewing)
- Reflection producing intrabeam viewing
- Extended source viewing

Note that whether produced from intrabeam or extended sources, retinal damage is possible from exposure to laser energy in the wavelength region between 400 to 1400 nm.

Although no definite boundaries exist between injury mechanisms, certain effects dominate depending on the exposure time.

For example:

- Thermal effects play a more dominate role for longer wavelengths where the photochemical effect is lessened.

- For laser generated pulses lasting a few microseconds, the minimal damage criteria is most likely due to plasma formation.

- For Q-switched pulses lasting on the order of a few nanoseconds, mechanical effects such as acoustic waves dominate in the damage processes.

- Photochemical effects dominate in the wavelength region of 400 to 550 nm for lengthy exposure times (generally > 10 sec.) and for ultraviolet (<400 nm) exposures.

Since the same effects are present for both small and large retinal images, the extended source criteria are based upon intrabeam (point source) viewing limits.

MAXIMUM PERMISSIBLE EXPOSURES

MPE Criteria

The level of laser radiation to which the human eye or skin may be exposed without hazardous effect or adverse biological changes is called the Maximum Permissible Exposure (MPE). The MPE's are below known hazard levels. It should be emphasized that actual viewing of MPE's would most likely be extremely annoying and/or uncomfortable; some may even say that intrabeam viewing a visible laser at these levels (perhaps 1 μW/cm^2) would be dazzling. Research was done by many laboratories over the period 1965-1990 to gather the data upon which the MPE's are based. In these cases the researchers exposed animal eyes (usually primates) to various doses of laser light. The criteria generally was that one-hour following the exposure, an assessment was made as to whether retinal, corneal or skin damage had been produced in the animal.

In the assessment the data was often displayed using a regression line on probability graph as shown in Figure 2. The data as collected is expressed in terms of probability. One often cited value is the so-called MRD$_{50}$ point or the laser dose level at which effects are seen in one-half of the exposures. The ANSI committee established that if the MPE level was set a factor of 10 below the 50% probability point it would represent a negligible probability for damage. That criteria was used to establish the MPE values given in the ANSI Z-136.1 standard. The MPE's are summarized in Table 1 of this section.

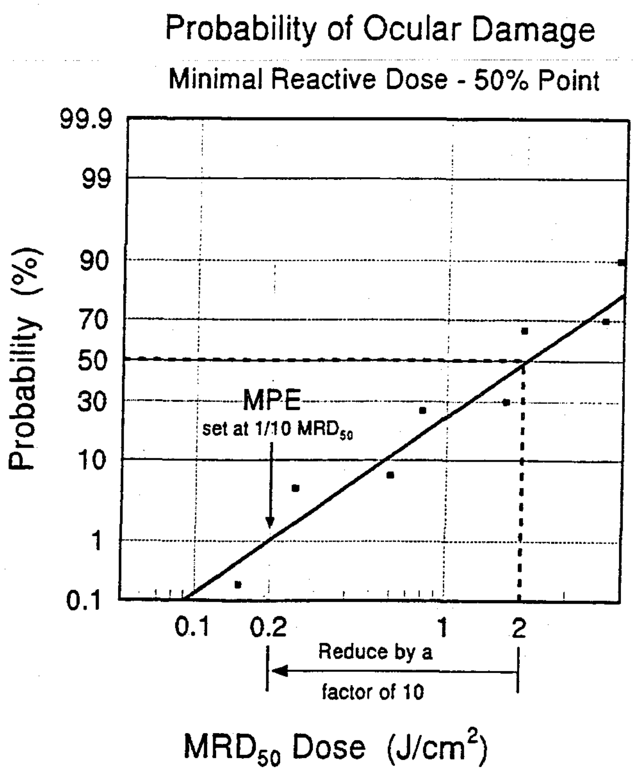


Figure 2

Typical regression plot converting MRD$_{50}$ data into MPE data. Note that MPE is set a factor of 10 below the 50% probability point for damage effect. That point is then set as the MPE level.

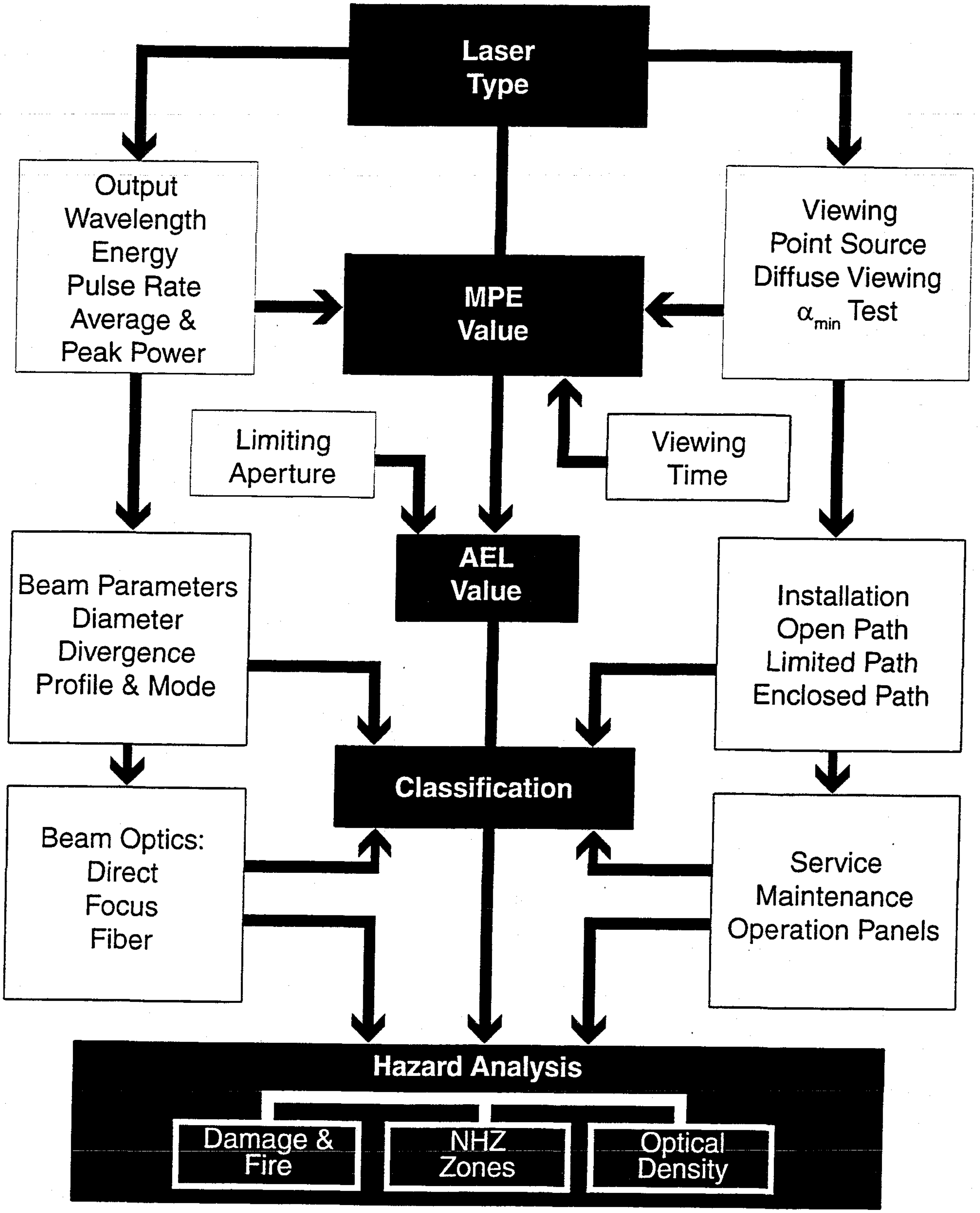
MPE CORRECTION FACTORS

The ANSI Z-136.1 MPE limits change over the wavelength range between 0.400 and 1.4 μm. These variations are effected using three wavelength-based corrections (C_A, C_B, C_C) and a correction for multiple pulse lasers (C_p) and another factor for extended sources (C_E). These factors are:

Near Infrared Correction Factor: C_A

This factor increases the MPE values in the near infrared (0.7 - 1.4 μm) based on the reduction in absorption properties of melanin pigment granules located in skin and retinal pigment epithelium. The value varies from a minimum of C_A=1.0 in the range from 0.400 to 0.700 μm to a maximum of C_A=5.0 in the range 1.051 to 1.400 μm. The factor varies in the range 0.701 to 1.050 μm according to the relationship: $C_A = 10^{2.0(\lambda - 0.700)}$.

Figure 3
Flowchart for Laser Hazard Analysis
Following ANSI Z136.1 (1993)



“Blue Light” Correction Factor: CB

This factor permits increased MPE values in the spectral region that covers the yellow, orange and red portions of the visible spectrum (0.550 - 0.700 μm). Often referred to as the “blue light” factor because it was discovered during studies on the biological effect of blue laser light. Then is was observed that the damage process on retinal tissue changed from thermal to photochemical for exposures lasting for certain time periods which are described by the function: $T_1 = 10x10^{20(\lambda - 0.550)}$ in the wavelength range 0.550 to 0.700 μm. Thus, the factor T_1 defines the divider between thermal and photochemical retinal damage effects.

The MPE’s are then modified according to the correction factor C_B, such that $C_B = 1.0$ in the range 0.400-0.550 μm and by the correction factor $C_B = 10^{15(\lambda - 0.550)}$ in the range 0.551 to 0.700 μm.

This correction factor has a value of 17.5 at the 633 nm HeNe laser wavelength, and, thus, permits a radiant exposure of 185 mJ/cm^2 accumulated exposure for periods of $T_1 = 453$ sec. to 10^4 s, and 17.5 μW/cm^2 (7 μW in a 7 mm limiting aperture) for continuous operation of exposure durations exceeding 10^4 s. The comparable exposure for an argon laser at 0.488 to 0.514 μm would be 1.0 μW/cm^2 (0.4 μW in a 7 mm limiting aperture).

Mid Infrared Correction Factor: C_C

This factor increases the MPE values in the mid infrared (1.050 - 1.4 μm) based upon the absorption properties of water. The value varies from a minimum of C_C=1.0 in the wavelength range from 1.050 to 1.150 μm to a maximum of C_C=8.0 in the range 1.201 to 1.400 μm. The factor varies in the range 1.151 to 1.200 μm according to the relationship: $C_C=10^{2.0(\lambda - 0.700)}$.

Repetitively Pulsed Exposures: Cp

The ANSI Z-136 requires a decrease in the MPE per pulse for repetitively pulsed or scanned laser radiation for exposures where the pulse repetition frequency (PRF) exceeds 1.0 Hz. Scanned and repetitively pulsed radiation have a lower retinal damage threshold levels than CW radiation of comparable average power.

The ANSI standard requires that such multiple pulse lasers have a correction to the single pulse MPE. The correction factor has been determined to be based upon the forth root of the total number of pulses (N) in a pulse train. The correction factor C_p is calculated such that the MPE radiant exposure of a single pulse in the pulse train is reduced as follows:

$$\text{MPE multiple}_{\text{pulse}} = [N^{-1/4}] \text{ x MPE single}_{\text{pulse}}$$

Where:

N = number of pulses in the train

MPE single$_{\text{pulse}}$ = MPE applicable to a single pulse

The allowable exposures given in all of the present safety standards attempt to follow as closely as possible, the actual biological data obtained with the different lasers.

Determining MPE Values

The Maximum Permissible Exposure (MPE) levels specified by the ANSI Z-136.1 standard involve the use of specific formulas with specific correction factors (see Appendix B). The use is shown in the flowchart in Figure 3 is described by the following:

1. Based upon laser wavelength(s), select the proper wavelength sector.

2. Select the MPE function corresponding to the time appropriate to the anticipated exposure. This could be:

- The time of a single laser pulse (t_p)

- The pulse time envelope - sometimes called the "total-on-time" (T_t)

Table 1

Summary of Maximum Permissible Exposure Limits*

LASER TYPE	WAVELENGTH (um)	MPE Level (W/cm^2)			
	Exposure Time:(s)	0.25	10	600	$3x10^4$
CO_2 (CW)	10.6	-	$100x10^{-3}$	-	$100x10^{-3}$
Nd:YAG[a] (CW)	1.33	-	$5.1x10^{-3}$	-	$1.6x10^{-3}$
Nd:YAG (CW)	1.064	-	$5.1x10^{-3}$	-	$1.6x10^{-3}$
Nd:YAG (Q-switched)[b]	1.064	-	$17x10^{-6}$	-	$2.3x10^{-6}$
GaAs (Diode/CW)	0.840	-	$1.9x10^{-3}$	-	$610x10^{-6}$
HeNe (CW)	0.633	$2.5x10^{-3}$	-	$293x10^{-6}$	$17.6x10^{-6}$
Krypton (CW)	0.647	$2.5x10^{-3}$	-	$364x10^{-6}$	$28.5x10^{-6}$
	0.568	$2.5x10^{-3}$	-	$31 x10^{-6}$	$18.6x10^{-6}$
	0.530	$2.5x10^{-3}$	-	$16.7x10^{-6}$	$1.0x10^{-6}$
Argon (CW)	0.514	$2.5x10^{-3}$	-	$16.7x10^{-6}$	$1.0x10^{-6}$
XeFl (Excimer/CW)	0.351	-	-	-	$33.3x10^{-6}$
XeCl (Excimer/CW)	0.308	-	-	-	$1.3x10^{-6}$

[a] Nd:YAG operating at less common 1.33 um wavelength.
[b] Repetitively pulsed @ 11 Hz., 12 ns pulses.
* MPE values determined using ANSI Z-136.1 (1986).

- The maximum time (T_{max}) that an exposure is possible for a given CW laser.

3. Note that the exposure times can be chosen as actual exposure conditions, or from one of the following time factors:

   - *The Aversion Response Time*: The time it requires to avoid a bright light stimulus. This is selected as 0.25 seconds.

   - *Long - Term Diffuse Reflection Viewing Time*: The maximum time that a person might view a diffuse laser beam reflection. This is selected as 600 seconds.

   - *Near-infrared viewing Time*: The maximum time that a person might view an invisible (near infrared) before eye motions cause the beam to refocus to another retinal location. This is selected as 10 seconds.

   - *Occupational Exposure Time*: The maximum time in one day that a person might view a laser beam. This is selected as the eight-hour time of $3x10^4$ seconds.

   - *Cumulative Daily Exposure Time*: The time period over which a cumulative laser light exposure might be additive. This is selected as 24 hours. This is usually applied only for laser exposures in the ultraviolet spectral region.

4. The ocular MPE is determined directly from Table 5 in the ANSI Z-136.1 standard using the various criteria and formulas given. The skin MPE is found in Table 7 in the ANSI Z-136.1 standard. (See Appendix A)

MAXIMUM PERMISSIBLE EXPOSURES

A summary of Maximum Permissible Exposure (MPE) limits for direct ocular exposures (intrabeam) for several of the more common lasers is given in Table 1. For additional information on MPE values, refer to the Z-136.1 standard.

LIMITING APERTURE

The Limiting Aperture (LA) is defined as: ***"the maximum diameter of a circle over which irradiance and radiant exposure can be averaged"***. This concept, therefore, denotes a minimum aperture opening through which the beam passes. The limiting apertures range from 1 mm and 3.5mm (UV/Medium & Far IR), 7mm (Visible/NIR) and 11 mm (Submillimeter) as defined in Table 2 in this document.

The original argument for using a 1mm value for the ultraviolet and/or medium and far infrared spectral regions was based upon the general argument that "hot-spots" in laser beams were physically about 1mm in dimension and that the bioeffects in these spectral regions were surface effects, hence the small regions needed to be considered in the hazard assessment. In the 1993 revision, an additional criteria was introduced to employ a 3.5 mm aperture for many of the UV and middle infrared spectral regions.

The rationale for use of a 3.5 mm LA for the UV and middle- infrared is that an aperture of this size more closely approximates the area covered by the beam hot spots on the cornea and/or skin surface for longer exposure times (0.25 to $3x10^4$ s.) including the effects of motion of the surface during the exposure.

CLASSIFICATION AND HAZARD EVALUATION

Section 3 of the ANSI Z136 standard provides detailed requirements for classification into one of the four major class categories (Class 1, 2a, 2, 3a, 3b and 4).

It should be noted that the standard advises (Section 1.2) that: ***"lasers or laser systems certified for a specific class by a manufacturer in accordance with the Federal Laser Product Performance Standard may be considered as fulfilling all classification requirements of this standard."*** Thus, the Laser Safety Officer (LSO) can accept the CDRH based classification for

Table 2

Limiting Apertures for Hazard Evaluation

Spectral Region (µm)	Duration (s)	Aperture Diameter (mm)	
		Eye	Skin
0.180 to 0.400	10^{-9} to 0.25	1.0	3.5
	0.25 to 3×10^4	3.5	3.5
0.400 to 1.400	10^{-9} to 3×10^4	7.0	3.5
1.400 to 10^2	10^{-9} to 0.3	1.0	3.5
	0.3 to 10 *	$1.5\, t^{3/8}$	3.5
	10 to 3×10^4	3.5	3.5
10^2 to 10^3	10^{-9} to 3×10^4	11.0	11.0

* Under normal conditions these exposure durations would not be used for hazard evaluation.

Note: The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$ µm, e.g., 0.315 to 0.400 µm means $0.315 \le \lambda < 0.400$ µm.

Measurement Apertures for Classification *

Spectral Region (µm)	Duration (s)	Aperture Diameter (mm)
0.180 - 0.302	10^{-9} to 0.25	1.0
	0.25 to 3×10^4	3.5
0.302 - 2.8	10^{-9} to 3×10^4	50.0 **
2.8 - 10^2	10^{-9} to 0.3	1.0
	0.3 to 10 ***	$1.5\, t^{3/8}$
	10 to 3×10^4	3.5
10^2 - 10^3	10^{-9} to 3×10^4	11.0

* These apertures are used for the measurement of optical power or energy for purposes of laser classification (see 3.3).

** When the laser output is intended to be viewed with optics (excluding ordinary eyeglasses) or the Laser Safety Officer determines that there is a reasonable probability of accidental viewing with optics, a 50 mm aperture is used if the following conditions are met:

(1) Viewing with optics presents a more severe hazard than unaided viewing.
(2) The viewing time is sufficient to constitute a hazard.

Otherwise, the limiting apertures for the eye and skin from Table 8 apply. For the specific case of optical viewing with beam collecting instruments, the apertures listed in Table 8 for hazard evaluation apply to the exit beam of the optical instrument.

*** Under normal conditions, these exposure durations would not be used for classification.

Note: The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$ µm, e.g., 0.315 to 0.400 µm means $0.315 \le \lambda < 0.400$ µm.

manufacturer certified laser products.

There are, however, cases where a laser may have been altered so as to change the class, or the laser may have been built "in house" at the facility. In these cases, the LSO shall classify the laser in accordance with the requirements of the Z-136 standard. (Note: In some cases, this may also require certification and classification as specified by 21CFR Parts 1040.10 and 1040.11).

Classification first requires determination of the Maximum Permissible Exposure (MPE) and the AEL (accessible emission limit) values.

Classification Computations:

Consider the case of a Ho:YAG laser operating at a wavelength of 2.1μm. The classification is determined by first computing the MPE for this laser. Using the ANSI Z-136 standard, the MPE can be shown to be 100 mW/cm² for a 10s. exposure. The area of a 3.5mm Limiting Aperture (A_{LA}) can be computed using the formula for a circle:

$$A_{LA} = \pi D^2/4$$

$$= (3.14)x(0.1225)/4$$

$$= 0.0963 \text{ cm}^2$$

The classification is determined by computing the value of the ***Accessible Emission Limit*** (AEL), which is given by the relationship:

$$AEL = MPE \text{ x } A_{LA}$$

$$= [100 \text{ x } 10^{-3}]x[0.0962)]$$

$$= 9.62 \text{ mW.}$$

Thus the limit for Class 1 emissions for a Ho:YAG laser is 9.6 mW. Consequently Ho:YAG lasers that emit power outputs less than or equal to the AEL of 9.6 mW will be Classified as a Class 1 laser.

EXTENDED SOURCE CORRECTION (C_E)

Background Criteria

The MPE limits were derived from research activities (principally done in the 1970's) where the intrabeam (point source) limits were derived from a multitude of data covering a wide range of exposure times and wavelengths. In comparison, the biological base for laser sources with the capability of producing larger retinal images (extended sources) was (and still is) limited.

In the past, so called extended source criteria have generally been of limited concern in a practical sense and generally were applied only to viewing diffuse reflections of large laser beams at close range. Today, however, diode lasers, either used singly or in large arrays, are becoming more prevalent and sometimes serve as an extended source. A similar argument applies to the so-called "laser paint". Also, the treatment of diffuse reflection hazards has received much more attention with the introduction of the diffuse reflection nominal hazard zone (NHZ) requirements.

A method has been included in the ANSI Z-136.1 standard to allow for determination and computation of extended source lasers. The LSO first determines whether a given "viewing" situation meet extended source criteria. This is done by computing the limiting angular substance (α) and then determining whether this was equal or larger than a viewing angle designated α_{min} (defined by data given in the standard). Then, if a viewing situation meets extended source criteria, a modified MPE criteria is used for MPE determinations.

This method was initially proposed by D. Courant and others which bases extended source criteria on the intrabeam MPE's (point source criteria) using a correction factor multiplier which is based upon geometrical factors. This is defined in the standard as a correction factor called C_E which is a function of the α, α_{min} and α_{max} factors.

Limiting Angular Substance Criteria (α_{min})

It is necessary to determine at what distance the laser "changes" to an intrabeam condition. This is included in a geometrical factor called the ***limiting angular substance angle*** (α_{min}) which may vary widely, especially for pulsed lasers.

The limiting angular substance (α_{min}) is defined as: ***"The apparent visual angle which divides intrabeam viewing from extended source viewing".*** The α_{min} factor is used to determine at what distance away from a laser source or from a diffuse reflecting source one must be before the source is considered a point source.

Extended Source Concepts

The extended source exposure is expressed in terms of a corneal exposure which, through a linear equation, can be shown to be dependent upon the diameter of the retinal image. (The corneal limit is, in fact, based on the square of the retinal image size.) This linear dependence has been found to at least more closely follow the biological data for angular source sizes which area less than 100 mr. Other factors which influence the determination between intrabeam viewing and extended source viewing include the minimal retinal image size for intrabeam viewing and the pupil diameter. It should be noted also that ***both of these factors*** also depend on the viewing time.

The minimum value for the retinal image size for pulsed sources has been determined to be about 24 μm (which corresponds to a source angle of 1.5 mr). ***This factor and biologic studies of saccadic or micronysogmic eye movements have shown that a point source will not remain for extended time periods in one spot of the retina unless the eye has been anesthetized.*** When exposure times are greater than about 10 sec., these eye movements will, therefore, cause the image size to cover a much larger area (about 11 mr).

Therefore, the Z-136.1 standard now defines the difference between a point-source exposure (intrabeam viewing) and extended source exposure in terms of the α_{min} angle which are given below:

$\alpha_{min} = 1.5$ mr for: $t < 0.7$ sec.

$\alpha_{min} = 2 \cdot t^{3/4}$ mr for: 0.7 sec. $\leq t \leq 10$ sec.

$\alpha_{min} = 11$ mr for: $t > 10$ sec.

The MPEs for extended sources (sources which have an angular source size exceeding α_{min}) are expressed in terms of the correction factor C_E which is multiplied by the intrabeam MPE value. The correction factor is:

$C_E = 1.0$ for: all $\alpha < \alpha_{min}$

$C_E = \alpha/\alpha_{min}$ for: $\alpha_{min} < \alpha < \alpha_{max}$,

where $\alpha_{max} = 100$ mr.

The concept of using retinal irradiance or radiant exposure levels for larger source sizes has also been utilized in the revisions. In this case the corneal exposure depends on the square of the image size and the correction factor is given by:

$C_E = \alpha^2/(\alpha_{min} \cdot \alpha max)$ for: $\alpha > \alpha_{max}$

It was determined that the $1/d_r$ dependence of thermal injury (where d_r is the retinal image size) led to an α-dependent correction factor C_E that always provided a more conservative AEL than the blue-light extended source criteria. This is true since the blue-light criteria has already been factored into the MPE limits.

The existing MPE levels do not include any specific factors based upon changes in pupil size. In most cases, the pupil will experience a reduction in size upon the exposure to bright light. This is a normal built-in human response that effectively limits the amount of laser light that can enter the eye. This "built-in" reduction factor is implicit for viewing visible exposures greater than a few tenths of a second.

Extended Source Computation:

For example, consider a 5.0 Watt argon laser beam that is expanded by optics to produce a spot diameter of 20 cm on a laboratory wall. Assume that lab personnel could possibly view the spot as a diffuse reflection at a distance as close as 0.5 meter.

In this case, one first determines whether the viewing angle meets the α_{min} criteria. If one assumes an exposure time T=100 seconds then α_{min}= 11 mrad., then the 20 cm diffuse spot acts as an extended source up to a maximum viewing distance: $r_{1max} = D_L \cos\theta/\alpha_{min} = (20)x(1.0)/11x10^{-3} = 1.82$ M. Beyond that distance, the spot would produce retinal images that are treated as if they were point source (intrabeam criteria) images.

The actual limiting angular substance for the viewing condition described above would be: $\alpha = D_L \cos\theta/r = (20)x(1.0)/(500) = 40$ mr; clearly larger than α_{min} limit of 11 mrad. ***Thus the lab personnel would be viewing an extended source.***

In order to compute the MPE for the extended source criteria, first one must first show that the point source MPE for this laser and exposure time is 100 μW/cm². Next, one determines the magnitude of correction factor C_E. As given above $C_E = \alpha/\alpha_{min} = 40/11 = 3.64$. Thus the revised extended source MPE value is given as: MPE_{ES} = 364 μW/cm². This is the maximum corneal exposure limit in the extended source region at $r_1 = 0.50$ M.

Pulsed Extended Source Laser Criteria

One factor that can, at times, provide difficulty is the computation for the AEL's for Class 3B pulsed lasers. The AEL for CW and repetitively pulsed Class 3B lasers is 0.5 W for emission durations exceeding 0.25 sec.

Note that with most common lasers, the 0.5 W criterion is the limiting factor which divides Class 3B and Class 4 lasers.

A laser is considered to either (or not) present a diffuse reflection hazard. In reality, the size of the laser beam striking the surface is usually small enough so that intrabeam viewing limits could be applied after a few meters of separation (viewing distance).

A special approach is used to limit the beam energy from a pulsed laser (usually Q-switched) which is directed onto a diffuse surface. In this scenario, ***the hazard is dependent on the beam diameter at the diffuser and the viewing distance.*** In this special pulsed laser case, a minimum viewing distance was chosen at 20 cm, even though a viewer at that distance might be at risk from the primary laser beam. The permitted energy for each viewing condition was determined so that the new extended source criteria would not be exceeded.

Lambert's Law (inverse square) is used to calculate the radiant exposure at the viewer's eye. In the computation, a modification is included in the equation which takes into account the large beam diameter - since the corneal exposure would be slightly reduced for very short viewing distances. ***Thus to affect this approximation, an apparent additional image distance was added to the viewing distance which was equal to one-half of the beam diameter.***

The formula for determining corneal exposure is then:

$$H = \rho(\lambda)\cdot Q\cdot\cos\theta/[\pi\cdot(r_1 + D_B/2)^2] \quad (\text{J/cm}^2)$$

where:

$\rho(\lambda)$ = Reflection coefficient
Q = Laser pulse energy (J).
θ = Viewing angle (off normal).
r_1 = Distance from diffuser (cm)
D_B = Beam diameter (cm)

Three viewing distances are listed in the standard. ***Note that the Class 4 classification is dependent only upon the 20 cm viewing criteria.***

Pulsed Laser Diffuse Extended Source Computation

As an example, one can compute that pulse energy incident upon a diffuse surface that would meet a safe diffuse reflection (Class 3B) criteria. In this computation, the modified inverse square law is solved for pulse energy when the ocular exposure is equal to the allowed MPE (with all correction factors applied) for the laser pulse.

For example, consider the case of a single pulse Nd:YAG laser operating at 1.064 µm and emitting a 30 nsec Q-switch pulse. ***The equation as described above is used to determine the maximum incident pulse energy (Q) incident upon the diffuser that meets Class 3B ("safe" diffuse reflection) criteria.***

That is:

$$Q = \frac{\pi \cdot (5x10^{-7}) \cdot (r_1 + D_B/2)^2 \cdot C_A \cdot C_E}{\rho(\lambda) \cdot \cos\theta} \quad (J)$$

For this laser wavelength C_A=5.0. Given that the viewing angle is directly onto the target (θ=0°) with a complete (100%) reflection ($\rho(\lambda)$=1.0) and a spot diameter on the diffuser of D_B=1cm and a viewing range of r_1=20cm, then:

$$Q = \frac{\pi \cdot (5x10\text{-}7) \cdot (20 + 1.0/2)^2 \cdot (5.0) \cdot C_E}{(1.0) \cdot (1.0)}$$

One can now compute the limiting angular substance $\alpha = DL \cos\theta / r_1 = (1.0) \cdot (1.0)/(20) = 50$ mr which is greater than α_{min} = 1.5 mrad but less than α_{max}=100 mr for this exposure time. Thus the correction factor is determined by the following ratio: $C_E = \alpha/\alpha_{min} = 50/1.5 = 33.33$. Finally the maximum Class 3B pulse energy can be computed:

$$Q = \pi \cdot (5x10^{-7}) \cdot (20 + 1.0/2)^2 \cdot (5.0) \cdot (33.33)$$

$$= 110 \text{ mJ/pulse}$$

Thus, the "allowed" emission from this Q-switched Nd:YAG laser to maintain Class 3B status is 110 mJ/pulse. If the pulse energy would ever exceed this magnitude, the laser would fall in the Class 4 category.

Note if the laser operates in the wavelength range 1.15-1.4 µm, an additional correction factor is to be applied. If multiple pulse lasers are used, then the pulse energies resulting from the above computations would also be multiplied by the multiple pulse correction factor $C_P = N^{-1/4}$.

OPTICAL DENSITY

The most important factor necessary to specify the adequate protection for a given laser is the ***optical density*** (OD). OD is based upon a ratio which compares the "worst case" laser beam exposure incident on the filter material to the maximum allowed exposure to the eye - called the maximum permissible exposure (MPE). Note that this ratio is a "static" consideration which does not take material damage levels or other dynamic factors into consideration.

OD is derived from a logarithmic computation and numerically expresses the filters ability to reject or absorb the incident laser light. For example, an OD of three represents a one-thousand fold rejection; an OD of 6 rejects one-million times.

Sample Intrabeam OD Computation

Based upon typical exposure conditions, the optical density required for suitable filtration can be determined. Optical density (OD) is a logarithmic function defined by:

$$OD = \log_{10} \left[\frac{H_o}{MPE} \right]$$

Where:

H_o = Anticipated worst case exposure (J/cm^2 or W/cm^2).

MPE = Maximum permissible exposure level expressed in the same units as H_o.

Based upon the worst case exposure conditions, one can determine the optical density recommended to provide adequate eye protection for this laser. For example, the minimum optical density at the 0.514 μm argon laser wavelength for a 600 second direct intrabeam exposure to the 5 Watt maximum laser output can be determined as follows:

Where:

Φ = 5 Watts
MPE = 16.7 μW/cm^2 (using 600 sec. criteria)
d = 7 mm (worst case pupil size)

Computing the worst case exposure Ho:

$$H_o = \text{Power/Area} = \Phi/A = 4\Phi/\pi d^2$$

$$H_o = [4\,(5.0)]/[\pi\,(0.7)^2]$$

$$= 12.99 \quad \text{W/cm}^2$$

Substituting, we have:

$$\text{Thus:} \quad \text{OD} = \log_{10}\left[\frac{12.9}{16.7\text{x}10^{-6}}\right]$$
$$= 5.9$$

A more conservative approach would be to choose an 8 hour (occupational) exposure. In this case, the optical density at 0.514 μm is increased to OD = 7.1 for a 5.0 watt intrabeam exposure because the 8-hour (30,000 sec.) MPE is reduced to $1.0\text{x}10^{-6}$ W/cm^2.

The OD values for various lasers, computed for various appropriate exposure times, is given below in Table 3. It should be stressed these values are for intrabeam viewing (worst case) only. The OD criteria are dependent on viewing time because the MPE's are time dependent.

OD values may now be easily determined using computer software packages such as LAZAN based upon the ANSI Z-136 requirements.

Sample Task Design or Alignment Eyewear (Diffuse Reflection) OD Computation

Viewing Class IV diffuse reflections (such as during alignment tasks) requires, in general, less OD. These should be determined for each situation using the ANSI point source MPE criteria and the inverse square law to calculate the irradiance at a distance. Again, each situation would be dependent upon the laser parameters and viewing distance.

Using the example above, assume an 80% diffuse reflection of the 5 W argon laser when viewed at 0.5 meter (approximately arm's length). Thus, assuming normal incidence viewing (θ=90°) the exposure (irradiance) at the eyewear is computed using the inverse square law:

$$\text{Ho} = \frac{\rho\,\Phi\cos\theta}{\pi\,r^2} = \frac{(0.80)\,(5.0)\,(1.0)}{(3.14)\,(50)^2}$$

$$= 0.51 \ \text{mW/cm}^2$$

Thus, assuming a "worst case" 600 second exposure to the eye during the alignment task, the MPE = 16.7 μW/cm^2. Thus the OD can be computed:

$$\text{OD} = \log_{10}\left[\frac{5.1\text{x}10^{-4}}{16.7\text{x}10^{-6}}\right]$$
$$= 1.48$$

Thus, an OD $\geq$1.5 would be sufficient for protection for alignment tasks at "arm's length".

ADDITIONAL READING

1. American National Standards Institute, American National Standard for the Safe Use of Lasers: ANSI Z-136.1 (1993), Publisher: Laser Institute of America, Orlando, FL, 1993.

2. Food and Drug Administration: Performance Standard for Laser Products, Center for Devices and Radiological Health, Food and Drug Administration (DHHS), Code of Federal

Table 3

Optical Density For Various Laser Types

Laser Type/Power	*Wavelength (µm)*	*OPTICAL DENSITY*			
Exposure Time:(s)		*0.25*	*10*	*600*	*$3x10^4$*
XeCl 50 Watts	0.308[b]	-*-	6.2	8.0	9.7
XeFl 50 Watts	0.351[b]	-*-	4.8	6.6	8.3
Argon 1.0 Watt	0.514	3.0	3.4	5.2	6.4
Krypton 1.0 Watt	0.530	3.0	3.4	5.2	6.4
Krypton 1.0 Watt	0.568	3.0	3.4	4.9	6.1
HeNe 0.005 Watt	0.633	0.7	1.1	1.7	2.9
Krypton 1 Watt	0.647	3.0	3.4	3.9	5.0
GaAs 50 mW	0.840[b]	-*-	1.8	2.3	3.7
Nd:YAG 100 Watt	1.064[b]	-*-	4.7	5.2	5.2
Nd:YAG (Q-switched)[a]	1.064[b]	-*-	4.5	5.0	5.4
CO_2 1000 Watts	10.6[c]	-*-	6.2	8.0	9.7

[a] Repetitively pulsed @ 11 Hz., 12 ns pulses, 20 mJ/pulse.

[b] OD for UV & FIR beams computed using 1mm limiting aperture which presents a "worst case" scenario. All visible/NIR computations assume 7mm limiting aperture.

-*- Invisible beams; aversion response time does not apply.

NOTE: OD values obtained using ANSI Z-136.1 (1986) MPE criteria.

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4. R. James Rockwell, Jr., Selecting Laser Eyewear, Medical Laser Buyer's Guide, Penn Well Books, Tulsa, Okla., pp: 84-92, January, 1989

5. LAZAN: Laser Hazard Analysis Computer Program. Rockwell Laser Industries, P.O. Box 43010, Cincinnati, OH, USA 43010. (Phone: 513-271-1568).

6. R. James Rockwell, Jr., Wesley J. Marshall, Myron L. Wolbarsht and David H. Sliney, ANSI Z-136.1 Proposed 1992 Changes, Journal of Laser Applications, pp:45-50, Vol. 4, No.1, 1992

7. R. James Rockwell, Jr., Utilization of the Nominal Hazard Zone in Control Measure Selection, Proceedings of the International Laser Safety Conference, Publisher: Laser Institute of America, Orlando, FL, 1991

8. Rockwell, R. James, Jr., Editor, Laser Safety Training Manual - Sixth Edition, Rockwell Associates, Inc., publisher, Cincinnati, Ohio, 1989.

9. R. James Rockwell, Jr., Analyzing Laser Hazards , Lasers and Applications, Vol. 5, No. 5, pp. 97-103, May, 1986.

10. R. James Rockwell, Jr, Fundamentals of Industrial Laser Safety. In: Industrial Laser Annual Handbook, edited by M. Levitt and D. Belforte, Penn Well Books, Tulsa, Okla., pp. 131-148, 1986.

APPENDIX A

ANSI Z136.1 MPE TABLES

Table 5

Maximum Permissible Exposure (MPE) for Ocular Exposure (Intrabeam Viewing) to a Laser Beam †

Wavelength	Exposure Duration, t	MPE		Notes
(μm)	(s)	($J \cdot cm^{-2}$)	($W \cdot cm^{-2}$)	
Ultraviolet				
0.180 to 0.302	10^{-9} to 3×10^4	3×10^{-3}		or $0.56\, t^{1/4}$, whichever is lower. (See Tables 8 and 9 for limiting apertures)
0.303	10^{-9} to 3×10^4	4×10^{-3}		
0.304	10^{-9} to 3×10^4	6×10^{-3}		
0.305	10^{-9} to 3×10^4	10×10^{-3}		
0.306	10^{-9} to 3×10^4	16×10^{-3}		
0.307	10^{-9} to 3×10^4	25×10^{-3}		
0.308	10^{-9} to 3×10^4	40×10^{-3}		
0.309	10^{-9} to 3×10^4	63×10^{-3}		
0.310	10^{-9} to 3×10^4	0.1		
0.311	10^{-9} to 3×10^4	0.16		
0.312	10^{-9} to 3×10^4	0.25		
0.313	10^{-9} to 3×10^4	0.40		
0.314	10^{-9} to 3×10^4	0.63		
0.315 to 0.400	10^{-9} to 10	$0.56\, t^{1/4}$		
0.315 to 0.400	10 to 3×10^4	1.0		
Visible and Near Infrared				
0.400 to 0.700	10^{-9} to 18×10^{-6}	0.5×10^{-6}		(See Tables 8 and 9 for limiting apertures)
0.400 to 0.700	18×10^{-6} to 10	$1.8\, t^{3/4} \times 10^{-3}$		
0.400 to 0.550	10 to 10^4	10×10^{-3}		
0.550 to 0.700	10 to T_1	$1.8\, t^{3/4} \times 10^{-3}$		
0.550 to 0.700	T_1 to 10^4	$10\, C_B \times 10^{-3}$		
0.400 to 0.700	10^4 to 3×10^4		$C_B \times 10^{-6}$	
0.700 to 1.050	10^{-9} to 18×10^{-6}	$0.5\, C_A \times 10^{-6}$		
0.700 to 1.050	18×10^{-6} to 10^3	$1.8\, C_A\, t^{3/4} \times 10^{-3}$		
0.700 to 1.050	10^3 to 3×10^4		$320\, C_A \times 10^{-6}$	
1.050 to 1.400	10^{-9} to 50×10^{-6}	$5\, C_C \times 10^{-6}$		
1.050 to 1.400	50×10^{-6} to 10^3	$9.0\, C_C\, t^{3/4} \times 10^{-3}$		
1.050 to 1.400	10^3 to 3×10^4		$1.6\, C_C \times 10^{-3}$	
Far Infrared				
1.400 to 1.500	10^{-9} to 10^{-3}	0.1		(See Tables 8 and 9 for limiting apertures)
1.400 to 1.500	10^{-3} to 10	$0.56\, t^{1/4}$		
1.400 to 1.500	10 to 3×10^4		0.1	
1.500 to 1.800	10^{-9} to 10	1.0		
1.500 to 1.800	10 to 3×10^4		0.1	
1.800 to 2.600	10^{-9} to 10^{-3}	0.1		
1.800 to 2.600	10^{-3} to 10	$0.56\, t^{1/4}$		
1.800 to 2.600	10 to 3×10^4		0.1	
2.600 to 10^3	10^{-9} to 10^{-7}	10×10^{-3}		
2.600 to 10^3	10^{-7} to 10	$0.56\, t^{1/4}$		
2.600 to 10^3	10 to 3×10^4		0.1	

† The MPE for diffuse reflections at wavelengths between 0.400 and 1.400 µm is obtained by multiplying the corresponding MPEs above by C_E. (See Table 6 and Figure 9 for correction factors and T_1.)

Notes: 1. For repeated (pulsed) exposures, see 8.2.2.

2. The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$, e.g., 0.180 to 0.302 µm means $0.180 \le \lambda < 0.302$ µm.

Table 6

Parameters and Correction Factors

Correction Factor	Wavelength (µm)	Figure*
$T_1 = 10 \times 10^{20(\lambda - 0.550)}$	0.550 to 0.700	9
$C_B = 1.0$	0.400 to 0.550	9
$C_B = 10^{15(\lambda - 0.550)}$	0.550 to 0.700	9
$C_A = 1.0$	0.400 to 0.700	8a
$C_A = 10^{2(\lambda - 0.700)}$	0.700 to 1.050	8a
$C_A = 5.0$	1.050 to 1.400	8a
$C_P = n^{-1/4}$ **	0.400 to 1.400	13
$C_E = 1.0 \quad \alpha < \alpha_{\min}$	0.400 to 1.400	-
$C_E = \alpha / \alpha_{\min} \quad \alpha_{\min} < \alpha < 100$	0.400 to 1.400	-
$C_E = \alpha^2 / (100\, \alpha_{\min}) \quad \alpha > 100$	0.400 to 1.400	-
$C_C = 1.0$	1.050 to 1.150	8b
$C_C = 10^{18(\lambda - 1.150)}$	1.150 to 1.200	8b
$C_C = 8$	1.200 to 1.400	8b

* See figures for graphic representation.

** For pulse repetition frequencies below 55 kHz (0.4 to 1.05 µm) and below 20 kHz (1.05 to 1.4 µm). (See 8.2.2.2.)

Notes: 1. For wavelengths between 0.400 and 1.400 µm :

$\alpha_{\min} = 1.5$ mrad for $t \leq 0.7$ s
$\alpha_{\min} = 2\, t^{3/4}$ mrad for $0.7 \text{ s} < t < 10$ s
$\alpha_{\min} = 11$ mrad for $t \geq 10$ s

(See Figure 3 for graphical representation of $\alpha_{\min}$.)

2. The wavelength region λ_1 to λ_2 means $\lambda_1 \leq \lambda < \lambda_2$, e.g., 0.550 to 0.700 µm means $0.550 \leq \lambda < 0.700$ µm.

Table 7

Maximum Permissible Exposure (MPE) for Skin Exposure to a Laser Beam

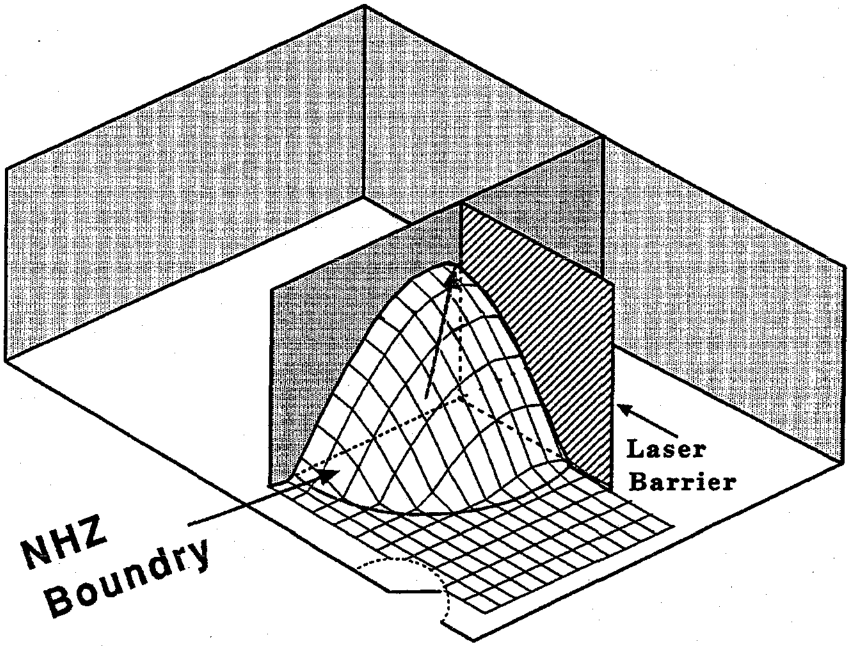
Wavelength (µm)	Exposure Duration t (s)	MPE ($J \cdot cm^{-2}$)	MPE ($W \cdot cm^{-2}$)	Notes
Ultraviolet				
0.180 to 0.302	10^{-9} to 3×10^4	3×10^{-3}		or 0.56 $t^{1/4}$, whichever is lower. 3.5 mm limiting aperture: (See Table 8)
0.303	10^{-9} to 3×10^4	4×10^{-3}		
0.304	10^{-9} to 3×10^4	6×10^{-3}		
0.305	10^{-9} to 3×10^4	1.0×10^{-2}		
0.306	10^{-9} to 3×10^4	1.6×10^{-2}		
0.307	10^{-9} to 3×10^4	2.5×10^{-2}		
0.308	10^{-9} to 3×10^4	4.0×10^{-2}		
0.309	10^{-9} to 3×10^4	6.3×10^{-2}		
0.310	10^{-9} to 3×10^4	1.0×10^{-1}		
0.311	10^{-9} to 3×10^4	1.6×10^{-1}		
0.312	10^{-9} to 3×10^4	2.5×10^{-1}		
0.313	10^{-9} to 3×10^4	4.0×10^{-1}		
0.314	10^{-9} to 3×10^4	6.3×10^{-1}		
0.315 to 0.400	10^{-9} to 10	$0.56 t^{1/4}$		
0.315 to 0.400	10 to 10^3	1		
0.315 to 0.400	10^3 to 3×10^4		1×10^{-3}	
Visible and Near Infrared				
0.400 to 1.400	10^{-9} to 10^{-7}	$2 C_A \times 10^{-2}$		3.5 mm limiting aperture. (See Table 8)
	10^{-7} to 10	$1.1 C_A t^{1/4}$		
	10 to 3×10^4		$0.2 C_A$	
Far Infrared *				
1.400 to 10^3	10^{-9} to 10^{-7}	10^{-2}		(See Table 8 for limiting apertures)
	10^{-7} to 10	$0.56 t^{1/4}$		
	> 10		0.1	

* See 8.4.2 for large beam cross-sections and Table 6 for correction factor C_A.

Note: The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$, e.g., 0.315 to 0.400 µm means $0.315 \le \lambda < 0.400$ µm.

MINI MODULE: NHZ

THE NOMINAL HAZARD ZONE



Education

THE NOMINAL HAZARD ZONE

A review of the methods of determining and implementing the concept of the Nominal Hazard Zone

DEFINING THE NHZ

It is often necessary in some applications where open beams are required (vis: industrial processing, laser robotics...etc.) to define the area where the possibility exists for potentially hazardous exposure. This is done by determining the Nominal Hazard Zone (NHZ) which is, by definition, described by the space within which the level of direct, reflected or scattered radiation exceeds the level of the applicable MPE. Consequently, persons outside the NHZ boundary would be exposed below the MPE level and are considered to be in a "safe" location. The NHZ boundary may be defined by direct (intrabeam) beams, diffusely scattered laser beams as-well-as beams transmitted from fiber optics and/or through lens trains... etc. In other words, the NHZ perimeter is the envelope of MPE exposure levels from any specific laser in a given application or installation geometry.

The purpose of an NHZ evaluation is to define that region where control measures are required. Thus, as the scope of laser uses has expanded, the classic method of controlling lasers by enclosing them in an interlocked room has become limiting and, in many instances, can be an expensive over-reaction to the real hazards present.

Important in all controls is the distinction between the functions of operation, maintenance and service. First, most laser systems are classified on the basis of the laser radiation accessible during operation. Maintenance functions are considered as those tasks required to maintain routine system operation (vis: cleaning a lens, changing gas bottles...etc.) Service functions are usually performed with far less frequency than maintenance functions (vis: replacing the laser resonator mirrors, repair of faulty components...etc.) and often will require access to the laser beam by those performing the service functions.

The ANSI Z-136.1 Standard "For The Safe Use Of Lasers" specifies that the LSO shall effect a laser hazard analysis, including the determination of the Nominal Hazard Zone (NHZ), prior to establishing the control measures for either indoor or out-of-door laser controlled areas when they contain Class IIIB and/or Class IV lasers or laser systems. The purpose of the NHZ evaluation is to provide guidance in the selection of controls applicable for the specific laser installation.

This section will review:

- The NHZ concept and computations;
- An outline of the types of guidance that the NHZ analysis provides;
- How the choice of controls can be linked to the NHZ analysis.

NHZ examples will be given for five typical laser types. A selection matrix will be introduced that provides guidance to the LSO in the selection of control measures for a specific laser installation.

THE NHZ CONCEPT AND COMPUTATIONS

The Nominal Hazard Zone (NHZ) describes the space within which the level of direct, reflected, or scattered radiation during normal operation exceeds the MPE. The NHZ associated with open-beam Class IIIB and Class IV laser installations can be useful in assessing area hazards and implementing controls.

The evaluation of NHZ's is one of the stated duties of the Laser Safety Officer (LSO). This is specified in the ANSI Z-136.1 standard, for example, when it is stated that the LSO duties shall include: "***such actions as establishing an NHZ, approving (SOP's), avoiding unnecessary or duplicate controls, selecting of alternate controls, conducting periodic facility and equipment audits, and training.***" [ANSI Z-136.1 (1993): Section 4.2]

For example, in some applications where open beams are required (vis: industrial processing, laser robotics, surgical uses) it is necessary to define the area where the possibility exists for potentially hazardous exposure. The Nominal Hazard Zone defines such a zone of hazard. Consequently, persons outside the NHZ boundary, if exposed at all, would be exposed below the MPE level and are considered to be in a non-hazardous location.

If the NHZ evaluation produces NHZ values that are small when compared to the dimensions of the laser unit and, more specifically, small when compared to the area around the laser unit where workers are permitted during the use of the device, then the control measures that are required can be significantly reduced.

In many cases, the laser units may be reclassified by the LSO as Class I under the specifications of the ANSI Z-136 standard.

Origins of NHZ Concept

When laser devices first found meaningful application in the military for various distance ranging and target designation uses, it became necessary for safety personnel to be able to estimate the distance that a beam would need to propagate before the irradiance (or pulse radiant exposure) was reduced to the applicable Maximum Permissible Exposure (MPE) limit. This distance was given various acronyms (SEED, PEER, NOHD...etc.) in the military publications.

In most all cases, the hazard range computations utilized specific laser parameters. No external optics were involved. The equations used for such analysis were referred to as ***laser range equations***. The hazard distances which resulted from the analysis of most Q-switched pulsed lasers as used in the military were in the range from 5-25 kilometers!

Simplified equations were used which ignored loss mechanisms in the atmosphere such as absorption and scattering. When these factors are included, the solutions are not easily done in a closed mathematical form and a method of iteration is required. Solutions involve either the use of computers or graphical methods.

Area Hazard Analysis

Concurrent with the military range analysis, other forms of computational hazard analysis were done for various conditions of laser use. Specifically, since the conceptual dividing line between pulsed Class IIIB and Class IV lasers is linked to whether a given laser is capable of producing a hazardous diffuse reflection, the concept of a zone or region of diffused laser light can be developed.

Such a concept suggests that control measure selection for open beam units can be strongly influenced by the nature of the installation and how those factors influence the overall NHZ analysis.

The ANSI Z-136.1 standard also provides specific analysis for diffuse reflection hazards for extended sources. This is given using the MPE's applicable for viewing a diffuse reflection of a laser beam or an extended-source laser which meet certain viewing angle criteria. Data is provided in the standard for the maximum radiant exposure incident upon a diffuse surface which will not produce hazardous reflections (See, for example Table 3 ANSI Z136.1).

Extended source viewing is based upon the hazard criteria for large retinal burn hazards which involve evaluation of the limiting angular subtense (apparent visual angle) denoted angle α_{min}. It should

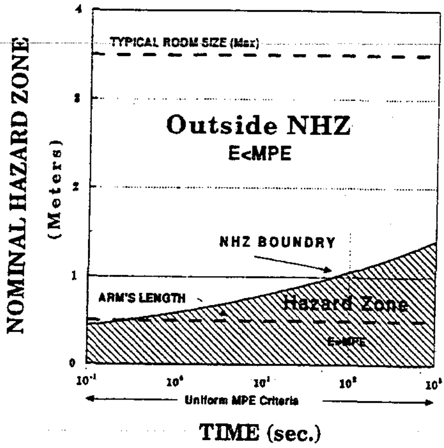


Figure 3
Diffuse Reflection NHZ
100 Watt Nd:YAG @ 1060nm

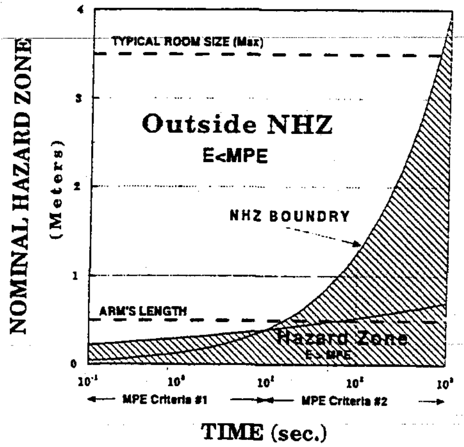


Figure 4
Diffuse Reflection NHZ
5 Watt Argon Laser @ 514nm

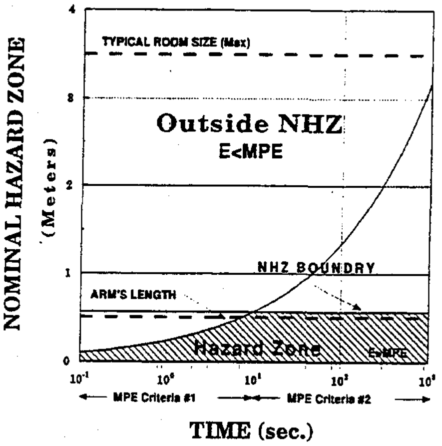


Figure 5
Diffuse Reflection NHZ
1000 Watt Carbon Dioxide
@ 10.6µm

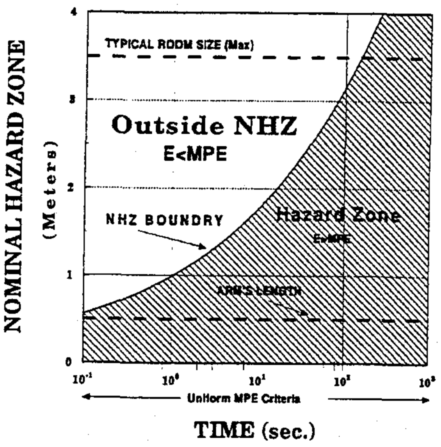


Figure 6
Diffuse Reflection NHZ
Q-Switched Nd:YAG; 1 KHZ
50 mJ/pulse

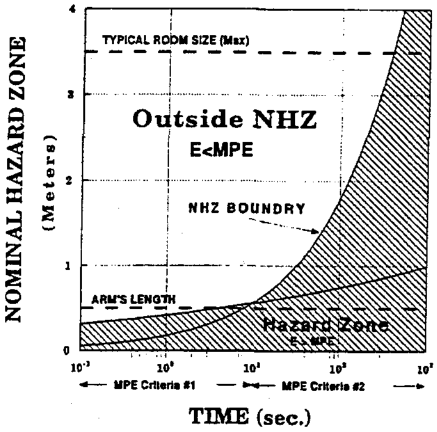


Figure 7
Diffuse Reflection NHZ
Frequency-doubled Nd:YAG
Laser 10 W/cw

Table 1
NHZ Distance Values for Various Laser Types

Laser Type	Exposure Criteria	Nominal Hazard Zone Hazard Range (meters)			
		Diffuse (100 %)	Lens-on Laser	Direct Beam	Fiber Optic
Nd:YAG 100 W 1.064 µm	8 hr.	1.4	11.3	1410	12.0
	10 s.	0.8	6.3	792	6.74
CO_2 1000 W 10.6 µm	8 hr.	0.56	7.5	555	n/a
	10 s.	0.56	7.5	555	n/a
Argon 5.0 W 0.488 µm	8 hr.	12.6	$1.7 X 10^3$	$2.5 X 10^4$	107.2
	0.25 s.	0.25	33.3	240	2.1
QS:Nd:YAG 50mJ 1.064 µm	8 hr.	4.9	277	$2.2 X 10^3$	n/a
	10 s.	1.8	102	810	n/a
Doub. YAG 10 W 0.532 µm	8 hr.	17.8	$1.4 X 10^3$	$8.9 X 10^3$	151.6
	0.25 s.	0.35	28.3	175	3.1

Laser Criteria Used for NHZ Distance Calculations:

Laser Parameters	**Nd:YAG**	**CO_2**	**Argon**	**Q-Switched Nd:YAG**	**Doubled Nd:YAG**
Wavelength (µm):	1.064	10.6	0.488	1.064	0.532
Beam Power (Watts):	100.0	1000.0	5.0	-	10.0
Pulse Energy (J):	-	-	-	0.05	-
Divergence (mrad):	2.0	2.0	1.0	4.4	4.0
Beam at Aperture (mm):	2.0	20.0	2.0	6.0	4.0
Beam at Lens (mm):	6.3	30.0	3.0	7.0	5.0
Focal Length (mm):	25.4	200.0	200.0	200.0	200.0
Pulse Length (µsec):	CW	CW	CW	$1 X 10^{-2}$	CW
Pulse Rate (Hz):	-	-	-	1000	-
Numerical Aperture:	0.2	-	0.2	-	0.2
MPE Criteria:					
8 hr. (µw/cm^2):	$1.6 X 10^3$	$1.0 X 10^5$	1.0	68.0	1.0
10 sec. (µw/cm^2):	$5.1 X 10^3$	$1.0 X 10^5$	-	500	-
0.25 sec. (µw/cm^2):	-	-	$2.5 X 10^3$	-	$2.5 X 10^3$

Clearly, the diffuse reflection case yields the lowest magnitude of NHZ values. Also, as stated earlier, the time factor chosen (especially for visible output lasers) can be a major factor in the extent of the NHZ.

The significant factor regarding the NHZ's associated with the direct (intrabeam), lens-on-laser and fiber-optic cases is that the beam paths associated with those situations are highly directional. Thus, personnel outside of that space envelope are out of the NHZ. This space can be significantly limited in some dedicated laser uses by combining directional limitations together with engineering controls such as interlocking, vision systems and beam traps or baffles.

The resultant situation is what is referred to in the ANSI standard as the Limited Open Beam Path: (Section 4.3.6.2) and is applicable to Class IIIb or Class IV lasers or laser systems. In such applications where the beam path is confined by design to significantly limit the degree of accessibility of the open beam, a hazard analysis shall be effected by the LSO to establish the NHZ. The LSO shall establish controls appropriate to the magnitude and extent of the accessible radiation.

Frequently the hazard analysis will define an extremely limited NHZ and procedural controls can provide adequate protection. Procedural controls are methods or instructions which specify rules, or work practices, or both, which implement or supplement engineering controls.

For Class IIIB and Class IV lasers, this includes factors such as:

- Written Standard Operating Procedures (SOP's) which are maintained with the laser equipment for reference by the operator, maintenance or service personnel.

- Limitation of the levels of accessible laser beam power to only that required for the specific task.
- Personnel shall be afforded education and training at a level commensurate with the classification and magnitude of the potential hazard.

- Only authorized and trained personnel shall be operate, maintain or service lasers.

- Experience has shown that a significant ocular hazards exist during alignment procedures, hence alignment of laser optics shall be done using techniques where eye exposures cannot occur at laser levels that exceed the applicable MPE.

- Eye protection devices which are specifically designed for protection against radiation shall be required and their use enforced when engineering or other procedural and administrative controls are inadequate.

- Spectators shall not be permitted within a laser controlled area unless the following has been done:

  (a) appropriate supervisory approval
  (b) explanation of hazard and avoidance procedures
  (c) appropriate protective measures effected

- Service personnel shall have the education and training commensurate with the class of the laser being serviced

Table 2
SAMPLE RANGE OF NHZ VALUES
For Common Laser Sources

	NHZ Range Low (meters)	NHZ Range High (meters)
Diffuse Reflection:	0.25	17.8
Direct (Intrabeam):	175	25000
Lens-on-Laser:	6.3	1700
Fiber Optic:	2.1	151

The Diffuse Reflection NHZ Concept

Conversely, the NHZ associated with the diffuse reflections fills a volume of nearly 2π steradians that is dependent upon the cosine of the angle as measured off the normal from the target surface as well as the surface reflection coefficient (e.g. see equations reviewed in the Appendix).

The consequence of this argument is:

- Allow only diffuse reflection access at as oblique an angle as possible. For example, an angle of θ=80 degrees, the intensity is less than 20% of the intensity at the normal. Permanent beam blocks can significantly limit the near normal viewing conditions.

- Maintain the diffuse reflection coefficient of the target to the lowest value possible.

- Maintain personnel outside the limited diffuse reflection NHZ area that has been reduced by low reflectance and by limitations placed by beam blocks around the target site.

The analysis also suggests that personnel and support staff working within the NHZ volume would require personnel safety equipment such as laser eye protection.

One can graphically depict (two dimensionally) the diffuse reflection as shown in Figure 8. This shows the zone of hazard (shaded area) for a CO_2 laser emitting 78.5 watts. This yields a worst case NHZ of 0.5 meters (approximately arms length) when the MPE for "large area exposure" (MPE=10 mW/cm2) is chosen. LSO's are sometimes required to use the "large area" MPE correction in situations of open area diffuse reflections where "whole body" coverage is possible. This situation might occur, for example, in a CO_2 industrial laser welding shop where workers may, in the summer, work without shirts.

To get some comparison of diffuse viewing, purposes, consider that staring directly at a standard 100 watt frosted light bulb at close range is equal to viewing a diffuse light source with a radiance of about 40 mW/cm^{2}sr. By comparison, a 1 mW HeNe "aiming laser" beam aimed at a 10 meter distance onto a 100% diffusely reflecting wall will produce an irradiance on the wall of 1.1 mW/cm^2. Assuming a 100% reflectivity , one can compute a radiance from this diffused source of 0.35 x 10^{-3} W/cm^{2}sr. Thus, the diffuse reflection of a 1 mW HeNe laser is more than 100 times less "bright" than viewing a 100 watt diffused light bulb! Thus diffuse viewing of low power laser light offers no more hazard (and maybe less) than more conventional light sources. Note that the dividing point between hazardous and non-hazardous diffuse reflections is generally considered to be 0.5 watt (the dividing point between cw Class IIIB and Class IV lasers).

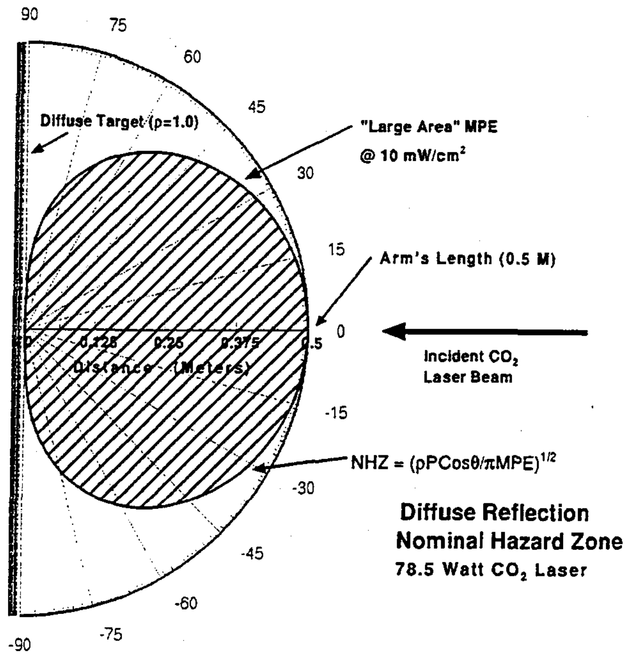


Figure 8

Two-dimensional graphical diffuse reflection volume of a 78.5 W CO_2 laser. MPE used was 10 mW/cm2 (large area). Note hazard zone dramatically reduces as the "viewing angle" approaches 90° off the normal.

Effective Nominal Hazard Zones

The actual formal definition of the NHZ is "that space within which the level of direct, reflected, or scattered radiation exceeds the applicable maximum permissible exposure level". This is equivalent to saying that the NHZ perimeter is an envelope in space around a laser which is defined at the MPE exposure level produced by a specific laser in a given application or geometry. It is important to define the NHZ location since the space usually requires certain engineering or administrative control measures.

For the purpose of this discussion, assume an exposure involving a lens-on-laser situation. Allow that the application employs a 1000 CO_2 laser operating in a CW mode with a lens having a focal length of 200 mm and a beam diameter (at the lens) of 30 mm. The "lens-on-laser" NHZ Figure 9B can be shown to be a distance of 7.5 meters as shown in the Appendix. Such a distance would be of the magnitudeof a large laboratory or work facility.

After making such calculations, the assumption often is made that the NHZ is a circle ata radius equal to the NHZ aroundthe emitting laser as shown inFigure 9A. In reality, the calculated NHZ is more correctly aspherical shaped region since the laser beam could travel in all directions as shown in Figure 9B.

Note that such idealized calculations do not give attention to the effect or presence of objects found in and around the work site. Inclusion of "objects" can alter the shape of the real NHZ. Locations of walls, furniture, cabinets, barriers...etc., can usually reduce the NHZ perimeter and affect the "space within which" described in the definition. It should be noted that reflecting objects in the room can also create additional "effective zones". This concept, when viewed in three dimensions as shown in Figure 9C, can lead to a "effective NHZ" that is more realistic in establishing control measures for laser installations.

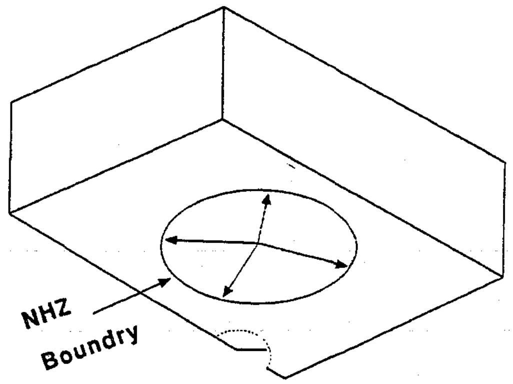


Figure 9a
Two dimensional top view NHZ

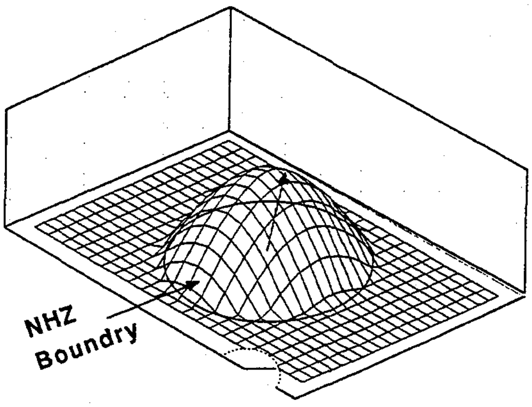


Figure 9b
Unobstructed three dimensional NHZ

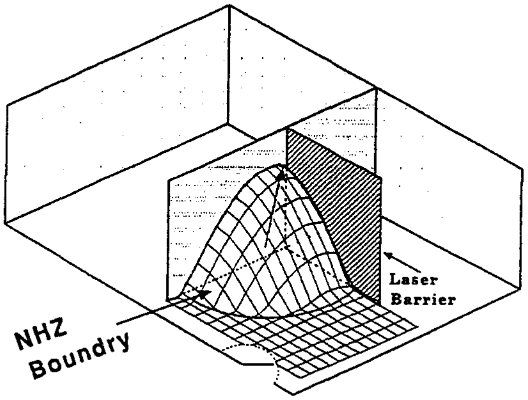
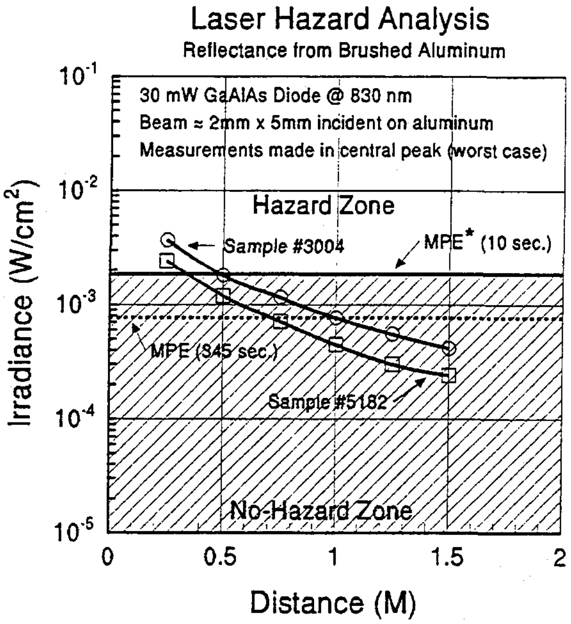


Figure 9c
"Effective NHZ" with area obstructions

Special NHZ Measurement Evaluations

There are some situations where numerical evaluations are either not well defined and/or virtually impossible in a practical sense. In these cases, actual beam measurements may be required. Consider, for example the situation of a laser diode that is being used in a "vision system" where the beam is used to inspect a flat, brushed aluminum sheet stock that is moving under the beam. In this case, measurements determined that the brushed surface produced a "line" reflection (not too unlike the beam being directed through a cylindrical lens.

Measurements were made, as shown below in Figure 8. In this case, the detector was moved to detect the "worst case" hot spot in the center of the reflected "line" of laser light. The plot shows that personnel are maintained a distance > 0.5 meters (approximately arms length) they would be out of the hazard zone for this diode using the allowable 10 second MPE criteria.



*NOTE: ANSI Z-136 accepts 10 sec. MPE criteria for near-infrared staring.

Figure 10

Measured NHZ for laser diode reflected from brushed aluminum. NHZ = 0.5 meter using 10 s MPE criteria

Sample Overall NHZ Analysis

Some discussion and explanation can be helpful to understand the conclusions drawn from NHZ calculations. For example, Figure 5 shows comparisons between the NHZ associated with intrabeam, diffuse, and lens-on-laser situations as a function of total beam power for a typical industrial CO_2 laser system. The laser parameters used to calculate the curves are given on the figure.

The following general conclusions from the NHZ evaluation can be stated:

- The intrabeam NHZ exceeds most plant dimensions (400 meters) when the laser power exceeds 500 watts for long term (>10 s) ANSI MPE exposure criteria. The intrabeam NHZ for a momentary one second exposure to a 500 W CO_2 laser is only reduced to 160 meters.
- The lens-on-laser NHZ exceeds most room dimensions (10 meters) when the laser power exceeds 1800 watts. The specific conditions obviously depend on the focal length of the lens being used.
- A NHZ separation distance of 2 meters from a diffuse reflection will provide adequate safety for laser powers up to 12.5 KW. This has some importance in defining the safe working envelope distance associated with a laser on a robot.
- "Arms length" NHZ separations from a diffuse reflection of 50 cm is adequate for laser powers up to 800 watts. Users should be aware of the potential for partial body heat stress conditions when working at these distances.
- At distances less than 50 cm from the interaction site users must be reminded that various gases, fumes, and vapors may exist at concentration levels that would be considered dangerous. Consideration must be given to utilizing properly designed exhaust systems.

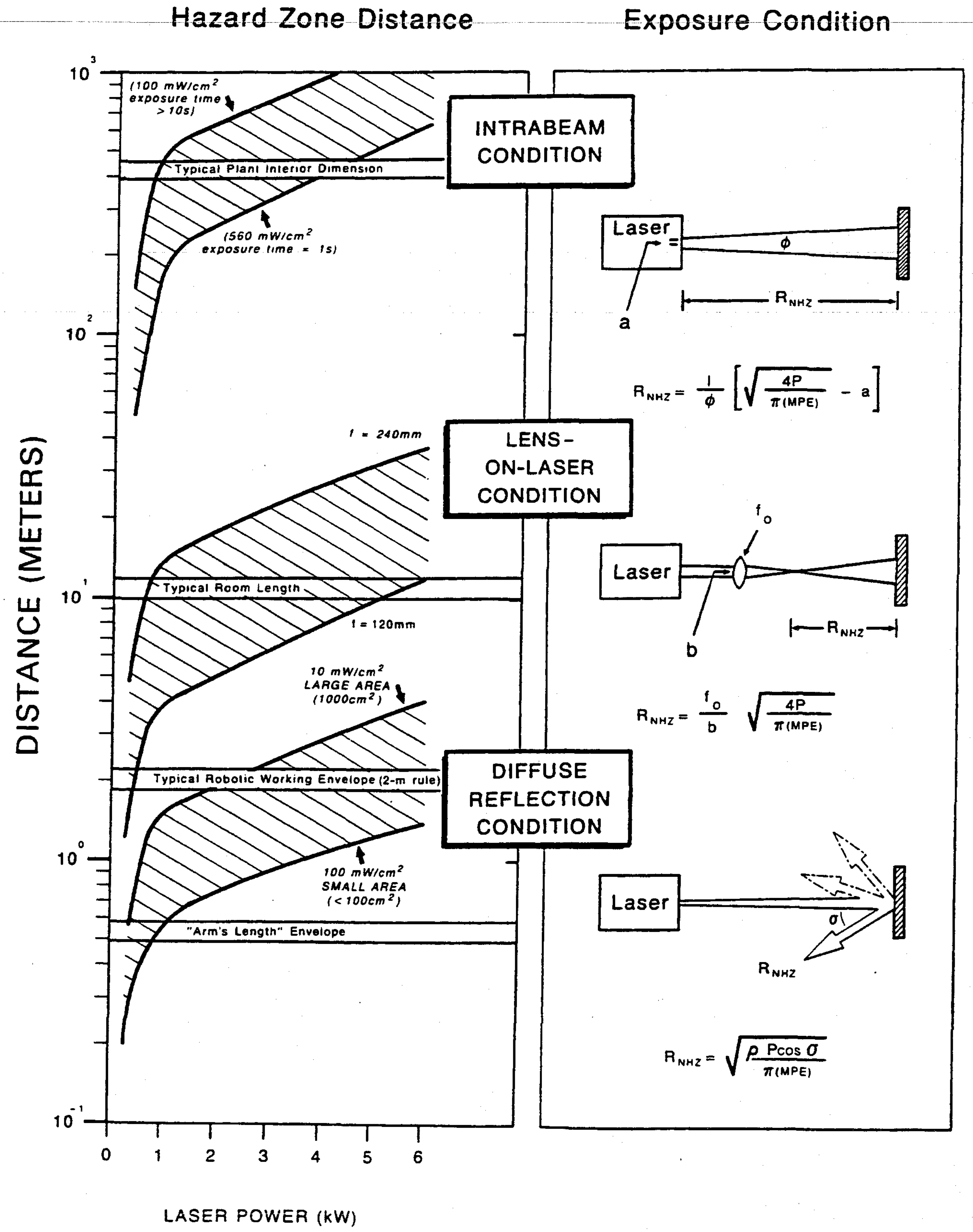


Figure 11
Nominal Hazard Zone as a function of distance for carbon dioxide lasers in an industrial setting

TOTAL EVALUATION

Three aspects of the application of a laser or laser system influence the total hazard evaluation:

- The laser or laser system's ability to injure personnel
- The environment in which the laser is used
- The personnel who may use or be exposed to the beam

All three aspects must be considered in order to establish control measures commensurate with the potential hazard.

The environment in which the laser is used may vary with each application. It is extremely important, however, that the environment in which the laser is used be considered in order to determine whether or not the control measures in are adequate, or if some are unnecessary. For example, the controls for a laser robotic system used on a production floor would be expected to be considerably different from those used in a research laboratory.

As a minimum, the following factors shall be considered:

- Number of lasers or laser systems.
- Degree of isolation (lab, production floor...etc.).
- Probability of the presence of untrained, unprotected transient personnel.
- Permanence of beam path(s).
- Permanence of specularly reflecting objects in or near the beam path.
- The use of optics (e.g., lenses, microscopes, optical fibers).

CONCLUSIONS

The key to implementing NHZ based controls is first to understand when such analysis is required. Reference to the Control Measure Matrix for NHZ Analysis in Table 3 will highlight those situations where NHZ analysis is deemed appropriate.

The ANSI Z-136.1 (1986) standard calls for NHZ analysis to be considered in several major parts of the standards (see Section 4.3). These are:

- Laser Robotic Installations
- Protective Windows
- Warning Signs and Labels
- Area Posting

All of these relate to situations of unenclosed Class IIIB and Class IV lasers in a specified laser area. The factors deemed appropriate may include control measures such as:

- Personnel who regularly require entry into a Class IV NHZ area shall be adequately trained, provided with appropriate protective equipment, and follow all applicable administrative and procedural controls.

- Posting with the appropriate laser "danger" warning signs(s). Note that during service procedures, a "notice" sign is recommended outside a temporary laser controlled area to warn of the potential hazard.

- Appropriate combinations of physical barriers, screening, protective eye and body wear or appropriate administrative controls shall be used if personnel are permitted within the NHZ. The barrier, screen, curtains, etc. shall have been determined to be laser resistant for at least 60 seconds.

- Unprotected, untrained and unauthorized personnel shall beexcluded from the NHZ zone.

- Have any potentially hazardous beam terminated in a beam stop of an appropriate material.

- Have only diffuse reflective materials in or near the beam path, where feasible.

- Have the beam path secured, where ever possible, to reduce the NHZ zone, especially for directional NHZ geometries.

- All windows, doorways, open portals, etc. shall be restricted (covered, filtered, blocked) limit the NHZ.

- All Class IV NHZ's shall have area/entryway safety controls designed to allow both rapid egress by laser personnel at all times and admittance to the laser controlled area under emergency conditions.

- For emergency conditions there shall be a clearly marked "Panic Button" (remote controlled connector or equivalent device) available for deactivating the laser or reducing the output to the appropriate MPE levels.

- Appropriate Area/Entryway Safety Controls shall be provided. For automated (robotic) systems, this shall include non-defeatable safety entryway or area interlocks which deactivate the laser in the event of improper perform- ance or unexpected entry into the laser controlled area.

- From the entryway there shall be a visible or audible signal indicating that the laser is energized and operating at Class IV levels. A lighted laser warning sign or flashing light are two of the appropriate methods to accomplish this requirement.

- Area/entryway controls allow rapid entrance and exit using one of these options:
  a. Non-defeatable entryway controls:
  b. Defeatable entryway controls:
  c. Procedural entryway controls:

- Entryway Warning/Control Systems:

In order to safely operate a Class IV laser or laser system, a laser warning system shall be installed as described:

a. A laser activation warning light assembly shall be installed outside the entrance to each laser room facility containing a Class IVlaser or laser system.

b. An alternative to an entryway warning is a three-cycle light assembly that operates in such a manner that one light will indicate when the laser is not operational (high voltage off); and by an additional light when the laser is powered up (high voltage applied) but not operating; and by an additional (flashing) light when the laser is operating.

LASER SAFETY PROBLEM SET

ANSI Z136.1 - 1993

A selection of sample problems that feature the major revisions that occur in the ANSI Z-136.1 (1993) standard. Emphasis on the new correction factors: CC, CP, CE; the new beam diameter formulation; the new extended source determination and the new pulsed Class 3B criteria.

LASER PARAMETERS FOR HAZARD ANALYSIS

The following laser output factors are required in various laser hazard analysis computations:

1. Laser power (Φ) or pulse energy (Q) outputs
2. Beam diameter (a) exiting the laser
3. Beam divergence (ϕ)
4. Operational mode: pulsed/cw/repetitively pulsed
5. Exposure time (t), pulse duration (τ) and/or pulse repetition frequency (PRF) - as applicable
6. Wavelength
7. Beam optics and beam path
8. Maximum anticipated exposure duration (T)
9. The Maximum Permissible Exposure (MPE)

LASER BEAM DIAMETER

Near-Field Region

The beam spread (divergence) of a typical laser beam is constantly changing in the region close to the laser generally called the "near field". The near-field is commonly as the distance (D_{nf}) which is defined by the ratio of laser aperture area and the laser wavelength:

$$D_{nf} \leq \frac{\text{Area of aperture}}{\text{Wavelength}}$$

For example, assume an argon laser with a beam diameter of 2 mm exiting the laser. The circular area of this beam aperture is:

$$A = [\pi \cdot d^2]/4 = \pi \cdot [(0.002)^2]/4$$

$$= [(3.14) \cdot (4x10^{-6})]/4 = 3.14 \times 10^{-6} \quad m^2$$

Assumming the argon laser operates at a wavelength of 0.488 μm, the near field distance can be computed:

$$D_{nf} \leq \frac{3.14 \times 10^{-6} \quad m^2}{0.488 \times 10^{-6} \quad m} = 6.44 \text{ meters}$$

$$\boxed{D_{nf} \leq 6.44 \text{ meters}}$$

Laser Beam Diameter

The diameter of a circular laser beam expands in size as it propagates from the laser. The beam spread follows a hyperbolic path in space; not a straight line pathway usually depicted. The first estimates used a linear equation: $D_L = a + r \cdot \phi$ to express beam diameter (D_L) as a function of the emergent beam size (a) and the beam divergence angle (ϕ) and the distance (r). This equation is only valid when $a \ll r \cdot \phi$; which does not apply in the near field region.

On order to more accurately compute beam size in the near (or far) field, the following more comprehensive formula for beam diameter (D_L) is used:

$$D_L = (a^2 + r^2 \cdot \phi^2)^{\frac{1}{2}} \qquad \text{(cm)}$$

where:

a = Emergent beam diameter (cm).
r = Range (distance) from laser (cm).
ϕ = Laser beam divergence (rad.)

For example, compute the beam diameter at a range of 10 meters for a dye laser operating at at wavelength of 0.504 μm, where the beam divergence is 1.5 mrad and the emergent beam diameter is 3 mm.

Then, substituting into the equation above:

$$\begin{aligned} D_L &= [(0.3)^2 + (10\text{x}10^2)^2 \cdot (1.5\text{x}10^{-3})^2]^{\frac{1}{2}} \\ &= [(0.09) + (1\text{x}10^6) \cdot (2.25\text{x}10^{-6})]^{\frac{1}{2}} \\ &= [(0.09) + (2.25)]^{\frac{1}{2}} \\ &= 1.53 \quad \text{cm} \end{aligned}$$

It informative to note that the value that would have been computed using the "old" linear equation would have been: $D_L = a + r \cdot \phi = 0.3 + (1000 \cdot 1.5\text{x}10^{-3}) = 0.3 + 1.5 = 1.8$ cm. Consequently, the linear equation is really only valid after the beam has propagated far enough to have expanded to several times the initial beam diameter. Consequently, use of the linear formulation does present errors in the near field.

Note that when the beam waist is located <u>in front of</u> the laser exit port (as is sometimes the case), the above relationship may be modified by substituting the diameter of the beam waist (w_0) for the term a, and $r-r_0$ for the term r (where r_0 is the distance to the beam waist). Thus the beam diameter equation for out-of-cavity beam waist conditions becomes:

$$D_L = [w_0{}^2 + (r-r_0)^2 \cdot \phi^2]^{\frac{1}{2}}$$

Using such values of beam spot diameter, the laser range equation can then compute a closer estimate of irradiance or radiant exposure at a given distance from the laser. The linear equation cannot simply be modified to allow for the possibility of an external waist.

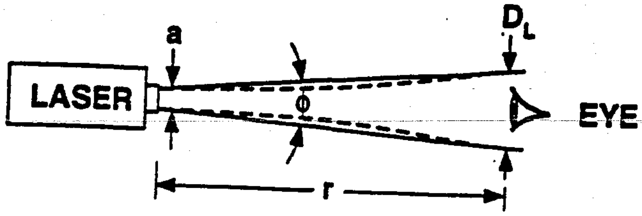


Fig. B1
Intrabeam Viewing - Direct (Primary) Beam.

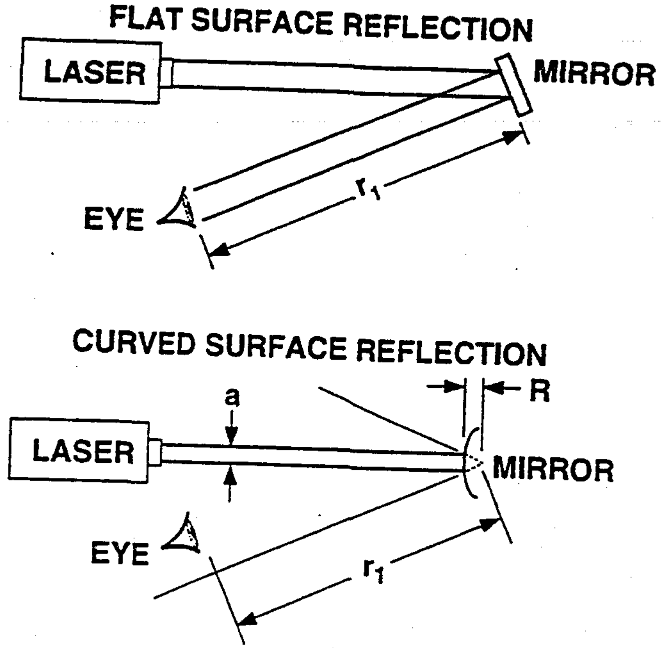
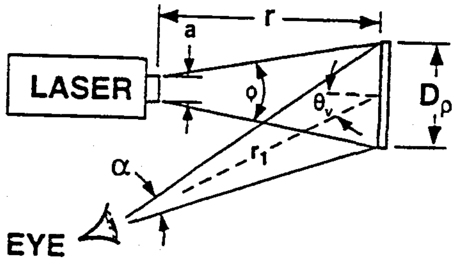


Fig. B2
Intrabeam Viewing - Specularly Reflected
(Secondary) Beam.



Note: r = total beam distance (direct plus reflected) from laser to eye

Fig. B3
Extended Source Viewing - Normally Diffuse Reflection.

Geometry for Basic Laser Safety Parameters

SUMMARY OF CORRECTION FACTORS

The Maximum Permissible Exposure (MPE) levels specified by the ANSI Z-136.1 standard involve the use of specific formulas with specific correction factors. These are described in the following:

Summary of ANSI Z136.1 (1992) MPE Correction Factors

Correction Factor		Wavelength Range (μm)
Near Infrared Correction Factor:		
$C_A = 1.0$		$0.400 \leq \lambda \leq 0.700$
$C_A = 10^{2.0(\lambda - 0.700)}$		$0.701 \leq \lambda \leq 1.050$
$C_A = 5$		$1.051 \leq \lambda \leq 1.400$
Blue Light Correction Factor:		
$T_1 = 10 \times 10^{20(\lambda - 0.550)}$		$0.550 \leq \lambda \leq 0.700$
$C_B = 1.0$		$0.400 \leq \lambda \leq 0.550$
$C_B = 10^{15(\lambda - 0.550)}$		$0.551 \leq \lambda \leq 0.700$
Mid-Infrared Correction Factor:		
$C_C = 1.0$		$1.050 \leq \lambda \leq 1.150$
$C_C = 10^{18(\lambda - 1.150)}$		$1.151 \leq \lambda \leq 1.200$
$C_C = 8$		$1.201 \leq \lambda \leq 1.400$
Multiple Pulse Correction Factor:		
$C_P = n^{-\frac{1}{4}}$		$0.400 \leq \lambda \leq 1.400$
Extended Source Correction Factor:		
$C_E = 1.0$	for: $\alpha < \alpha_{min}$	$0.400 \leq \lambda \leq 1.400$
$C_E = \alpha / \alpha_{min}$	for: $\alpha_{min} < \alpha < 100$	$0.400 \leq \lambda \leq 1.400$
$C_E = \alpha^2 / [100 \alpha_{min}]$	for: $\alpha > 100$	$0.400 \leq \lambda \leq 1.400$

Summary of α_{min} Factors:

α_{min} = 1.5 mrad for: $t \leq 0.7$ s.
α_{min} = $2 \cdot t^{3/4}$ mrad for: 0.7 s. < t < 10 s.
α_{min} = 11 mrad for: t >= 10 s.

MAXIMUM PERMISSIBLE EXPOSURES

The Maximum Permissible Exposure (MPE) levels specified by the ANSI Z-136.1 standard involve the use of specific formulas given in the standard. These are described in the following:

SKIN EXPOSURE MPE VALUES

The MPE's for skin exposure are given in Table 7 in ANSI Z-136.1. These provide guidance for determining skin exposures in all wavelength ranges. [Note: the MPE criteria in the UV (0.180 - 400 μm) and Far Infrared (1.4 - 10^3 μm) are the <u>same</u> for either skin (Table 7) or eye exposures (Table 5).]

SOLVE THE PROBLEM: Given a CO_2 laser at 10.6 μm wavelength. Determine the skin MPE for a 1.0 second exposure. Express MPE in terms of a radiant exposure.

Review Table 7 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

For the 10.6 μm wavelength of the CO_2 laser, the MPE is expressed as follows in exposure time of 1.0 seconds:

$$\text{MPE} = 0.56 \times t^{\frac{1}{4}}$$

Thus:

$$\text{MPE} = 0.56 \times \boxed{1.0}^{\frac{1}{4}}$$

$$\text{MPE} = 0.56 \times \boxed{1.0}$$

This is expressed as a radiant exposure:

$$\text{MPE} = \boxed{\mathbf{0.56}} \quad (\text{J/cm2})$$

SKIN EXPOSURE MPE VALUES

The MPE's for skin exposure are given in Table 7 in ANSI Z-136.1. These provide guidance for determining skin exposures in all wavelength ranges. [Note: the MPE criteria in the UV (0.180 - 400 μm) and Far Infrared (1.4 - 10^3 μm) are the <u>same</u> for either skin (Table 7) or eye exposures (Table 5).]

SOLVE THE PROBLEM: Given a Alexandrite tunable laser operating at the wavelength of 0.720 μm. Determine the skin MPE for a 1.0 second exposure. Express MPE in terms of a radiant exposure.

Review Table 7 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

For the 0.720 μm wavelength of the tunable Alexandrite laser, the MPE is expressed as follows in exposure time of 1.0 seconds:

$$\text{MPE} = 1.1\ \text{CA} \times t^{1/4}$$

where: $C_A = 10^{2.0(\lambda - 0.700)}$ in the wavelength range of 0.701 to 1.050 μm. Thus, at the wavelength of 0.720 μm, one substitutes:

$$\text{MPE} = 1.1 \times \boxed{10^{2.0(0.720 - 0.700)}} \times \boxed{1.0}^{1/4}$$

$$\text{MPE} = 1.1 \times \boxed{10^{0.04}} \times \boxed{1.0}$$

$$\text{MPE} = 1.1 \times \boxed{1.096} = 1.20$$

This is expressed as a radiant exposure:

$$\text{MPE} = \boxed{1.20} \qquad (\text{J/cm}^2)$$

INTRABEAM OCULAR MPE VALUES

The intrabeam MPE's for eye exposure are given in Table 5 in ANSI Z-136.1. These provide guidance for determining eye exposures in all wavelength ranges.

Far-infrared (1.4 - 10^3 um) MPE Values

SOLVE THE PROBLEM: Given a CO_2 laser at 10.6 μm wavelength. Determine the ocular MPE for an all-day ($3x10^4$ second) exposure. Use only "small area criteria. Express MPE in terms of irradiance.

Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

From Table 5, at the 10.6 μm wavelength of the CO_2 laser, the MPE in exposure time of $3x10^4$ seconds is expressed as follows:

$$\text{MPE} = \boxed{0.100}$$

which is expressed as an irradiance:

$$\text{MPE} = \boxed{0.100} \quad (\text{W/cm}^2)$$

Visible (cw) (0.4 - 0.7 um) MPE Values

Case #1: The Argon Laser

SOLVE THE PROBLEM: Given an argon laser at 0.514 μm wavelength. Determine the ocular MPE for an all-day ($3x10^4$ second) exposure. Express MPE in terms of irradiance.

Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

From Table 5, at the 0.514 μm wavelength of the argon laser, the MPE in exposure time of $3x10^4$ seconds is expressed as follows:

$$MPE = C_B \times 10^{-6} \quad (W/cm^2)$$

where: $C_B = \boxed{1.0}$ in the wavelength range 0.400-0.550 μm.

Thus:

$$MPE = \boxed{1x10^{-6}}$$

which is expressed as an irradiance:

$$MPE = \boxed{\mathbf{1x10^{-6}}} \quad (W/cm^2)$$

Visible (cw) (0.4 - 0.7 um) MPE Values

Case #2: The Helium Neon Laser

> SOLVE THE PROBLEM: Given a HeNe laser at 0.633 μm wavelength. Determine the ocular MPE for an "aversion response" (0.25 second) exposure. Express MPE in terms of an irradiance.

> Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

From Table 5, at the 0.633 μm wavelength of the HeNe laser, the MPE in exposure time of 0.25 seconds is expressed as follows:

$$\text{MPE} = 1.8\, t^{3/4} \times 10^{-3} \quad \text{(J/cm2)}$$

where: $$t^{3/4} = \boxed{0.25}^{3/4} = \boxed{0.3535}$$

Thus, expressed as a radiant exposure:

$$\text{MPE} = \boxed{0.64\text{x}10^{-3}} \quad \text{(J/cm2)}$$

To express this as an irradiance, divide the result by the exposure time:

$$\text{MPE} = \frac{\boxed{0.64\text{x}10^{-3}}}{\boxed{0.25}}$$

$$\text{MPE} = \boxed{\mathbf{2.54x10^{-3}}} \quad (\text{W/cm}^2)$$

Near-infrared (0.7 - 1.4 um) MPE Values

Case #1: The Nd:YAG (cw) Laser

> SOLVE THE PROBLEM: Given a Nd:YAG laser at 1.064 μm wavelength. Determine the ocular MPE for a 10 second exposure. Express MPE in terms of an irradiance.

> Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

From Table 5, at the 1.064 μm wavelength of the Nd:YAG laser, the MPE in exposure time of 10 seconds is expressed as follows:

$$\text{MPE} = 9\ t^{3/4} \times 10^{-3} \quad (\text{J/cm2})$$

where: $$t^{3/4} = \boxed{10.0}^{3/4} = \boxed{5.62}$$

Thus, expressed as a radiant exposure:

$$\text{MPE} = \boxed{50.6\text{x}10^{-3}} \quad (\text{J/cm2})$$

To express this as an irradiance, divide the result by the exposure time:

$$\text{MPE} = \frac{\boxed{50.6\text{x}10^{-3}}}{\boxed{10.0}}$$

$$\text{MPE} = \boxed{\mathbf{5.1x10^{-3}}} \quad (\text{W/cm}^2)$$

Near-infrared (0.7 - 1.4 um) MPE Values

Case #2: The Nd:YAG (pulsed:Q-switched) Laser

SOLVE THE PROBLEM: Given a Nd:YAG laser at 1.064 μm wavelength. Determine the ocular MPE for a 10 nsec, exposure. Express MPE in terms of a radiant exposure.

Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

From Table 5, at the 1.064 μm wavelength of the Nd:YAG laser, the MPE in exposure time of 10 nsec. is expressed as follows:

$$\text{MPE} = \boxed{5.0\text{x}10^{-6}}$$

Thus, expressed as a radiant exposure:

$$\text{MPE} = \boxed{5.0\text{x}10^{-6}} \qquad \text{(J/cm2)}$$

SOLVE ANOTHER PROBLEM: Using the Nd:YAG laser in the problem above, assume the laser is operated at a Pulse Repetition Rate (PRF) of 1000 Hertz for a time (T) of 10 seconds. Determine the <u>MPE per pulse</u> for the 10 s. pulse train. Express MPE in terms of a radiant exposure.

For repetitive pulses, each pulse will have the MPE modified by the multiple pulse correction factor (MPCF) as follows:

$$\text{MPCF} = N^{-\frac{1}{4}} = [\ (\text{PRF}) \text{ x } (\text{T})\ ]^{-\frac{1}{4}}$$

Thus:

$$N^{-\frac{1}{4}} = \boxed{(1000)\text{x}10}^{-\frac{1}{4}} = \boxed{0.10}$$

The revised MPE for the pulse train is then:

$$\text{MPE}_{(\text{revised})} = N^{-\frac{1}{4}} \text{ x MPE} = \boxed{0.10} \text{ x } \boxed{5.0\text{x}10^{-6}}$$

Finally:

$$\text{MPE}_{(\text{revised})} = \boxed{\mathbf{0.5x10^{-6}}} \qquad \text{(J/cm2)}$$

Multiple Pulse Correction Factor

The pulsed:Q-switched) Laser

> SOLVE THE PROBLEM: Using a Nd:YAG laser, assume the laser is operated at a Pulse Repetition Rate (PRF) of 1000 Hertz for a time (T) of 10 seconds. Determine the <u>MPE per pulse</u> for the 10 s. pulse train.

From Table 5, at the 1.064 μm wavelength of the Nd:YAG laser, the MPE/pulse in exposure time of 10 nsec. is expressed as follows:

$$\text{MPE} = \boxed{5.0\text{x}10^{-6}} \quad (\text{J/cm2})$$

For repetitive pulses, each pulse will have the MPE modified by the multiple pulse correction factor $C_P=n^{-\frac{1}{4}}$.

$$C_P = N^{-1/4} = [(\text{PRF}) \text{ x } (\text{T})]^{-1/4}$$

Thus:

$$N^{-1/4} = \boxed{(1000)\text{x}10}^{-1/4} = \boxed{0.10}$$

The revised MPE for the pulse train is then:

$$\text{MPE}_{(\text{revised})} = N^{-1/4} \text{ x MPE} = \boxed{0.10} \text{ x } \boxed{5.0\text{x}10^{-6}}$$

Finally:

$$\text{MPE}_{(\text{revised})} = \boxed{0.5\text{x}10^{-6}} \quad (\text{J/cm2})$$

Mid-infrared (1.05 - 1.4 um) MPE Values

SOLVE THE PROBLEM: Given a HeNe laser operating at the mid-infrared wavelength of 1.152 μm. Compute the ocular MPE for an all-day (3×10^4 second) exposure. Express the MPE in terms of irradiance.

Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

From Table 5, at the 1.152 μm wavelength of the HeNe laser, the MPE in exposure time of 3×10^4 seconds is expressed as follows:

$$\text{MPE} = 1.6\ C_C \times 10^{-3}$$

Where the Mid-Infrared Correction Factor is given by:

$$C_C = 10^{18(\lambda - 1.150)}$$

in the wavelength range of 1.151 to 1.200 μm. Thus, substituting at the HeNe wavelength: $\lambda = 1.152$ μm, we have:

$$\text{MPE} = \boxed{1.6 \cdot [10^{18(1.152 - 1.150)}] \times 10^{-3}}$$

$$\text{MPE} = \boxed{1.6 \cdot [10^{18(0.002)}] \times 10^{-3}}$$

$$\text{MPE} = \boxed{1.6 \cdot [10^{(0.036)}] \times 10^{-3}}$$

$$\text{MPE} = \boxed{1.6 \cdot [1.086] \times 10^{-3}}$$

$$\text{MPE} = \boxed{1.74 \times 10^{-3}} \qquad (\text{W/cm}^2)$$

Far-infrared (1.4 - 10^3 um) MPE Values

SOLVE THE PROBLEM: Given a Holmium YAG laser at 2.1 μm wavelength. Determine the ocular MPE for a 1000 second exposure.

Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

From Table 5, at the 2.1 μm wavelength of the Ho:YAG laser, the MPE in exposure time of 1000 seconds is expressed as follows:

$$\text{MPE} = \boxed{0.100}$$

which is expressed as an irradiance:

$$\text{MPE} = \boxed{0.100} \quad (\text{W/cm}^2)$$

INTRABEAM OCULAR MPE VALUES

Mid-Infrared Correction Factor

A new wavelength dependent correction factor now is applicable for the mid-infrared spectral region. The factor (C_C) is in the region from 1.15 - 1.4 μm and provides a wavelength dependent increase in MPE limits in this spectral range up to a maximum of 8 times over previous MPE values. This applies to some diode lasers and select solid state and gas lasers.

SOLVE THE PROBLEM: Given a Nd:YAG laser operating at the not-so-common 1.33 μm wavelength. Compute the MPE and AEL values for this laser for a 1000 second exposure.

Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

Operating a CW Nd:YAG laser operating for an exposure time of 1000 seconds at the not-so-common 1.33 μm wavelength, the Mid- Infrared correction factor in the spectral range 1.200 to 1.400 μm is $C_C = 8$. The MPE is given by:

$$MPE = 1.6 \cdot C_C \times 10^{-3}$$

$$= \boxed{1.6 \cdot (8.0) \times 10^{-3}} = \boxed{12.8 \ mW/cm^2}$$

Using a 3.5mm limiting aperture, the area of a circular aperture (ALA) is computed:

$$ALA = [\pi \cdot (LA)^2]/4$$

$$= \boxed{[(3.14) \cdot (0.35)^2]/4} = \boxed{9.62 \times 10^{-2}}$$

This laser would have a Class 1 AEL value:

$$AEL = MPE \times ALA$$

$$AEL = \boxed{(12.8 \times 10^{-3}) \times (9.62 \times 10^{-2})} = \boxed{1.23 \ mW}$$

EXTENDED SOURCE OCULAR MPE VALUES

Visible (cw) (0.4 - 0.7 um) Extended Source MPE Values
Case #1: The Argon Laser

> SOLVE THE PROBLEM: Given argon laser at 0.514 μm wavelength. Compute ocular MPE for condition of viewing a diffuse reflection from a 5.0 Watt argon laser that has been expanded to produce a 20 cm beam spot on a lab wall. Assume persons could possibly view the spot as a diffuse reflection for 100 seconds at a distance of 0.5 meter.

First determine whether the viewing angle meets the extended source criteria: α_{min} = 11 mrad @ t >= 10 s. The 20 cm spot (D_L) is an EXTENDED SOURCE up to a maximum viewing distance (r_{1max}) of:

$$r_{1max} = D_L \cdot \cos\theta / \alpha_{min}$$

$$= \boxed{(20)\text{x}(1.0)/11\text{x}10^{-3}} = \boxed{1.82 \text{ meter}}$$

Beyond that distance, the spot would generate retinal spot sizes that are treated as point source (intrabeam) images. The actual limiting angular subtense (α) for the viewing condition at the range (r) of 0.5 meters is:

$$\alpha = D_L \cdot \cos\theta / r$$

$$= \boxed{(20)\text{x}(1.0)/(50)} = \boxed{400 \text{ mrad}}$$

This is clearly <u>larger</u> than α_{min} limit of 11 mrad. Thus all lab personnel would be viewing an extended source. In order to compute the extended source MPE_{ES} one must <u>first</u> compute the point source MPE_{PS} for this laser and exposure time. This is done by determining (see ANSI Table 5) that the point source MPE_{PS} = 10 x 10^{-3} J/cm^2. Thus, for a 100 second exposure time, this may be expressed as the average irradiance:

$$MPE_{PS} = \boxed{[10 \text{ x } 10^{-3}]/100} = \boxed{100\ \mu\text{W/cm}^2}$$

Next, one then computes the extended source correction factor C_E. This is given by the formula below for the case where α>100:

$$C_E = \alpha^2/[(\alpha_{min}) \cdot (100)]$$

$$= \boxed{(400)^2/[(11) \cdot (100)]} = \boxed{145}$$

Thus the extended source MPE value is:

$$MPE_{ES} = C_E \cdot MPE_{PS}$$

$$= \boxed{(145) \cdot (100\text{x}10^{-6})} = \boxed{14.5 \text{ mW/cm}^2}$$

This is the maximum corneal exposure limit in the extended source region at r_1 = 0.50 M.

CLASSIFICATION

Case #1: Holmium: YAG laser: Middle Infrared (cw) (1.4 - 5.0 um)

Classifications of lasers operating in the ultraviolet (UV) and middle infrared (MIR) range determined using the revised ANSI Z136 (1992) may be markedly different than earlier versions of the standard. This results because the Limiting Apertures (LA) have been increased from 1.0 to 3.5 mm (see Table 2).

Table 2
Limiting Apertures for Hazard Evaluation

Spectral Region (μm)	Duration (sec)	Aperture Diameter (mm)	
		Eye	Skin
0.180 to 0.400	$1\text{x}10^{-9}$ to 0.25	1.0	3.5
	0.25 to $3\text{x}10^{4}$	3.5	3.5
0.400 to 1.400	$1\text{x}10^{-9}$ to $3\text{x}10^{4}$	7.0	3.5
1.400 to $1\text{x}10^{2}$	$1\text{x}10^{-9}$ to 0.3	1.0	3.5
	0.3 to 10	1.5 $t^{3/8}$	3.5
	10 to $3\text{x}10^{4}$	3.5	3.5
$1\text{x}10^{2}$ to $1\text{x}10^{3}$	$1\text{x}10^{-9}$ to $3\text{x}10^{4}$	11.0	11.0

Since the magnitude of the AEL values (used in classification) are proportional to the area of a circle with the diameter the limiting aperture, the AEL's in the UV and MIR will increase by a factor of over 12 based on this factor alone.

SOLVE THE PROBLEM: Compute the MPE and AEL values for a Ho:YAG laser operating at a wavelength of 2.1 μm for an exposure time of 100 seconds.

Review Table 5 for MPE criteria. Note MPEs are dependent upon both exposure time and laser wavelength.

The MPE is given by the

$$\text{MPE} = 0.1 \quad \text{W/cm}^2$$

The AEL is determined by computing the product of the MPE for a 100 s. exposure and the area of a 3.5 mm Limiting Aperture

$$\text{ALA} = [\pi \cdot (\text{LA})^2]/4$$

$$= \boxed{[(3.14)\cdot(0.35)^2]/4} = \boxed{9.62 \text{ x } 10^{-2}}$$

Thus:

$$\text{AEL} = \text{MPE x ALA}$$

$$\text{AEL} = \boxed{(100\text{x}10^{-3})\text{x}(9.62\text{x}10^{-2})} = \boxed{9.62 \text{ mW}}$$

Class 3B Q-switched Pulsed Laser Criteria

The ANSI Z136.1 (1992) uses a new approach to establish Class 3B criteria for pulsed (Q-switched) lasers. The method determines the maximum allowable pulse energy that can strike a diffuse surface and still maintain a safe diffuse viewing criteria.

This is determined using a modified inverse square law formulation. Because this is not truly a point source condition, the equation is modified by adding an additional image distance equal to one-half of the beam diameter($D_L/2$). In this computation, the modified inverse square law is solved for pulse energy when the ocular exposure is equal to the allowed MPE with all correction factors applied for the laser pulse. This is expressed by the formula:

$$Q = \frac{\pi \cdot (\mathrm{MPE}) \cdot (r_1 + D_B/2)^2 \cdot C_A \cdot C_E}{\sigma(\lambda) \cdot \cos\theta}$$

Where:

r_1 = Range (20 cm)
D_B = Beam spot size (cm)
C_A, C_E = Correction factors
$\sigma(\lambda)$ = Reflection coefficient
$\cos\theta$ = Viewing angle

SOLVE THE PROBLEM: Consider a single pulse Nd:YAG laser (1.064 μm) emitting a 30 nsec Q-switch pulse. Determine the maximum incident pulse energy incident on a diffuser that meets Class 3B - safe diffuse reflection criteria.

Substututing in the equation, the MPE = $5\text{x}10^{-7}$ for a single pulse Q-switched Nd:YAG. At this laser wavelength, the correction factor C_A=5.0. Given that the viewing angle is directly onto the target ($\theta=0°$) with a complete (100%) reflection [$\sigma(\lambda)=1.0$] and a spot diameter on the diffuser of D_B=1cm and a viewing range of r_1=20cm, then:

$$Q = \boxed{\frac{\pi \cdot (5\text{x}10^{-7}) \cdot (20 + 1.0/2)^2 \cdot (5.0) \cdot C_E}{(1.0) \cdot (1.0)}}$$

One can now compute the limiting angular subtense $\alpha = D_L \cos\theta / r_1 = (1.0) \cdot (1.0)/(20)$ = 50 mrad which is greater than $\alpha_{\min}$ = 1.5 mrad but less than 100 mrad for this exposure time. Thus the correction factor is determined to be CE = $\alpha/\alpha_{\min}$ = 50/1.5 = 33.33. Finally the maximum Class 3B pulse rgy can be computed as:

$$Q = \boxed{\pi \cdot (5\text{x}10^{-7}) \cdot (20 + 1.0/2)^2 \cdot (5.0) \cdot (33.33)}$$

$$= \boxed{110 \text{ mJ/puls}}$$

Thus, the "allowed" emission from this Q-switched Nd:YAG laser to maintain Class 3B status is 110 mJ/pulse. If the pulse energy exceeds this magnitude, the laser would be Class 4.

INTRABEAM OD COMPUTATION

Based upon given exposure conditions, the optical density (OD) is computed with a logarithmic function defined by:

$$OD = \log_{10}\left[\frac{H_o}{MPE}\right]$$

Where: H_o = Anticipated worst case exposure (J/cm2 or W/cm^2).

MPE = Maximum permissible exposure level expressed in the same units as H_o.

Based upon the worst case exposure conditions, one can determine the optical density needed to provide adequate eye protection.

SOLVE THE PROBLEM: Given a 100 Watt Nd:YAG (cw) laser at 1.064 μm wavelength. Determine the OD required for a 10 second exposure. Assume "worst case" exposure.

Using the equation above, one must <u>first</u> compute the ANSI MPE value for 10 seconds, that is:

$$MPE = \boxed{50.6\text{x}10^{-3}} \quad J/cm^2 = \boxed{5.06\text{x}10^{-3}} \quad W/cm^2$$

Next, we must compute the anticipated worst case exposure

$$H_o = \frac{4 \text{ x } [\ 100\ ]}{3.14 \text{ x } [(0.7)]^2}$$

$$\boxed{H_o = 259.8} \quad W/cm^2$$

Thus; substituting, we have:

$$\boxed{OD = \log_{10}\left[\frac{259.8}{5.06\text{x}10^{-3}}\right] = \log_{10}(5.135\text{x}10^4)}$$

Thus, the value for the required OD is:

$$OD = \boxed{\mathbf{4.7}}$$

DIFFUSE REFLECTION OD COMPUTATION

Viewing Class IV diffuse reflections (such as during alignment tasks) requires, in general, less OD which can be determined using the ANSI point source MPEs and the inverse square law:

$$H_o = \frac{\sigma \ \Phi \ \cos \Theta}{\pi \ R^2}$$

where:

R = The distance from the diffuser (cm).
Φ = Laser beam output (Watts or Joules).
σ = The coefficient of reflectance.
Θ = The angle of incidence (measured off normal)
H_o = Worst case exposure (W/cm^2 or J/cm2).

SOLVE THE PROBLEM: Given a 5 Watt argon laser at 0.514 μm wavelength. Determine the OD required for an exposure time of 600 seconds for a 90% diffuse reflection when one is standing at "arms length" away (eg: 0.5 meter). Assume worst case viewing angle.

First, one must compute the anticipated worst case exposure:

$$\boxed{H_o = \frac{[\ 0.90\ ] \times [\ 5.0\ ] \times [\ 1.0\ ]}{3.14 \times [\ (50)\ ]^2}}$$

$$\boxed{H_o = 572.9\text{x}10^{-6}} \quad \text{W/cm}^2$$

Then, using the equation for OD, one must <u>next</u> determine the ANSI MPE value for 600 seconds, that is:

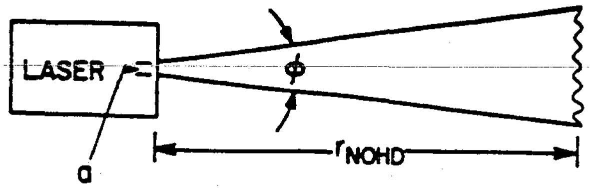
$$\text{MPE} = \boxed{10.0\text{x}10^{-3}} \ \text{J/cm2} = \boxed{16.7\text{x}10^{-6}} \ \text{W/cm2}$$

Thus; (making sure the radiometric units are the same) we can substituting into the equation:

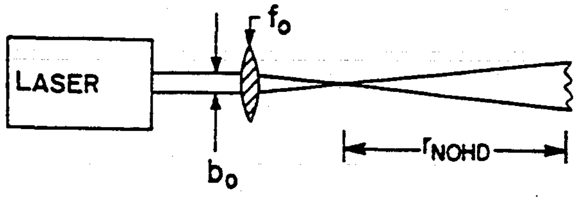
$$\boxed{\text{OD} = \log_{10} \left[\frac{572.9\text{x}10^{-6}}{16.7\text{x}10^{-6}} \right]}$$

Thus, the value for the required OD is:

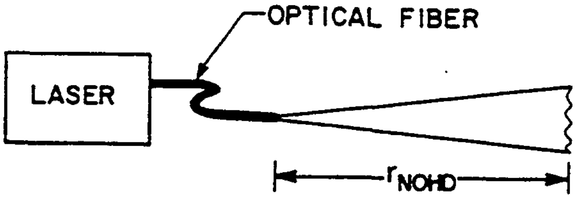
$$\text{OD} = \boxed{\mathbf{1.5}}$$



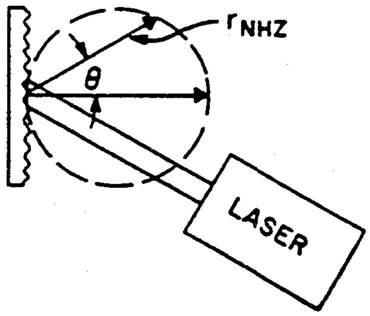
$$r_{NOHD} = \frac{1}{\phi}\left[\left(\frac{4\Phi}{\pi \cdot MPE}\right)^{1/2} - a\right]$$



$$r_{NOHD} = \left(\frac{f_o}{b_o}\right)\left(\frac{4\Phi}{\pi \cdot MPE}\right)^{1/2}$$



$$r_{NOHD} = \begin{cases} \dfrac{1.7}{NA}\left[\dfrac{\Phi}{\pi \cdot MPE}\right]^{1/2} & \text{(MULTIMODE)} \\ \dfrac{\omega_o}{\lambda}\left[\dfrac{\Phi}{MPE}\right]^{1/2} & \text{(SINGLEMODE)} \end{cases}$$



$$r_{NHZ} = \left(\frac{\rho \Phi \cos\theta}{\pi \cdot MPE}\right)^{1/2}$$

Geometry for Nominal Hazard Zones

INTRABEAM NOMINAL HAZARD ZONE

If the value of the irradiance at a distance (R) away from the laser is maintained at (or below) the MPE, then the distance is considered the intrabeam NHZ range ($R_{I.B.NHZ}$) or "safe range" value. This may be expressed in terms of the laser parameters as follows:

$$R_{I.B.NHZ} = \frac{1}{\phi}\left[\left[\frac{4\ \Phi}{\pi \mathrm{x} MPE}\right] - a^2\right]^{\frac{1}{2}}$$

where: $R_{I.B.NHZ}$ = The intrabeam NHZ distance (cm).
ϕ = The laser beam divergence (radians).
Φ = Laser beam output (Watts).
a = The laser beam dimension at the system aperture (cm).
MPE = Maximum permissible exposure limit (W/cm^2).

SOLVE THE PROBLEM: Consider the case of the following laser:
Type: Carbon Dioxide
Wavelength: 10.6 μm
Laser Power: 1000 W
Beam Divergence: 3 m rad.
Beam aperture diameter: 5 mm
Exposure time: 1000 sec.

One must <u>first</u> compute the ANSI MPE value for 1000 seconds, that is, the MPE is:

$$MPE = \boxed{0.100}\ \mathrm{W/cm^2}$$

Thus; substituting, we have:

$$R_{I.B.NHZ} = \frac{1}{(3\mathrm{x}10^{-3})}\left[\left[\frac{4 \mathrm{\ x\ } (\ 1000\ )}{3.14 \mathrm{\ x\ } (\ 0.100\ )}\right] - [\ 0.5\ ]^2\right]^{\frac{1}{2}}$$

Thus, the value of the intrabeam NHZ is:

$$\boxed{R_{I.B.NHZ} = \mathbf{376.1}}\ \mathrm{Meters}$$

Intrabeam Nominal Hazard Zone

Carbon Dioxide Laser

When the new beam size formulation is incorporated into the intra- beam nominal hazard zone relationship, the revised NHZ equation becomes:

$$NHZ = \frac{1}{\phi} \cdot \left[\frac{4 \cdot \Phi}{\pi \cdot (MPE)} - a^2 \right]^{\frac{1}{2}}$$

SOLVE THE PROBLEM: Compute the NHZ for a CO_2 laser where the emergent beam is 3 cm, the beam divergence is 2.0 mrad for a laser power of to 100 watts.

The MPE for this laser is given in Table 5 as: MPE=0.100 W/cm^2. Thus, substituting:

$$NHZ = \boxed{\frac{1}{2.0 \times 10^{-3}} \cdot \left[\frac{4 \times 100}{\pi \cdot (0.1)} - (3.0)^2 \right]^{\frac{1}{2}}}$$

$$= \boxed{(500) \cdot \left[(1273.24) - 9 \right]^{\frac{1}{2}}}$$

$$= \boxed{1.778 \times 10^4 \text{ cm}}$$

$$= \boxed{177.8 \text{ meters}}$$

DIFFUSE REFLECTION NOMINAL HAZARD ZONE

There are some instances where it is useful to calculate the distance away from a "point source" diffuse reflector at which a specific irradiance occurs. The diffuse reflection nominal hazard zone ($R_{D.R.NHZ}$) can be written :

$$R_{D.R.NHZ} = \left[\frac{\sigma\ \Phi\ \cos\theta}{\pi \times MPE}\right]^{\frac{1}{2}}$$

where: $R_{D.R.NHZ}$ = The diffuse reflection NHZ distance (cm).
Φ = Laser beam output (Watts).
σ = The coefficient of reflectance.
θ = The angle of incidence (measured off the normal and expressed in degrees).
MPE = Maximum permissible exposure limit (W/cm^2).

SOLVE THE PROBLEM: Consider the case of the following laser:
Type: Argon Laser
Wavelength: 0.488 μm
Laser Power: 20 W
Viewing Angle: 0 degrees
Reflection Coefficient: 80 % (0.8)
Exposure time: 0.25 sec.

One must <u>first</u> compute the ANSI MPE value for 0.25 seconds, that is, the MPE is:

$$MPE = \boxed{2.5\text{x}10^{-3}}\quad W/cm^2$$

Thus; substituting, we have:

$$R_{D.R.NHZ} = \left[\frac{[\ 0.8\ ] \times [\ 20\ ] \times \cos[\ 0^{\circ}\ ]}{3.14 \times [\ 2.5\text{x}10^{-3}\ ]}\right]^{\frac{1}{2}}$$

Thus, the value of the diffuse reflection NHZ is:

$$\boxed{R_{D.R.NHZ} = \mathbf{0.45}}\quad \text{Meters}$$

LENS-ON-LASER NOMINAL HAZARD ZONE

Many laser uses incorporate a lens as the final component in the beam path which provides an increased irradiance in the focal plane of the lens. This causes the beam to spread with an angle usually many times larger than the inherent laser beam divergence in the space <u>beyond</u> the focal plane. Consequently, the MPE irradiance is reached in a distance much less than the intrabeam NHZ. This is called the lens-on-the-laser nominal hazard zone range ($R_{L.L.NHZ}$) as given by:

$$R_{L.L.NHZ} = \left[\frac{f_o}{b}\right] x \left[\frac{4\ \Phi}{\pi x MPE}\right]^{\frac{1}{2}}$$

where:
$R_{L.L.NHZ}$ = The lens-on-laser NHZ distance (cm).
Φ = Laser beam output (Watts).
f_o = The lens focal length (mm).
b = The beam diameter as it strikes the lens (mm).
MPE = Maximum permissible exposure limit (W/cm^2).

SOLVE THE PROBLEM: Consider the case of the following laser:
Type: Nd:YAG Laser (cw)
Wavelength: 1.064 μm
Laser Power: 200 W
Beam Diameter @ lens: 5 mm
Focal length of the lens: 100 mm
Exposure time: 1000 sec.

One must <u>first</u> compute the ANSI MPE value for 1000 seconds, that is, the MPE is:

$$MPE = \boxed{1.6x10^{-3}} \quad W/cm^2$$

Thus; substituting, we have:

$$\boxed{R_{L.L.NHZ} = \left[\frac{[\ 100\ ]}{[\ 5.0\ ]}\right] x \left[\frac{4 \quad x \quad [\ 200\ ]}{3.14 \quad x \quad [1.6x10^{-3}]}\right]^{\frac{1}{2}}}$$

Thus, the value of the lens-on-laser NHZ is:

$$\boxed{R_{L.L.NHZ} = \mathbf{79.8}} \quad \text{Meters}$$

FIBER-OPTIC NOMINAL HAZARD ZONE

In a manner similar to the lens-on-laser condition, a fiber optic attached in the beam path also provides a beam expanding element that shrinks the hazard range depending upon the characteristics of the fiber. For a typical multi-mode fiber used for some industrial Nd-YAG applications, the fiber optic NHZ range ($R_{F.O.NHZ}$) is given by:

$$R_{F.O.NHZ} = \left[\frac{1.7}{NA}\right] \times \left[\frac{\Phi}{\pi \times MPE}\right]^{\frac{1}{2}}$$

where:

$R_{F.O.NHZ}$ = The fiber optic NHZ distance (cm).

NA = The fiber optic numerical aperture: ($NA = [n_1^2 - n_2^2]^{0.5}$; where n_1=core index, and n_2=cladding index).

Φ = Laser beam output (Watts).

MPE = Maximum permissible exposure limit (W/cm^2).

SOLVE THE PROBLEM: Consider the case of the following laser:

Type:	Laser Diode (cw)
Wavelength:	0.860 μm
Laser Power:	0.5 W
Fiber Numerical Aperture:	0.23
Exposure time:	100 sec.

One must <u>first</u> compute the ANSI MPE value for 100 seconds, that is, the MPE is:

$$MPE = \boxed{1.8 x C_A x t^{3/4} = 1.8 x (2.09) x (100)^{3/4}}$$

$$MPE = \boxed{1.8 x (2.09) x (31.6) = 118.9 x 10^{-3}} \quad J/cm^2$$

Thus; substituting, we have:

$$\boxed{R_{F.O.NHZ} = \left[\frac{1.7}{[\ 0.23\ ]}\right] \times \left[\frac{[\ 0.5\ ]}{3.14 \times [11.9 x 10^{-4}]}\right]^{\frac{1}{2}}}$$

Thus, the value of the fiber-optic NHZ is:

$$\boxed{R_{F.O.NHZ} = \mathbf{0.85}} \quad \text{Meters}$$

NOTE: The computational results for various NHZ conditions are summarized below in Table 2.

SOURCES OF ADDITIONAL COMPUTATIONS

Examples of additional OD and NHZ calculations are also detailed in the Appendix of ANSI Z136.1 (1986) and the Appendix of the Guide for Laser Safety published by the ACGIH as-well-as several other publications as detailed in the references.

In addition, computer software is also available to assist in the computations for OD and NHZ. One such program is a menu driven MS-DOS program called LAZAN(C) is available from Rockwell Laser Industries.

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Table 1

Intrabeam OD Values For Various Laser Types

Laser Type/Power	*Wavelength (µm)*	*OPTICAL DENSITY*			
	Exposure Time: (s)	*0.25*	*10*	*600*	*$3x10^4$*
XeCl 50 Watts	0.308[b]	-*-	6.2	8.0	9.7
XeFl 50 Watts	0.351[b]	-*-	4.8	6.6	8.3
Argon 1.0 Watt	0.514	3.0	3.4	5.2	6.4
Krypton 1.0 Watt	0.530	3.0	3.4	5.2	6.4
Krypton 1.0 Watt	0.568	3.0	3.4	4.9	6.1
HeNe 0.005 Watt	0.633	0.7	1.1	1.7	2.9
Krypton 1 Watt	0.647	3.0	3.4	3.9	5.0
GaAs 50 mW	0.840[b]	-*-	1.8	2.3	3.7
Nd:YAG 100 Watt	1.064[b]	-*-	4.7	5.2	5.2
Nd:YAG (Q-switched)[a]	1.064[b]	-*-	4.5	5.0	5.4
CO_2 1000 Watts	10.6[c]	-*-	6.2	8.0	9.7

[a] Repetitively pulsed @ 11 Hz., 12 ns pulses, 20 mJ/pulse.

[b] OD for UV & FIR beams computed using 1mm limiting aperture which presents a "worst case" scenario. All visible/NIR computations assume 7mm limiting aperture.

-*- Invisible beams; aversion response time does not apply.

NOTE: OD values obtained using ANSI Z-136.1 (1986) MPE criteria.

Table 2

NHZ Distance Values for Various Laser Types

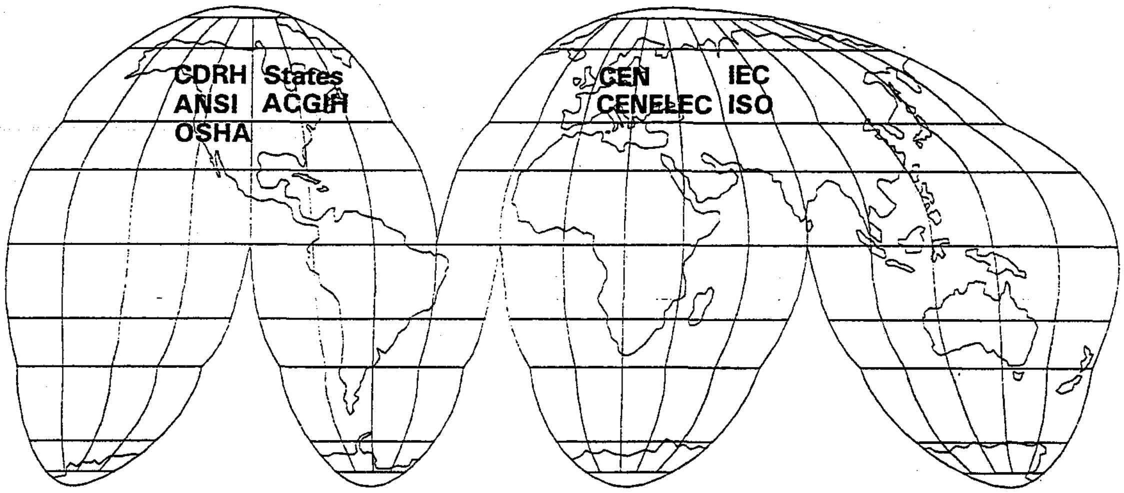
Laser Type	Exposure Criteria	Nominal Hazard Zone Hazard Range (meters)			
		Diffuse (100%)	Lens-on Laser	Direct Beam	Fiber Optic
Nd:YAG 100 W 1.064 µm	8 hr.	1.4	11.3	1410	12.0
	10 s.	0.8	6.3	792	6.7
CO_2 1000 W 10.6 µm	8 hr.	0.56	7.5	555	n/a
	10 s.	0.56	7.5	555	n/a
Argon 5.0 W 0.488 µm	8 hr.	12.6	1.7×10^3	2.5×10^4	107.2
	0.25 s.	0.25	33.3	240	2.1
QS:Nd:YAG 50 mJ 1.064 µm	8 hr.	4.9	277	2.2×10^3	n/a
	10 s.	1.8	102	810	n/a
Doub. YAG 10 W 0.532 µm	8 hr.	17.8	1.4×10^3	8.9×10^3	151.6
	0.25 s.	0.35	28.3	175	3.1

Laser criteria used for NHZ distance calculations:

Laser Parameters	Nd-YAG	CO_2	Argon	Q-swi. Nd:YAG	Doub. Nd:YAG
Wavelength (µm)	1.064	10.6	0.488	1.064	0.532
Beam power (Watts)	100.0	1000.0	5.0	-	10.0
Pulse Energy (J)	-	-	-	0.05	-
Divergence (mrad):	2.0	2.0	1.0	4.4	4.0
Beam @ aperture(mm):	2.0	20.0	2.0	6.0	4.0
Beam @ lens: (mm):	6.3	30.0	3.0	7.0	5.0
Focal length: (mm):	25.4	200.0	200.0	200.0	200.0
Pulse Length: (µsec.)	CW	CW	CW	1×10^{-2}	CW
Pulse Rate: (Hz)	-	-	-	1000	-
Numerical Aperture:	0.2		0.2		0.2
MPE Criteria:					
8 hr. ($\mu W/cm^2$):	1.6×10^3	1.0×10^5	1.0	68.0	1.0
10 sec. ($\mu W/cm^2$):	5.1×10^3	1.0×10^5	-	500.0	-
0.25 sec. ($\mu W/cm^2$):	-	-	2.5×10^3	-	2.5×10^3

MODULE 7.0

LASER SAFETY STANDARDS



RII Education

LASER SAFETY STANDARDS

In the United States, laser safety standards are established by the American National Standards Institute (ANSI), the Center for Devices and Radiological Health (CDRH), the Occupational Safety and Health Administration (OSHA), the American Conference of Governmental Industrial Hygienists (ACGIH), and various state governments. Outside of the United States, laser safety standards are internationally set by the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO). In Europe, the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) have developed standards relative to laser safety.

A major challenge in the coming decades will be to achieve global harmonization of laser standards. This module explains the roles of the various organizations engaged in formulating and enforcing laser safety standards.

- An Overview of Laser Safety Standards in the United States
- CDRH and ANSI Standards
- International Laser Safety Standards

TABLE OF CONTENTS

LASER SAFETY STANDARDS

AN OVERVIEW OF LASER SAFETY STANDARDS IN THE UNITED STATES

SECTION OBJECTIVES

- Identify the four major laser safety organizations in the United States
- Contrast the roles of ANSI and CDRH in establishing laser standards
- Explain how the ANSI laser safety standard is applied by OSHA
- Relate SSRL to individual state laser regulations

STANDARDS

In the United States there are six major entities concerned with regulations regarding safety of laser systems. These groups are the Center for Devices and Radiological Health (CDRH), the American National Standards Institute (ANSI), the Occupational Safety and Health Administration (OSHA), the American Conference of Governmental Industrial Hygienists (ACGIH), and state governments. Table 1 lists the major laser safety organizations and their associated laser standards.

CDRH

The **Center for Devices and Radiological Health** (CDRH) is a regulatory bureau within the Federal Food and Drug Administration (FDA) of the Department of Health and Human Services. CDRH has been chartered by Congress to standardize the performance safety of manufactured laser products. All laser products manufactured after August 2, 1976 that have been entered into commerce must comply with these regulations. The regulation is known as the Federal Laser Product Performance Standard (FLPPS) and is identified as 21CFR subchapter parts 1040.10 and 1040.11.

In addition, FDA also enforces compliance with the Medical Devices Legislation. All medical laser manufacturers must obtain either premarket approval or clearance of their laser surgical devices. The FDA also sanctions the exploratory use of lasers for specific procedures through a process known as an **investigational device exemption** (IDE). Approval of an IDE permits the limited use of a laser expressly for the purpose of conducting an investigation of the laser's safety and effectiveness. Once an IDE has been done and the CDRH has cleared the laser device, the manufacturer may then actively market the laser for that specific medical procedure.

ANSI

The **American National Standards Institute** (ANSI) is an organization for which expert volunteers participate on committees to set industry consensus standards in various fields. ANSI has been the basis for existing federal standards, as well as for the Suggested State Regulations for Lasers (SSRL) legislation.

TABLE 1

NATIONAL LASER SAFETY STANDARDS

AGENCY	VOLUNTARY STANDARD	REQUIRED STANDARD
CDRH		*U.S. Federal Laser Product Standard*: Title 21 of the Code of Federal Regulations; Part 1000 (parts: 1040.10 and 1040.11)
OSHA		*Guidelines for Laser Safety and Hazard Assessment*: OSHA Instruction Pub 8-1.7, Aug. 19, 1991 OSHA Directorate of Technical Support *Construction Laser Standard* 29 CFR 1926.54 (non-ionizing radiation) *Eye Protection for Construction Lasers* 29 CFR 1926.102 *General Duty Clause* Section 5(a)(1) OSHA Act *Face and Eye Protection (general)* 29 CFR 1910.132 *Lockout/Tagout* 29 CFR 1910.147
States	Conference of Radiation Control Program Directors: *Suggested State Regulation for Lasers*	AL: Title 18, Art. 7 AZ: Title 12, Art. 14 AR: Act 460 FL: Ch. 10D-89 GA: Ch: 270-5-27 IL: Ch. 111 1/2 MA: 105 CMR 21 MT: 92-003 NY: Code Rule 50 PA: Ch. 203, Title 25 TX: RCA: parts 50, 60, 70 WA: Ch. 296-62-WAC
ACGIH	*Industrial Ventilation*	
ANSI	*For the Safe Use of Lasers (ANSI Z136.1)* *For the Safe Use of Optical Fiber Communication Systems (ANSI Z136.2)* *For the Safe Use of Lasers in Health Care Facilities (ANSI Z136.3)* *The National Electrical Code ANSI/NFPA 70-1990* *Practice for Occupational and Educational Eye and Face Protection (ANSI Z87.1)*	

ANSI has established three major laser safety standards: ANSI Z136.1, ANSI Z136.2, and ANSI Z136.3. ANSI Z136.1 provides requirements and recommendations for the safe use of lasers. ANSI Z136.2 defines control measures for optical fiber communication systems, utilizing lasers and light emitting diodes, and ANSI Z136.3 establishes engineering, procedural, and administrative control measures for health care facilities. CDRH and ANSI are discussed in more detail in a later section.

OSHA

Another Federal agency involved with laser safety is the **Occupational Safety and Health Administration** (OSHA), which is responsible for assuring a safe work place. At the present time, OSHA does not have a comprehensive laser standard. Instead, the OSHA policy has been to rely on ANSI Z136.1, the generally accepted industry laser standards, and FDA/CDRH laser manufacturer requirements. Although OSHA does not have a comprehensive laser standard, it does publish several specific laser-standard and guideline documents. These documents include:

Construction Laser Standard (29 CFR 1926.54). This standard, which only applies to the use of lasers in the construction industry, requires trained operators, posting of laser areas, and equipment labels. The standard also establishes alignment and beam positioning procedures and weather-related laser requirements. In addition, the standard limits laser power to 5 mW, unless eyewear is provided.

Protective Eye and Face Equipment (29 CFR 1910.132) — describes general specifications for all protective eyewear (comfort, fit, durability).

Laser Eye Protection Standard (29 CFR 1926.102) — specifies the optical density at the required wavelength.

General Duty Clause (OSHA Act: Public Law 91-596) — states that the, "work place must be free from recognized hazards." OSHA inspectors have used this clause to cite laser installations. Typical citations refer to conformance with ANSI Z136.1 as a means of correcting the laser hazard.

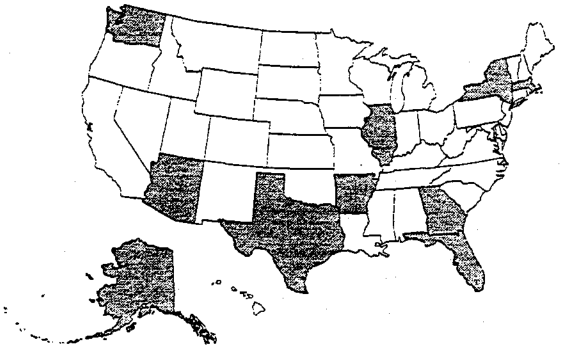
Lockout/Tagout Standard (29 CFR 1910.147) — applies to the maintenance and service of laser power supplies. The standard requires a full lockout or tagout program to ensure that employees are protected against hazardous exposure to electrical energy.

ACGIH

The **American Conference of Governmental Industrial Hygienists** (ACGIH) publishes the Guide for Laser Safety, which is an excellent supplement to ANSI standard Z136.1. ACGIH also publishes Industrial Ventilation, which has been recognized as the industry standard on industrial ventilation for more than 40 years.

STATE REGULATIONS

Laser regulations vary considerably from state to state and are generally concerned with the registration of lasers and the licensing of operators and institutions. At present, physicians and medical lasers generally are exempt from most state requirements. Table 1 summarizes the current state laser regulations.



Alaska

The Alaska rules are contained in Title 18 of the Alaska Annotated Code, Part 85, Article 7, Sections 670-730. These rules were published in October 1971. Very little enforcement is made on these regulations. For more information contact (907) 465-3019.

Arizona

The Arizona rules are contained in Article 14, Rules for the Control of Non-ionizing Radiation, Sections R12-1-1421 to 1444. According to this regulation, all laser facilities must register with the State if they possess or maintain Class 3 or Class 4 lasers. For more information contact (602) 255-4845.

Arkansas

The Arkansas rules are contained in Act 460, Electronic Products Radiation Control Act. Historically, laser regulation has been given a low priority. For more information contact (501) 661-2306.

Florida

The Florida rules are contained in Chapter 10D-85 of Florida's Administrative Code, Section 101-134. These rules, which became effective in September 1984, regulate all facilities with any lasers higher than Class 1. Action is under way, however, to amend this requirement to only Class 3b and 4 laser systems. Registration of lasers is required; and no fee is assessed. For more information contact (904) 487-1004.

Georgia

The Georgia rules are contained in Chapter 270-5-27, Rules and Regulations for Laser Radiation. These rules, which require the registration of all lasers regardless of Class, have no specific exposure limitations. Enforcement of this regulation, however, has been very limited due to staff and funding restrictions. For more information contact (404) 894-5795.

Illinois

This state has enabling legislation, only. No regulations have been promulgated. Citation for the Illinois position is found in the Revised Statutes 1985, Chapter 111 1/2, paragraphs 701-709. Registration of all lasers is required by this law, regardless of the presence or absence of regulations. The law also requires that all laser accidents be reported. For more information contact (217) 785-9868.

Massachusetts

The Massachusetts rules are contained in Section 51, Chapter 111, General Laws-adopted September 1, 1970, Rules and Regulations Relative to the Use of Laser Systems, Devices, or Equipment to Control the Hazards of Laser Rays or Beams. Registration of all lasers is required by this law, but the law is currently being enforced only for Class 3b and 4 laser systems. Exposure limits are out of date, and are not used. Registration and accident reporting are the essential active elements of this regulation. For more information contact (617) 522-3700, ext. 444.

New York

The New York laser program is unique in that it is administered under the Department of Labor, yet it is considered to be a radiological health program. New York requires certificates of competence for mobile laser operators. Obtaining a certificate requires application and examination of prospective operators, unless they have adequate and acceptable education. Registration of laser systems is required and fees are assessed for registration and certificates. Laser classification is either high or low intensity and there exists exposure limitation tables. For more information contact (718) 797-7641.

Texas

In September 1974, Texas adopted Regulations for the Control of Laser Radiation Hazards. These regulations have been amended five times as of September 1989. This active program has requirements for registration, reporting of laser incidents, and exposure limits. For more information contact (512) 835-7000.

Washington

Laser regulation is administered by the Department of Labor and Industries, but it is not considered a radiological health program. The regulations are contained in Chapter 296-62-09005, Washington Administrative Code, General Occupational Health Standards. According to this regulation, all laser systems must be classified in accordance with FDA and ANSI. Protective eyewear requirements are given. For more information contact (206) 281-5436.

SSRL

Regulations for lasers vary significantly among the various states. This inconsistency could be reduced if the states were all to adopt the **Suggested State Regulation for Lasers** (SSRL), which has been proposed by the Conference of Radiation Control Program Directors. SSRL has been adopted, in part, by the States of Florida and Arizona.

SKILL REVIEW
1

Categorize CDRH, ANSI, OSHA, ACGIH, SSRL and state laser standards as regulatory or voluntary.

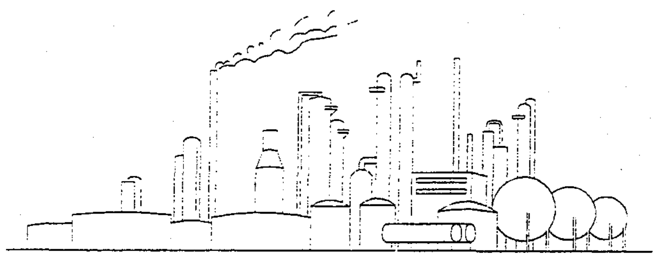
Answer here:

CDRH AND ANSI STANDARDS

SECTION OBJECTIVES

- Summarize the CDRH laser classification system
- Explain the terms modification, certification, and compliance as they are relative to the CDRH laser regulations
- Describe the role of ANSI in laser safety
- Identify ANSI standards Z136.1-3

CDRH



CDRH is a division of the FDA. The mission of the CDRH as established by Congress is to standardize the manufacture of lasers relative to safety performance. In this regard CDRH administers The Federal Laser Product Performance Standard (Federal Law 21 CFR 1040.10 and 1040.11). This law requires any organization in the business of manufacturing, modifying, or importing laser products into the United States after August 1976 for commercial purposes to comply with the provisions of this regulation. Under this law, manufacturers of laser products are required to certify their products to be in conformance with the requirements of 21 CFR 1040.11 and 1040.11. The requirements are based on classification of products to the human access of relative safe or hazardous levels of radiation; and providing the various performance features, labeling and documentation required for each level of classification.

Manufacturers must classify lasers and laser systems according to the lasers ability to cause injury to the eye or skin from direct or reflected laser beams. According to the CDRH classification scheme, a Class 1 laser is a low-power laser that is incapable of causing injury to the eye or skin from exposure to the laser beam. A Class 2 laser is a low-power device that cannot cause injury if the direct beam is viewed for no more than 0.25 seconds; a Class 2a laser does not present a hazard if the beam is viewed for no more than 1,000 seconds. A Class 3a laser is a low-to-medium power laser (less than 5 mW output power) that is relatively safe as long as eye exposure to the direct beam is avoided and optical instruments are not used to view the beam. A Class 3b laser is a medium-to-high power laser

TABLE 2

CDRH LASER CLASSIFICATION

Laser Class	Power	Hazard
1	low	none
2a	low	none for < 1000-sec exposures
2	low	none for < 0.25-sec exposures
3a	low-medium	Avoid eye exposure to direct beam and viewing with optical instruments
3b	medium-high	direct viewing is hazardous
4	high	direct viewing is hazardous; diffuse reflection is hazardous

that presents a hazard if the beam is viewed directly. A Class 4 laser is a high-power laser that can cause eye and skin injury by viewing the direct beam or a diffuse reflection. Class 4 lasers are so powerful that the beam can ignite combustible materials and may therefore present a fire hazard. The CDRH classification scheme is illustrated in Table 2.

Modification

In the event that a laser product is modified, the organization that made the modification must re-certify the product. For this purpose, modification occurs when any function or safety feature of the laser product is changed. For example, when a laser is integrated into a work station or combined with other accessories for a specific purpose, the integration is considered to be a modification since the function of the device is changed. Similarly, if a laser is transferred from a group that made the modifications to any other personnel, even within the same company, the modifications have been done for commercial purposes provided the organization is "in the business of" making these modifications. "In the business of" modifying lasers is normally taken to mean that more than one laser has been modified and re-entered into commerce.

Certification

Certification occurs when the manufacturer (a) sends a certification report to the CDRH and (b) places a "Certified" label on the laser product. The report consists of documenting that the design, production quality, labeling, and user information meet the standard. Since the manufacturer certifies the product, a positive response (approval) from the CDRH is not given. However, if deficiencies are recognized by the CDRH, the manufacturer is required to correct the problem.

Compliance

Compliance with CDRH is required by law. Compliance means that the laser product meets certain minimum safety requirements. Under no circumstances should a non-certified laser product be used in a production environment. In this regard, laser users should be especially cautious about using any laser that was built prior to August 1976 because such devices may not have the necessary safety features. If re-certification of a laser is not appropriate; then prior to using an uncertified laser, the ANSI Z136.1 standard, which is described in the next section, should be applied to determine the classification of the laser and to identify any additional engineering controls that must be added to the laser product.

ANSI

ANSI is an organization of laser experts who volunteer to serve on committees to establish industry consensus standards on laser safety issues. The ANSI standards are intended as a guide for manufacturers, consumers, and the public.

ANSI Standards are voluntary standards that suggest industry-wide consensus on requirements for the safe use of lasers for personnel who operate, maintain, or service lasers. Although the ANSI Standards are voluntary, these standards have been specifically cited by OSHA, which requires compliance with the ANSI Standards. Similarly, the Federal Department of Energy requires its personnel and contractors to adhere to the ANSI Standards.

ANSI Z136.1

ANSI Z136.1 *For the Safe Use of Lasers*, takes over where the CDRH regulation ends. The CDRH regulation is limited to laser product issues, but the ANSI standard is used to establish the appropriate control measures for laser usage. Only if engineering laser controls are added or removed or if the laser is built as an experimental or research device, is it usually necessary to use the ANSI guide to re-classify a laser.

The CDRH and ANSI classifications are nearly identical, and any laser classified in accordance with the CDRH regulation fulfills the ANSI classification requirement. Nevertheless, there are slight differences between the ANSI and CDRH exposure criteria.

SKILL REVIEW
2

Identify two important differences between the CDRH regulation and the ANSI standard.

Answer here:

ANSI Z136.1 sets the standards for laser hazard assessment including nominal hazard zone (NHZ) and maximum permissible exposure (MPE). The standard also establishes control measures for laser and nonbeam hazards, suggests medical surveillance practices, and outlines laser training requirements.

ANSI Z136.2

ANSI Z136.2 *For the Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources* provides guidance for the maintenance and service of **Optical Fiber Communication Systems** (OFCSs) utilizing laser diodes or light emitting diodes with an average output powers of 0.5 W or less and wavelengths between 0.4 and 1000 mm. This standard is intended for manufacturers of OFCSs, and for installation and service personnel. This standard only applies to systems in which the radiant energy is confined to an optical fiber during intended use.

Since all OFCSs are designed to normally operate as Class 1, the only risk of exposure would occur during installation or service. Accordingly, OFCSs have been assigned to one of four **Service Groups** (SG1, SG2, SG3a, SG3b). SG1 is for an OFCS for which there is no risk of exceeding the **maximum permissible irradiance** (MPI)[1] when viewing the end of an optical fiber with a microscope, eye-loupe, or the unaided eye. An OFCS is classified SG2 if it emits at wavelengths between 0.4 and 0.7 mm, and if it is potentially hazardous if viewed for more than 0.25 seconds. The SG3a classification applies to systems that are hazardous when viewed with a microscope or an eye-loupe, but that are not hazardous when viewed with the unaided eye. An OFCS is classified SG3b if it exceeds the above criteria, provided that the total power does not exceed 0.5 W.

SG1 does not require control measures. Control measures for service and installation are required for SG2, SG3a, and SG3b. Medical surveillance of service personnel is required only for SG3B.

Normally, the emission from a Class 3b diode laser at wavelengths between 0.4 and 1.4 mm is highly divergent so that the beam irradiance decreases rapidly with distance away from the output connector. For this reason inadvertent viewing of a disconnected or unterminated energized optical fiber with the unaided eye at distances greater than 10 cm from the connector normally will not cause eye injury. Damage may be possible, however, when viewing a fiber with optical aids. Injury may also occur when using lens connectors, which decrease beam divergence.

ANSI Z136.3

ANSI Z136.3 *For the Safe Use of Lasers in Health Care Facilities* establishes standards for therapeutic and diagnostic uses of lasers in health care facilities. The standard establishes engineer-

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1. MPI — For wavelengths less than 1.4 m, MPI is related to MPE by the ratio of the areas of a 5-mm diameter and 7-mm limiting aperture; for wavelengths > 1.4 m, MPI = MPE.

ing, procedural, and administrative control measures. The standard also establishes procedures for medical surveillance and details training requirements.

INTERNATIONAL AND EUROPEAN LASER SAFETY STANDARDS

SECTION OBJECTIVES

- Compare and contrast the roles of the IEC, ISO, and JESI
- Describe the organization of the IEC, ISO, and European Standards

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EUROPEAN

International standards for laser safety have been established by several organizations. These organizations include the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO). European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC). CEN and CENELEC, together form a major part of the Joint European Standards Institution (JESI).

In addition, Germany has established safety requirements and testing procedures for laser protective eyewear. Table 3 lists the major international laser safety organizations and their associated standards.

IEC

The **International Electrotechnical Commission** (IEC) is an international standards organization that is responsible for developing electrical and electronic standards for the international laser community. The IEC uses a network of volunteer **Technical Committees** (TCs), **Working Groups** (WGs), and **Subcommittees** (SCs) to develop laser safety standards. For example, TC62, TC76, and TC86 are involved with the development of laser standards. The various IEC WGs and TCs are listed in Table 4.

Each committee, which is made up of experts who represent the member countries, may or may not have major topic SC's. Smaller WG's of experts prepare draft standards to the SC's and TC's. These drafts are submitted to the national committees of the member countries for review comments, and eventually for balloting.

The national committees in turn make comments and recommendations on the draft standards. When a draft standard has been voted on and approved by the national committees, the standard is then submitted to the IEC. When the IEC approves the standard for content and form, it becomes an IEC standard.

Like ANSI standards in the United States, IEC standards are voluntary. Many countries, however, have adopted the IEC standards as their required laser safety standards. The IEC has published three laser standards developed by TC76: IEC 820, IEC 825 and IEC 1040. The IEC 820 standard, Electrical Safety of Laser Equipment and Installations, does not apply to equipment containing lasers for which there are other specific electrical standards, such as office products or computer equipment, except for the laser system portion if when removed from equipment is operable as a stand-alone laser system.

IEC 825, Radiation Safety of Laser Products, Equipment Classification, Requirements and User's Guide is divided into three sections. Section 1 is a general section. Section 2, Manufacturer's Requirements, is analogous to FDA 21 CFR 1040.10. Section 3, User's Guide, is analogous to ANSI Z136.1. Compliance and/or certification to IEC 825 is required in many countries.

The IEC 1040, "Power and Energy Measuring

TABLE 3

INTERNATIONAL LASER SAFETY STANDARDS

ORGANIZATION	VOLUNTARY STANDARD	REQUIRED STANDARD
IEC	IEC 820 Electrical safety of laser equipment and installations IEC 825 Radiation Safety of Laser Products, Equipment Classification, Requirements and User's Guide IEC 1040 Power and Energy Measuring Detectors, Instruments and Equipment for Laser Radiation	
ISO	D15 11553 Draft International Standard "Safety of Machines Using Laser Radiation to Process Materials" Note: Will be obligatory in similar EN document under parallel approval through CEN	
CENELEC	EN: 60825	(In balloting phase)
Germany		Filters and Eye Protectors Against Laser Radiation: Safety Requirements and Testing (DIN-58-215) Laser Adjusting Goggles: Safety Requirements and Testing (DIN-58-219)

TABLE 4

IEC TC'S and WG'S

TC	WG	DESCRIPTION
76	1	Radiation Safety
76	2	Electrical and Other Hazards
76	3	Measurements
76	4	Medical Lasers
76	5	Safety of Fiber Optic Systems
76	6	Partitioning of IEC825, symbols, misc.
76	7	High Power Lasers
86		Fiber Optics
62D		Electromedical Equipment

Detector, Instruments and Equipment for Laser Radiation", is a standard laser safety measurements equipment. IEC 601-2-22, Medical Electrical Equipment-Part 2: Particular Requirements for the Safety of Diagnostics and Therapeutic Laser Equipment" is a standard produced out of TC62D with a joint project with TC76.

ISO

The **International Organization for Standardization** (ISO) is similar to the IEC. The two organizations are organized in the same manner, with TCs, SCs and WGs. One major difference between these two organizations is that ISO does not address electrical standards. The various ISO WGs and TCs are described in Table 5.

TABLE 5

ISO WGs and TCs

TC	WG	Description
172/SC9	1	Terms, Test Methods, and Test Instruments for Lasers
172/SC9	2	Interfaces and System Specifications for Lasers
172/SC9	3	Safety
172/SC9	4	Laser Systems for Medical Applications
172/SC9	5	Laser Systems for General Applications
172/SC9	6	Optical Components and their Test Methods

EUROPEAN STANDARDS

JESI

The **Joint European Standards Institution** (JESI) is an organization consisting of European standards organizations, two of which are involved with lasers: The **European Committee for Standardization** (CEN) and the **European Committee for Electrotechnical Standardization** (CENELEC). The primary function of CEN and CENELEC is to prepare European standards (EN) for the countries that make up the European Economic Communities (EEC) and the European Free Trade Area (EFTA). CEN and CENELEC have common rules of procedure, are headquartered in the same facility, and share some of their staff and equipment with each other. Their primary difference is the same as with ISO and IEC. CEN is concerned with non-electrical standards, and CENELEC is concerned with electrical standard. The various CEN and CENELEC WGs and TCs are described in Table 6.

TABLE 6

European
CEN and CENELEC

CEN		
TC	WG	DESCRIPTION
123	1	Terminology, Test Methods, and System Specifications
123	2	Interfaces
123	3	Safety
123	4	Reporting Groups

CENELEC		
TC	WG	DESCRIPTION
76		Laser Equipment

Ideally, CEN would adopt existing ISO standards, modifying the standards if needed. In this way, CEN standards would consist of ISO base standards and common modifications. Similarly, CENELEC would adapt IEC standards. In actual practice, however, ISO and IEC standards are used by both CEN and CENELEC. CEN and CENELEC standards are listed in Table 7.

When CEN and CENELEC standards reach the ultimate level of a European Standard (EN), they no longer are referred to as CEN or CENELEC, but only as a "European Norm". They are, however, maintained and revised by the CEN or CENELEC committee responsible for their development.

In addition to preparing European laser standards, CEN and CENELEC also issue another level of standard, called a **Harmonization Document** (HD). When an HD is issued, it must be adopted by all member countries that have a current requirement of the same title. If a member country has no current requirement, it may or may not choose to adopt the HD. The EN, however, must be adopted by all member countries, and becomes a requirement throughout all member countries (EEC and EFTA).

TABLE 7

CEN AND CENELEC STANDARDS
(European)

STANDARD	DESCRIPTION
CENELEC HD 194	A harmonized document standard that is nearly equivalent to IEC 820
EN 60 825	A European standard that consists of IEC 825 plus first amendment. This standard is a requirement in several countries. Each country may modify Section 3 according to national requirements.
CENELEC EN 61040	Adopted IEC 1040
CEN EN 207	Personal Eye-Protection-Filters and Eye-Protectors Against Laser Radiation (Laser Safety Eye-Protectors)
CEN EN 208	Personal Eye-Protection-Eye-Protectors for Adjustment Work on Lasers and Laser Systems (Laser Adjustment Eye-Protectors).

SKILL REVIEW
3

Which organizations are involved in the development of European Laser Standards?

Answer here:

CHAPTER REVIEW

SUMMARY

1. ANSI, ACGIH, CDRH, OSHA, and various states are involved in establishing laser safety standards in the United States.

2. CDRH is a Federal regulatory agency that classifies new or modified lasers according to their ability to cause injury.

3. ANSI is an organization of laser experts that establishes voluntary laser standards. Unlike OSHA, ANSI also establishes laser control measures.

4. ANSI Z136.1 provides requirements for the safe use of lasers; Z136.2 defines control measures for OFCSs, Z136.3 establishes control measures for health care facilities.

5. OSHA is a Federal regulatory agency that recommends ANSI Z136.1 as the guideline standard.

6. ACGIH has established voluntary laser standards.

7. SSRL is a model regulation that is aimed at reducing inconsistencies in laser regulations among states.

8. IEC is an international organization that has established voluntary electric and electronic laser standards for the international community.

9. ISO is similar to IEC except that ISO does not establish electrical laser standards.

10. JESI is the organization that consists of European standards organizations.

11. CEN and CENELEC are European standards organizations that develop European laser standards.

KEY TERMS Define each term

ACGIH
ANSI Z136.1
ANSI Z136.2
ANSI Z136.3
ANSI
CDRH
CEN
CENELEC
Certification
Compliance
Harmonization Document
IDE
IEC
ISO
JESI
MPI
OFCS
OSHA
SC
SG
SSRL
TC
WG

FOR FURTHER READING

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Lundergan, D.K. (Nov, 1990). Implementing the ANSI Z136.3 Standard in Health Care Facilities. International Laser Safety Conference, Section 8 pp. 1-5.

Laser Institute of America (1993). American National Standard for the Safe Use of Lasers (ANSI Z136.1). Orlando, FL.

Laser Institute of America (1988). American National Standard for the Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources (ANSI Z136.2). Orlando, FL.

Laser Institute of America (1988). American National Standard for the Safe Use of Lasers in the Health Care Environment (ANSI Z136.3). Orlando, FL.

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REVIEW QUESTIONS

1. The agency most concerned with certifying new lasers is:
    a. ACGIH
    b. ANSI
    c. CDRH
    d. OSHA

2. A major difference between ANSI and CDRH standards is that:
    a. ANSI standards are required
    b. CDRH standards are required
    c. CDRH standards apply to lasers built prior to 1976
    d. ANSI is federal agency

3. ANSI standard Z136.1 refers to :
    a. safe use of lasers
    b. optical fibers
    c. health care facilities
    d. medical lasers

4. The comprehensive laser standard used by OSHA is:
    a. 29 CFR 1910.146
    b. U.S. Federal Laser Product Standard
    c. ANSI Z136.1
    d. SSRL

5. A laser user in Florida would have to satisfy the requirements of:
    a. FL regulation CH 100-89
    b. OSHA
    c. ANSI
    d. all of the above

6. A major advantage of SSRL is that it would:
    a. standardize laser requirements among states
    b. establish a single laser standard for the United States
    c. standardize OSHA and CDRH laser requirements
    d. standardize CDRH and ANSI laser requirements

7. CDRH is responsible for all the following except:
    a. administering The Federal Laser Product Performance Standard
    b. establishing laser control measures
    c. the classification of new lasers
    d. recertification of modified lasers

8. The entity most concerned with establishing laser safety standards within Europe is:
    a. Germany
    b. IEC
    c. ISO
    d. CENELEC

9. The major obstacle in producing lasers for the international and U.S. markets is:
    a. tariffs
    b. metric standards
    c. the absence of a single generally accepted laser standard
    d. nationalism

SKILL REVIEW ANSWERS

1. Regulatory: CDRH, OSHA, state laser standards
   Voluntary: ANSI, ACGIH laser standards
   Voluntary: SSRL

2. (a) The CDRH standard is a regulation; the ANSI standard is voluntary
   (b) The CDRH standard is a product standard which specifies classification, performance features, labeling and user information. The ANSI Standard is voluntary and discusses the user aspects of such items as facilities, personnel protective equipment, and administrative requirements of a laser safety program.

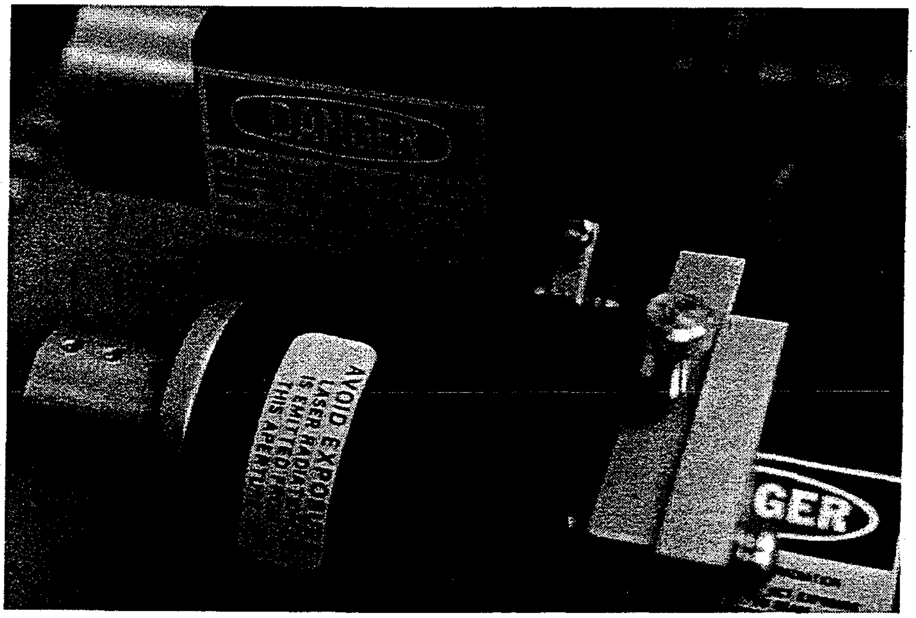
3. CEN and CENELEC

CHAPTER REVIEW ANSWERS

1. c
2. b
3. a
4. c
5. a
6. a
7. a
8. d
9. c

MINI MODULE: CLASS

LASER CLASSIFICATION



RII Education

LASER CLASSIFICATION

A review of the biological basis and description of the laser hazard classes

CONCEPTS OF THE CLASSIFICATION SCHEME

The laser classification scheme is a numbered system that is used to describe the capability of a laser system to produce injury to personnel. The classification method outlined below is the present classification requirement of the Z 136.1 (1986) " Safe Use of Lasers" Standard of the American National Standards Institute. This basic classification method has been adopted by every major national and international standards board, including the Center for Devices and Radiological Health (CDRH) in the US Federal Laser Product Performance Standard which governs the manufacturer of lasers in the United States. A laser system previously classified by the manufacturer will not generally require further classification unless alterations are made to the laser. One common alteration, for example, is total enclosure of a potentially hazardous laser so as to render the enclosed system into a Class I configuration.

The Basis of Class I and Class II

Both the CDRH standard and the ANSI-Z136 standard (from which the CDRH regulation evolved) have the nearly same concepts of classification. However, but due to slightly different interpretations of biological data and the fact that there have been two major revisions of the ANSI standard (in 1976 and 1980) after the CDRH regulation had been promulgated, there are slight differences between the ANSI and CDRH exposure criteria.

These differences are reviewed in the following paragraphs. They will be reviewed in order to indicate those areas where there appears to be a lack of consensus amongst biological and safety experts and to indicate the direction of possible future changes in the CDRH regulations.

A CDRH Class I laser is considered safe by all present measures of potential hazards. In theory, no individual, regardless of exposure conditions, would be expected to be injured by a Class I laser. The occupational exposure standard of the American Conference of Governmental Industrial Hygienists (ACGIH) suggests that there may be rare individuals such as photosensitive individuals who may actually be vulnerable to some form of injury at levels below the maximum permissible exposure level (MPE), but do not further clarify that this could also apply to the Class I limits.

Class II lasers in the other hand, are limited to visible lasers (either CW or repetitively pulsed) where the exposure within the normal aversion response of the eye would not be hazardous. For true continuous wave visible lasers, the upper limit for a CDRH for Class II laser is 1.0 mW total emitted power that can be collected within a 80 mm aperture. If the laser beam is scanning, this aperture is reduced to 7 mm. In reality, there is little basis for the smaller 7 mm collecting aperture for scanning lasers. It is the result of data presented by industrial technical personnel during the early stages of development of the CDRH standard.

Comparing hazards for lasers that are emitting in the visible through the near-infrared retinal hazard region, there are several physical aspects which are known to influence the degree of retinal hazard. These physical parameters are the ***wavelength***, the ***spatial character*** of the source (that is, whether it's a point source or whether the radiation incident upon the eye is coming from an extended source such as laser light reflected from a diffuse surface), and finally, the ***entrance aperture*** for the eye which, for the normal pupil, is limited to a maximum of about 7mm (unless the pupil has been dilated by a drug). If collecting optics such as a binocular or a telescope are employed in front of the eye, the effective entrance aperture can be considerably larger. All present laser safety standards, that is CDRH, ANSI and that of the International Electrotechnical Commission (IEC) standard, IEC, assume a single "worst-case" telescopic collecting aperture of 80 mm. Practically all binoculars fall into this category.

Industrial pressure was somehow successful in convincing CDRH personnel that the only exposure condition for a scanning laser ***would*** be without collecting optics. Whatever the case, all scanning lasers regardless of intended use, (including those which can be used out-of-doors where collecting optics such as binoculars are frequently used to view the source, or a point-of-sale scanner used in a supermarket) are evaluated from a hazard standpoint for the purpose of CDRH classification using only a 7mm aperture. This distinction should be kept in mind where the environment may allow the use of collecting optics.

The Human Aversion Response

The determination of the maximum exposure duration of an individual viewing a laser is a major problem in any laser hazard analysis. The upper limit of Class II, (1 mW total power) was originally determined by a consensus of biological experts to be the maximum permissible exposure (MPE) level resulting from an incident ***corneal*** irradiance of 2.5 mW/cm^2 entering a 7 mm pupil (approximate area: 0.4 cm^2) and focused to a point image on the retina. This exposure is "safe" for an exposure duration of 0.25 s, or less, and the duration is based upon the human aversion response.

When an individual views a bright source such as the sun, the natural response is to blink and turn away from the source of the intense glare and discomfort. Although this aversion response is not questioned, there are some people in the laser community with an extreme version of the worst-case approach to hazard analysis who fell that even this 0.25 s physiological limit to bright source viewing is not reliable. This apparently a minority view, although its proponents argue that some cases have been reported of people staring at bright sources and not turning away from such a source.

In reality, it is illogical to assert that it is ***impossible*** for people to stare at the sun or at a Class II laser for more than a quarter of a second. The important point is if this occurs, ***the individual has consciously decided to do so.*** A quarter of a second is a slightly conservative overstatement of the time, as the typical blink reflex elicited by a brilliant flash of light has complete eyelid closure within 150 to 200 ms. Those who have looked into a 1.0 mW laser generally describe the experience very much like momentarily looking at the noonday sun, which is certainly uncomfortable. In fact, the ***lower limit*** of Class II in the CDRH classification scheme (and in the original 1973 ANSI Z-136 scheme) is 0.4 μW entering the eye which corresponds to a corneal irradiance of 1.0 $\mu W/cm^2$. It is noteworthy that a source of this intensity viewed directly (intrabeam viewing) would be considered as extremely brilliant even in an outdoor daylight environment.

The Classification Duration

The ANSI 136 consensus standard applies to the laser user and is normally enforced by a "laser safety officer" who is empowered to assess the maximum expected exposure duration for the intended application (the classification duration) for the purpose of classifying a laser. Thus, if there were no CDRH standard, any person who purchased a laser would require, in principal, a laser safety officer to make a judgment as to the worst-case maximum duration of individual exposure to this source. It could be decided that this was 1, 1000, or perhaps even 3×10^4 s which determines the appropriate classification.

Not Intended for Viewing - CLASS IIa

In contrast to the ANSI-Z136 approach which leaves the degree of choice to the user, the CDRH recognized that their enforcement powers were limited only to control of manufacturers from which they could not assume any specific laser usage.

Therefore, the CDRH assumes in all cases, a worst-case exposure duration of 10^4 s. However, the recent development of a Class IIa "not intended for viewing" category resulted from the practical evaluation that there were some applications of lasers where even the most worst-case safety enthusiast would probably have to admit that human exposure was essentially impossible or extremely unlikely. In this case, therefore, a 1000 s duration is used for classification and the allowable power is increased from 0.4 μW to 4.0 μW. This IIa classification was effected in 1977 when CDRH made revisions to the original 1975 performance standard. Also, in addition to the Class IIa concept, other changes included restricting the field of view of measurements, thereby limiting the number of point sources that could be collected in the collecting aperture for classification measurements.

It is of note that ANSI standard already recognized that a worst-case (3×10^4) s exposure duration is unrealistic in many applications and special engineering controls on these lasers need not be required of the manufacturer. CDRH chose a 16 2/3 min (1000 s) exposure as a reasonable upper limit for the new Class IIa designation. This regulation now allows manufacturers of not-for-viewing laser devices to classify their products as Class II a if evidence is provided to demonstrate that only momentary, unintentional viewing is intended for the product's normal use.

ANSI-Z136 Classification Concepts

The ANSI-Z136 standard is much more flexible than the federal standard since the classification duration (T_{max}) depends upon the judgment of the user in determining exposure limit for classification purposes. This greater flexibility in the ANSI standard provides a better indication of the real biological hazard than the legal and more restrictive federal regulations. For enforcement, T_{max} must be exactly defined in order to avoid controversy.

The basic classification philosophy of ANSI, which had been adopted by most other countries in the International Electrotechnical Commission's (IEC) TC-76 Standard, holds that the risk of a Class II laser as minimal. The eye hazard of a Class II laser can best be compared to a motion picture projector, the sun, or a welding arc, all of which could be hazardous if the natural aversion to bright light is overcome and one stare recklessly at the source, risking potential retinal injury. The architects of ANSI considered that the only real requirement for a Class II laser was the application of a cautionary warning label. Because in the early 1970's (and even today) lasers were relatively unfamiliar sources with which the general public had little experience, it was certainly possible to fear a craze among a group of enthusiasts who might get a kick out of staring at a point source laser. This problem was resolved by requiring a caution label on the laser. Many manufacturers opposed this solution by the ANSI committee as unrealistic and unfair, but in the end agreed that perhaps the label had its value for medical-legal purposes.

ANSI Z-136 CLASSIFICATION PARAMETERS

Classification of essentially all lasers requires the following parameters:

1) Wavelength(s) or wavelength range
2) For continuous wave (cw) or repetitively pulsed (or scanned) lasers: average power output and limiting exposure duration (T_{max}) within a period of an eight-hour working day (3×10^4 seconds), inherent in the design or intended use of the laser or laser system.
3) For pulsed lasers: the total energy per pulse (or peak power), pulse duration, pulse repetition frequency (prf), and emergent beam radiant exposure.

Classification of extended-source lasers or laser systems (such as laser arrays, injection laser diodes and those lasers having a permanent diffuser as part of the laser output) requires, in addition to those parameters listed above the laser source radiance

(W/cm^2 sr) or integrated radiance (J/cm^{2}sr) and the maximum viewing limiting angular subtense (apparent visual angle) referred to as the α_{min} function. Extended source criteria will be used when the angular subtense (apparent visual angles) is greater than or equal to α_{min}. Conditions where the angular subtense (apparent visual angle) is less than α_{min} are considered intrabeam viewing (point source) cases.

To determine the potential for a laser or laser system to produce injury, it is necessary to consider not only the laser output irradiance or radiant exposure, but also whether a hazard would exist if the total laser output were confined within the limiting aperture for the applicable MPE. For visible lasers, the diameter of the limiting aperture is 7 mm (approximately the size of the "worst case" pupil diameter under conditions of a well-lighted environment). Note: In conditions where visible lasers are to be viewed using collecting optics (such as binoculars), an 80 mm limiting aperture shall be used instead of the 7 mm aperture.

The amount of radiant power or energy confined in the limiting aperture is defined (for classification purposes) as the Accessible Emission Limits - (AEL) for Class I lasers. The "AEL" is defined in two different ways, depending upon whether the laser is considered a point source or an extended source (the latter being an unusual case).

Most lasers can be considered point sources. For such, the AELs (Class I) are each the product of two factors:

$$\mathbf{AEL = MPE \times ALA}$$

where:

MPE = The intrabeam MPE for the eye for the limiting exposure time, and:

ALA = The area of the limiting aperture for that MPE value, expressed on cm^2.

For example, the MPE for a 10 ns Q-switched (pulsed) ruby laser (wavelength:0.694 μm) is 5 x 10^{-7} J/cm^2. The limiting aperture is 7 mm, thus the area of the limiting aperture is approximately 0.4 cm^2 (calculating the area of a circle 7 mm in diameter: Area = $\pi d^2/4$). Thus, the

$$\text{AEL} = (5 \times 10^{-7}) \times (0.4) = 0.2 \times 10^{-6} \text{ joules.}$$

Classification Definitions

The basis for the laser hazard classifications that follow is the ANSI Z-136.1 Standard of the American National Standards Institute (ANSI). As this standard indicates, classifications done using the U.S. Federal Laser Product Performance Standard (FLPPS): Title 21 of the Code of Federal Regulations; Part 1000; [Parts 1040.10 and 1040.11, as applicable] will satisfy all classification requirements of the ANSI Z-136.1 standard.

The intent of laser hazard classification is to provide warning to users by identifying the potential hazards associated with the corresponding levels of accessible laser radiation through the use of labels and instruction. It also serves as a basis for defining appropriate control measures and medical surveillance.

Lasers and laser systems received from manufacturers shall be classified and appropriately labeled by the manufacturer. However, the classification may change whenever the laser or laser system is modified to accomplish a given task. Also, the LSO shall effect the classification designation in cases where the laser or laser system classification is not provided or where the class level may change because of alterations to the laser or laser system.

It should be mentioned that the ***U.S. Federal Government does not "approve" laser systems. The manufacturer of the laser system first classifies the laser and then certifies that it meets all performance requirements of the Federal Laser Product Performance Standard (FLPPS).***

Therefore, all lasers and laser systems that are manufactured by a company, or purchased by a company and relabeled and placed into commerce, or incorporated into a system and placed into commerce, shall be classified in accordance with the FLPPS. The classification shall be confirmed by the LSO at the laser installation.

The Laser Hazard Classes

Virtually all of the U.S. domestic as-well-as all inter- national standards divide lasers into four major hazard categories called the ***laser hazard classifications.***

The basis of the classification scheme is the ability of the primary or reflected primary beam to cause biological damage to the eye or skin during intended use. The criteria is established relative to the Maximum Permissible Exposure (MPE) levels that are accessible during operation of the laser.

The classes are based upon a scheme of graded risk. They are based upon the ability of a beam to cause biological damage to the eye or skin. In the FLPPS, the classes are established relative to the Accessible Emission Limits (AEL) provided in tables in the standard. In the ANSI Z-136.1 standard, the AEL is defined as the product of the Maximum Permissible Exposure (MPE) level and the area of the limiting aperture. For visible and near infrared lasers, the limiting aperture is based upon the "worst case" pupil opening and is a 7 mm circular opening.

Lasers and laser systems are assigned one of four broad Classes (I to IV) depending on the potential for causing biological damage. The biological basis of the hazard classes are summarized below in Table 1 and are defined as follows:

Class I: cannot emit laser radiation at known hazard levels (typically cw: 0.4 μW at visible wavelengths). Users of a Class I laser products are generally exempt from radiation hazard controls during operation and maintenance (but not necessarily during service).

Since lasers are not classified on beam access during service, most all Class I industrial lasers will consist of a higher class (high power) laser ***enclosed*** in a properly interlocked and labeled protective enclosure. In some cases, the enclosure may be a room (walk-in protective housing) which requires a means to prevent operation when operators are inside the room.

Class IIA: is a special designation that is based upon a 1000 second exposure and applies ***only*** to lasers that are "not intended for viewing" such as a supermarket laser scanner. The upper power limit of Class IIA is 4.0 μW. The emission from a Class IIA laser is defined such that the emission does not exceed the Class I limit for an emission duration of 1000 seconds.

Class II: low power visible lasers which emit above Class I levels but emitting a radiant power not above 1 mW. The concept is that the human aversion reaction to bright light will protect a person. Only limited controls are specified.

Class IIIA: intermediate power lasers (cw: 1-5 mW). Only hazardous for intrabeam viewing. Some limited controls are usually recommended. Class IIIB: moderate power lasers (cw: 5-500 mW, pulsed: 10 J/cm^2 - or the diffuse reflection limit, which ever is lower). In general, Class IIIB lasers will not be a fire hazard nor are not generally capable of producing a hazardous diffuse reflection except for conditions of staring done at distances close to the diffuser. Specific controls are recommended.

Class IV: High power lasers (cw: > 500 mW, pulsed: >10 J/cm^2 - or the diffuse reflection limit) are hazardous to view under any condition (directly or diffusely scattered) and are a potential fire hazard and a skin hazard. Significant controls are required of Class IV laser facilities.

Embedded Laser: A Class II, Class III, or Class IV laser or laser system contained in a protective housing and operated in a lower classification (Class I, Class II or Class III). Specific control measures may be required to maintain the lower classification.

How to Determine The Class of Lasers During Inspection

The classification of a laser or laser product is, in some instances, a rather detailed process. It can involve determination of the AEL, measurement of the laser emission, measurement/determination of the emission pulse characteristics (if applicable), evaluation of various performance requirements (protective housing, interlocks...etc.) as specified by the FLPPS and/or ANSI standards.

Note: There are different logotype labeling requirements for Class IIIA lasers with a beam irradiance that does not exceed 2.5 mW/cm^2 (Caution logotype) and those where the beam irradiance does exceed 2.5 mW/cm^2 (Danger logotype).

It should be stressed that classification is a required specification provided by the laser manufacturer and the label that specifies the class is found in only one location on the laser product. The class of the laser will be specified only on the lower left-hand corner (position three) of the warning logotype label. (See sign/labels: Appendix B)

Table 1
Laser Classifications: Summary of Hazard Basis

CLASS	APPLIES TO WAVELENGTH RANGES				HAZARDS		
					OCULAR		FIRE
	UV	VIS	NIR	IR	DIRECT	DIFFUSE	
I	X	X	X	X	NO	NO	NO
IIA	-	X*	-	-	AFTER 1000 SEC.	NO	NO
II	-	X	-	-	AFTER 0.25 SEC.	NO	NO
IIIA	X	X**	X	X	YES	NO	NO
IIIB	X	X	X	X	YES	ONLY WHEN OUTPUT NEAR IIIB LIMIT OF = 0.5 WATTS	NO
IV	X	X	X	X	YES	YES	YES

X: Indicates Class applies in Wavelength range.

*: Class IIA applicable to lasers "not intended for viewing" only.

**: CDRH Standard assigns Class IIIA to visible wavelengths ONLY. ANSI Z-136.1 assigns to ALL wavelength ranges.

The logotype is the rectangular label that has the laser "sunburst" symbol and the warning statement of CAUTION (Class II and some Class IIIA) or DANGER (some Class IIIA, all Class IIIB and Class IV). This label will also have the type of laser designated (HeNe, Argon, CO_2...etc.) and the power or energy output specified (1 mW CW/ MAX, 100 mJ pulsed...etc.).

Class I lasers have no required labeling indicating the Class I status. Although the FLPPS requires no classification labeling of Class I lasers it does require detailed compliance with numerous other performance requirements (ie: protective housing, identification and compliance labeling, inter- locking...etc.)

Specifics of Laser Classification

All lasers and laser systems are classified (ANSI Z-136) in accordance with the accessible emission limits (AEL) as follows:

CLASS - I Lasers and Laser Systems

Any laser or laser system containing such a laser that cannot emit accessible laser radiation levels in excess of the AELs (Class I) for the maximum possible duration inherent in the design or intended use of the laser or laser systems. Such Class I lasers or laser systems cannot, under normal operating conditions, produce an eye or skin hazard.

CLASS IIa - Lasers and Laser Systems ("Not intended for Viewing"

Visible (400 - 700 nm) repetitively-pulsed- or cw lasers or laser systems may be designated as Class IIa if the laser or laser system is to be used in a manner where the output beam is not intended to be viewed in normal use. The AEL for Class IIa is based upon a maximum exposure time of 1000 seconds.

CLASS II - Visible Lasers and Laser Systems (Low-power)

1. Visible (400 - 700 nm) continuous wave lasers or laser systems which can emit accessible radiant power exceeding the Class I AEL for the maximum possible duration inherent in the design of the laser or laser system (0.4 microwatts for an emission duration greater than 3×10^4 seconds), but not exceeding 1 mW. Because of the normal human response to bright radiant sources, Class II lasers do not normally present a hazard, but may present some potential for hazard if viewed directly for extended periods of time (greater than 0.25 seconds).
2. Visible (400 - 700 nm) repetitively pulsed lasers (and scanning lasers) and laser systems which can emit accessible radiant power exceeding the appropriate Class I AEL for the maximum possible duration inherent in the design or intended use of the laser system, but not exceeding the Class I AEL for a 0.25-second exposure. Note that the 0.25 second limit is considered to be the human aversion response time factor.

CLASS IIIa- Lasers and Laser Systems (Medium power)

1. Lasers and laser systems having an accessible output power between 1 and 5 times the lowest appropriate Class III AEL, and which does not exceed the appropriate MPE as measured over the limiting aperture are designated as Class IIIa.

NOTE: For visible (400 - 700 nm) lasers and laser systems, the lowest Class III AEL is 1.0 mW, hence the Class IIIa output may range from 1.0 to 5.0 mW. The MPE applicable is that for 0.25 seconds. Thus, the MPE limit is: $1.8 x C_A x (0.25)^{3/4}$ mJ/cm^2: where $C_A = 1.0$ for visible frequencies. Thus, MPE = $1.8 \times 0.353 = 0.64$ mJ/cm^2.

On an average power basis, the irradiance for 0.25 second exposure is: $E = 0.64/0.25 = 2.5$ mW/cm^2. Thus a Class IIIa visible laser has an output of 1 to 5 mW within an irradiance of 2.5 mW/cm^2.

CLASS IIIb - Lasers and Laser Systems (Medium power)

1. Far-Infrared and ultraviolet lasers and laser systems which can emit accessible radiant power in excess of the Class I AEL for the maximum possible duration inherent in the design or intended use of the laser system, but cannot emit: (a) an average radiant power in excess of 0.5 W for a classification duration greater than 0.25 second; or: (b) a radiant exposure of 10 J/cm^2 within an exposure time equal or greater than 0.25 seconds.

2. Visible ***cw or repetitively-pulsed*** lasers or laser systems producing accessible radiant power in excess of the Class I AEL for a 0.25 second exposure (1 mW for a cw exposure), but which cannot emit an average radiant power greater than 0.25 watts. Note: CW visible (0.400 - 0.700 µm) lasers having an output power of 1-5 mW are designated Class IIIa lasers and would not normally produce a hazard if viewed with an unaided eye for momentary periods (0.25 seconds). They may present a hazard if viewed with collecting optics. All lasers not meeting Class IIIa criteria are designated as Class IIIb lasers or laser systems.

3. Visible and near-infrared ***single-pulse*** lasers and laser systems which can emit accessible radiant energy in excess of the Class I AEL, but which cannot emit a radiant exposure that exceeds 10 j/cm^2 (approximate fire-hazard point) or that required to produce a hazardous diffuse reflection. In general, Class IIIb can produce a hazard if viewed directly. Except for the most powerful Class IIIb lasers, focused on a diffuser under short-range viewing conditions, this class will not produce a hazardous diffuse reflection.

4. Near-infrared ***cw lasers-or-repetitively pulsed*** lasers which can emit accessible radiant power in excess of the Class I AEL for the maximum duration inherent in the design or intended use of the laser or laser system, but cannot emit an average power of 0.5 W or greater for periods in excess of 0.25 seconds.

CLASS IV - Lasers and Laser Systems (High power)

1. Ultraviolet and infrared lasers and laser systems which emit: 1) an average accessible radiant power in excess of 0.5 W for periods greater than 0.25 seconds; or 2) a radiant exposure of 10 J/cm^2 within an exposure duration of 0.25 second or less.

2. Visible and near-infrared lasers and laser systems which emit: 1) an average accessible radiant power of 0.5 W or greater for periods greater than 0.25 second, or 2) a radiant exposure in excess of 10 J/cm^2, or that required to produce a hazardous diffuse reflection for periods less than 0.25 seconds.

Laser System Classification - A Case Example

In order to amplify the previous section, let us consider how to classify a laser system. Consider the case of a single pulse Nd:YAG laser with a pulse energy of 80 mJ/pulse and a pulse duration of 20 nsec. From the ANSI standard, the single-pulse MPE for such an infrared wavelength laser (1.06 µm) operating in the nanosecond time frame is given by the relationship: $MPE = 5 \times 10^{-6}$ J/cm^2. In order to classify the laser, one must determine the AEL for the laser, that is: $AEL = MPE \times ALA$, or substituting: $AEL = 5 \times 10^{-6} \times 0.4 = 2.0$ µJ/pulse. (Area of limiting aperture is 0.4 cm^2).

The energy in the single pulse (80 mJ) is certainly greater than the AEL = 2.0 μJ, hence the system is not Class I. Since the system operates in the infrared (1.06 μm), the laser is ***not*** Class II. (Class II only applies to visible wavelength lasers where the aversion response can provide the first level of hazard avoidance).

The Class III criteria for single-pulse operation requires either that the energy output is greater than the Class I AEL (2.0 μJ), but less than 10 J/cm², or it is not a hazardous diffuse reflection.

Given that the emergent beam diameter (e-1 power point) is 2.0 mm, one can calculate that the beam area at that point ($\pi d^2/4$) is: $A = 3.14 \times 10^{-2}$ cm². Thus the emergent beam irradiance is: $H = 80 \times 10^{-3}/(3.14 \times 10^{-2}) = 2.55$ J/cm² which is clearly less than the 10 J/cm² criteria for Class III.

The MPE for a diffuse reflection of a 20 ns pulse (1.06μm) is given in ANSI MPE Standard (see Table 5) by the relation- ship: $MPE = 10\ C_A\ t^{1/3}$ J/cm² sr. where CA = 5 as given from the near-infrared wavelength correction factor. Computing $t^{1/3} = (20 \times 10^{9})^{1/3} = 2.714 \times 10^{-3}$, hence the $MPE = 10 \times 5 \times 2.714 \times 10^{-3} = 0.136$ J/cm² sr. Now, the radiant exposure required to produce the integrated radiance is simply $\pi \times 0.136 = 0.426$ J/cm². This is clearly less than the system output, thus the laser is a hazardous diffuse reflection potential and ***is***, therefore, a ***Class IV*** laser.

Laser Classification Measurements

The measurement and test parameters for purposes of laser classification are outlined in detail in the Federal Laser Product Performance Standard: 21 CFR Part 1040.

Tests on lasers and laser systems, for purposes of classification, shall be made during operation, maintenance or service as appropriate:

Under those conditions and procedures which maximize the accessible emission levels, including start-up, stabilized emission, and shutdown of the laser or laser system; and,

With all controls and adjustments listed in the operation, maintenance, and service instruction adjusted in combination to result in the maximum accessible emission level of radiation; and, for the case of laser diodes, with the device biased to operate at the output power levels specified in the data sheet for the intended use.

At points in space to which human access is possible in the configuration which is necessary to determine compliance with each requirement, e.g., if operation may require removal of portions of the protective housing e.g., disconnection of an optical connector for OFCS, and defeat of safety interlocks, measurements shall be made at accessible points with the measuring instrument detector positioned and so oriented with respect to the laser or laser system as to result in the maximum detection of radiation by the instrument.

Accessible emission levels of laser and collateral radiation shall be based upon the following measurements (or their equivalent) as appropriate:.

For laser products intended to be used in a locale where the emitted laser radiation is unlikely to be viewed with optical instruments, the radiant power (W) or radiant energy (J) detectable through a circular aperture stop having a diameter of 7 millimeters and within a circular solid angle of acceptance of 10^{-3} steradians with collimating optics of 5 diopters or less (i.e., a maximum distance of 20 cm). A 50 millimeter diameter aperture stop with the same collimating optics and acceptance angle shall be used for all other laser products. For scanned laser radiation, the direction of the solid angle of acceptance shall change as needed to maximize detectable radiation, with an angular speed of up to 5 rad./second. A 50 millimeter diameter aperture stop with the same collimating optics and acceptance angle stated above shall be used for all other laser products.

The irradiance (W/cm²) or radiant exposure (J/cm²) equivalent to the radiant power (W) or radiant energy (J) detectable through a circular aperture stop having a diameter of 7 millimeters and, for irradiance, within a circular solid angle of acceptance of 10^{-3} steradian with collimating optics of 5 diopters or less, divided by the area of the aperture stop (cm^2).

The radiance (W/cm^2 sr) equivalent to the radiant power (W) or radiant energy (J) detectable through a circular aperture stop having a diameter of 7 millimeters and within a circular solid angle of acceptance of 10^{-5} steradians with collimating optics of 5 diopters or less, divided by solid angle (sr) and by the area of the aperture stop (cm^2).

For diode lasers coupled to an optical fiber, the radiant power (W) or radiant energy (J) detectable through a circular aperture stop having a diameter of 7 mm can be calculated from the output power measured at the connector (closed system) and the numerical aperture (for a multimode fiber) or the mode field diameter (for a single mode fiber). This procedure, described in ANSI Z136.2, provides a conservative estimate, i.e., yields values slightly in excess of the corresponding measured values.

OPTICAL FIBER SERVICE GROUPS

Optical Fiber Communication Systems (OFCS) and the associated optical test sets use semiconductor lasers or LED transmitters that emit energy at wavelengths typically greater than 700 nm into the light guide fiber optic cables. This is detailed in the ANSI Z-136.2 (1988) standard: ***For the Safe Use of Optical Fiber Communication Systems Utilizing laser Diode and LED Sources.***

All OFCS are designed to operate with the beam totally enclosed within the fiber optic and associated equipment and, therefore, are always considered as Class I in normal operation. The only risk for exposure would occur during installation and service when light guide cables are disconnected or during an accidental cable break. Optical Fiber Communication Systems (OFCS) are assigned into one of four service group designations: SG1, SG2, SG3a, SG3b, depending on the potential for an accessible beam to cause biological damage. The service group designations relate to the potential for ocular hazards to occur only during accessible beam conditions. This would normally occur only during periods of service to a OFCS. Optical Fiber Communications Systems (OFCS) are assigned one of four service groups (SG1, SG2, SG3a, SG3b) depending on the potential for causing biological damage. Such designations apply only during periods of service in one of the following four service groups (SG):

Service Group 1: An OFCS that is SG1 has a total output power that is less than the Accessible Emission Limit (AEL) for Class I and there is ***no risk*** of exceeding the Maximum Permissible Exposure (MPE) when viewing the end of a fiber with a microscope, an eye loupe or with the unaided eye.

Service Group 2: An OFCS is SG2 only if wavelengths between 400 and 700 nm are emitted and is potentially hazardous if viewed for more than 0.25 s. (Note: at present, there are virtually no OFCS that operate in this wavelength range.)

Service Group 3A: A SG 3A OFCS is not hazardous when viewed with the unaided eye and is hazardous only when viewed with a microscope or an eye-loupe.

Service Group 3B: OFCS which meet none of the above criteria are designated as SG 3B.

Note: OFCS where the total power is at or above 0.5W ***do not meet*** the criteria for optical fiber service group designation. In this case, the OFCS are treated as a standard laser system.

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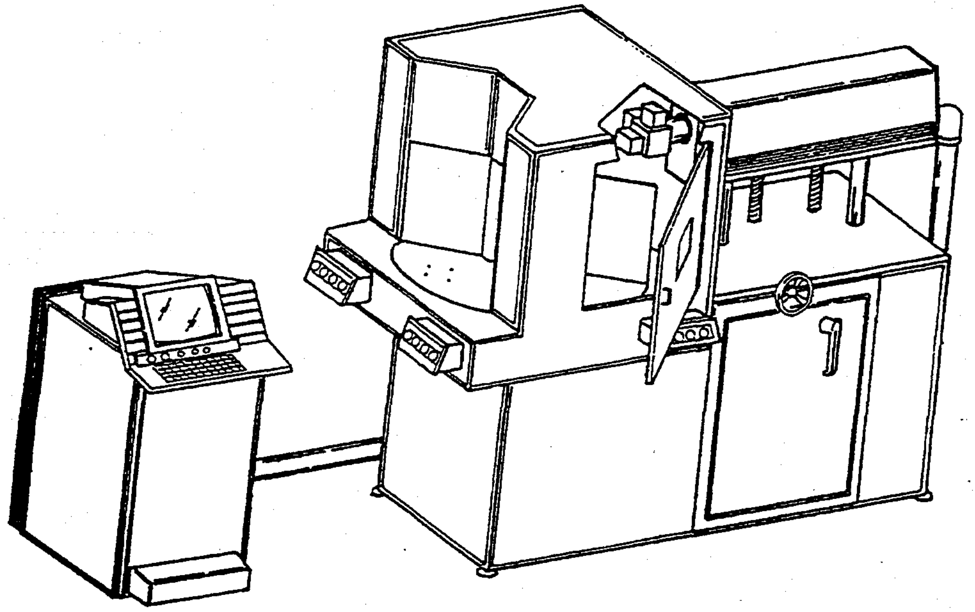
Module 8.0

LASER CONTROL MEASURES



RII Education

LASER CONTROL MEASURES

Control measures reduce the risk of accidental exposure to hazardous laser beams that can cause eye or skin damage. Control measures also help to protect against exposure to non-beam laser hazards involving the power supply, vapors, gases, and chemicals.

This module explains the four basic categories of laser control measures engineering controls, administrative and procedural controls, special controls and personal protective equipment.

- Laser Control Measures
- Engineering Control Measures
- Administrative and Procedural Controls
- Labels & Signs
- Special Control Measures

Table of Contents

LASER CONTROL MEASURES

LASER CONTROL MEASURES

SECTION OBJECTIVES

- *Define* accessible radiation, maintenance, MPE, NHZ, normal operation, and service according to ANSI Z136.1
- *Identify the four* basic categories of laser control measures
- *Describe* the function and duties of the LSO

CATEGORIES OF CONTROL MEASURES

The purpose of control measures is to reduce the possibility of eye or skin injury from exposure to hazardous levels of radiation. There are four categories of controls: engineering, administrative and procedural, special controls, and personal protective equipment. Engineering controls are built into a laser product by the manufacturer or designed into the installation by the user. Procedural and administrative controls, special controls, and protective equipment are not part of the laser or laser system. The four categories are detailed in Table 1.

It is important to remember that ANSI Z136.1 specifies appropriate controls based solely on the class of laser being used. The summary of these controls is given in Appendix A. The selection of the proper controls will depend on the class of laser, and the environment in which the laser is used. The level of training of laser operators and other personnel who could have access to laser radiation are factors that must also be considered in establishing controls. For example, if there is any possibility that untrained personnel could be exposed to a hazardous laser beam, more extensive controls may be required than if the laser is used in a limited access area by trained personnel.

On the other hand, when existing controls reduce the possible exposure below the maximum permissible exposure level (MPE), additional controls are not required. When a laser is serviced, however, temporary controls may be called for if the accessible radiation exceeds the MPE.

SKILL REVIEW
1

List three items that effect the controls applied to a given laser scenario.

List here:

DEFINITIONS

The definitions given here are used throughout this module. Unless otherwise indicated, the terms are those used in the Z136.1 American National Standards Institute (**ANSI**) Standard for the Safe Use of Lasers. In some cases the definitions are those of the Center for the Devices and Radiological Health (**CDRH**).

Accessible radiation "radiation to which it is possible for the human eye or skin to be exposed in normal usage." In addition, according to the

TABLE 1

BASIC LASER CONTROLS FOR SAFE LASER USE

Engineering Controls	**Administrative and Procedural Controls**
Protective housing Safety interlocks Beam enclosures Beam shutter or attenuator Remote interlock connector Key switch control Viewing optics and windows Service panels Emission delay Warning systems Remote firing & monitoring Equipment labels Control areas: indoor, outdoor, temporary	Laser Safety Officer Written SOP's Output limitations Education and training Maintenance Alignment procedures Personal protection devices Spectator limitations Warning signs
Special Controls	**Protective Equipment**
IR and UV requirements Demonstrtions involving the general public (laser light shows) Fiber optic systems Responsibility of manufacturers, others Repair and maintenance Modification of laser systems	Eyewear Clothing Windows Barriers and Screens

Federal Laser Product Performance Standard, for products that contain Class 3b or 4 levels of laser radiation, "'human access' also means access to laser radiation that can be reflected directly by any *single introduced flat surface* from the interior of the product through any opening in the protective housing of the product."

Maintenance "performance of those adjustments or procedures specified in user information provided by the manufacturer with the laser or laser system, which are to be performed by the user to ensure the intended performance of the product."

Maximum Permissible Exposure (MPE) "the level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin."

Nominal Hazard Zone (NHZ) "describes the space within which the level of the direct, reflected, or scattered radiation during normal operation exceeds the applicable MPE. Exposure levels beyond the boundary of the NHZ are below the appropriate MPE level."

Normal operation "the performance of the laser or laser system over the full range of its intended functions. It does not include maintenance or service."

Service "the performance of those procedures or adjustments described in the manufacturer's service instructions which may affect any aspect of the performance of the laser or laser system."

SKILL REVIEW
2

What distinguishes engineering controls from other control measures?

Answer here:

LASER SAFETY OFFICER

The key person in any laser safety control program is the laser safety officer (LSO). The function of the LSO is to "have authority and responsibility to monitor and enforce the control of laser hazards, and to effect the knowledgeable evaluation and control of laser hazards" (ANSI Z136.1). It is the responsibility of the LSO to ensure that effective control measures have been established and that the controls are being used.

As part of their duties, the LSO administers the overall laser safety program. Specific responsibilities may include, but are not limited to, items such as confirming the classification of lasers, effecting (or doing) the NHZ evaluation, assuring that the proper control measures are in place and approving substitute controls, approving SOP's, recommend and/or approve eyewear and other protective equipment, specify appropriate signs and labels, approve overall facility controls, effect proper laser safety training as needed, effect medical surveillance and designate the laser/incidental personnel categories. See Table 2 for LSO duties.

The LSO should receive detailed training and must have an understanding of lasers, laser bioeffects, exposure limits, classifications, NHZ computations, control measures (including area controls, eyewear, barriers ...etc.) and medical surveillance.

Depending upon the size of the organization, the number and type of lasers, and the extent of laser activity, the LSO may be a full-time or a part-time duty. The individual is often in the corporate industrial hygiene, or radiation safety department but in other facilities, the LSO is an engineer or biomedical technician with safety responsibility. Some of the specific LSO responsibilities are:

* Classify Lasers or Laser Systems
* Perform Hazard Evaluations
* Specify Control Measures
* Approve Operating Procedures
* Specify Protective Equipment
* Specify Signs & Labels
* Approval of Laser Systems & Facilities
* Assure Safety Training of Laser Personnel
* Specify Medical Surveillance Program
* Provide Consultative Services
* Maintain Records
* Conduct Surveys and Inspections

In some very large facilities, it may be necessary for the LSO to appoint one or a series of deputy LSO's, who report to the LSO on all laser safety matters. The deputy LSO performs the duties when the LSO is not available or serves as the LSO for a specific division within the organization.

Organizations such as **OSHA** (Occupational Safety and Health Administration) recommend the establishment of a laser safety program such as that *stipulated in the ANSI Z136.1* "Standard for the Safe Use of Lasers". In addition, many corporations have designated the ANSI Z136 Standard as their corporate policy for laser safety but often will have their own corporate safety requirements in addition. The LSO must be well trained in the requirements of these standards as well as requirements imposed on laser use by other federal, state or local agencies.

The LSO has some very "technical" duties such as laser classification, MPE and nominal hazard zone evaluation, protective equipment recommendations and inspection and audits (see Appendix B for audit forms). There are many administrative requirements also including standard operating procedure (SOP) approval, area warning sign specification, establishment of training programs, record keeping and other laser safety consultation services.

It should be noted that designation of an LSO is generally not required for operation of a Class 2 or Class 3a laser or laser system or for Class 1 laser products. An LSO is usually not required if maintenance and service are limited to Class 1 and Class 2 laser systems that do not contain enclosed lasers rated higher than Class 3a. If service is performed on a laser product with an enclosed Class 3b, or Class 4 laser, it is necessary to designate an LSO.

identified with the laser operation. Verbal "countdown" commands are an acceptable audible warning if they are always required by the SOP associated with the use of a laser or laser system such as may be the case in a research laboratory. This concept will be addressed in the section on SOP's. The warnings should be activated prior to laser emission and give adequate time to avoid exposure when the beam comes on. If a warning light is used, it must be of a color that is visible through laser protective eyewear.

ADMINISTRATIVE AND PROCEDURAL CONTROLS

SECTION OBJECTIVES

- *Define* the term administrative and procedural controls and give five examples
- *Discuss* the advantages of using indirect viewing systems during alignment procedures
- *List* three options that can be used for entryway controls into a room where a Class 4 laser is operating.
- *Explain* when temporary controls are needed and how they differ from the controls for fixed laser areas

INTRODUCTION

ANSI Z136.1 defines administrative and procedural controls as "methods or instructions which specify rules, or work practices, or both, which implement or supplement engineering controls and which may specify the use of personal protective equipment." These controls include SOPs, output emissions limitations, education and training, limiting laser access to authorized personnel, alignment procedures, and personal protective equipment such as laser eyewear.

STANDARD OPERATING PROCEDURES

For Class 3b lasers, written SOPs for maintenance and service are advised but are required for Class 4 lasers. Standard Operating Procedures need to be approved by the LSO and kept with the laser product for reference by laser operators as well as maintenance and service personnel. Guidelines for preparing SOPs are listed in Table 3.

These guidelines are intended to assist supervisors and management personnel who are responsible for the preparation of SOPs. It is intended that these procedures apply for operation of Class 3b and Class 4 lasers only. SOPs are only needed for lower classes of lasers if they are used in unique situations that may enhance their danger.

OUTPUT EMISSION LIMITATIONS

One way to reduce the possibility of injury from exposure to laser radiation is to use the minimum laser power needed for the application. If levels higher than the maximum permissible exposure (MPE) are required, ANSI recommends that such higher power lasers be enclosed whenever feasible. If the LSO determines that the laser accessible power exceeds the level required for the application, the LSO shall take appropriate steps to reduce the accessible power level. ANSI also recommends locating the laser beam at a height other than normal eye level for a person who is standing or seated.

EDUCATION AND TRAINING

Management (employer) of a laser facility must provide a laser safety program that includes training. Laser Safety training programs are required for the users of Class 3b or Class 4 lasers or laser systems and are also suggested for users of Class 2 and Class 3a lasers or laser systems. The users include operators, technicians, engineers, nurses, doctors, other operating room staff, maintenance and service personnel, and any others who routinely work with or around lasers. The training must insure that the users are knowledgeable of the potential hazards and the control measures for the

TABLE 3

OUTLINE FOR THE STANDARD OPERATING PROCEDURE

1. INTRODUCTION
    a. Location of laser(site, building, room)
    b. Description of laser (beam characteristics, divergence, aperture diameter, and maximum output)
    c. Purpose/applicable of beam
    d. ANSI Z136.1 Classification
    e. Other (if applicable, include proposed use at the site, arrival date, pulse length, and repetition rate)

2. HAZARDS
    a. Identification of the hazards (beam, electrical, chemical)
    b. Analysis of hazards (include target area, absorbing media)

3. CONTROLS
    a. Access controls (door interlocks, signs, signals)
    b. Beam controls (key-lock, enclosures, shutters, stops)
    c. Electrical controls (light on power supply, HV signs)
    d. Eye protection (eye examination, type of eyewear, optical density for beam)
    e. Other

4. OPERATING PROCEDURES
    a. Initial preparation of laboratory environment (key position, warning lights on, interlock activated, identification of personnel)
    b. Personnel protection (eyewear, isolation, barrier)
    c. Target preparations
    d. Countdown procedures
    e. Alignment procedures
    f. Shut down procedures

5. EMERGENCY PROCEDURES
    a. List potential emergencies and corresponding procedures
    b. Describe specific rescue evacuation procedures

6. TRAINING
    a. Indoctrination of operating personnel
    b. Training of on-site laser safety officer

7. RESPONSIBILITIES
    a. Supervisory (include emergency contact)
    b. Support personnel

LABELS & SIGNS

SECTION OBJECTIVES

- *Describe* the class warning logotype label required on Class 2 lasers including the wording that would be on the label
- *List* two types of labels that are required on all classifications of lasers
- *Give* the wording on a protective housing label where the protective housing encloses the beam from an invisible Class 4 laser if the opening has a defeatable, fail-safe interlock
- *Describe* the sign that should be posted at the entrance to a Class 3b laser area where a 200 milliwatt argon laser is operating

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EQUIPMENT LABELS

There are several types of labels on laser systems. The wording of the label varies depending upon the specific hazard and the class of laser.

Both the ANSI Z136 and The Federal Laser Product Performance Standard require certain labels on all lasers or laser systems. Labeling requirements are similar in each of the two standards. Since the Federal Laser Product Performance Standard is a product orientated standard, the label information presented here will conform to that standard.

Certification Label

A **certification label** is required on all laser products; even Class 1. Words similar to "This product complies with 21CFR 1040.10 and 1040.11" appear. This label indicates that the manufacturer certifies that the product complies with the Federal Laser Product Performance Standard.

Identification Label

This label identifies the manufacturer of the product, gives their address and the date that the laser product was manufactured. An identification label is required on all laser products regardless of Class.

This equipment conforms
to provisions of
US 21 CFR 1040.10
and 1040.11

Figure 10. Certification Label

Class Warning Label

This is the only label that actually identifies the laser classification. For lasers above Class 2a, a signal word and the common laser burst is required. The label must be affixed to a conspicuous place on the laser housing or control panel.

Class 2a lasers do not require the signal word nor the laser burst, but do require a warning label that says "Class 2a Laser Product—Avoid Long-Term Viewing of Direct Laser Radiation."

For Class 2 lasers the signal word is CAUTION and the label is yellow and black. The words "Laser Radiation—Do Not Stare Into Beam" must be included on Class 2 warning logotype labels. Class 3a lasers also use this format if their output irradiance is less than 2.5 mW/cm^2.

Class 3a laser labels contain the wording "Laser Radiation—Do Not Stare Into Beam or View Directly with Optical Instruments."

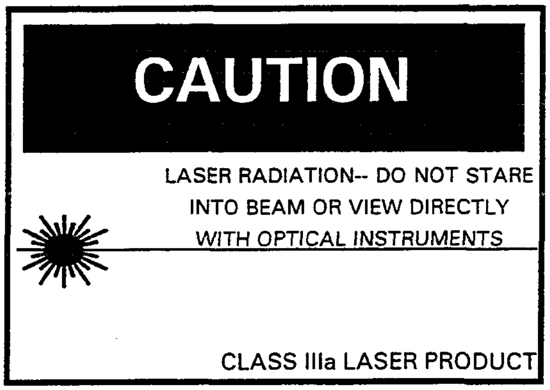


Figure 11. Caution Label

If the output irradiance of a Class 3a laser is greater than 2.5 mW/cm^2, the label must be red, black and white with the signal word DANGER. The wording would then be "Laser Radiation—Avoid Direct Eye Exposure."

Class 3b and Class 4 lasers have labels that are red, black and white with the signal word DANGER. The wording on Class 3b would be "Laser Radiation—Avoid Direct Exposure to Beam". If the laser is Class 4 the wording would be "Laser Radiation—Avoid Eye or Skin Exposure to Direct or Scattered Radiation."

With all warning logotype labels, specific information about the laser output must be included. This information may be the wavelength, type of laser, output power or energy, and whether the laser is CW or pulsed. To avoid unnecessary concern on the part of the individual reading the label, the word "Radiation" may be replaced with the word "Light" provided the laser can only emit visible energy.

Aperture Label

An aperture label indicates the location of the beam output. The label must be visible without being exposed to the beam. An aperture label is not used if there is no hazardous output (Class 1). An example of an aperture label is shown in Figure 13.

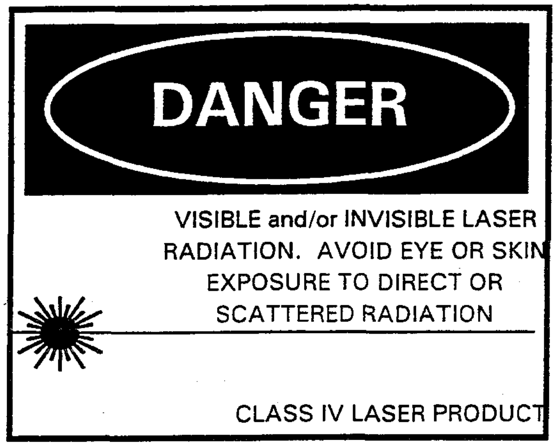


Figure 12. Danger Label

Protective Housing Label

A protective housing label is to be located where the protective housing is opened or removed for operation, service and maintenance, if removal or opening the housing will expose an individual to a level of radiation that exceeds the MPE. An example of a protective housing label is shown in Figure 14.

EXPOSURE
VISIBLE and/or INVISIBLE
LASER RADIATION IS EMITTED
FROM THIS APERTURE

Figure 13. Aperature Label

There are many different ways that the warning may be stated on protective housing labels depending on the amount of laser power accessible if the housing is opened, and whether there is an interlock and if the style of interlock allows it to be defeated.

Referring to the Figure 14, the word "DANGER" indicates that a Class 3b or Class 4 laser is enclosed. The word "Invisible" tells us that the radiation inside the protective housing is not between 0.4 µm and 0.7 µm. If several wavelengths exist inside the enclosure, the words visible and invisible may appear.

If the laser inside the enclosure produces Class 4 levels of radiation, the word "scattered" will appear. The word scattered does not appear on an embedded Class 3b laser system. If the words "interlock defeated" appear on the label it means that the style of interlock allows it to be defeated for maintenance or service functions. The word "failed" indicates that the type of interlock is not considered to be fail-safe and extra caution is advised.

ENTRYWAY CONTROL WARNING SIGNS

Signs placed at the entrance to controlled laser areas are very similar to the Class Warning Logotype Label described above. The style, signal words, color and wording are virtually identical to the labels. Warning signs are not required for Class 2 and Class 3a (<2.5 mW/cm^2) laser areas, but are recommended.

DANGER

VISIBLE and/or INVISIBLE LASER RADIATION
WHEN OPEN AND INTERLOCK FAILED OR
DEFEATED AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION

Figure 14. Protective Housing Labels

Entryway signs are required for Class 3a (> 2.5 mW/cm^2), 3b and Class 4 lasers and are red, black, and white. The word DANGER appears at the top, and the laser burst symbol is displayed at the left-center of the sign, with the line extending to the right. At the bottom left corner of the sign, the classification of the laser is given. Laser type and output power information are also listed. Specific information such as AUTHORIZED, PERSONNEL ONLY, or EYE PROTECTION REQUIRED may be added. It is essential that all personnel carefully follow the sign instructions.

Temporary controlled areas that are set-up during times of service should have a NOTICE sign posted at the entrance to the controlled area.

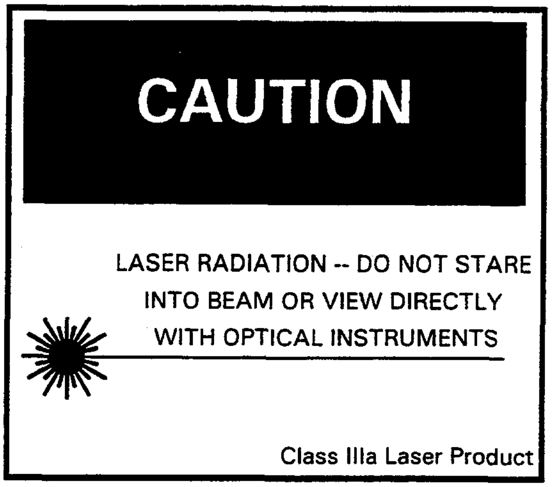


Figure 15. Caution Sign

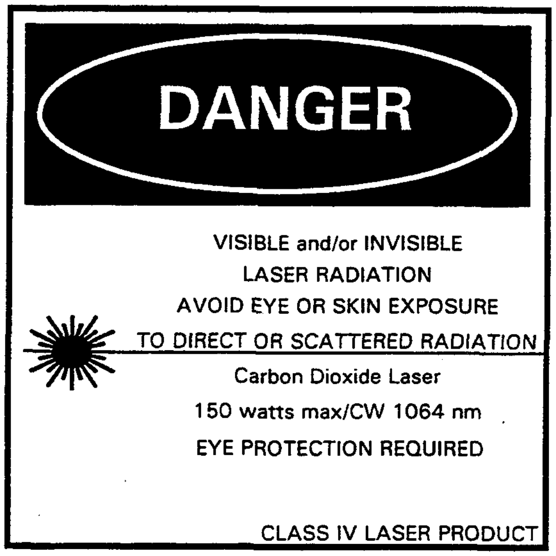


Figure 16. Danger Sign

SPECIAL CONTROL MEASURES

SECTION OBJECTIVES

- *List* three "good work practices" to employ when working with any laser
- *Discuss* special control measures that must be implemented for laser demonstrations that involve the general public
- *Explain* two special controls to use when working with fiber optics systems
- *Explain* why "walk-in workstations" present a unique safety hazard

GOOD WORK PRACTICES

In addition to the requirements for engineering controls, procedural controls, labels and protective equipment, there are also several common-sense work practices that will reduce the potential for exposure to hazardous laser beams.

Termination of the laser beam at the end of its useful path length is extremely important. The beams from Class 3b and Class 4 lasers should be terminated in highly absorbent, non-specular reflecting materials wherever practicable. Whenever possible, a "beam trap" should be used to capture the laser energy rather that a diffuse reflector that simply scatters the energy over a large area. Optical elements on a laboratory table should have "back stops" if the beam could miss the element and exit the table area.

Keeping the beam well above or below eye level will greatly reduce the chances of getting the beam in the eye.

Remove all unnecessary reflective objects from areas near the beams path. Tools and other such instruments may be specular reflectors and may accidentally direct a hazardous beam in the wrong direction.

Cover all doors and windows in a laser controlled area so that the nominal hazard zone (NHZ) is not able to escape the controlled area.

LASER LIGHT SHOWS

Laser demonstrations that involve the general public require special control measures. Such demonstrations include discotheque and stage lighting effects and laser light shows that emit visible laser radiation. The Federal Laser Product Performance Standards applies to laser demonstration shows, since the "show" is a product containing a laser. Producers of these shows must certify that no laser energy in excess of Class 1 limits can enter an area where the audience is expected to be.

The ANSI Z136 Standard states: "only Class 1 lasers shall be used for general public demonstration, display, or entertainment in unsupervised areas without additional requirements." Class 2 and Class 3a lasers may be used in an unsupervised setting only if it is not possible to access direct or partially reflected beams and the exposure does not exceed the appropriate MPE. The use of Class 3b or Class 4 lasers for public demonstrations requires even more stringent controls, which are described in detail in the ANSI Z136 Standard related to minimum distances overhead and laterally that a beam may approach an audience area.

Special limitations are also specified for lasers that emit invisible radiation. The general public shall not be exposed to invisible radiation that exceeds the appropriate MPE.

In addition to CDRH/FDA and ANSI Z136.1, other agencies may be involved with regulations of laser light shows. For instance, unterminated laser beams that can enter navigable air space during an outdoor laser show must have FAA clearance. Several state and local government agencies actively regulate laser shows to the public.

SKILL REVIEW
4

Which control measure would not be appropriate for a laser demonstration involving the general public?

Justify your answer here:

FIBER OPTICS

Under normal operation, fiber optic communication systems, are completely enclosed (Class 1) with the optical fiber and optical connectors forming the enclosure. Under installation or service conditions, or when an accidental break in the cable occurs, the system can no longer be considered enclosed. If engineering controls limit the accessible emission to levels below the applicable MPE (irradiance), no controls are necessary. If the accessible emission is above the MPE, the following requirements shall apply:

* Only authorized trained personnel shall be permitted to perform service on lightwave transmission systems if access to laser emission is required.

* Only authorized trained personnel shall be permitted to use the laser test equipment (Optical Loss Test Set, Optical Time Domain Reflectometer, etc.) during installation and/or service.

* All unauthorized personnel shall be excluded from the immediate area of access to laser radiation during service and installation when there is a possibility that the system may become energized. The immediate area shall be considered a temporary laser controlled area.

* Staring into the end of any broken, severed or unterminated optical fiber or cable shall be avoided.

* The end of any broken, severed or unterminated optical fiber shall not be viewed with unfiltered optical instruments (microscopes, telescopes, etc.) An exception to this is the use of indirect image converters such as an infrared image converter or closed circuit television system for verification that a fiber is not energized.

* During a splicing operation (either installation or service) if it is required that the ends of the fiber be examined with an eyeloupe for a satisfactory cut, only an eyeloupe containing an appropriate filter shall be used. If a fusion splicer is used, the appropriate operating safety procedures shall be rigidly adhered to.

WALK-IN WORK STATIONS

Lasers or laser systems containing embedded Class 3b or class 4 lasers with protective housing enclosures which are of sufficient size to allow personnel within the enclosure are called "walk-in work stations". If the laser were to be allowed to

PROTECTIVE EQUIPMENT

SECTION OBJECTIVES

- Explain why protective equipment is not the preferred control method
- Calculate the optical density of eyewear filters needed for protection from a given laser
- Identify ten requirements for laser eye protection devices
- Explain the term "Barrier Threshold Limit"

PROTECTIVE EQUIPMENT

The preferred method of limiting accessible radiation to the appropriate MPE is through the use of engineering controls. When these cannot be used, then administrative and procedural controls are needed. The use of **protective equipment**, such as protective barriers or curtains, protective clothing, or protective eyewear, should only be relied upon if the other control measures do not provide adequate protection.

LASER BARRIERS AND PROTECTIVE CURTAINS

Area control can be effected in some cases using special barriers or curtains that may be similar in appearance to welding curtains but which have been specifically designed to withstand either direct and/or diffusely scattered laser beams. Barriers and curtains must be opaque to the laser wavelength, cannot be combustible and must be designed to withstand the intensity of the laser beam they are expected to be exposed to. Laser barrier materials exhibit a Barrier Threshold Limit (BTL) for beam penetration. This threshold is the amount of laser beam irradiance that the barrier will withstand without penetration for a specified exposure time (typically 60 s). If the barrier threshold is less than the actual irradiance produced by a direct laser beam exposure, the beam must be terminated by some other device before it can contact the barrier.

PROTECTIVE CLOTHING

Where personnel may be exposed to levels of radiation that clearly exceed the MPE for the skin, protective clothing must be used. Ultraviolet lasers and Class 4 lasers pose the most serious threat of skin injury. When specifying protective clothing for use with Class 4 lasers, the material should be fire resistant and not melt. For diffuse reflections of UV energy, tightly woven clothing provides adequate protection.

PROTECTIVE EYEWEAR

In general, it is recommended that engineering controls be employed rather than placing total reliance for eye safety on the use of protective eyewear. This argument is predicated on the fact that so many *accidents* have occurred when eyewear was available but not worn. There are many reasons cited for this, but the most common is that laser protective eyewear is often dark, uncomfortable to wear and limits vision. According to the ANSI Standard, whenever there is any possibility that an individual could be exposed to radiation levels in excess of the MPE, appropriate eyewear for the laser wavelength and power must be used.

The filters used for laser eye protection are typically made of absorbing glass or plastic. The transmission curve of each filter is available from the eyewear supplier. The transmission curves for three common plastic filters are shown in Figure 19. The transmission values given on the curve for each filter are dependent upon the wavelength of light striking the filter and the thickness of the filter material.

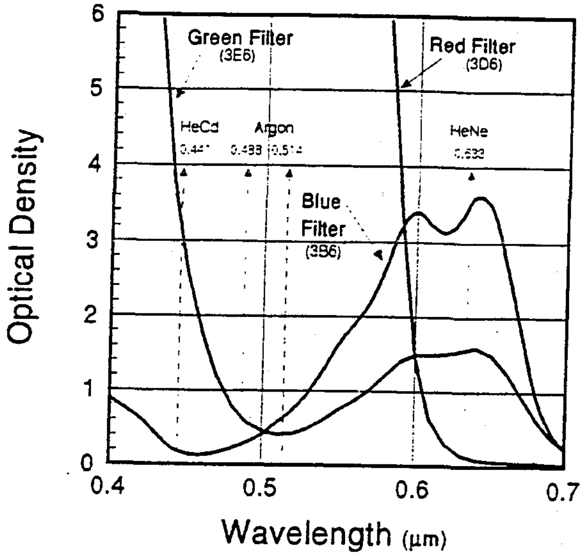


Figure 19. Optical Density curves for plastic filters

Laser eye protection devices can consist of goggles, spectacles or special prescription eyewear fitted with high-optical-density filter materials.

OPTICAL DENSITY

Laser protective eyewear filters are specified in terms of the optical density at specific wavelength(s). The **optical density** of a filter specified at a given laser wavelength (D_l) is determined by one of the logarithmic equations below:

$$D_l = \log_{10}(H_o/MPE) \quad (1)$$

or

$$D_l = \log_{10}(E_o/MPE) \quad (2)$$

H_o and E_o are the anticipated worst case exposure. They are usually assumed to be exposure to the direct beam at the laser aperture. H_o is expressed in the units of J/cm^2 while E_o is expressed in W/cm^2, depending upon whether the laser is pulsed or continuous wave (CW). Which of the two equations is actually used for determining OD will depend upon the units for MPE. If MPE is given in J/cm^2 then H_o will be used in J/cm^2 but if MPE is given in W/cm^2 then E_o will be given in W/cm^2.

Because the MPE values are distributed over the limiting aperture, the calculation for H_o and E_o for beams smaller than the limiting aperture requires that the area of the limiting aperture (ALA) be used instead of the actual area produced by the smaller beam size. That is, the calculation is made as though the beam were spread over the entire limiting aperture area, which in many situations, is the area of a 7mm or a 1mm circle depending on the laser wavelength. In determining OD values there is no need to use area values less than the area of the limiting aperture.

The required value of optical density depends on several factors. One of the most important factors in determining optical density requirements is the MPE. Since MPE is time dependent, so is optical density. Therefore the level of protection required for a 0.25 second (aversion response) exposure is much less than is required if the exposure to the same laser is for 30,000 seconds (8 hour occupational exposure).

SKILL REVIEW
5

A filter with an optical density of 1 protects against a worst case exposure of 0.25 J/cm^2. For what exposure would the filter provide protection if the optical density was 3?

Calculate here:

11. Need for prescription glasses.

12. Comfort and fit.

13. Degradation of absorbing media, such as photobleaching.

14. Strength of materials (resistance to mechanical trauma and shock) (see ANSI Z87-1989 for appropriate criteria).

15. Capability of the front surface to produce a specular reflection.

16. Requirement for anti-fog design or coatings.

Items 3, 4, and 5 in the list above must be used to determine the optical density as indicated in item 6.

Example

Calculate the optical density (OD) necessary for protection from a 0.6 watt, CW, dye laser beam that has a wavelength of 0.630 µm.

Solution

One must first determine the length of time expected for the exposure. If 0.25 seconds is selected for the exposure time (the bright light aversion response time is appropriate since this is a visible wavelength) the MPE = 2.5×10^{-3} W/cm^2.

On the other hand, if a person is intentionally viewing the laser light for a prolonged period of time, 30,000 seconds may be selected for the exposure duration and the MPE = 1.58×10^{-5} W/cm^2.

Case 1

$$OD = \log_{10} (E_o/MPE)$$
$$\text{where } E_o = 0.6 / [\pi\, 0.49] / (4)$$
$$E_o = 1.56 \text{ w/cm}^2$$

$$OD = \log_{10} (1.56/2.5\text{x}10^{-3})$$
$$OD = \log_{10} (6.23\text{x}10^{2})$$
$$OD = 2.79$$

Case 2

$$OD = \log_{10} (1.56/1.58\text{x}10^{-5})$$
$$OD = \log_{10} (9.8\text{x}10^{4})$$
$$OD = 4.99$$

TABLE 4

OPTICAL DENSITIES REQUIRED FOR INTRA BEAM VIEWING AT SELECTED LASER WAVELENGTHS

			Optical Density			
			Exposure Time: (s)			
Laser Type	Wavelength (µm)	Power	0.25	10	600	3 x 10^4
XeCl	0.308[b]	50 Watts	-.-	6.2	8.0	9.7
XeFl	0.351[b]	50 Watts	-.-	4.8	6.6	8.3
Argon	0.514	1.0 Watt	3.0	3.4	5.2	6.4
Argon	0.514	5.0 Watts	3.7	4.1	5.9	7.1
Krypton	0.530	1.0 Watt	3.0	3.4	5.2	6.4
Krypton	0.568	1.0 Watt	3.0	3.4	4.9	6.1
HeNe	0.633	0.005 Watt	0.7	1.1	1.7	2.9
Krypton	0.647	1 Watt	3.0	3.4	3.9	5.0
GaAs	0.840[b]	50mW	-.-	1.8	2.3	3.7
Nd:YAG	1.064[b]	100Watt (CW)	-.-	4.7	5.2	5.2
Nd:YAG	1.064[b]	(Q-switched)[a]	-.-	4.5	5.0	5.4

[a] Repetitively pulsed at 11 Hz., 12ns pulses, 20mJ/pulse.

[b] OD for UV & FIR beams computed using 1mm limiting aperture which presents a "worst case" scenario. All visible/NIR computations assume 7mm limiting aperture.

-.- Invisible beams; aversion response time does not apply.

NOTE: OD values obtained using ANSI Z-136.1 (1986) MPE critieria.

EXAMPLE

Calculate the optical density required for exposure to an 80-mJ single-pulse Nd:YAG laser ($\lambda = 1.06\ \mu m$) with a 2-mm diameter output beam.
($MPE = 5.0\ \mu J/cm^2$)

SOLUTION

First calculate the worst case exposure (H_o) for a 7-mm limiting aperture since 7-mm is defined to be the limiting aperture for this wavelength.

$$H_o = \frac{\text{energy}}{\text{ALA}}$$

$$= \frac{80 \times 10^{-3}}{\pi (0.7)^2 / 4}$$

$$= \frac{80 \times 10^{-3}}{39 \times 10^{-3}}$$

$$= 0.21\ J/cm^2$$

Substituting for H_o and MPE in equation (1), we obtain

$$D_\lambda = \log_{10}(H_o/MPE)$$

$$= \log_{10} \frac{(0.21)}{5 \times 10^{-6}}$$

$$= 4.6\ @\ 1.06\ \mu m$$

CHAPTER REVIEW

SUMMARY

1. In the United States, CDRH governs the classification and certification of lasers; ANSI establishes the recommendations for laser control measures.

2. Compliance with the CDRH regulation is required by law; compliance with ANSI Standards is normally voluntary unless required by a governmental agency.

3. The function of a LSO is to monitor, evaluate, and enforce laser safety controls.

4. Engineering controls are those safety features built into a laser product by the manufacturer or designed into the installation by the user.

5. Engineering controls include protective housings, interlocks, beam path control, beam stops, beam attenuators, and warning systems.

6. All lasers are required to have a certificaion and indentification label; all lasers, except Class 1 are required to have a protective housing and aperture label; all lasers above Class 1 are required to display a class warning label and above Class 2a the class warning label has a signal word and the laser burst.

7. Entryway control signs provide information about the type and classification of lasers operating inside a closed area, as well as appropriate safety precautions.

8. Administrative and procedural controls specify rules and work practices such as SOP's, output emission limitations, and training.

9. Special controls are required for laser demonstrations, except Class 1, that involve the general public.

10. Personal protection equipment such as protective eyewear and clothing may be required if other control measures do not limit radiation levels to the MPE.

KEY TERMS Define each term

accessible radiation
administrative and procedural controls
ANSI Z136.1
aperature label
beam stop
beam attenuator
CDRH
certification
certification label
class warning label
compliance
engineering controls
identification label
interlock
LSO
maintenance
master switch
MPE
NHZ
normal operation
OSHA
optical density
performance features
protective equipment
protective housing
protective housing label
service
SOP

For Further Reading

Laser Institute of America (1992). American National Standard for the Safe Use of Lasers. Orlando, FL. The ANSI standard classifies lasers according to their hazard level and defines appropriate control measures for each laser class to ensure the safe use of lasers and laser systems.

OSHA - Guidelines for Laser Safety and Hazard Assessment (1991). The guide provides a general overview of industrial laser standards and regulatory requirements.

Smith, J. (Ed.). (1989). *Laser Safety Guide* (1989). Orlando, FL: The Laser Institute of America. This guide presents an overview of laser hazards, the ANSI laser classification system, control measures, and hazard analysis. The guide is a an excellent simple-to-read reference for all levels of laser users.

REVIEW QUESTIONS

1. Operation refers to:

   a. User related activities
   b. Maintenance
   c. Service
   d. All of the above

2. The CDRH Federal Laser Product Performance Standard requires certain control measures built-in the laser by the manufacturer. These are called:

   a. Engineered safety features
   b. Manufacturer required controls
   c. Control measures
   d. Performance features

3. Optical density is best described as:

   a. The density of a filter plate material
   b. The logarithmic filtering ability
   c. The concentration of a transmitting media
   d. The ratio of the intensity incident on a filter to the transmitted intensity

4. A Class 2 HeNe laser requires which label?

   a. LASER DANGER
   b. LASER CAUTION
   c. LASER CAUTION Do Not View With Optical Instruments
   d. No label

5. The ANSI Z136.1 Standard requires a protective housing interlock on which laser classes?

   a. All Classes
   b. Class 2, 3a, 3b, and 4
   c. Class 3b and 4
   d. Class 4 lasers

6. Discuss the role of each of the four categories of laser control measures in preventing laser injuries.

7. When turning on a Class 4 CW argon laser, which of the following engineering controls might apply?

   a. A panel light signals beam emission
   b. A beam delay of six to eight seconds after turn on
   c. A doorway interlock attached to the remote interlock connector engages
   d. All of the above

8. A Q-switched neodymium-glass laser (beam diameter 5 mm) emits 1.0 J in a single 50-nsec pulse. Calculate the "worst-case" optical density required for the laser eye-protective goggles.

   a. 5.0
   b. 5.7
   c. 6.0
   d. 6.7
   e. 7.0

9. The yellow and black laser "CAUTION" warning label applies to which of the following class lasers?

   a. Class 2
   b. Class 3a
   c. Class 2 and 3a
   d. Class 3b and 4

10. The best safety measure to follow during laser alignment is:

    a. Limit lab personnel to only one individual to minimize potential exposures
    b. Require audible warnings signs in the hallways and on the laboratory door.
    c. Post temporary warning signs in the hallways and on the laboratory door
    d. Follow an approved alignment SOP

SKILL REVIEW ANSWERS

1. The class of laser which determines the level of hazard, the environment in which the laser is used and the training of the individuals using the laser.

2. Engineering controls are built into a laser product by the manufacturer or designed into the installation by the user. Procedural and administrative controls, special controls, and protective equipment are not part of the laser or laser system.

3. Enclosure of the laser equipment or beam path is the preferred method of control.

4. Protective equipment would not be appropriate because the general public is not trained in laser safety. Individuals might not wear the equipment properly or might even remove it while the laser is in operation.

5. 25 J/cm^2: $3/1 = \log_{10} (H_o/.025)/\log_{10}(.25/0.25)$

CHAPTER REVIEW ANSWERS

1. a
2. d
3. b
4. b
5. c
6. Engineering controls are the first line of defense in preventing injuries. When additional controls are needed, administrative and procedural controls are the next preferred method of preventing injuries. Personal protective equipment should only be resorted to when it has been determined that engineering and administrative and procedural controls do not provide adequate protection. Special controls apply to laser demonstrations for the general public and to certain other special instances.
7. d
8. b (D l = 5.7)
9. c
10. d

APPENDIX A

ANSI Z136.1
TABLE 10

Table 10

Control Measures for the Four Laser Classes

Control Measures	Classification					
Engineering Control	1	2a	2	3a	3b	4
Protective Housing (4.3.1)	X	X	X	X	X	X
Without Protective Housing (4.3.1.1)	LSO shall establish Alternate Controls					
Interlocks on Protective Housing (4.3.2)	▽	▽	▽	▽	X	X
Service Access Panel (4.3.3)	▽	▽	▽	▽	X	X
Key Control (4.3.4)	—	—	—	—	•	X
Viewing Portals (4.3.5.1)	—	—	MPE	MPE	MPE	MPE
Collecting Optics (4.3.5.2)	MPE	—	MPE	MPE	MPE	MPE
Totally Open Beam Path (4.3.6.1)	—	—	—	—	X NHZ	X NHZ
Limited Open Beam Path (4.3.6.2)	—	—	—	—	X NHZ	X NHZ
Enclosed Beam Path (4.3.6.3)	None is required if 4.3.1 and 4.3.2 fulfilled					
Remote Interlock Connector (4.3.7)	—	—	—	—	•	X
Beam Stop or Attenuator (4.3.8)	—	—	—	—	•	X
Activation Warning Systems (4.3.9)	—	—	—	—	•	X
Emission Delay (4.3.9.1)	—	—	—	—	—	X
Indoor Laser Controlled Area (4.3.10)	—	—	—	—	X NHZ	X NHZ
Class 3b Laser Controlled Area (4.3.10.1)	—	—	—	—	X	—
Class 4 Laser Controlled Area (4.3.10.2)	—	—	—	—	—	X
Laser Outdoor Controls (4.3.11)	—	—	—	—	X NHZ	X NHZ
Laser in Navigable Airspace (4.3.11.2)	—	—	—	•	•	•
Temporary Laser Controlled Area (4.3.12)	▽ MPE	▽ MPE	▽ MPE	▽ MPE	—	—
Remote Firing & Monitoring (4.3.13)	—	—	—	—	—	•
Labels (4.3.14 and 4.7)	X	X	X	X	X	X
Area Posting (4.3.15)	—	—	—	•	X NHZ	X NHZ

LEGEND		
	X	- Shall
	•	- Should
	—	- No requirement
	▽	- Shall if enclosed Class 3b or Class 4
	MPE	- Shall if MPE is exceeded
	NHZ	- Nominal Hazard Zone analysis required

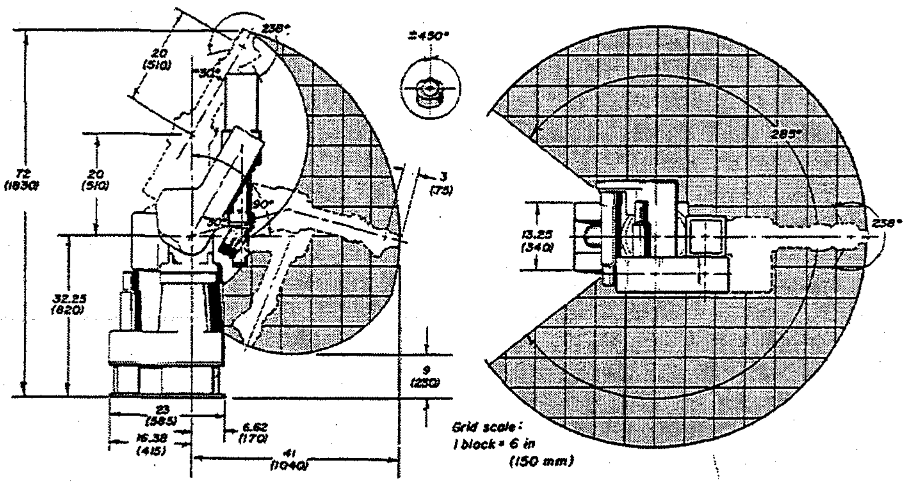
Table 10 (con't)

Control Measures for the Four Laser Classes

Control Measures	Classification					
Administrative & Procedural Controls	1	2a	2	3a	3b	4
Standard Operating Procedures (4.4.1)	—	—	—	—	•	X
Output Emission Limitations (4.4.2)	—	—	—	LSO Determination		
Education and Training (4.4.3)	—	—	•	•	X	X
Authorized Personnel (4.4.4)	—	—	—	—	X	X
Alignment Procedures (4.4.5)	—	—	X	X	X	X
Protective Equipment (4.4.6)	—	—	—	—	•	X
Spectator (4.4.7)	—	—	—	—	•	X
Service Personnel (4.4.8)	∇ MPE	∇ MPE	∇ MPE	∇ MPE	X	X
Demonstration with General Public (4.5.1)	MPE †	—	X	X	X	X
Laser Optical Fiber Systems (4.5.2)	MPE	MPE	MPE	MPE	X	X
Laser Robotic Installations (4.5.3)	—	—	—	—	X NHZ	X NHZ
Eye Protection (4.6.2)	—	—	—	—	• MPE	X MPE
Protective Windows (4.6.3)	—	—	—	—	X NHZ	X NHZ
Protective Barriers and Curtains (4.6.4)	—	—	—	—	•	•
Skin Protection (4.6.5)	—	—	—	—	X MPE	X MPE
Other Protective Equipment (4.6.5)	Use may be required					
Warning Signs and Labels (4.7) (Design Requirements)	—	—	•	•	X NHZ	X NHZ
Service and Repairs (4.8)	LSO Determination					
Modification of Laser Systems (4.9)	LSO Determination					

LEGEND
X - Shall
• - Should
— - No requirement
∇ - Shall if enclosed Class 3b or Class 4
MPE - Shall if MPE is exceeded
NHZ - Nominal Hazard Zone analysis required
† - Applicable only to UV and IR Lasers (4.5.1.2)

NON-BEAM HAZARDS



Education

NON-BEAM HAZARDS

A review of the electrical, fumes, toxic dyes and other ancillary hazards associated with laser use.

OVERVIEW

Laser safety issues now include both beam and non-beam issues. During safety audits of industrial and research laser facilities, the same type of basic safety problems are found repeatedly. This includes items such as:

1. Laser produced fires
2. Toxic fume production
3. Unprotected wiring and tubing
4. Water, dye and chemical spills
5. Unposted or improper warning signs
6. No dedicated laser control area
7. Improper fume exhaust systems
8. Improper viewing methods
9. Laser protective housing open or not in place
10. Interlocks defeated
11. No lockout/tag-out provisions
12. Lack of data on toxicity of chemicals and fumes (No MSDS data)

In many laser operations, particularly in the research laboratory, medical uses and industrial materials processing, other non-beam (ancillary) hazards aspects also require consideration.

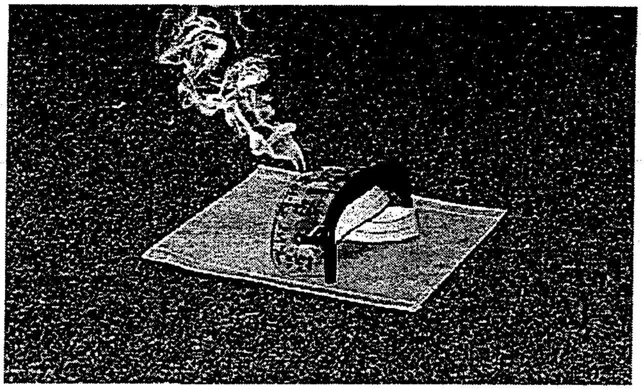


Figure 1
Dense smoke released from polycarbonate laser protective shield when exposed to 50W CO_2 laser for 10 sec.

One of the more important hazards associated with laser cutting of plastics is that of laser generated air contaminants (LGAC) such as shown in Figure 1. It has been shown in two independent studies that the analysis of the by-products produced by CO_2 laser cutting of polymethyl methacrylate and polyvinyl chloride samples contains potentially hazardous LGAC's which can include polycyclic aromatic hydrocarbons and other chemicals (See Table 1).

LASER CUTTING OF
POLYVINYL CHLORIDE
Condensed - Phase Pyrolysates

- 2-Phenlnaphthalene
- Phenathrene
- Fluoranthene
- 1-Methylpyrene
- Pyrene
- O-Terphenyl
- Naphthacene
- Benzo(a)pyrene

Table 1
Laser Cutting of PVC

LASER CUTTING OF KEVLAR
Analysis: GC,GC/MS, HPCL

- Benzene
- Phenylisocyanate
- Biphenyl
- Acenaphthylene
- Phenathrene
- Chrysene/ Benz(a)anthracene
- Benzo(k)floranthene
- Styrene
- Carbazole
- Napthalene
- Florene
- Anthracene
- Pyrene
- Flouranthene

Table 2
Laser Cutting of Kevlar

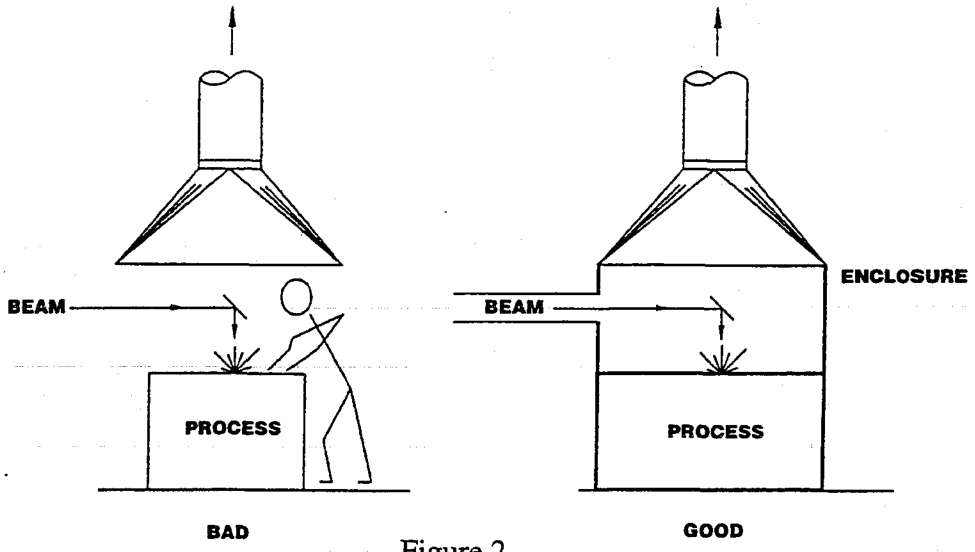


Figure 2
Proper Exhaust Systems are Required for Removal of Laser Generated Air Contaminants

Another recent study has shown that when high-temperature fabric, such as Kevlar, is cut with a CO_2 laser, several toxic and cancer-producing LGAC's may be produced. One of the highest concentration compounds reported in that study was benzene, a known carcinogen. It was shown that the time to reach the threshold level was about 40 minutes.

In all of these studies, attention was drawn to the need to adequately protect workers by the use of appropriate exhaust or containment systems as shown in Figure 2. ***Of interest was the fact that, it was shown that the use of argon as the shielding gas enhanced the formation of benzene.*** Therefore, it appears that the choice of a shielding gas is important for basic industrial hygiene reasons, as well as the engineering requirements in the process.

Users of Class IV laser systems often ignore that high power lasers, by definition, present not only laser radiation concerns but also a fire hazard as well. Fires have been reported as a result of equipment malfunction. These concerns for fire can impose the need for flame resistant safety barriers in controlled areas.

LSO's should require personnel to receive training in the appropriate fire safety practices-in particular when personnel are near flammable chemicals. In addition, it is also prudent to inform the local fire station of the type of sources and chemicals they could expect to be involved with in a fire emergency.

There have been a significant number of death and "near misses" from electrical shock among workers performing adjustments on laser systems. This is not surprising since certain pulsed laser systems can carry instantaneous electrical currents near 2000 amperes. A typical high power CW industrial CO_2 laser will support electrical currents in the order of 20 to 30 amperes during emission. Note that current levels of 50-100 milliamperes at 60 Hz into the body are considered fatal.

Industrial Hygiene Considerations

Industrial hygiene concerns include, for example, the potential hazards associated with compressed gases, cryogenic materials, toxic and carcinogenic materials and noise. Adequate ventilation is required to reduce noxious or potentially hazardous fumes and vapors, produced by laser welding, cutting and other target interactions, to levels below the appropriate threshold limit values, e.g., American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLV's).

Plasmas and Plume Radiation

Metal cutting is a major application for lasers. In fact, it is the largest single application for high power CO_2 lasers. It has been demonstrated that since a laser cutting process removes metal, rather than welding processes which bonds metal, the optical radiation levels in the produced plasma plume for laser cutting will be lower due to the fact that there is no weld puddle formed.

The 10.6 μm wavelength emitted by the CO_2 laser does not represent a retinal hazard. The weld plume radiation, rich in blue light, that is produced by the beam interactions with the metal can, however, present retinal concerns. Consequently, the emissions associated with the target beam interaction sites can be a significant occupational concern.

For example, the luminance levels produced are considerably lower in intensity during various CO_2 cutting processes than those observed during CO_2 welding events at comparable laser power levels. During cutting processes, material is constantly being removed and blown away, hence there is limited material left for luminescence and, hence minimal blackbody (plume) radiation is produced. As a result of low luminance levels, users have the tendency not to wear any or wear inappropriate protective eyewear. For example, the maximum plume luminance level is about 1-2 cd/cm^2 for a 3650 watt CO_2 laser during cutting processes.

Since many metals that are welded using lasers are specular reflectors at far infrared wavelengths. absorption of radiant energy into the metal is often very low. However, as the temperature increases and the metals approach liquid phase, the absorption of the beam power increases significantly. This particular absorption change occurs at a critical intensity, I_c, which is on the order of 10^5-10^7 W/cm^2 for a wide range of metals. This increase in absorption, or enhanced coupling of the laser energy into the material, is a result of surface plasma formation.

From a safety viewpoint once I_c has been reached there is increased absorption in the material and less reflection of the beam. It should be stated that for intensities greater than 10^7 W/cm^2 it is possible for the surface plasma to become detached and migrate into the laser beam. When this occurs, considerable loss of transmitted laser energy occurs leading to process interruption.

Table 3a: COMMON LASER GASSES

Substance Name	Toxicity Information	Exposure Limits TLV/PEL (ppm)
Argon, Helium Krypton, Nitrogen	Simple asphyxiants	NE
Carbon Monoxide	Chemical asphyxiant, depressed cardiac function	25/35
Carbon Dioxide	Asphyxiant, mild narcosis, respiratior stimulant	5000/10,000
Fluorine (+ nobel gas)	Corrosive to tissue, skin burns, pulmonary edema	1/0.1
Hydrogen Chloride	Irritant to eyes, skin and mucous membranes	5/5 (ceiling)

Table 3b: COMMON LASER GAS MIXTURES

Component	Concentration (%)	(ppm)	Permissible Exposure Limit (ppm)	IDLH
Carbon Monoxide	2	20,000	35	1500
Carbon Dioxide	8	80,000	10,000	50,000
Nitrogen	8	80,000	Simple asphyxiant	
Helium	82	820,000	Simple asphyxiant	

The use of shielding gases, such as argon, helium, and acetylene, helps to minimize plasma movement as well as eliminate oxidation embrittlement and porosity. Argon is a frequent choice for shielding gas at lower laser power levels but as the power is increased, the gas will ionize, producing a plasma that absorbs energy. Hence, helium or a helium-argon gas mixture, is used as a shielding medium. In addition, many CO_2 laser cutting systems utilize a jet of compressed air to help produce a clean cut by blowing away the molten metal. It should be noted that the use of shielding gases may also alter the distribution of scattered radiation levels reaching a worker. The toxicity of these and other common laser gasses is given in Table 3.

The data from laser welding illustrates that, under some exposure situations, it is possible to have a plume radiation component that occurs in the far ultraviolet (0.32-0.40 μm) region. In fact the actinic radiation level measured from a 3600 watt CO_2 welding event exceeded the ACGIH TLV within 10-30 seconds. Since the luminance level of the visible radiation is not excessive, it is possible that workers might view a reflected laser beam without appropriate UV protective eyewear and receive photokeratitis.

Interest has been expressed on the level of radiation produced within the "blue light" 400 to 500 nm spectral region where photochemical retinal damage is possible in some long term (>10 second) exposure conditions.

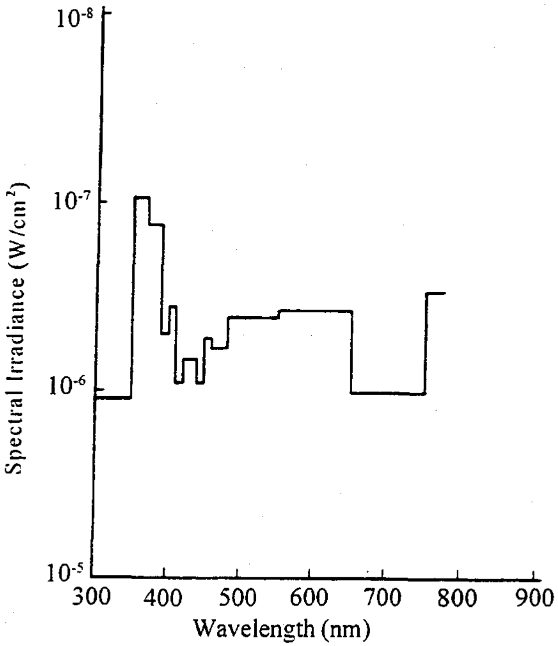


Figure 3.
Composite spectral irradiance of emission plasma (plume) from metals during 300 W Nd:YAG laser welding.

Data by Rockwell and Moss as shown in Figure 3 indicates the total integrated irradiance from 400 to 500 nm at a distance of one meter from the weld site for a 350 W Nd:YAG laser was found to be approximately 2-3 μW/cm². In similar tests, the total integrated results from 400 to 500 nm for the 2000 to 5000 Watt CO_2 lasers was about 60 μW/cm². Total average irradiance measured in the blue light (0.400-0.5;0μm) region is 3μW/cm². This just exceeds 8hr MPE limit of 1.0μW/cm². Peak of 0.11μW/cm² observed in UV at 0.35μm is well

Table 4a

Laser Generated Air Contaminant (LGAC) Thresholds

Approximate LGAC Thresholds and Guide to the Determination of Air Monitoring				
Irradiance ($W \cdot cm^{-2}$)	Plastic	Composites	Metals	Skin
$> 10^7$	X	X	X	X
$10^3 - 10^7$	X	Δ	Δ	Δ
$< 10^3$	O	O	O	O

Notes:

X - can exist
Δ - may exist
O - probably do not exist

Table 4b

Control Measures for Laser Generated Air Contaminants (LGAC)

IRRADIANCE ($W \cdot cm^{-2}$)	POTENTIAL BIOLOGICAL EFFECTS	POSSIBLE CONTROL MEASURES
$> 10^7$	Air contaminants associated with chronic effects	Process isolation Local exhaust ventilation Training and education Limit worker access Robotics/manipulators Housekeeping Preventive maintenance
$10^3 - 10^7$	Air contaminants associated with acute effects; noxious odors; visibility concerns	Local exhaust ventilation Respiratory protection Personal protective equipment Preventive maintenance Training and education
$< 10^3$	Potential for light odors	Adequate building ventilation Information

below the 8hr 1.0$\mu W/cm^2$ MPE limit. Similar results occur with CO_2 lasers with plasma emissions typically 20 times higher for equivalent welding events (1.0kW laser powers). Results suggest OD=2-3 in the blue light region (welding shade No.: 6-8) would be sufficient for long term protection of laser welding plasma for these laser types.

Laser Generated Air Contaminants (LGAC)

LGAC's may be generated when certain Class 3b and Class 4 laser beams interact with matter. The quantity, composition, and chemical complexity of the LGAC depends greatly upon the beam irradiance. The LSO shall ensure that industrial hygiene aspects of exposure to LGAC

Table 5 LASER GENERATED AIR CONTAMINANTS CO_2 LASERS

Process	LGAC	Comment
Cutting glassware	Amorphous fused sisica	Overexposure IARC 3
Cutting acrylic, lucite, plexiglass	Ethyl acrylate methyl methacrylate	IARC 2B
Machining graphite composites	Allphalic and aromatic organics	IARC 3 mutagens
Cutting PVC	Benzene, toluene, styrene, HCI, naphthalene	IARC 1 (Ben.)
Cutting sheet molding material,	Glass Beads	Respirable
Teflon	Prefluorinated polycyclic aromatics	Unknown
Cutting steel	Chromium Nickel	IARC 1 Respirable
Surgical procedures	Formaldehyde cyanides, anthracene, mutagens, viable HIV DNA	TWA Acceptable

Carcionogen Classification: IARC

• Group1	Carcinogenic to humans
• Group 2A	Probably carcinogenic to humans
• Group 2B	Possibly carcinogenic to humans
• Group 3	Not classifiable as to its carcinogenicity to humans
• Group 4	Probably not carcinogenic to humans

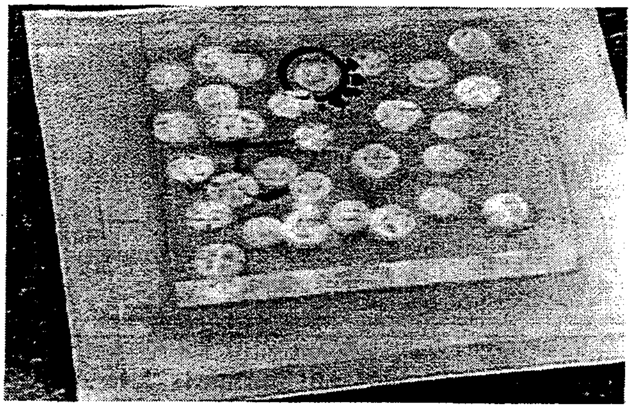


Figure 4
Typical laser mode burns on plastic. Fumes released during laser exposure frequently contain benzene and other toxic bi-products. Fume capture techniques are recommended during this process.

are addressed and that appropriate control measures are effected.

While it is difficult to predict what LGAC may be released in any given interaction situation, it is known that contaminants, including new compounds, can be produced with many types of lasers. When the target irradiance reaches a given threshold, approximately 10^7 W/cm^2, target materials including plastics, composites, metals, and tissues, may liberate toxic and noxious airborne contaminants (see Table 4). The amount of the LGAC may be greater for lasers that have most of their energy absorbed at the surface of the material. Such compounds may be gaseous or particulate and can, under certain conditions, pose occupational concern.

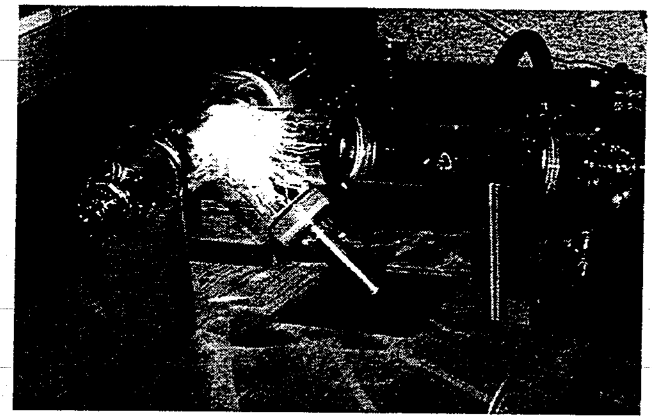


Figure 5
Showing contained LGAC's during laser metal drilling simulation. Study concluded that 50% of removed metal was released in particle sizes that were respirable.

LGAC include metallic fumes and dust, metallic oxide fumes, chemical and gaseous vapors, and biological fragments from human and animal tissues (bio-aerosols, dead and live cellular material, bacteria, fungi, and viruses). Some of the compounds from various materials include: polycyclic aromatic hydrocarbons from mode burns on poly-(methylmethacrylate) type polymers (see Figure 4); hydrogen cyanide and benzene from cutting of aromatic polyamide fibers; fused silica from cutting quartz; mutagenic agents from laser surgery; heavy metals from etching; benzene from cutting polyvinyl chloride; plus cyanide, formaldehyde and synthetic and natural fibers associated with other processes.

Special Optical materials used for far infrared windows and lenses have been the source of potentially hazardous levels of airborne contaminants. For example, calcium telluride and zinc telluride will burn in the presence of oxygen when irradiance limits are exceeded. Exposure to cadmium oxide, tellurium, and tellurium hexafluoride should also be controlled.

The LSO shall ensure that appropriate industrial hygiene characterizations of exposure to LGAC are affected in accordance with applicable federal, state, and local requirements. Exposure criteria are included in 29 CFR 1910 Subpart Z and *The Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices* (latest version) by the ACGIH.

The LSO should refer to the manufacturer's Material Safety Data Sheet (MSDS) section on hazardous decomposition products. This may provide some useful information but many MSDS's contain little information on the biological effects of decomposition products and/or LGAC. After characterization of the contaminant, it may be necessary for the LSO to effect appropriate control methods. Typical LGAC's for CO_2 laser processes are given in Table 5.

Lasers and Robots

The combination of a CO_2 laser with a robot is now very much a reality within many manufacturing industries. The anticipated growth of robotic use in the US is presently projected at 35% per year. The increase in use of such systems raises new safety questions, such as:

1. Is the NHZ within the protected working envelope of the robot?
2. Is there a hazard from the beam in the event of robot malfunction?
3. Are there potential hazards during servicing of the unit when beam access is often required?
4. Can the "pinch effect" occur? This occurs when a worker is pinned between a robot and some confining object-such as a rigid cinder block wall or ceiling support post.

A working envelope around the robot of 10 to 20 feet is typical for many industrial robot uses. However, when a laser is added to the robot, the "robot working envelope" should now also include the NHZ evaluation associated with the laser. This includes a dependence upon the optics and scattering from the target. Since "lens-on-laser" conditions usually will be required to maintain the

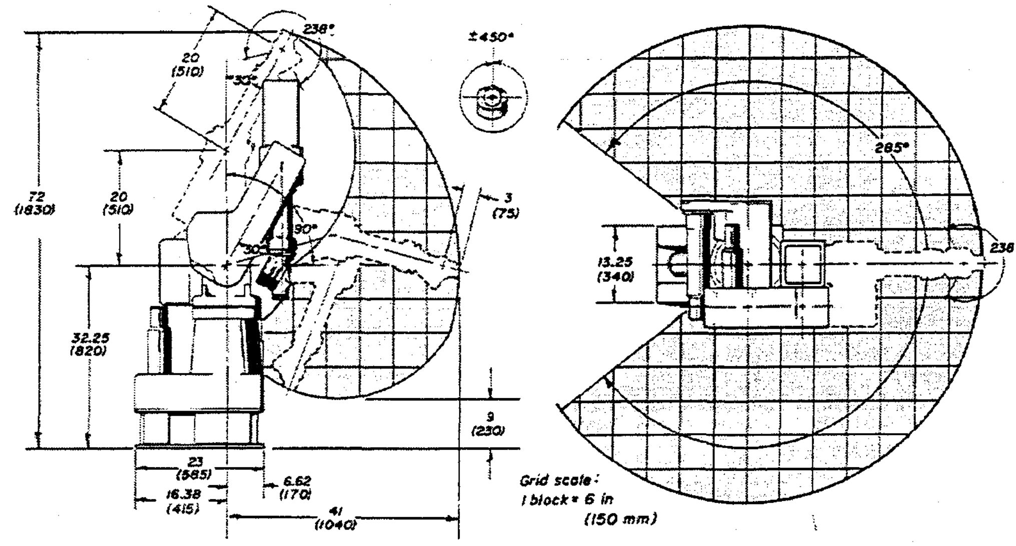


Figure 6
Showing Typical Robot Working Envelope (Shaded Areas In Both Vertical and Horizontal Planes)

NHZ within the robot's working envelope, there must be a means to insure that the focussing lens remains in position during operation.

In many industrial applications Class3b and Class 4 lasers and laser systems are used in conjunction with robots. In these situations, the robot working envelope (typically 3-6 meters) should also include the NHZ associated with the laser. Appropriate laser robotic safeguards are assured if the design or control measures provide for positive beam termination during operation, the beam geometry is limited to only the necessary work task, and all workers are located at distances greater than or equal to the lens-on-laser NHZ value for the laser robotic system.

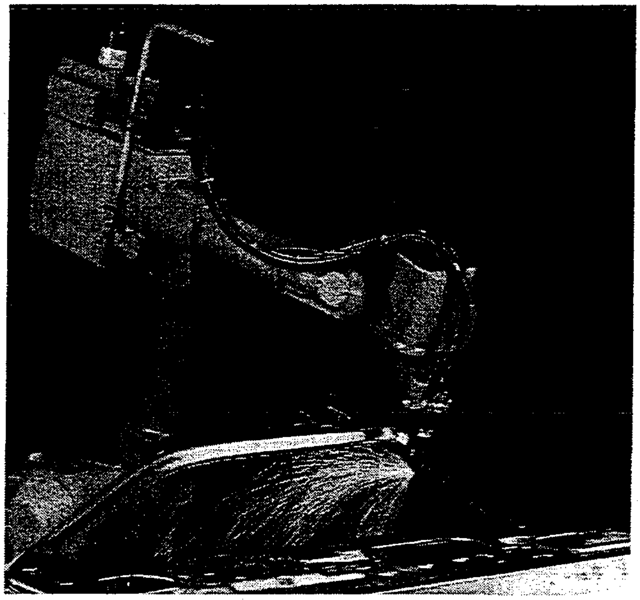


Figure 7
Showing Typical Nd:YAG Laser Robot System
The beam is delivered to the welding site
through a flexible fiber optic cable.

In many instances, including those created by hardware failure and software errors, the laser beam from robotic delivery systems can be incident on the target surface at angles that could lead to potential scattering geometries that are very complex and require extensive evaluation. Measurements are often required to confirm the NHZ boundaries.

Explosion Hazards

High pressure arc lamps and filament lamps or laser welding equipment shall be enclosed in housings which can withstand the maximum pressures resulting from lamp explosion or disintegration. The laser target and elements of the optical train which may shatter during laser operation shall also be enclosed.

Table 6
Summary of Dyes in Strict Control Class

Material/Synonyms	Class	Control Comments
Coumarin 30/515	S	Mutagenic. unknown toxicity
Coumarin 102/480 (41267-76-9)	S	Strong mutagin unknown toxicity
Coumarin 500	S	Mutagenic. unknown toxicity
Coumarin 535	S	Mutagenic. unknown toxicity
Cresyl violet 670	S	Very strong mutagen Unknown toxicity
DCM	S	Very strong mutagen Unknown toxicity
p.p'-diaminoterphenyl (60108-73-8)	S	Very strong mutagen Unknown tixicity
LD-490 (58336-35-9)	S	Mutagenic, unknown toxicity
LD-688 (51325-95-2)	S	Mutagenic. unknown toxicity
LD-698 (89846-19-5)	S	Mutagenic. unknown toxicity
LD-722	S	Strong mutagen. unknown toxicity
9-Methylanthracene (779-02-2)	S	Mutagenic, unknown toxicity
Nile blue 690	S	Comm. grade is strongly mutagenic**. Unknown toxicity
Rhodamine 6G/590	M	Special case*
Rhodamine 110/560	S	Weak mutagen Unknown toxicity
N,N,N,N-tetraethyl diaminoterphenyl	S	Strong mutagen Unknown toxicity

* Follow Moderate control class precautions, but conclude spill cleanups by wiping area with chlorine bleach (which attacks amine part of dye molecule).

** Commercial grade; purified dye is not mutagenic

This summary data of dye toxicity was compiled by Miller of Lawrence Livermore Laboratory.

Radiation, other than laser radiation, associated with the operation of a laser or laser system, e.g., radio- frequency (RF) energy associated with some plasma tubes, x-ray emission associated with the high voltage power supplies used with excimer lasers, shall be maintained below the applicable protection guides. The appropriate protection guide for RF and microwave energy is that given in the American National Standard "Safety levels with respect to human exposure to radio frequency electromagnetic fields, 300 kHz to 100 GHz," ANSI C95.1; the appropriate protection guides for exposure to X-ray emission is found in the Department of Labor Occupational Safety and Health Standards, 29 CFR Part 1910.96 and the applicable State Codes.

Lasers and laser systems which, by design, would be expected to generate appreciable levels of collateral radiation, should be monitored.

Flammability of Laser Enclosures

Enclosure of Class IV laser beams and terminations of some focussed Class IIIB lasers, can result in potential fire hazards if the enclosure materials are exposed to irradiances exceeding 10 W/cm^2. Plastic materials are not precluded as an enclosed material but their use and potential for flammability and toxic fume release following direct exposure should be considered. Flame resistant materials and commercially available products specifically designed for laser enclosures should also be considered.

LASER DYE TOXICITY AND CONTROL

Laser dyes are complex fluorescent organic compounds which, when in solution with organic solvents, form a lasing medium. The wavelength of a dye laser's output beam can vary with different dyes, concentrations, and solvents, giving it a tunable feature capable of emitting ultraviolet, visible, or infrared radiation. Because of this wavelength tunability, dye lasers are increasing in popularity. With this popularity comes the necessary to define hazards associated with dye handling, solution preparation, and dye laser operation.

Toxicity information on the approximately 100 commercially available laser dyes is very scarce.

Table 7
Acute Toxicity Classification Scheme

CLASS	DOSE (LD 50)
Practically nontoxic	> 15 g/kg
Slightly toxic	5 < 15 g/kg
Moderately toxic	0.5 < 5 g/kg
Very toxic	50 < 500 mg/kg
Extremely toxic	5 < 50 mg/kg
Super toxic	0.5 mg/kg

Limited animal experimentation has been performed with only a few dyes. Many dyes are manufactured in only small quantities; therefore, manufacturers become reluctant to do extensive toxicity tests.

The laser dyes can be categorized according to their central chemical structures. These include the xanthenes (rhodamines and flouresceins), polymethines (cyanines and carboncyanines), coumarins, and stilbenes. There are also a few other miscellaneous dyes that do not fall into one of these categories.

Some of the dyes have other uses: the rhodamines, for example, are used in drug products for internal use, mouthwashes, lipsticks, toothpastes, soaps and fabric dyeing. They've also been used in printing inks and as tracing agents in water pollution studies, and have been produced commercially in the United States for more than 50 years. Florescein dyes are also used in cosmetics and household products and have a therapeutic use in the detection of corneal epithelial defects (angiography). Some polmethine dyes are used in photographic developing processes. Stilbenes are used as scintillation counting dyes. Many complex stilbenes and coumarins are used as fluorescent whitening agents in detergents and a number of other consumer products.

Prepared laser dye solutions usually contain very small quantities of dye and typical dye concentrations are 10^{-2} to 10^{-5} molar. ***For this reason, the solution in which the dye is dissolved plays an important role when defining hazards.*** Practically all solvents used are flammable and toxic by inhalation and skin absorption, and therefore must be controlled.

If the general toxicity rating scheme as shown in Table 7 is used, the dyes such as those listed in Table 6 range from "super toxic" to "practically nontoxic." For example, coumarin dyes have relatively high LD50s. Studies of coumarins uses as fluorescent whitening agents have shown no evidence of dermal toxicity and very low systemic toxicity in acute exposure experiments. Very little information is available on the polymethine dyes. No LD50s have been cited, although experimental results dexcribed these dyes as "extremely" toxic substances. Many other fluorescent whitening agent studies have shown a number of stilbene compounds to be non-mutagenic, noncarcinogenic, non-teratogenic, and unable to produce lethality in mice. None of the tested stilbenes were laser dyes, and were sulfonated compounds unlike the known carcinogenic unsulfonated stilbenes.

CAUTION
LASER DYES ARE TOXIC CHEMICALS

Avoid breathing dust.
Avoid contact with eyes, skin, and clothing.
Wash thoroughly after handling.
Weigh and mix dyes in a fume hood.

Dye name ______________________

Manufacturer ____________________

Formula/mol.wt. _________________

Figure 8
Typical Laser Dye Label

Table 8: Common Dye Solvents

CHEMICAL SUBSTANCE (CAS #)	EXPOSURE^A LIMITS (TLV/PEL)	LD$_{50}^B$ (mg/kg)	CARCINOGEN^D	GLOVE^E
Benzonitrile (100-47-0)	NE	500	NI	---
Benzyl alcohol (100-51-6)	NE	3100	NI	B.V
Chlorobenzene (100-90-7)	10/75	400 to 1600	NI	PVA
Chloroform (66-67-3)	10/2	1060 to 2000	IARC-2B NTP-3	PVA
Cyclohexane (110-82-7)	300/300	6000 to 30.000	NI	B.V.Ni
o-Dichlorobenzene (95-50-1)	$25^S/50^C$	500	NI	V
1.2-Dichloroethane (107-06-2)	10/1	680	IARC-2B NTP-3	V
Dichloromethane (75-09-2)	50/25	2000	IARC-2B NTP-3	PVA
Diemethyflormamide (68-12-2)	$10^S/10^S$	280	NI	Ne
Dimethyl sulfoxide (67-68-5)	NE	19.700	NI	Ni.L.Ne.NR
1.4-Dioxane (123-91-1)	$25^S/25^S$	4200	IARC-2B NTP-3	NR^F
Ethys alcohol (64-17-5)	1000/1000	10.000	NI	Ni.Ne.PVC
Ethylene glycol (197-21-1)	$50^C/50^C$	8500	NI	Ni.L.Ne.PVC.NR
Ethylene glycol phenyl ether (122-99-6)	NE	1260	NI	B.Ni
Glycerol (56-81-5)	10M/10M	12.600	NI	Ne.Ni
Hexafluoroisopropanol (920-66-1)	NE	600 (Oral. Mouse)	NI	---
Methyl alcohol (67-56-1)	$200^S/200^S$	5600	NI	Ne
1-Methyl-2-pyrrolidione (872-50-4)	NE	4200	NI	NR
Propylene corbonate (108-32-7)	NE	29,000	NI	B.Ni
Tetrahydrofuran (109-99-9)	200/200	3000	NI	---
Tetrahydrothiopheneoxide (1600-44-8)	NE	3500	NI	---
Toluene (108-88-3)	50/100	5000	NI	PVA
1.1.1-Trichloroethane (71-55-6)	350/350	10.000	NI	PVC
Triethylamene (121-44-8)	10/10	460	NI	Ni
Trifluoroethanol (75898)	NE	2000	NI	NR.Ne.Po

A - Airborne concentrations; Units = parts per million by volume (ppm) unless indicated otherwise.
B - Established with oral administration to rats unless indicated otherwise. Rats were selected be cause of available data, but LD50 values for some solvents may be lower in other species
C - Ceiling limit
D - Includes listings by OSHA, IARC, or NTP.
E - Glove legend: B - butyl; L - latex; NR - natural rubber; Ne - neoprene; Ni - nitrile; Po-polyethylene; Pu - polyurethane; PVA - polyvinyl alcohol; PVC -polyvinyl chloride; V - Viton.
F - No individual glove material has shown exceptional resistance, but this glove may prove useful.
M - Aerosol concentration expressed in units of mg/m3.
NE - Not Established
NI - Not Indicated
S - Potential significant contribution to the overall exposure by this route.

Mutagenic Tests

Twenty-one dyes were tested at the Lawrence Livermore National Laboratory according to the Salmonella/mammalian-microsome mutagenicity test. Each dye was tested with three different tester strains (TA98, TA100, and TA1538) with and without Aroclor 1254-induced rat liver homogenate (S9). Twenty of the tested dyes showed no evidence of mutagenicity.

Rhodamine B and 6G have been found to be mutagenic by Nestmann; however, upon purification of the dyes, rhodamine B lost most of its mutagenicity. Rhodamine 6G lost 23% of its mutagenicity, but still induced a 24-fold increase in revertants over control. ***It was concluded in their study that pure rhodamine 6G is a mutagen.*** This discrepancy with the Livermore results may be due to the different products tested, and requires further investigation. No other published evidence of mutagenicity caused by these dyes is available. DMC(4-dicyanomethylene-2-methyl-6-p-diethylaminostyryl-4-H-pyran), manufactured by Exciton Chemical Company, Inc., was found to be mutagenic in TA98 and TA1538 with added rat liver homogenate for activation. Livermore found 300-400 revertant colonies per microgram with a threshold of activity of 0.5 microgram. These results describe DCM qualitatively as a moderately strong mutagen.

CONTROLS FOR LASER DYES

Potential exposures to dyes and solvents are most likely to occur during solution preparation. Failure of the dye laser's pressure system can also expose personnel, but dye concentrations are very low in solutions, and the potential for fire becomes much more of a concern when this occurs. Recommended controls for handling dyes, preparing solutions, and operating dye lasers are:

1. During solution preparation, dye and solvent mixing should be done inside a chemistry fume hood. Mutagenic dyes should be weighed out in a glove box. Dampers can be used to adjust air flow turbulence to a minimum during delicate weighing-out of fine dye powers. If because of air flow, dyes cannot be weighed out accurately, scales should be located inside suitable enclosures to limit the potential airborne hazard. Avoid creating dust.

2. Gloves, lab coats, and eye protection should be worn. Avoid skin contact.

3. During dye laser disassembly, use proper personal protective equipment and be alert to contaminated parts, e.g., dye filters. Be sure to cap off dye solution lines.
4. Don't smoke, eat, or drink in dye mixing areas.

5. Keep all containers of solvents, solutions, and dyes tightly closed, clearly labeled, and stored in a cool, dry place. Keep oxidizers away. Appropriate dye container labels should read:

6. Practice good hygiene. Wash hands after handling dyes and solutions.

7. For waste disposal and spills, emphasis should be placed upon solvent characteristics since dye concentrations are low.

8. Keep dye handling areas clean and segregate from other operations. Fortunately, the brilliant colors of dyes enable users to see spills from sloppy handling.

Laser dye toxicity is not well defined for many commercially available dyes, however, proper controls can be instituted to adequately protect personnel from possible unknown hazards. Available information shows variability in toxicity and a few conflicting experimental results. Ames testing has uncovered one mutagenic dye. A clear need exists for further toxicity, mutagenic and/or carcinogenic testing of dyes.

Table 9

EFFECTS OF ELECTRIC CURRENT ON MAN

	Current in Milliamperes					
	Direct		60 Hz		10.000 Hz	
	Men	Women	Men	Women	Men	Women
Slight sensation on hand	1	0.6	0.4	0.3	7	5
Perception threshold	5.2	3.5	1.1	0.7	12	8
Shock - not painful, muscular control not lost	9	6	1.8	1.2	7	11
Shock - painful, muscular control not lost	62	41	9	6	55	37
Shock - painful, let-go threshold	76	51	16	10.5	75	50
Shock - painful and severe, muscular contractions, breathing difficult	90	60	23	15	94	63
Shock - possible ventricular fibrillation effect from 3-second shocks	500	500	100	100		

*Energy in watt-second or joules

Lasing solutions contain very low concentrations of dyes; therefore, the solvents in which the dye is dissolved will play a major role in the hazard presented by the final solution. Almost all the solvents suitable for dye lasers are flammable and toxic. Dye-breakdown products may increase the hazardous nature of the final solution; however, this has not been investigated.

Because of the limited available toxicity information, dye handling and storage include laboratory procedures and controls commonly followed for toxic chemicals. Following these procedures will substantially reduce any risk involved. A good point to remember is that a given operation using a given dye and solvent will most likely use other dyes and solvents in order to fulfill varying wavelength requirements.

DYE SOLVENTS

Some of dye solvents are highly toxic, irritants, narcotics, and/or anesthetics. Some form hazardous compounds upon decomposition; others are highly reactive. These hazards need to be addressed in dye handling/solution preparation. In addition, some dye solutions came pre-mixed from the manufacturer, e.g., Q-switched dyes. The same care must be taken when handling these solutions as with any organic chemical. Efforts should determine what solvent was used, since this information is usually not included on the label.

In many instances, the solvent in which the dye is dissolved plays a major role in the hazard presented by the final solution. Solvents frequently used are included in Table 8:

ELECTRICAL SAFETY RECOMMENDATIONS

The intended application of the laser equipment determines the method of electrical installation and connection to the power supply circuit (for example, conduit versus flexible cord). All equipment shall be installed in accordance with the National Electrical Code and the Occupational Safety and Health Act. Detailed safety recommendations are given below.

The Human Body Versus Electricity

There are two basic categories of danger involved with exposure to electricity and the related equipment. These categories are the electrical dangers and the mechanical dangers. Since there can be large magnitudes of energy available in industrial electrical systems and equipment, some consideration must be given to possible mechanical dangers. Inadequate, improper, or faulty equipment along with electrical surges and faults can cause this energy to dissipate quickly in the physical destruction of a device. This destruction or damage can include splattering of molten metal, fire, and hurling of projectiles.

Consider the mildly perspiring electrician that hand-to-hand becomes part of a 120-volt circuit. The skin and body resistance would total approximately 12,000 ohms. Thus the current would be:

$$L = \frac{V}{R} = \frac{120}{12000} = 10 \times 10^{-3} \text{ amps}$$

This would mean 10 milliamperes could flow through the electrician's body. The longer the shock is maintained, the more the resistance would decrease and the amperage increase.

Consider the same situation, but with a circuit is at 12,000 volts. There is one ampere or 1000 milliampheres available to flow through the body.

There have been a significant number of death and "near misses" from electrical shock among workers performing adjustments on laser systems. This is not surprising since certain pulsed laser systems can carry instantaneous electrical currents near 2000 amperes. A typical high power CW industrial CO_2 laser will support electrical currents in the order of 20 to 30 amperes during emission. Note that current levels of 50-100 milliamperes at 60 Hz into the body are considered fatal.

$$L = \frac{V}{R} = \frac{600}{12000} = 50 \times 10^{-3} \text{ amps}$$

In order to safeguard personnel from the dangers, either electrical or mechanical, specific equipment and practices are needed. These are summarized into two basic rules.
In this case:

1. Do not become part of an electrical circuit; increase body resistance through increased distance or insulation.

2. Keep in a protective position; allow space for maneuvering or escape and use protective distance or hardware to increase shielding.

It is desirable to never service any electrical system energized. It is also difficult to troubleshoot some electrical circuits, when de-energized. When investigating voltages, current loads, sequence of operation, device performance, and similar checks the electrical system would be energized. But when changing devices, conductors, or any "hands on" contact, the system would be de-energized. So utilizing known and accepted safety practices, electrical systems under 600 volts can be safely serviced as described while energized.

However, exposed systems over 600 volts will not be serviced while energized. If this becomes a hardship to production goals or serviceability, circuit redesign or addition of meters or guards will be warranted.

The following information is considered as: The Operating Procedure for Servicing High Voltage and is the guide for safely servicing circuits over 600 volts. It should be adopted for utilization by all personnel servicing industrial high voltage machine tools.

Operating Procedure for Servicing High Voltage

The following items are the minimum precautions that must be followed when servicing high voltage sections of equipment, any voltage over 600 volts. Other sections of the equipment may be serviced using normal safety procedures. At all times, you must be alert with your mind on the job, familiar with the equipment, practice good communications and safety habits. Do not allow any part of your body to come into contact with the circuit until the following precautions have been taken, and then only when necessary.

The following are recommended electrical safety procedures:

1. Assume all unguarded potential points are ungrounded and all circuits are energized. Never touch a conductor, energized or not, if it can be avoided.

2. De-energize power sources, and lock and tag the disconnect switch.

3. Use appropriate test equipment to verify that the disconnect did open the and de-energize the circuit.

4. Use approved protective equipment from the time the high voltage is unguarded until ground straps are in place. Protective equipment includes, but is not limited to, high voltage gloves, sleeves, mats, blankets, helmet with face shield and leather apron. The helmet with face shield and leather apron are for mechanical protection and are not to be considered of any value for electrical insulation.

5. Have two electrically trained people present, one of whom is familiar with the equipment, when potential points of over 600 volts are unguarded and ungrounded.

6. Use appropriate test equipment to verify that the circuit is de-energized. If any potential exists in the circuit, and all supplies have been disconnected, appropriate discharge equipment must be used to drain off the charge.

7. Apply ground straps to all potential points only after all voltage and charge has been removed from the equipment.

8. Follow the above precautions, and when both people are satisfied that no hazardous potential exists, then the work may proceed using normal safety practices. At this point, two people may no longer be required.

9. Contact your foreman if both people are not satisfied that the equipment is de-energized.

10. If at any time there is anything questionable or any sensation of electrical shock (tingle), verify that Steps 2-9 have been implemented correctly. If no error is discovered and the condition still exists, contact your foreman and the Safety Department for further instructions.

11. Remove only the guards necessary to service the equipment and replace them immediately upon completion of the service.

12. Remove all ground straps, tags, safety locks, and replace all guards before the equipment is energized.

PROTECTIVE EQUIPMENT AND PROCEDURES - ALL VOLTAGES

Basic Safety Equipment and Practices

All personnel are expected to abide by all applicable safety rules. In the case of electrical personnel, The National Electrical Codes should be given special attention.

No attempt will be made to repeat all safety rules and procedures, but several deserve special mention.

1. Safety Glasses: Approved, nonmetallic eye protection should be worn by electrical personnel at all times. Besides the normal protection from debris, approved safety glasses will be especially protective in the event of the mechanical failure of a device. Metal-framed glasses can damage equipment, if dropped into an energized circuit. If metal-framed glasses come into contact with an energized electrical circuit while being worn, the close skin contact would mean low skin resistance and enhance the possibility of electrocution.

2. Metal Jewelry: Absolutely no metallic jewelry shall be worn by electrical personnel. In addition to the chance of entanglement or short circuit damage due to equipment, the risk is greatly increased for electrocution in much and same manner as with the metal-framed glasses.

3. Clothing and Safety Shoes: Clean, dry, properly-fitted clothing and shoes help provide good physical protection in addition to increasing the skin resistance. Long-sleeve shirts should be worn at all times, except when working on rotating equipment.

4. Hold Tags and Personal Safety Locks: Both of these items are invaluable as communication and protection devices. The Hold Tag, which is regarded as a padlock, should state the Who, What, Where, Why, and When of the device being held. It should be removed only by the person that attached it. The Hold Tag is used to inform other personnel of an unsafe situation, and to avoid someone creating an unsafe situation for the hold tag owner. All electrical personnel have been issued a personal safety lock. The safety lock is an additional safeguard insuring that a device will only be operated by the safety lock owner. Whenever multiple crews or trades are servicing the same equipment, each crew or trade should lock out the supply device.

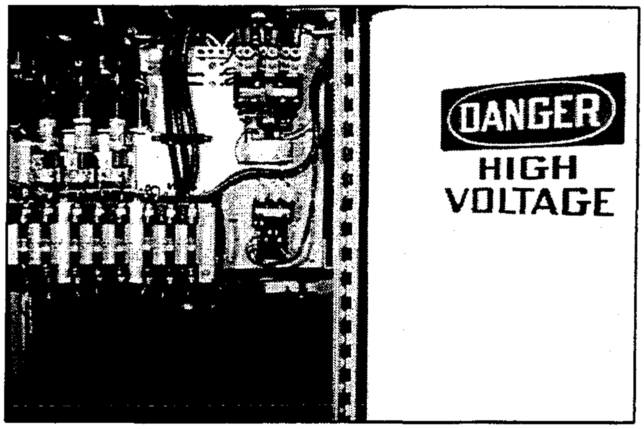


Figure 9
High voltage circuits should be properly labeled and special test procedures used when servicing high voltage components.

Test Equipment and Practices

There are several basic test devices that electrical personnel use on a regular basis. The capabilities and limitations of this equipment should be known and understood. Some of the more typical devices will be reviewed, but any device intended for use should have its operating ranges known before being used. All test equipment operation should be verified on a known source before use in servicing equipment.

Multimeters

Simpson 260: This device will indicate voltages either A.C. or D.C. up to 1000 volts. The voltage accuracy remains good up to 10 KHZ. Do not use alligator clips, when testing energized circuits. Use insulated handled probes to make this test.

Fluke Digital Multimeter: This device will indicate D.C. voltages up to 1000 volts and A.C. voltages up to 750 volts. A.C. voltage values remain accurate up to KHZ. As with the Simpson unit, insulated probes should be used when testing energized circuits.

Solenoid-type Voltage Testers

These units will provide an indication of nominal voltage ranges, either A.C. or D.C., up to 600 volts. The accuracy is good only to the extent of separating the different ranges and the units are limited to A.C. voltages 60 HZ or lower or D.C. voltages.

Clamp-on Ammeters

These units are limited to the maximum ampere value shown on the meter scale. The insulation rating is 600 volts, but care should be taken to avoid too close of hand contact with uninsulated conductors. Accuracy is poor, but improves when reading values at the upper end of the scale. Information when used on D.C. circuits is of little or no value.

General Tools

Tools should be maintained in good, clean condition. The proper tool should be used for its intended job. Improvising increases the risk of accident. Ladders and lifts should be in good working condition. Be aware of their construction material and their value in either insulating or completing an electrical circuit. Additional lighting may be required, due to the multitude of equipment service possibilities.

SPECIAL PROTECTIVE EQUIPMENT & PROCEDURES-OVER 600 VOLTS

In applications involving equipment over 600 volts, additional safety equipment and procedures must be utilized. Those applicable rules in the Safety Standards shall be followed as well as the Operating Procedure for Servicing/Handling High Voltage. The High Voltage Procedure shall take precedence over any conflicts between it and the Safety Standards.

Basic Equipment and Practices Over 600 Volts

The general practices and equipment used on systems below 600 volts must be reviewed to determine the compatability on systems over 600 volts. Nonmetallic safety glasses, absence of metallic jewelry; clean, dry, fitted clothing and shoes; hold tags and personal safety locks; these are all items which must be utilized. Proper utilization of these items become extremely important as the voltage levels increase. The use of basic text equipment on circuits over 600 volts can only be achieved on the extremely low end of the high voltage range or not at all. The best policy is not to use the basic multimeters, solenoid-type voltage testers, or clamp-on ammeters on any energized circuit over 600 volts. Multimeters can be used for continuity test once the high voltage circuit has been properly de-energized and grounded.

Special Safety Equipment and Practices

The primary objective of the specialized safety equipment and practices is to drastically increase body resistance and provide physical protection. It must be reemphasized that the higher the voltage, the easier it is to establish current flow. For this reason, high voltage demands greater respect and the utilization of special equipment and practices.

Rubber Gloves: Rubber gloves are probably the most important item of safety equipment for use in servicing high voltage. Normally, the hands are the closest interface with the high voltage and have the highest risk of contracting the high voltage circuit.

Good, clean rubber gloves can change the body resistance from its value of 0.5 to 20 million ohms. Before use, the rubber gloves should be visually inspected for cleanliness and lack of dry rot or defects. The opening should be folded over and the palm and fingers of the gloves checked for air leaks. Every three months, all rubber gloves will be cleaned and dielectrically tested to insure proper insulating capacity. The voltage level of the test will be marked on the glove or its storage case.

Any defective gloves that show evidence of dry rot, air leakage, or dielectric breakdown shall be cut and disposed of to avoid accidental use. Clean leather outers can be used over the rubber gloves to provide additional physical protection.

Rubber sleeves and mats: The sleeves and mats are safety items that serve to provide additional insulation from high voltage circuits. The sleeves increase body resistance in the wrist to shoulder area and provide protection when reaching or extending is involved. The mats normally serve to insulate the feet from electrical ground. Earth grounds, platform grounds, or cabinet grounds are often times involved in the path of current flow during electrocution. The mats can be draped, tied, or placed in such a manner as to isolate personnel from high voltage or possible conductors.

The sleeves and mats should be visually inspected for cleanliness and integrity before each use. They are dielectrically tested every three months. Any sleeve or mat found to be defective from dry rot, cuts, or embedded shavings should have defective area removed or the complete items destroyed.

Hard Hat, Face-shield, Leather Apron: To provide physical protection from device failure and electrical arcing; hard hats, face-shields, and leather aprons shall be worn. These items supplement the basic safety equipment, but do not replace them.

General Tools: Metallic, non-insulated tools are not to be used on any energized high voltage circuit. All meters, probes, tools, sticks, etc. that come in contact with high voltage energized circuits must be insulated to a value above the exposure value. Portable equipment should be labeled to signify the maximum voltage insulation value and be inspected for cleanliness and lack of defects before each use. Dielectric testing is recommended on a three-month basis to the maximum voltage insulation value.

Special Test Equipment and Practices

When servicing high voltage equipment, the primary concern is detecting the presence or absence of the high voltage. If other information is required, such as current flow, permanent metering should be considered. High voltage, portable test equipment should be checked for cleanliness, integrity, and proper operation before use on a high voltage circuit. Do not use test equipment, unless it is rated for the voltage to be detected.

All high voltage test equipment shall be used in conjunction with high voltage safety equipment. Personnel must be familiar with the circuit being serviced. Those devices and conductors included in the high voltage circuit should be known from standard voltage devices. The use of schematics, labels, training, and experience should aid in the determination of such devices.

Probes with Indicating Meters

Maximum voltage allowable to be tested is usually limited by the maximum range value on the scale or by a marking on the scale. These probes will normally indicate either A.C. or D.C. voltages and can be used on all frequencies. However, when checking high frequency circuits accuracy begins to decrease. These probes will have a ground clip connector or a second probe. This clip or probe should be connected first or contacted with a conductor. before the metered probe is used. It should also only be removed after the metered probe is removed.

Static Probes

These type probes have an indicating light, which only indicates the presence of voltage. They have no reliable method of determing magnitude, except for differences in the brilliance of the indicating light. The maximum voltage insulation value should be marked on the probe. These probes will give continuous indication of A.C. voltage at all frequencies. D.C. voltages will only cause a blip or flash of the indicating light as the conductor is approached. Static probes are not reliable at voltages below 2000 volts.

Grounding Equipment and Procedures

When de-energizing a high voltage electrical circuit to be serviced, a test shall be made to determine whether voltage is indeed absent from the circuit. If voltage is found to be present, the determination must be made as to the source of this voltage. By checking normal circuit supply devices and comparing the voltage magnitudes, it can be determined the voltage is a result of device failure or a stored energy device. In the event of a device failure, additional disconnects should be opened until the failed device is de-energized and available for repair. In the event astored energy device, like a compacitor, has retained some or all charge, special consideration is required. All equipment that utilizes high voltage capacitators should have mechanical or electrical discharge or shorting capabilities built into the circuitry. If such features do exist on the equipment, the integrity of such devices should be checked each time the circuit is de-energized.

Discharge Rods and Straps

When de-energizing high voltage circuits containing capacitors, special discharge equipment may be required. With all normal voltage sources disconnected, capacitors may retain or restore all or part of the initial charge. Depending upon the magnitudes of capacitance and voltage, the stored energy discharge rate may have to be controlled. Immediate, low resistance grounding may cause arcing or capacitor failure.

To control the discharge rate of a capacitor, a resistance must be installed in the discharge circuit. The discharge time to achieve a safe level for direct grounding is based upon voltage level, capacitance, and the value of this resistance. Some capacitors will not require this resistor and can be connected directly to ground.

Grounding Cables and Straps

Most high voltage circuits will de-energize completely upon the disconnection of voltage sources. These circuits and those containing low energy capacitors can be connected directly to ground. Voltage tests should still be made on these systems before attaching any ground straps. Ground straps shall always be attached to ground first and then to the conductor to be grounded. This order of procedure is to avoid the connection to an energized conductor resulting in the ground strap becoming a portable high voltage conductor. By connecting to ground first, ground then becomes portable. Ground straps should be mechanically strong enough to allow flexibility, without breakage.

All discharge or grounding connections made to a high voltage circuit must be removed before circuit is re-energized.

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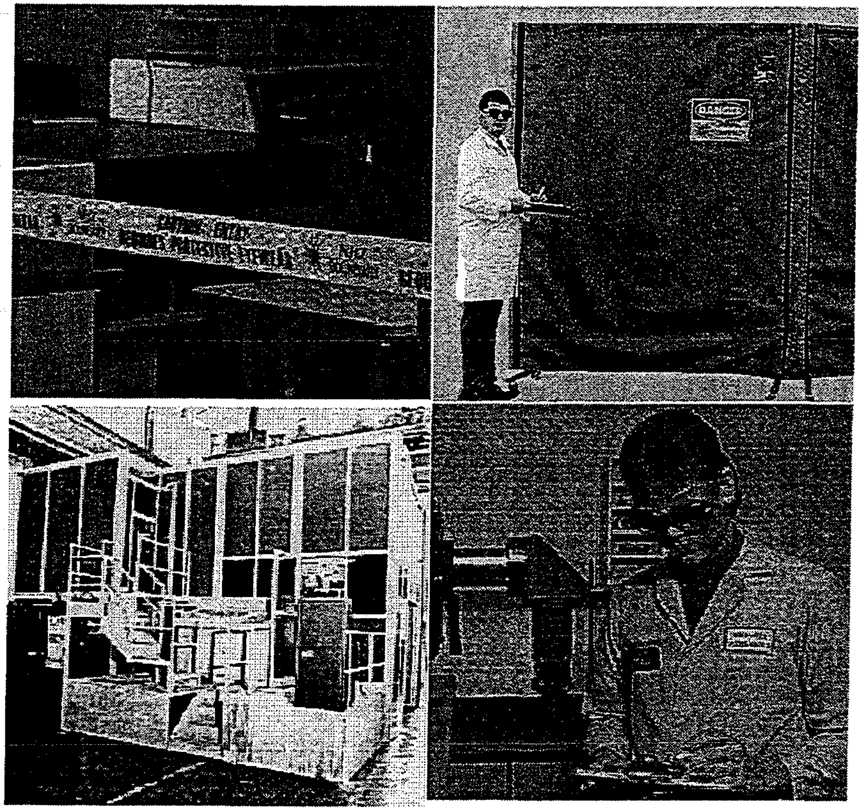
MODUL

LASER SAFETY PROGRAMS



Education

LASER SAFETY PROGRAMS

A laser safety program is essential to controlling laser-related hazards. Laser operators, support personnel, and other individuals who could possibly be exposed to a laser hazard must be properly trained and monitored to ensure that safe operating procedures are being followed.

This module explains the components of a laser safety program including duties and responsibilities of a Laser Safety Officer, training, medical surveillance, and laser safety audits.

TABLE OF CONTENTS

LASER SAFETY PROGRAMS

PERSONNEL RESPONSIBILITIES

SECTION OBJECTIVES

- *List* the responsibilities and duties of the LSO
- *Identify* the responsibilities and duties of managers and supervisors
- *Describe* the responsibilities and duties of employees
- *Identify* six non-beam laser hazards

THE LASER SAFETY OFFICER

The key element in any laser safety program is the laser safety officer (LSO). The LSO is a designated individual who has the responsibility and authority to manage the overall laser safety program. The LSO must ensure that all employees who operate, maintain, or service laser products are properly trained and the LSO is responsible for establishing, monitoring, and enforcing laser controls, as well as evaluating laser hazards.

The LSO duties include laser classification, evaluation of **Maximum Permissible Exposure** (MPE), Accessible Emission Limit (AEL) for specific laser classes, and **Nominal Hazard Zone** (NHZ), inspection and audits, approval of the laser **Standard Operating Procedure** (SOP), recommendation of protective equipment, specification of area warning signs, and consultation services. LSO duties are listed in Table 1.

According to the ANSI standard *For the Safe Use of Lasers* (ANSI Z136.1-1992), the designation of an LSO is generally not required for operation of a Class 2 or Class 3a laser or laser system. Nor is an LSO usually required if maintenance and service are limited to Class 1 and Class 2 laser systems that do not contain enclosed lasers rated higher than Class 3a. If, however, service is performed on a laser product with an enclosed Class 3b or Class 4 laser, it is necessary to designate an LSO.

The LSO is often a member of the corporate industrial hygiene department or a laser engineer with safety responsibility. Depending upon the size of the organization, the number and types of lasers, and the extent of laser activity, the LSO may be a full-time or a part-time duty. In some very large facilities, it may be necessary for the LSO to appoint a deputy LSO, who reports to the LSO on all laser safety matters. The deputy LSO performs the duties of the LSO when he or she is not available. In other large laser facilities a laser safety committee may be necessary.

Other functions of the LSO are to consult with design and develop staff for new manufacturing procedures and equipment. In this way, safety considerations can be addressed in the initial phases of new process development. By involving the LSO at the early design and development stages, safety requirements such as training, special protective equipment, and special area design can be determined prior to the introduction of new equipment into the work place.

The LSO also approves SOPs. The SOPs should be devised by those responsible for the operation of the systems with the approval given by the LSO. It is recommended that a written SOP be prepared for each laser system, and that employees be required to sign a form stating that they have read and understand the SOP. SOPs improve safety and eliminate uncertainty about specific

TABLE 1

DUTIES OF A LASER SAFETY OFFICER

Activity	LSO Duty
Laser Classification	Re-classify any laser that has not been classified by its manufacturer or if it has been modified.
Hazard Evaluation	Determine MPE and establish NHZ Review and approve control measures when necessary
Control Measures	Establish/monitor control measures Establish alternate control measures when necessary Establish control measures for a temporary laser controlled area
SOP	Approve all written laser procedures
Protective Equipment	Evaluate, recommend, and approve eyewear, protective clothing, etc.
Notification	Notify local/state radiation control officials or health departments prior to any laser activity involving the general public to ensure that all requirements are satisfied Contact local/national aviation authorities for out-of-door laser operations to ensure controlled air space
Warning Signs/Labels	Approve all laser area warning signs and equipment labels
Facility/Equipment	Approve laser facilities and equipment prior to use
Training	Ensure that all personnel receive appropriate laser safety training
Medical Surveillance	Determine which personnel categories require medical surveillance

procedures. SOPs are especially valuable guides for new laser workers. Guidelines for preparing a SOP for laser operations are presented in Appendix A.

MANAGERS AND SUPERVISORS

It is the responsibility of management to:

1. appoint the LSO,
2. verify that all appropriate controls are applied,
3. provide training to all laser workers,
4. provide medical surveillance practices.

It is the duty of managers and supervisors to:

1. Maintain the names of all persons trained, the date of training and to inform the LSO of training completions and requirements.
2. Issue appropriate instructions and training materials on laser hazards and the control of the hazards to all personnel working with lasers in their area.
3. Not permit the operation of lasers without adequate control of the hazards.
4. Work in conjunction with the LSO regarding the qualifications of laser users.
5. Report any known or suspected laser-related injury to the LSO.
6. Assist in obtaining medical attention for any employee involved in a laser accident or incident.
7. Approve laser system operation after consulting with the LSO.
8. Verify that meaningful SOPs have been prepared for the use of Class 3b and Class 4 lasers (lower classes if deemed necessary by the LSO).

LASER WORKERS

Duties and responsibilities of employees working with lasers consist of compliance with safety rules and regulations for the safe use of lasers as established by the LSO and area supervisors. Laser workers must be aware of visitors and spectators in the area, and terminate laser operations if unsafe conditions exist. It is the responsibility of laser workers to report all laser related incidents and accidents to the area supervisor.

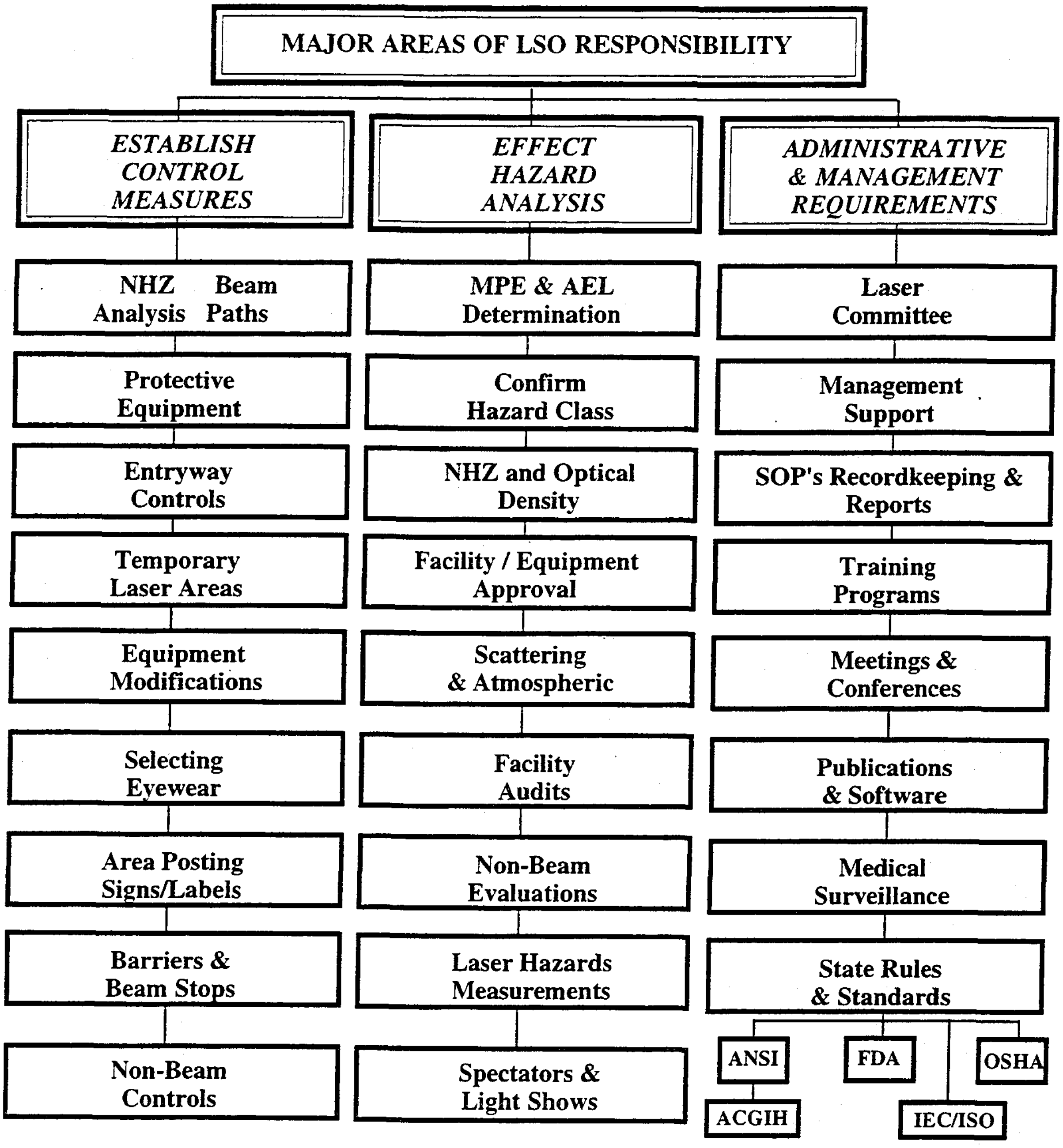
Users of high power lasers must also be aware of non-beam hazards associated with these laser systems. The extent of these hazards varies greatly, depending upon the laser class, type, and application.

SKILL REVIEW
1

Who is responsible for ensuring an adequate laser safety program?

Answer here:

Table 2


MAJOR AREAS OF LSO RESPONSIBILITY
ESTABLISH CONTROL MEASURES
NHZ Analysis
Beam Paths
Protective Equipment
Entryway Controls
Temporary Laser Areas
Equipment Modifications
Selecting Eyewear
Area Posting Signs/Labels
Barriers & Beam Stops
Non-Beam Controls
EFFECT HAZARD ANALYSIS
MPE & AEL Determination
Confirm Hazard Class
NHZ and Optical Density
Facility / Equipment Approval
Scattering & Atmospheric
Facility Audits
Non-Beam Evaluations
Laser Hazards Measurements
Spectators & Light Shows
ADMINISTRATIVE & MANAGEMENT REQUIREMENTS
Laser Committee
Management Support
SOP's Recordkeeping & Reports
Training Programs
Meetings & Conferences
Publications & Software
Medical Surveillance
State Rules & Standards
ANSI
ACGIH
FDA
IEC/ISO
OSHA

TRAINING

SECTION OBJECTIVES

- *Describe* the training requirements for the LSO, managers and supervisors, and laser workers
- *Distinguish* among the training requirements for different classes of lasers
- *Explain* the importance of update training
- *Discuss* the concept of tailored training and *recognize* why it is important

OVERVIEW

The ANSI *standard Z136.1 does not require* laser safety training for users of Class 1 or Class 2a lasers and laser systems. According to the standard, training should be provided for operators of Class 2 and Class 3a lasers and laser systems. Training is required for operators of Class 3b and Class 4 lasers and laser systems.

LASER SAFETY OFFICER

Laser safety training begins with the LSO. In order for the LSO to manage the laser safety program, he or she must be knowledgeable about all aspects of laser operation, biological effects produced by laser beams, hazard analysis, laser safety, and control measures. The LSO must also be able to determine MPE, NHZ and optical density. Finally, the training must be at least at the level of the highest class of laser for which the LSO is responsible.

The LSO training should consist of a comprehensive multi-day course that includes all key aspects of laser safety and a in-depth review of the appropriate standards, OSHA requirements, and needs for state and local compliance, as appropriate. A topical outline of a LSO training program is given in Table 3.

MANAGERS AND SUPERVISORS

Managers and supervisors of laser areas must be knowledgeable of the training requirements for laser safety. They must understand the potential hazards and control measures associated with the lasers in their area and the procedures pertaining to laser safety issues. Although managers and supervisors do not need to be trained to the level of the LSO, they do need to be adequately trained to establish and maintain a suitable laser safety program.

INCIDENTAL PERSONNEL

Incidental personnel are those who work near areas where lasers are used, and who therefore could possibly be exposed to laser radiation. Such personnel require laser awareness training. This training may include specific procedures to follow such as "Do not enter the laser room when the light by the door is illuminated," or "Never stare into a laser beam."

The purpose of awareness training is to help incidental personnel to understand that laser safety procedures must be followed to avoid the risk of injury. Such personnel, however, do not need extensive laser safety training, but they should receive periodic retraining to maintain proper awareness of the potential hazards.

TABLE 3

SAMPLE LSO LASER TRAINING CURRICULUM

Main Topic	Major Points
Operational Laser Characteristics	Laser operation Laser definitions Review of laser applications
Laser Hazards	Eye and skin hazards of direct and reflected beams Laser exposure criteria (MPE, AEL) Hazard assessment (OD, NHZ) Non-beam hazards: electrical, fire, fumes, particles, etc. Other associated hazards
Laser Safety Standards	Specific company laser regulations ANSI Z136.1 The Federal Laser Product Performance Standard OSHA laser regulations Applicable regional, state, and local regulations Applicable international laser regulations
Laser Controls	Reducing beam hazards Types/selection of eye protection Methods of electrical safety Methods for fume removal Methods to reduce fire hazards SOP for laser use
Safety Methods and Procedures	Beam alignment Barriers and other laser controls Beam measurements Laser system controls Laser area warning signs Entryway control options Control of unauthorized personnel Training requirements for laser workers

LASER WORKERS

All employees assigned to service, maintain, install, adjust, and operate laser equipment require specific training related to the adverse biological effects produced by the laser they are working on. Such laser workers must be trained in the safety features of the equipment, procedural controls such as alignment procedures, protective equipment requirements, and company policies and procedures related to laser safety. One essential component of the laser safety curriculum for laser workers is training in the proper safety procedures for the specific systems the individuals are using.

A second component of the training curriculum should be training appropriate to the Class of laser radiation accessible during the required tasks of the personnel.

TRAINING FOR CLASS 1 LASER USERS

Class 1 training can be limited, in general, to information contained in the operation/maintenance manuals of the laser manufacturer. No additional operator training is necessary provided the Class 1 status is maintained.

SKILL REVIEW
2

Who should be knowledgeable about the safety features of a particular laser, training requirements and hazard evaluation?

Answer here:

TRAINING FOR USERS OF CLASS 2, CLASS 2A, AND CLASS 3A

Class 2, Class 2a, and Class 3a training can include information contained in the operation/ maintenance manuals of the laser manufacturer and, where appropriate, additional basic laser safety information of a general nature. Audio-visual programs can be used to enhance understanding of laser hazards, especially in environments where Class 2, Class 2a or Class 3a laser systems are operated by a variety of laser workers.

TRAINING REQUIREMENTS FOR CLASS 3B AND CLASS 4 LASER USERS

The training of laser workers who use Class 3b or Class 4 laser systems should provide a complete understanding of the requirements of a safe laser environment. The training topics should include laser hazards, required safety devices, SOPs, warning sign, and medical surveillance. Emphasis should be placed on practical, safe laser techniques and procedures, as well as safety devices that provide an overall safe environment.

UPDATE TRAINING

Update training is necessary to: maintain laser safety information and skills, reduce the likelihood that personnel will develop unsafe laser practices, and satisfy legal requirements. Training updates are especially important for research and service personnel who do frequent beam alignments. Laser safety update training is essential to maintain a safe laser environment. One individual, who lost the sight in one eye because he had not worn protective eyewear, commented: "This incident could have been avoided. Don't let it happen to you or a co-worker. Take time to assess safety conditions, and do it again in 6 months or a year; additional hazards arise in an ever-changing research environment. Safety deserves your thoughtful consideration, now, before your accident."

TAILORED TRAINING

Where possible, the specific course content should be designed for the particular laser and the laser environment in which it is used. For example, the hazards and controls associated with a far-infrared (IR) CO_2 laser are usually different than those for a near-IR Nd:YAG laser, a visible argon ion laser, or an ultraviolet (UV) excimer laser.

Laser safety training should also be tailored to educational level and duties of the laser worker. For example, a mathematical treatment of laser theory may be appropriate for researchers, but not for medical personnel or production workers. It is essential to tailor the curriculum and instructional methods to the interests of the target audience. The training should meet the needs of the *students* — not the preferences of the instructor.

Training sessions may include materials such as this module, videotapes, or computer-based instruction. It has been shown that a balanced training approach that includes a variety of elements such as lecture, audiovisual materials, demonstration, and hands-on training is very effective. Appendix B contains two sample laser safety training outlines.

MEDICAL SURVEILLANCE

SECTION OBJECTIVES

- *Explain* the purpose of medical surveillance
- *Distinguish* among preassignment, routine, and terminal medical examinations and *explain* the purpose of each type of examination
- *Describe* the examination guidelines for the skin and the eye

OVERVIEW

Medical surveillance refers to preassignment, routine, and terminal medical examinations of individuals who could be exposed to laser radiation or other laser-related hazards, such as toxic gases or vapors. Medical surveillance is therefore not required for personnel using Class 1, Class 2, Class 2a, or Class 3a laser systems. Medical surveillance is required, according to ANSI Z136.1 for Class 3b and Class 4 lasers and laser systems.

The purpose of providing medical surveillance of personnel working in a laser environment is to:

1) Identify workers who may be especially susceptible to injury due to a pre-existing injury or condition
2) Provide early detection of any laser-related injury
3) Provide a baseline to judge the extent of any laser injury
4) Satisfy medical/legal requirements

Preassignment examinations screen out individuals with any pre-existing injury or condition, and the following protocols are recommended by ANSI Standard, Appendix E2.2: An ocular history and visual acuity for far and near vision should be measured with some standard and reproducible method. Macular function should be tested for distortions and scotomas. Contrast sensitivity, which includes low contrast images, should be documented.

Except for examinations following an injury, preassignment examinations are the only examinations required by the ANSI standard. Terminal examinations can provide the employer with legal protection against unwarranted claims for damages from a former employee. Whether or not to conduct terminal examinations is a decision that is left up to the employer.

Periodic, routine examinations of most laser workers have been found to be unnecessary in medical surveillance programs. Most users of lasers are not at risk from chronic exposure to low radiation levels, so routine examinations have no purpose in relation to medical surveillance. The one exception involves personnel working with UV radiation. Such radiation, even in a low dosage, has proven to produce carcinogenic and mutagenic effects.

Instead of requiring routine, periodic examinations, a better approach is to provide an examination immediately following a suspected exposure to hazardous levels of laser radiation, and periodic subsequent re-examination following the exposure. Such a course of action is more cost-effective and consistent with good medical follow-up. The examinations can assist in understanding the nature of the laser injury, and serve as a basis *for establishing potential compensation claims.*

Like routine examinations, retinal photographs have not proven to be useful in monitoring healthy individuals. However, if visual function is degraded following a laser exposure; then it is likely that damage has occurred, and retinal photographs can be an effective documentation of the condition. Table 4 presents a brief summary of types of ocular injuries that can be detected in a medical examination.

EXAMINATION GUIDELINES

Depending upon the length of the laser to which an individual has been exposed, different parts of the eye may be affected.

SKIN

Both UV and IR-C exposures can produce changes in the eye lids, brows, cheek, and nose. Exposure to UV can cause skin burns that are similar to sunburn, characterized by pigment migration, tenderness, and blistering. Threshold UV-exposure will produce pain, but only after a latent period of several hours of UV-exposure.

Exposure to IR radiation can produce erythema or a serious injury characteristic of a thermal burn. The burn should be present about the same time the cornea and conjunctiva become inflamed, but only if the beam was large enough to affect both the conjunctiva and surrounding skin.

CORNEA

The cornea can be damaged by exposure to either UV or IR-C laser wavelengths. Following such an exposure, the portions of the cornea and conjunctiva that are visible when the lids are open may be sensitive. The underside of the lid and unexposed portion of the conjunctiva should not be involved or irritated. Pain should appear only after a latent period of several hours of UV exposures. Examination with a slit lamp or biomicroscope should show characteristics of UV exposure or thermal burn from IR laser exposure, such as epithelial haze and granulation.

TABLE 4

LASER RELATED OCULAR INJURIES

	Laser Wavelength Spectrum						
Injury	UV-C	UV-B	UV-A	Vis	IR-A	IR-B	IR-C
Keratoconjunctivitis	VL	VL	L			L[1]	L
Aqueous Flare				L			
Lenticular Changes		VL			L		
Immediate Appearance of Retinal Lesions					L	L	
Delayed Appearance of Retinal Lesions					L		
Retinal Hemorrhage				UL	UL		

Key: L - likely
VL - very likely
UL - unlikely; must be from a short-pulsed source
1 - within Palpebral Fissure

SKILL REVIEW
3

Who benefits from medical surveillance?

Answer here:

LENS

Exposure to intense, focused IR wavelengths may cause opacity in the pupillary region and behind the iris. Longer exposures at lower power levels may only involve the pupillary region.

Exposure to UV wavelengths can also cause lens injury, *but only at or around the threshold* for corneal involvement. Usually, exposure to short-pulse high-intensity UV radiation affects both the lens and cornea.

IRIS

The iris is likely to be damaged only by exposure to very high intensity IR and visible wavelengths. In the UV spectral region, the threshold for corneal damage is far below that for iris damage. In any part of the spectrum, focal illumination is required for damage of the iris without markedly affecting the cornea. Exposure to high intensity, focused visible or IR radiation could cause irritation of the iris, leading to iritis. Exposure to high intensity IR could even burn a hole in the iris, causing hemorrhaging if blood vessels were involved.

RETINA

A threshold laser exposure may cause a retinal lesion. The lesion will appear as a whitened area in the retina. For very mild exposures, the lesion will quickly fade. After a few months, the exposed area will appear hyperpigmented, even though it may have been almost depigmented immediately after the exposure. The extent of loss of visual acuity will depend upon the size the lesion and its location on the retina.

A near threshold lesion from a visible laser should be painless. Only high level suprathreshold exposures will occasionally produce a sensation of pain in the cornea. The pain will be transient. Persistent pain would indicate considerable choroidal involvement.

VITREOUS

It is unlikely that any damage could be found in the vitreous, unless there was injury to another part of the eye, particularly the retina. Vitreous damage usually results from a vascular involvement of the retina leading to hemorrhage into the vitreous. A large hemorrhage in the vitreous can lead to retraction and retinal detachment, which may occur months or even *years after the injury*.

THE LASER SAFETY AUDIT

SECTION OBJECTIVES

- *Explain* two primary reasons for conducting a laser safety audit
- *Identify* the priorities for inspecting laser areas
- *Discuss* the need for laser safety audits and corrective action plans
- *Explain* the preferred method of laser safety controls

CONDUCTING AN AUDIT

Safety audits and inspections of laser equipment and laser facilities are part of a LSO's duties. The frequency of the audit and the inspection details will vary according to the type of facility (lab, operating room or manufacturing) and according to the level of cooperation given the LSO by the laser user.

The LSO should not be considered as a "photon-cop" travelling around the facility looking for stray, hazardous photons. In order to defeat that image, the LSO must have the authority of the ANSI Standards and local management. Individual company policies that clearly state the requirements for a laser safety program which includes the adaption of the ANSI Standard are necessary for a successful laser safety audit. A sample laser safety audit form is provided in Appendix (C).

Far too often the auditor looks for signs posted in the area and for laser safety eyewear. Even though these are important considerations, they should not be the first considerations. First, get to know the person in charge of laser operation in the specific area and determine attitudes regarding laser safety issues as well as the laser equipment they are working with. The LSO will gain valuable insights to the training requirements of the staff members through gathering this information. The LSO also needs to become familiar with the applications of the lasers being audited. Knowing the equipment, skill level of operators and other application orientated items, the LSO can better make more informed judgements about appropriate control measures.

While conducting an audit, it is necessary to determine the minimum level of exposure that is required to make the laser equipment perform as intended. If the beam is exposed more than is absolutely necessary, enclosures, beam covers, and beam termination points should be considered. Remember, enclosure of the beam is the preferred method of laser safety controls.

Interlocks on the protective enclosures should be considered next. If existing interlocks have been permanently defeated, they need to be fixed immediately. In some situations, additional interlocks may be suggested. An audit should determine if the laser equipment has been modified and if those modifications have increased the potential hazard.

Reflective surfaces in or near an open laser beam path is a likely source of accidental exposure. If the reflective surface is necessary such as the target of an optical surface, the potential reflection should be terminated in a safe location. If the reflective surfaces are not necessary (such as tools, bottles or other clutter), they should be eliminated through organizing and cleaning up the environment.

SKILL REVIEW
4

What is the preferred method of laser safety controls?

Answer here:

If the audit inspector determines that an open beam (less than Class 3a) is necessary, the procedures for its use should be investigated. Perhaps intentional direct viewing of the beam is not necessary. If a reasonable argument can be made for viewing the beam perhaps indirect viewing instruments could be suggested, such as diffuse reflective screens or other devices that prevent the direct beam from entering the eye.

EYEWEAR

High power lasers, Class 3b or 4, demand the use of laser protective eyewear if there is a possibility of the beam (or even diffuse reflections from a Class 4 beam only) can enter the eye. The auditor must make certain the correct optical density is chosen for the laser wavelength being used. Make certain that all laser wavelengths and any collateral radiations (such as UV) are accounted for in the analysis. Even though it is important to have a high enough optical density for protection, excessively high optical density values may reduce visible light and result in the user having greatly restricted vision. Make certain that the eyewear is in good condition and is being used. If viewing windows or optically aided instruments such as microscopes or telescopes are being used, check to be certain that filters or shutters are built into the viewing systems to prevent hazardous radiation from transmitting through it to the operators eyes.

When all options for enclosing the beams path and all methods of protecting personnel in the immediate laser area have been exhausted, it is time to look for methods of restricting the access to the laser area. In addition to warning signs, the ANSI Standard gives optional methods of restricting the access to a controlled area. These include doorway controls, signs, and warning systems (like flashing lights). The LSO must determine which is most effective and appropriate for the specific environment. The audit simply verifies that the controls are working as intended.

An audit must provide "feed-back" to the laser users in the area. A corrective action plan must be organized if deficiencies are determined as a result of the audit. These deficiencies are communicated to management and laser users and, then implemented.

Laser equipment used in laboratories are often revised and modified to conduct different experiments. This can result in certain safety measures being removed or eliminated. In production facilities, enclosures designed to prevent access to the beam are occasionally modified. Safety labels are often damaged, removed or worn off due to the environment of usage. A routine safety audit can spot potential problem areas and correct them before they lead to an injury.

CHAPTER REVIEW

SUMMARY

1. The LSO is responsible for the laser safety program, for safety controls, and for hazard evaluation.
2. Managers and supervisors are responsible for laser safety and for providing laser safety training for employees.
3. Employees are responsible for complying with all safety rules.
4. The LSO must be trained in all aspects of laser theory, operation, controls, and hazard evaluation.
5. Managers and supervisors must understand the training requirements for laser safety.
6. Laser training for employees must be appropriate for the job category and for the class of laser being used.
7. Update training is required to maintain a safe laser environment.
8. Medical surveillance provides protection for employees and management.
9. Preassignment medical exams can screen out individuals with pre-existing injuries or conditions; terminal exams help protect against unwarranted claims of injury.
10. The portion of the eye susceptible to injury from laser radiation depends upon the wavelength.
11. Audits should consider an analysis of the equipment; the environment in which the laser is being used; and the employees understanding of laser safety.

KEY TERMS Define each term

incidental personnel
laser workers
LSO
medical surveillance
MPE
NHZ
SOP
OD
update training

For Further Reading

American national standard for the safe use of lasers(1992). American National Standards Institute, Inc. New York, NY The ANSI standard classifies lasers according to their hazard level and defines appropriate control measures for each laser class to ensure the safe use of lasers and laser systems.

Guidelines for Laser Safety and Hazard Assessment (1991). The guide provides a general overview of industrial laser standards and regulatory requirements.

Rockwell Laser Industries. *Laser safety in surgery and medicine* (1985). Cincinnati, OH: The text describes the role of the LSO in a medical environment and includes sample SOPs and training outlines for nurses.

REVIEW QUESTIONS

1. Laser safety training is the responsibility of:
   a. LSO
   b. managers and supervisors
   c. employees
   d. LSO, managers and supervisors

2. The principal reason for using laser SOPs is to:
   a. provide legal protection
   b. satisfy OSHA requirements
   c. improve safety
   d. reduce medical costs

3. The individual most responsible for approving laser system operation is the:
   a. LSO
   b. manager or supervisor
   c. laser worker
   d. OSHA representative

4. Managers and supervisors should be most knowledgeable about:
   a. laser safety training requirements
   b. MPE determination
   c. NHZ calculation
   d. laser theory

5. A laser worker should receive:
   a. a preassignment medical baseline examination
   b. update training
   c. tailored training
   d. all of the above

6. The least effective type of medical surveillance is:
   a. preassignment medical examinations
   b .routine medical examinations
   c. terminal medical examinations
   d. none of the above

7. Following a suspected laser accident, the first action should be to:
   a. take a retinal photograph
   b. conduct a laser safety examination
   c. perform a medical examination on the individual
   d. suspend laser operations

8. The retina is most likely to be damaged by exposure to _____ wavelengths:
   a. infrared
   b. visible
   c. ultraviolet
   d. all of the above

9. Unwarranted legal claims for injury can be best protected against by:
   a. routine medical examinations
   b. terminal medical examinations
   c. preassignment medical examinations
   d. all of the above

10. Providing examples of unsafe laser safety practices in a training class for production workers is an example of:
    a. update training
    b. relevance training
    c. periodic training
    d. tailored training

SKILL REVIEW ANSWERS

1. The LSO, managers, and supervisors

2. LSO and managers and supervisors

3. The employee benefits from medical surveillance because it helps to protect the individual's health; the company benefits from medical surveillance because it offers legal protection and helps to minimize medical costs by providing early detection of medical injuries.

4. Enclosure of the laser beam

CHAPTER REVIEW ANSWERS

1. d
2. c
3. b
4. a
5. d
6. b
7. c
8. a
9. b
10. d

APPENDIX B

LASER SAFETY INVENTORY DATA SHEET

REPORT NO.: ____________
PHOTO NO.: ____________

LASER SAFETY INVENTORY
DATA SHEET

LASER PRODUCT

LASER SYSTEM MFR.: ____________ MODEL NO.: ____________ SERIAL NO.: ____________

B.T. NO.: ____________ LOCATION: ____________ ACTIVE STATUS?: (Y) (N)

APPLICATION: ____________

EMBEDDED LASER MFTR.: (IF APPLICABLE): ____________

MODEL NO.: ____________ SERIAL NO.: ____________

PRODUCT CONTAINS SEPARATE AIMING LASER?: (Y) (N) (NA)

AIMING LASER TYPE: ____________ WAVELENGTH: ____________ μm

POWER: ____________ mW

MANUFACTURER: ____________ MODEL NO.: ____________

CDRH

PERFORMANCE FEATURES

BEAM ATTENUATOR: (Y) (N)
KEY SWITCH: (Y) (N)
EMISSION INDICATOR: (Y) (N)
REMOTE INTERLOCK CONNECTOR: (Y) (N)
P.H. INTERLOCKS FUNCTIONAL: (Y) (N)

CLASSIFICATION:

MFR. CERTIFIED & CLASSIFIED (Y) (N)

SYSTEM:	[1] [2] [2A] [3A] [3B] [4]
EMBEDDED:	[1] [2] [2A] [3A] [3B] [4]
AIMING:	[1] [2] [2A] [3A] [3B] [4]

LABELING REQUIREMENTS

MFR. LABEL: (Y) (N)
CERTIFICATION LABEL: (Y) (N)
P.H. LABEL: (Y) (N)
LOGOTYPE LABEL: (Y) (N)
APERTURE LABEL: (Y) (N)

COMMENTS: ____________

ROCKWELL LASER INDUSTRIES

LASER - OPTICS SPECIFICATIONS

TYPE OF LASER MEDIA: ____________ MAX. POWER/ENERGY: ____________ (W/J)

OPERATIONAL WAVELENGTHS: ________ µm ________ µm ________ µm

TUNABLE WAVELENGTH RANGE (IF APPLICABLE): ____________ µm

BEAM DIVERGENCE: ________ mrad.

BEAM SIZE @ LASER APERTURE: ________ mm BEAM SIZE @ LENS: ________ mm

LENS FOCAL LENGTH: ________ mm (LONGEST) FIBER OPTIC NA: ________ mm

TIMED CHARACTERISTICS: CONTINUOUS WAVE: [ ]

SINGLE PULSED MODE (PRF< = 1 Hz): [ ] DURATION: ______ sec RATE: ______ Hz

REPETITIVELY PULSED (PRF > 1 Hz): [ ] DURATION: ______ sec RATE: ______ Hz

---

HAZARD ANALYSIS

ANSI MPE: ________ EYEWEAR O.D. REQUIRED: ________ @WAVELENGTH: ________ µm

NOMINAL HAZARD ZONES: DIRECT BEAM: ________ m LENS: ________ m

DIFFUSE: ________ m OTHER: ________ m

AREA CONTROLS & ADMINISTRATIVE

WRITTEN SOP WITH LASER?: (Y) (N) PROPER AREA SIGNS POSTED?: (Y) (N) (NA)

ADAQUATE WINDOW COVERING?: (Y) (N) (NA) CLASS OF WARNING SIGNS: [2] [3A] [3B] [4]

EXHAUST SYSTEM OPERABLE: (Y) (N) (NA) VIEWING SYSTEMS?: (Y) (N) (NA)

ENTRY WAY CONTROLS: BARRIER: (Y) (N) (NA) DOOR INTERLOCK: (Y) (N) (NA) OTHER: ________

EVIDENCE OF STRAY BEAM BURNS ON WALLS/ENCLOSURES: (Y) (N) (NA)

EYE PROTECTION PROVIDED: MANUFACTURER: ____________

OPTICAL DENSITY: ____________ TYPE/MODEL NO.: ____________

NON-BEAM HAZARDS: FIRE: [ ] PLUME RADIATION: [ ]

ELECTRICAL SHOCK: [ ] CHEMICALS/VAPORS: [ ]

AUDIBLE NOISE: [ ] AMBIENT LIGHT LEVEL: [ ]

GAS PRESSURE TANK STORAGE: [ ]

COMMENTS: ____________

LASER SAFETY OFFICER: ____________

CONTACT PERSON: ____________ PHONE NO.: ____________

DATE FORM COMPLETED: ____________ BY: ____________

Glossary of Laser Terminology

Absorb	To transform radiant energy into a different form, usually with a resultant rise in temperature.
Absorption	Transformation of radiant energy to a different form of energy by the interaction of matter, depending on temperature and wavelength.
Absorption	Factor describing light's ability to be absorbed per unit of path length.
Coefficient	Optical properties of different tissue alters the absorption.
Accessible Emission Limit (AEL)	The maximum output power or energy (or in the case of pulsed visible and near infrared Class 3 lasers) radiant exposure acceptable for a given class.
Active Medium	Collection of atoms or molecules capable of undergoing stimulated emission rather than absorption at a given wavelength.
Afocal	Literally, "without a focal length"; an optical system with its object and image point at infinity.
Aiming Beam	A HeNe laser (or other light source) used as a guide light. Used coaxially with infrared or other invisible light.
Amplification	The growth of the radiation field in the laser resonator cavity. As the light wave bounces back and forth between the cavity mirrors, it is amplified by stimulated emission on each pass through the active medium.
Amplitude	The maximum value of the electromagnetic wave, measured from the mean to the extreme; put simply, the height of the wave.
Angle of Incidence	See Incident Ray
Angstrom	A unit of measure of wavelength equal to 10^{-10} meter 0.1 nanometer or 10^{-4} micrometer, no longer widely used nor recognized in the SI system of units.
Anode	An electrical element in laser excitation which attracts electrons from a cathode.
Aperture	An opening through which radiation can pass.
Apparent Visual Angle	The angular subtense of the source as calculated from the source size and distance from the eye. It is not the beam divergence of the source.
AR Coatings	Antireflection coatings used on optical components to suppress unwanted reflections, which reduce power.
Argon	The gas used as a laser medium. It emits blue/green light primarily at 448 and 515 nm.
Articulated Arm	CO_2 laser beam delivery device consisting of a series of hollow tubes and mirrors interconnected in such a manner as to maintain alignment of the laser beam along the path of the arm.
Attenuation	The decrease in energy (or power) as a beam passes through an absorbing or scattering medium.

Autocollimator	A single instrument combining the functions of a telescope and a collimator to detect small angular displacements of a mirror by means of its own collimated light.
Average Power	The total energy imparted during exposure divided by the exposure duration.
Aversion Response	Movement of the eyelid or the head to avoid an exposure to a noxious stimulant, bright light. It can occur within 0.25 seconds, and it includes the blink reflex time.
Axial-Flow Laser	A laser in which an axial flow of gas is maintained through the tube to replace those gas molecules depleted by the electrical discharge used to excite the gas molecules to the lasing state. See gas discharge laser.
Axicon Lens	A conical lens which, when followed by a conventional lens, can focus laser light to a ring shape.
Axis, Optical Axis	The optical centerline for a lens system; the line passing through the centers of curvature of the optical surfaces of a lens.
Beam	A collection of rays that may be parallel, convergent, or divergent.
Beam Bender	A hardware assembly containing an optical device, such as a mirror, capable of changing the direction of a laser beam; used to repoint the beam and in "folded," compact delivery systems.
Beam Diameter	The distance between diametrically opposed points in the cross section of a circular beam where the power-per-unit-area is 1/e or 34% of the peak for safety standards or is $1/e^2$ for manufacturing specification.
Beam Divergence	Angle of beam spread measured in radians or milliradians (1 milliradian = 3.4 minutes-of-arc or approximately 1 mil). For small angles where the cord is approximately equal to the arc, the increase in the diameter of the beam is numerically equal to 1,000th of the range in meters multiplied by the number of milliradians of beam divergence.
Beam Expander	An optical device that increases beam diameter and reduces divergency. In its simplest form consists of two lenses, the first to diverge the beam and the second to re-collimate it. Also called an upcollimator.
Beam Splitter	An optical device using controlled reflection to produce two beams from a single incident beam.
Blink Reflex	See Adversion Response.
Brewster Windows	The transmissive end (or both ends) of the laser tube, made of transparent optical material and set at Brewster's angle in gas lasers to achieve zero reflective loss of vertically polarized light. They are nonstandard on industrial lasers, but a must if polarization is desired.
Brightness	The visual sensation of the luminous intensity of a light beam. The brightness of a laser beam is most closely associated with the radiometric measurement of radiance.
C.I.E.	Abbreviation for Commission International de L'Eclairage, the French translation for International Commission on Illumination.
Calorimeter	An instrument which measures the heat generated by absorption of the laser beam.
Carbon Dioxide	Molecule used as a laser medium. Emits far infrared light at 10,600 nm (10.6μ).

Cathode	A negatively charged electrical element providing electrons for the electrical discharge.
Closed Installation	Any location where lasers are used which will be closed to unprotected personnel during laser operation.
CO_2 Laser	A widely used laser in which the primary lasing medium is carbon dioxide gas. The output wavelength is 10,600 nm in the far infrared spectrum. It can be operated in either CW or pulsed.
Coaxial Gas	A shield of inert gas flowing over the target material to prevent plasma oxidation and absorption, to blow away debris, and to control heat reaction. The gas jet has the same axis as the beam, so the two can be aimed together.
Coherence	A term describing light as waves which are in phases in both time and space. Monochromacity and low divergence are two properties of coherent light.
Collimated Light	Divergent light rays rendered parallel by means of a lens or other device, allowing a sharp image of the object to be focussed at the focal plane of the lens.
Collimation	Ability of the laser beam to not spread significantly (low divergence) with distance.
Combiner Mirror	The mirror in a laser which combines two or more wavelengths into a coaxial beam.
Continuous Mode	The *duration of laser exposure* is controlled by the user (by foot or hand switch); exposure is maintained as long as switch is depressed.
Continuous Wave (CW)	Constant, steady state delivery of laser power.
Controlled Area	An area where the occupancy and activity of those within are subject to control and supervision for the purpose of protection from optical radiation hazards.
Convergence	The bending of light rays toward each other, as by a positive (convex) lens.
Corrected Lens	A compound lens *that is made measurably free of aberrations through the careful* selection of its dimensions.
Crystal	A solid with a regular array of atoms. Ruby and YAG are crystalline materials used as laser sources.
Current Regulation	Laser system regulation in which discharge current is kept constant.
Current Saturation	The maximum flow of electric current in a conductor; in a laser, the point at which further electrical charge will not increase lasing action.
CW	Abbreviation for continuous wave; the continuous-emission mode of a laser as opposed to pulsed operation.
Depth of Field	The working of the beam in or near the focal plane of a lens; a function of wavelength, diameter of the unfocussed beam, and focal length of the lens.
Depth of Focus	The distance over which the focused laser spot has a constant diameter and thus constant irradiance.
Dichroic Filter	Filter that allows selective transmission of colors desired wavelengths.

Diffraction	Deviation of part of a beam, determined by the wave nature of radiation and occurring when the radiation passes the edge of an opaque obstacle.
Diffuse Reflection	Takes place when different parts of a beam incident on a surface are reflected over a wide range of angles in accordance with Lambert's Law (or the Cosine Law) of reflection.
Diffuser	An optical device or material that homogenizes the output of light causing a very smooth, scattered, even distribution over the area affected.
Divergence	The increase in the diameter of the laser beam with distance from the exit aperture. (The value gives the full angle at the point where the laser radiant exposure or irradiance is 1/e or 1/e^2 of the maximum value.
Dosimetry	Measuring the power, energy, irradiance or radiant exposure of light delivered to tissue.
Drift, Angular Drift	All undesirable variations in output (either amplitude or frequency); angular drift of the beam before, during, and after warm up; measured in milliradians.
Duty Cycle	Ratio of "on" duration to total exposure duration for a repetitively pulsed laser.
Electric Vector	The electric field associated with a light wave which has both direction and amplitude.
Electromagnetic Radiation	The propagation of varying electric and magnetic fields through space at the velocity of light.
Electromagnetic Spectrum	The range of frequencies and wavelengths emitted by atomic systems. The total spectrum includes long radio waves as well as very short cosmic rays.
Electromagnetic Wave	A disturbance which propagates outward from an electric charge that oscillates or is accelerated. Includes radio waves; X-rays; gamma rays; and infrared, ultraviolet, and visible light.
Electron	Negatively charged particle of an atom.
Embedded Laser	A laser with an assigned class number higher than the inherent capability of the laser system in which it is incorporated, where the systems lower classification is appropriate to the engineering features limiting accessible emission.
Emergent Beam Diameter	Diameter of the laser beam at the exit aperture of the system in centimeters (cm) defined at 1/e or 1/e^2 irradiance points.
Emission	Act of giving off radiant energy by an atom or molecule.
Emissivity, Emitance	The rate at which emission takes place; the ratio of the radiant energy emitted by a source or surface to that emitted by a blackbody at the same temperature.
Enclosed Laser Device	Any laser or laser system located within an enclosure which does not permit hazardous optical radiation emission from the enclosure. The laser inside is termed an "embedded laser".
Energy	The product of power (watts) and duration (seconds). One watt second = one joule.
Energy (Q)	The capacity for doing work. Energy is commonly used to characterize the output from pulsed lasers and it is generally measured in joules (J). The product of power (watts) and duration (seconds). One watt second = one joule.

Energy Source	High voltage electricity, radiowaves, flashes of light, or another laser used to excite the laser medium.
Enhanced Pulsing	Electronic modulation of a laser beam to produce high peak power at the initial stage of the pulse. This allows rapid vaporization of the material without heating the surrounding area. Such pulses are many times the peak power of the CW mode (also called "Super Pulse").
Excimer	"Excited dimer". A gas mixture used as the active medium in a family of lasers emitting ultraviolet light.
Excitation	Energizing a material into a state of population inversion.
Excited State	Atom with an electron in a higher energy level.
Exempted Laser Product	In the U.S., a laser device exempted by the U.S. Food and Drug Administration from all or some of the requirements of 21 CFR 1040.
Extended Source	An extended source of radiation can be resolved into a geometrical image in contract with a point source of radiation, which cannot be resolved into a geometrical image. A light source whose diameter subtends a relatively large angle at the targets surface.
F-Number	The focal length of lens divided by its usable diameter. In the case of a laser the usable diameter is the diameter of the laser beam or an aperture which restricts a laser beam.
Failsafe Interlock	An interlock where the failure of a single mechanical or electrical component of the interlock will cause the system to go into, or remain in, a safe mode.
Femtoseconds	10^{-15} seconds.
Fiberoptics	A system of flexible quartz or glass fibers with internal reflective surfaces that pass light through thousands of glancing reflections.
Flashlamp	A tube typically filled with Krypton or Xenon. Produces a high intensity white light in short duration pulses.
Fluorescence	The emission of light of a particular wavelength resulting from absorption of energy typically from light of shorter wavelengths.
Flux	The radiant, or luminous, power of a light beam; the time rate of the flow of radiant energy across a given surface.
Focal Length	Distance between the center of a lens and the point on the optical axis to which parallel rays of light are converged by the laser.
Focal Point	That distance from the focusing lens where the laser beam has the smallest diameter.
Focus	As a noun, the point where rays of light meet which have been reflected by a mirror or refracted by a lens, giving rise to an image of the source. As a verb, to adjust focal length for the clearest image and smallest spot size.
Folded Resonator	Construction in which the interior optical path is bent by mirrors; permit compact packaging of a long laser cavity.
Frequency	The number of light waves passing a fixed point in a given unit of time, or the number of complete vibrations in that period of time.

Gain	Another term for amplification, usually referring to the ability of a lasing medium in attaining a population inversion.
Gas Discharge Laser	A laser containing a gaseous lasing medium in a glass tube in which a constant flow of gas replenishes the molecules depleted by the electricity or chemicals used for excitation.
Gas Laser	A type of laser in which the laser action takes place in a gas medium.
Gated Pulse	A discontinuous burst of laser light, made by timing (gating) a continuous wave output - usually in fractions of a second.
Gaussian Curve Normal	Statistical curve showing a peak with even distribution on either side. May either be a sharp peak with steep sides, or a blunt peak with shallower sides. Used to show power distribution in a beam. The concept is important in controlling the geometry of the laser impact.
Ground State	Lowest energy level of an atom.
Half-Power Point	The value on either the leading or trailing edge of a laser pulse at which the power is one-half of its maximum value.
Heat Sink	A substance or device used to dissipate or absorb unwanted heat.
Helium-Neon Laser	A laser in which the active medium is a mixture of helium and neon. Its wavelength is in the visible range. Used widely for alignment, recording, printing, and measuring.
HeNe Laser	See Helium-Neon Laser.
Hertz	Unit of frequency in the International System of Units (SI), abbreviated Hz; replaces cps for cycles per second.
Hologram	A three dimensional picture made by interference patterns created by the coherence of laser light. Created as transmission, reflection or integral holograms.
Image	The optical reproduction of an object, produced by a lens or mirror. A typical positive lens converges rays to form a "real" image which can be photographed. A negative lens spreads rays to form a "virtual" image which can't be projected.
Incident Light	A ray of light that falls on the surface of a lens or any other object. The "angle of incidence" is the angle made by the ray with a perpendicular to the surface.
Infrared Radiation (IR)	Electromagnetic radiation with wavelengths which lie within the range of 0.76 to 1000 um. This region is often broken up into IR-A, IR-B and IR-C.
Integrated Radiance	Product of the exposure duration times the radiance. Also known as pulsed radiance.
Intensity	The magnitude of radiant energy.
Intrabeam Viewing	The viewing condition whereby the eye is exposed to all or part of a direct laser beam or a specular reflection.
Ion Laser	A type of laser employing a very high discharge current, passing down a small bore to ionize a noble gas such as argon or krypton.

Ionizing Radiation	Radiation commonly associated with X-Ray or other high energy electromagnetic radiation which will cause DNA damage with no direct, immediate thermal effect. Contrasts with non-ionizing radiation of lasers.
Irradiance (E)	Radiant flux (radiant power) per unit area incident upon a given surface. Units-watts per square centimeter. Also called power density.
Joule (J)	A unit of energy (1 watt-second) used to describe the rate of energy delivery. It is equal to one watt-second or 0.239 calorie.
Joule/cm^2	A unit of radiant exposure used in measuring the amount of energy per unit area.
KTP	Potassium Titanyl Phosphate. A crystal used to change the wavelength of a Nd:YAG laser from 1060 nm (infrared) to 532 nm (green).
Lambertian Surface	An ideal diffuse surface whose emitted or reflected radiance (brightness) is dependent on the viewing angle.
Laser	An acronym for *L*ight *A*mplification by *S*timulated *E*mission of *R*adiation. A laser is a cavity, with mirrors at the ends, filled with material such as crystal, glass, liquid, gas or dye. A device which produces an intense beam of light with the unique properties of coherency, collimation and monochromaticity.
Laser Accessories	The hardware and options available for lasers, such as secondary gases, Brewster windows, Q-switches and electronic shutters.
Laser Controlled Area	See Controlled Area.
Laser Device	Either a laser or a laser system.
Laser Medium	(Active Medium) material used to emit the laser light and for which the laser is named.
Laser Oscillation	The buildup of the coherent wave between laser cavity end mirrors producing standing waves.
Laser Product	A legal term in the U.S. See 21 CFR 1040.10.
Laser Rod	A solid-state, rod-shaped lasing medium in which ion excitation is caused by a source of intense light, such as a flashlamp. Various materials are used for the rod, the earliest of which was synthetic ruby crystal.
Laser Safety Officer (LSO)	One who has authority to monitor and enforce the control of laser hazards and effect the knowledgeable evaluation and control of laser hazards.
Laser System	An assembly of electrical, mechanical and optical components which includes a laser.
Leading Edge Spike	The initial pulse in a series of pulsed laser emissions, often useful in starting a reaction at the target surface. The trailing edge of the laser power is used to maintain the reaction after the initial burst of energy.
Lens	A curved piece of optically transparent material which depending on its shape is used to either converge or diverge light.
Light	The range of electromagnetic radiation frequencies detected by the eye, or the wavelength range from about 400 to 760 nanometers. It is sometimes extended to include radiation beyond visible limits.

Light Regulation	A form of power regulation in which output power is maintained at a constant level by controlling discharge current.
Limiting Angular Subtense	The apparent visual angle which divides intrabeam viewing from extended-source viewing.
Limiting Aperture	The maximum circular area over which radiance and radiant exposure can be averaged when determining safety hazards.
Limiting Exposure Duration	An exposure duration which is specifically limited by the design or intended use(s).
Longitudinal or Axial Mode	Determines the wavelength bandwidth produced by a given laser system controlled by the distance between the two mirrors of the laser cavity. Individual longitudual modes are produced by standing waves within a laser cavity.
Lossy Medium	A medium which absorbs or scatters radiation passing through it.
Maintenance	Performance of those adjustments or procedures specified in user information provided by the manufacturer with the laser or laser system, which are to be performed by the user to ensure the intended performance of the product. It does not include operation or service as defined in this glossary.
Maximum Permissible Exposure (MPE)	The level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin.
Meniscus Lens	A lens which has one side convex, the other concave.
Metastable State	The state of an atom, just below a higher excited state, which an electron occupies momentarily before destabilizing and emitting light. The upper of the two lasing levels.
Micrometer	A unit of length in the International System of Units (SI) equal to one-millionth of a meter. Once called a micron.
Micron	A unit of length equal to 1 millionth of a meter. See micrometer.
Microprocessor	A digital chip (computer) that operates, controls and monitors some lasers.
Mode	A term used to describe how the power of a laser beam is distributed within the geometry of the beam. Also used to describe the operating mode of a laser such as continuous or pulsed.
Mode Locked	A method of producing laser pulses in which short pulses (approximately 10^{-12} second) are produced and emitted in bursts or continuously.
Modulation	The ability to superimpose an external signal on the output beam of the laser as a control.
Monochromatic Light	Theoretically, light consisting of just one wavelength. Since no light is completely monochromatic, it usually consists of a very narrow bank of wavelength. Lasers provide the narrowest bands.
Multi-mode	Laser emission at several closely-spaced frequencies.
Nanometer (nm)	A unit of length in the International System of Units (SI) equal to one-billionth of a meter. Abbreviated nm - a measure of length. One nm equals 10^{-9} meter, and is the usual measure of light wavelength. Visible light ranges from about 400 nm in the purple to about 760 nm in the deep red.

Nanosecond	10^{-9} (one billionth) of a second. Longer than a picosecond or femtosecond, but shorter than a microsecond. Associated with Q-switched ophthalmic Nd:YAG lasers.
Nd:Glass Laser	A solid-state laser of neodymium: glass offering high power in short pulses.
Nd:YAG Laser	Neodymium: Yttrium Aluminum Garnet. A mineral crystal used as a laser medium to produce 1060 nm light.
Near Field Imaging	A solid-state laser imaging technique offering control of spot size and hole geometry, adjustable working distance, uniform energy distribution, and a wide range of spot sizes.
NEMA	Abbreviation for National Electrical Manufacturers' Association, a group which defines and recommends safety standards for electrical equipment.
Neodymium	The rare earth element that is the active element in Nd:YAG lasers and Nd:Glass lasers.
Noise	Unwanted minor currents or voltages in an electrical system.
Nominal Hazard Zone (NHZ)	The nominal hazard zone describes the space within which the level of the direct, reflected or scattered radiation during normal operation exceeds the applicable MPE. Exposure levels beyond the boundary of the NHZ are below the appropriate MPE level.
Nominal Ocular Hazard Distance (NOHD)	The axial beam distance from the laser where the radiant exposure or irradiance falls below the applicable exposure limit.
Object	The subject matter or figure imaged by or seen through, an optical system.
Opacity	The condition of being nontransparent.
Open Installation	Any location where lasers are used which will be open to operating personnel during operation and may or may not specifically restrict entry to observers.
Operation	The performance of the laser or laser system over the full range of its intended functions (normal operation). It does not include maintenance or services as defined in this glossary.
Optic Disc	The portion of the optic nerve within the eye which is formed by the meeting of all the retinal nerve fibers at the level of the retina.
Optical Cavity	(Resonator) Space between the laser mirrors where lasing action occurs.
Optical Density	A logarithmic expression for the attenuation produced by an attenuating medium, such as an eye protection filter.
Optical Fiber	A filament of quartz or other optical material capable of transmitting light along its length by multiple internal reflection and emitting it at the end.
Optical Pumping	The excitation of the lasing medium by the application of light rather than electrical discharge.
Optical Radiation	UV, visible and IR radiation (10nm - 1mm).
Optical Resonator	See Resonator.

Optically Pumped Lasers	A type of laser that derives energy from another light source such as a xenon or krypton flashlamp or other laser source.
Output Coupler	Partially reflective mirror in laser cavity which allows emission of laser light.
Output Power	The energy per second measured in watts emitted from the laser in the form of coherent light.
Phase	Waves are in phase with each other when all the troughs and peaks coincide and are "locked" together. The result is a reinforced wave in increased amplitude (brightness).
Photocoagulation	Use of the laser beam to heat tissue below vaporization temperatures with the principle objective being to stop bleeding and coagulate tissue.
Photometer	An instrument which measures luminous intensity.
Photon	In quantum theory, the elemental unit of light, having both wave and particle behavior. It has motion, but no mass or charge.
Photosensitizers	Chemical substances which increase the sensitivity of the skin or eye to irradiation by optical radiation, usually to UV.
Picosecond	10^{-12} seconds.
Pigment Epithelium	A layer of cells at the back of the retina containing pigment granules.
Plasma Shield	The ability of plasma to stop transmission of laser light.
Pockel's Cell	An electro-optical crystal used as a Q-switch.
Point Source	Ideally, a source with infinitesimal dimensions. Practically, a source of radiation whose dimensions are small compared with the viewing distance.
Pointing Errors	Beam movement and divergence, due to instability within the laser or other optical distation.
Polarization	Restriction of the vibrations of the electromagnetic field to a single plane, rather than the innumerable planes rotating about the vector axis. Various forms of polarization include random, linear, vertical, horizontal, elliptical and circular.
Population Inversion	A state in which a substance has been energized, or excited, so that more atoms or molecules are in a higher given excited state than in a lower resting state. This is a necessary prerequisite for laser action.
Power	The rate of energy delivery expressed in watts (joules per second).
Power Density	(Irradiance) The amount of optical power concentrated into a spot of particular size. It is expressed in watts per square centimeter.
Power Meter	An accessory used to measure laser beam power.
PRF	Pulse Repetition Frequency. The number of pulses produced per second by a laser.
Protective Housing	A protective housing is a device designed to prevent access to radiant power or energy at levels higher than the intended classification limits.

Pulse	A discontinuous burst of laser as opposed to a continuous beam. A true pulse achieves higher peak powers than that attainable in a continuous wave output.
Pulse Duration	The "on" time of a pulsed laser, it may be measured in terms of millisecond, microsecond, or nanosecond as defined by half-peak-power points on the leading and trailing edges of the pulse.
Pulse Mode	Operation of a laser when the beam is intermittently on in fractions of a second.
Pulsed Laser	Laser which delivers energy in the form of a single or train of pulses.
Pump	To excite the lasing medium. See Optical Pumping or Pumping.
Pumped Medium	Energized laser medium.
Pumping	Addition of energy (thermal, electrical, or optical) into the atomic population of the laser medium, necessary to produce a state of population inversion.
Q-Switch	A device that has the effect of a shutter moving rapidly in and out of the beam to "spoil" the resonator's normal Q, keeping it low to prevent lasing action until a high level of energy is stored. The result is a giant pulse when normal Q is restored.
Q-Switched Laser	A laser which stores energy in the laser media to produce extremely short, extremely high intensity bursts of energy.
Radian	A unit of angular measure equal to the angle subtended at the center of a circle by a chord whose length is equal to the radius of the circle.
Radiance	Brightness; the radiant power per unit solid angle and per unit projected area of a radiating surface.
Radiant Energy (Q)	Energy in the form of electromagnetic waves usually expressed in units of joules (watt-seconds).
Radiant Exposure (H)	The total energy per unit area incident upon a given surface. It is used to express exposure to pulsed laser radiation and is commonly expressed in J/cm^{-2}.
Radiant Flux	Radiant Power - The time rate of flow of radiant energy. Units - watts. (One [1] watt = 1 Joule-per-second). The rate of emission of transmission of radiant energy.
Radiant Intensity	The radiant power expressed per unit solid angle about the direction of the light.
Radiant Power	See Radiant Flux.
Radiation	In the context of optics, electromagnetic energy is released; the process of releasing electromagnetic energy.
Radiometry	A branch of science which deals with the measurement of radiation.
Rayleigh Scattering	Scattering of radiation in the course of its passage through a medium containing particles, the size of which are small compared with the wavelength of the radiation.
Reflectance or Reflectivity	The ratio of the reflected radiant power to the incident radiant power.
Reflection	The return of radiant energy (incident light) by a surface, with no change in wavelength.

Refraction	The change of direction of propagation of any wave, such as an electromagnetic wave, when it passes from one medium to another in which the wave velocity is different. The bending of incident rays as they pass from one medium to another, such as from air to glass.
Repetitively Pulsed Laser	A pulsed laser with reoccurring pulsed output.
Resolution	Resolving power or the quantitative measure of the ability of an optical instrument to produce separable images of different points on an object.
Resonator	The mirrors (or reflectors) making up the laser cavity including the laser rod or tube. The mirrors reflect light back and forth to build up amplification.
RMS	Averaged electronic signal, the letters stand for root-mean-square.
Rotating Lens	A beam delivery lens designed to move in a circle and thus rotate the laser beam around a circle.
Ruby	The first laser type; a crystal of aluminum oxide containing trace amounts of chromium oxide.
Scanning Laser	A laser having a time-varying direction, origin or pattern of propagation with respect to a stationary frame of reference.
Scintillation	This term is used to describe the rapid changes in irradiance levels in a cross section of a laser beam produced by atmospheric turbulence.
Secured Enclosure	An enclosure to which casual access is impeded by an appropriate means (e.g., door secured by lock, magnetically or electrically operated, latch, or by screws.).
Semi-conductor or Injection Laser	A type of laser which produces relatively low power outputs from semi-conductor materials such as GaAs.
Service	Performance of adjustments, repair or procedures on a non routine basis, required to return the equipment to its intended state.
Solid Angle	The ratio of the area on the surface of a sphere to the square of the radius of that sphere. It is expressed in steradians (sr).
Source	The term source means either laser or laser-illuminated reflecting surface.
Spectral Response	The response of a device or material to monochromatic light as a function of wavelength.
Specular Reflection	A mirror-like reflection.
Spontaneous Emission	Decay of an excited atom to a ground or resting state causing the emission of one photon. The decay is determined by the lifetime of the excited state.
Spot Size	The mathematical measurement of the diameter of the laser beam.
Stability	The ability of a laser system to resist changes in its operating characteristics. Temperature, electrical, dimensional and power stability are included.
Steradian (sr)	The unit of measure for a solid angle.

Stimulated Emission	When an atom, ion or molecule capable of lasing is excited to a higher energy level by an electric charge or other means, it will spontaneously emit a photon as it decays to the normal ground state. If that photon passes near another atom of the same frequency, the second atom will be simulated to emit a photon.
Superpulse	Electronic pulsing on the CO_2 laser producing a pulsed output (250 - 1000 times per second), with peak powers per pulse higher than the maximum attainable in the continuous wave mode. Average powers of superpulse are always lower than the maximum in continuous wave.
TEM	Abbreviation for transverse electro-magnetic mode, the cross-sectional shape of the working laser beam.
TEM_{∞}	The lowest order mode possible with a bell shaped (or Gaussian) distribution of light across the laser beam.
Thermal Relaxation Time	The time to dissipate the heat absorbed during excitation of the laser medium.
Threshold	The point where lasing begins during excitation of the laser medium.
Transmission	Passage of electromagnetic radiation through a medium.
Transmittance	The ratio of transmitted radiant energy to incident radiant energy, or the fraction of light that passes through a medium.
Transverse Electromagnetic Mode	The radial distribution of intensity across a beam as it exits the optical cavity. See TEM.
Tunable Laser	A laser system that can be "tuned" to emit laser light over a continuous range of wavelengths or frequencies.
Turnable Dye Laser	A laser whose active medium is a liquid dye, pumped by another laser or flashlamps, to produce various colors of light. The color of light may be tuned by adjusting optical elements and/or changing the dye used.
Ultraviolet Radiation (UV)	Electromagnetic radiation with wavelengths between soft X-rays and visible violet light, often broken down into UV-A (315 - 400 nm), UV-B (280 - 315 nm), and UV-C (100 - 280 nm).
Vaporization	Conversion of a solid or liquid into a vapor.
Vignetting	The loss of light through an optical element when the entire bundle of light rays does not pass through; an image or picture that shades off gradually into the background.
Visible Radiation (light)	Electromagnetic radiation which can be detected by the human eye. It is commonly used to describe wavelengths which lie in the range between 400 nm and 700 - 780 nm.
Watt	A unit of power used in measuring the amount of power per area of absorbing surface, or per area of CW laser beam.
Watt/cm^2	A unit of irradiance used in measuring the amount of power per area of absorbing surface, or per area of CW laser beam.
Wave	An undulation or vibration; a form of movement by which all radiant electromagnetic energy travels.

Wavelength	The length of the light wave, usually measured from crest to crest, which determines its color. Common units of measurement are the micrometer (micron), the nanometer, and (earlier) the angstrom.
Window	A piece of glass with plane parallel sides which admits *light into or through an* optical system and excludes dirt and moisture.
YAG	Yttrium aluminum garnet; the most widely used crystalline laser and is composed of yttrium oxide and aluminum oxide with a small amount of neodymium.

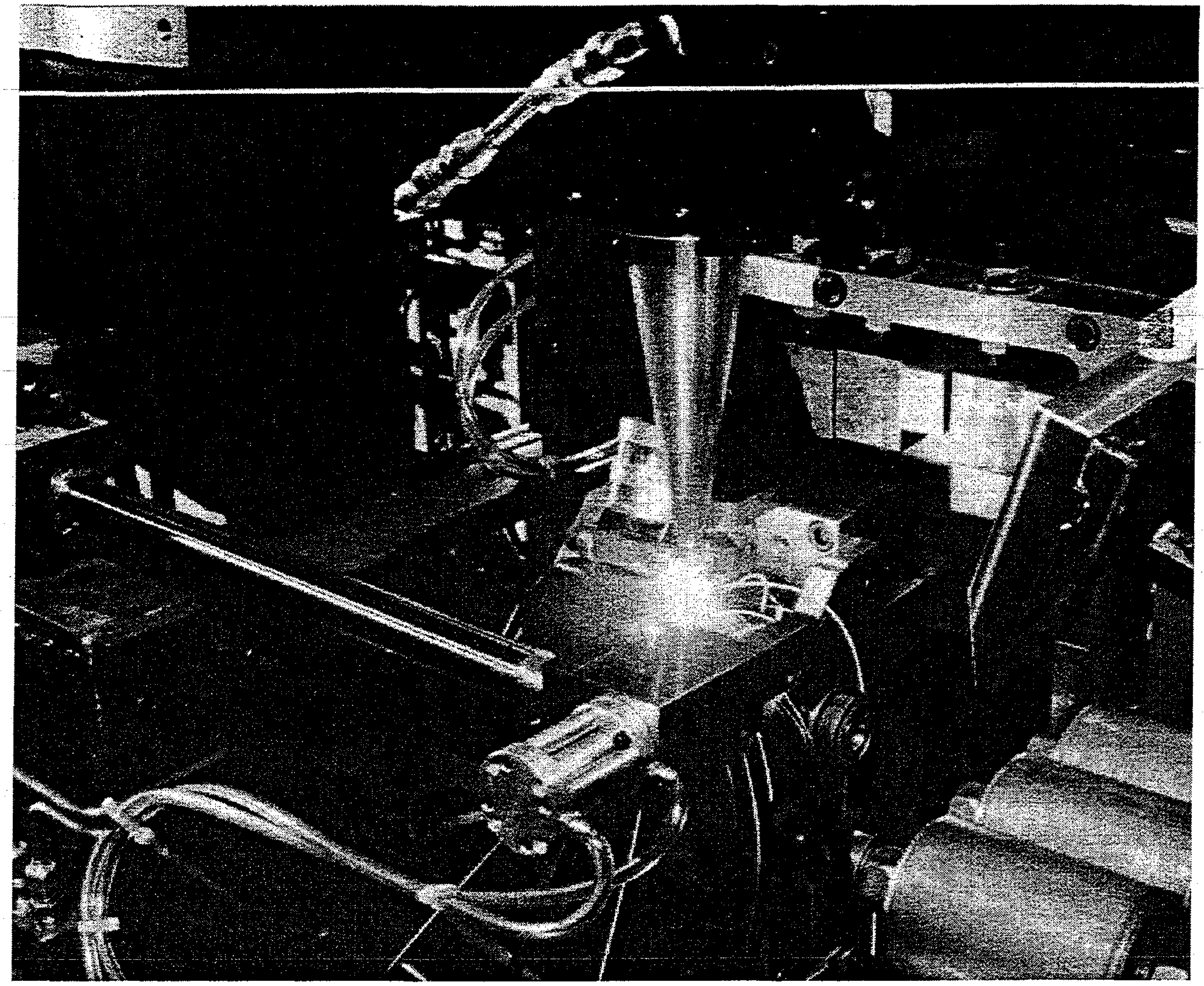


Figure 1. Increasing industrial laser power and processing rates are creating new challenges for designers of laser-safety equipment. Courtesy of Utilase Systems.

Playing It Safe With Industrial Lasers

Powerful, flexible laser processing equipment can be safe — with appropriate precautions.

by R. James Rockwell Jr., James F. Smith and William J. Ertle

Increasing laser power and flexibility are enabling large manufacturing industries to produce better products in less time. However, these new capabilities come with added concerns about the safety of those who operate and service the equipment.

In the past, after a manufacturer certified its laser, the average industrial user placed limited additional emphasis on the control measures that might be required.[1] The most common action was to totally enclose the laser (e.g., operate a Class IV laser as a Class I system) and use personnel controls such as laser protective eyewear and/or temporary laser-rated barriers during periods of open beam when beam access was needed (such as for servicing). This affords safety while imposing some limitations on the

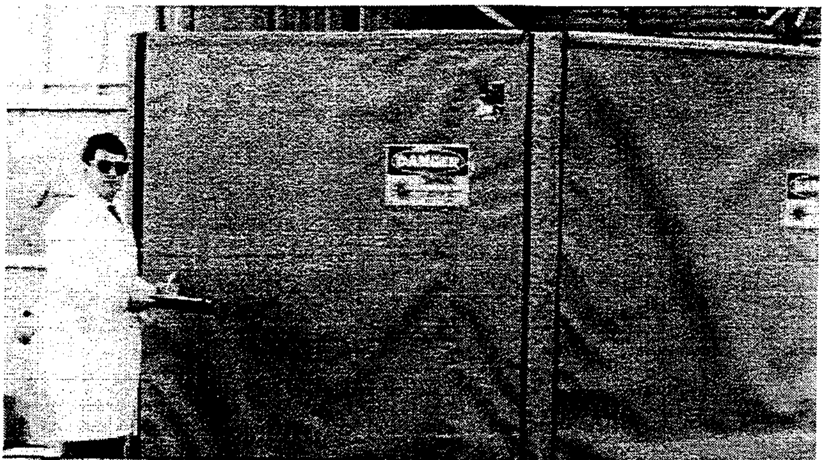


Figure 2. *Laser-rated barriers can create a temporary laser-controlled area.*

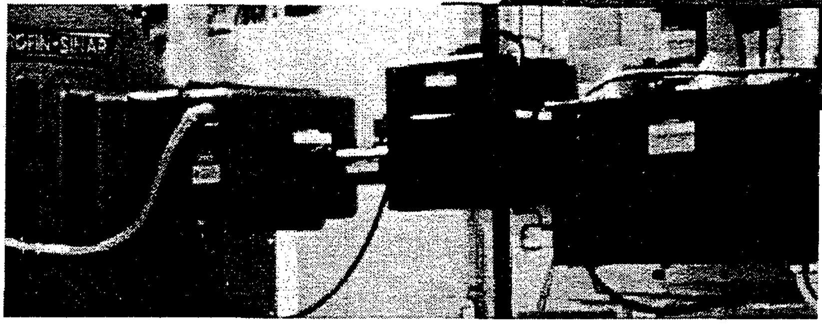


Figure 3. *The laser unit, below, directs the beam first into an optics chamber and then into the "burn box" before it is eventually directed to the workpiece.*

overall system performance.

As industry demands increased processing rates, however, more flexibility is required. This produces new systems and facility designs that are both safe and productive. One such design is the enclosure design where a part being machined itself becomes part of the protective housing. Another involves multiple work stations that operate via beam conduits and/or fiber optics from a single master laser generator unit. Totally open (Class IV) limited-open-beam-path installations interfaced with robotic beam delivery controls comprise yet another design type.

Respiration dangers from fumes and skin and eye protection remain problematic, especially as laser powers increase. Special features can mitigate these dangers, but more research must be done to ensure that users are protected from the ultra-high-power lasers that are expected in the near future.

Servicing concerns

In an industrial environment, usually only designated "service personnel" — generally the laser manufacturer, third-party repair personnel, or designated in-house maintenance staff — need access to the laser beams contained within a Class I unit.

The American National Standards Institute (ANSI) Z-136.1 standard[2] requires that during servicing procedures when laser radiation exceeds the maximum permissible exposure (MPE) for the eye, a temporary laser-controlled area must be established. This can be temporarily segmented using dividers such as laser-rated barriers (Figure 2). In addition, ANSI recommends a specific written standard operating procedure be established for those conditions where the protective housings must be removed. In these cases, a method of confinement (barriers, etc.) and warning signs should be temporarily implemented.

Beam access may also be required to burn spatial-mode distribution patterns into a plastic block, a common beam diagnostic performed when a laser's internal optics have changed with use or because of misalignment. This test not only provides human access to the beam but also produces a second potential laser danger: harmful fumes.[3]

While some instruction manuals imply that mode burns are done infrequently, "real world" evidence suggests that they may be done several times a month or more. Only four or five burns are usually necessary, but for a difficult alignment, up to 15 mode burns may be required. The burns are often done on small blocks of plastic, which can relase irratating or harmful gases when burned. It is essential that such gases be captured and filtered.

Today, some laser systems are supplied with mode-burn enclosures that are a part of the enclosed optical train between the laser unit and the workpiece (Figure 3). Thus no human access to the beam is required for mode burns, and the fumes are directly vented into a localized exhaust system that traps the fumes in a filter.

In another solution to the fume problem, new diagnostic methods use straight-edge sampling of the beam, which produces the so-called M^2 factor that relates to the beam-distribution quality. This static diagnostic requires no burning and thus does not release potentially toxic fumes. It does, however, require special equipment, which may be interfaced with the system controls.

Flow-through systems

If a laser product is to meet FDA/CDRH (Center for Devices and Radiological Health) Class I criteria[4], all paths of unwanted or stray laser radiation that could reach the human body must be eliminated. This has been accomplished in most cases by enclosure designs that totally contain the beam. However, flow-through laser production systems, such as those over an assembly line, can create a "human access" concern.

A particular problem arises in some "straight through" systems where parts to be processed enter the machine through an open portal.

Openings in the housing allow human access if internal baffles do not block the beam. Safety audits often reveal clear openings in the protective housing(s) that do not meet the "human access" limitations for Class I lasers. (The definition of "human access" applies to a "theoretical possibility" of a reflected beam and not necessarily to an actual beam when the embedded laser is Class IIIB or Class IV.)

One trend in "flow through" laser material processing systems is to design the units so that the parts in the flow path become a part of the protective housing. To comply with the standard, though, each of the access ports in the parts' flow path require double interlocks (Figure 4). Thus, both the "parts-in" and "parts-out" lines would each require two series-connected interlocks or a "failsafe" single interlock to comply with Class I status.

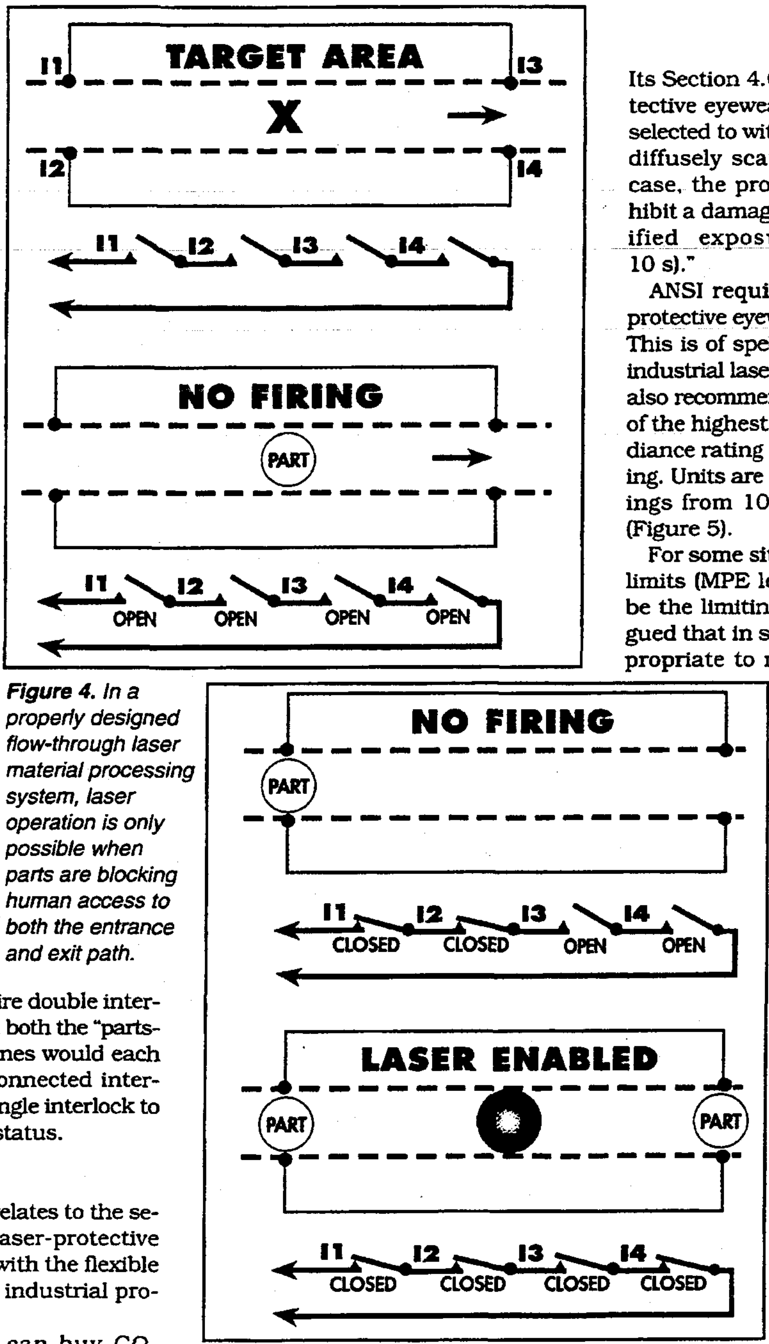


Figure 4. In a properly designed flow-through laser material processing system, laser operation is only possible when parts are blocking human access to both the entrance and exit path.

Eye protection

One new problem relates to the selection process for laser-protective eyewear used today with the flexible high-power lasers in industrial processing.

Industrial users can buy CO_2 lasers with single-use powers ranging from 20 to 40 kW; Nd:YAG lasers are available with single-use powers from 3 to 5 kW; and open, Class IV excimer lasers with 100-W average powers are now being used in photolithography, microscribing, cutting and welding applications.[5,6]

Newly ruggedized solid-state lasers such as Ti:sapphire and alexandrite also now enable wavelength tunability in an industrial environment. These lasers require special eyewear designed to protect against all wavelength combinations.

One multikilowatt-laser supplier recommends plastic shop safety glasses for eye protection. Another manufacturer indicates that normal prescription eyewear is sufficient. Some equipment manuals instruct that "laser safety eyewear" is to be worn but describe neither the eyewear nor the criteria for its selection. These approaches do not fulfill the requirements of the ANSI standard. Its Section 4.6.2.1 says, "Laser protective eyewear shall be specifically selected to withstand either direct or diffusely scattered beams. In this case, the protective filter shall exhibit a damage threshold for a specified exposure time (typically 10 s)."

ANSI requires specialized laser-protective eyewear, not shop glasses. This is of special significance when industrial lasers are being used. ANSI also recommends that eye protection of the highest possible spectral irradiance rating be used during servicing. Units are now available with ratings from 1000 to 10,000 W/cm² (Figure 5).

For some situations, the exposure limits (MPE level) for the skin may be the limiting factor. It can be argued that in such cases it is not appropriate to require laser eyewear while permitting unprotected skin exposure that exceeds the skin MPE. This becomes a special concern when considering diffuse beams that could expose the face and upper torso.

If this argument is extrapolated to the higher laser powers projected for future industrial applications, one could conceive of personnel in an area where the diffuse reflection of the beam would exceed not only the eye and skin MPE but also the damage threshold for the laser protective equipment such as eyewear and barriers.

In the example to follow, a worst-case damage threshold for standard polycarbonate laser eyewear of about 5 W/cm² is assumed. This is sometimes referred to as the initial damage threshold or dimple criteria. It is also assumed that the eyewear is completely exposed by the diffused beam (a condition for which precise damage-threshold values do not now exist).

As shown in Figure 6, a person positioned at arm's length (0.5 m) from

Figure 5. *This new ceramic-based laser eye protection is rated at an irradiance of 2000 W/cm².*

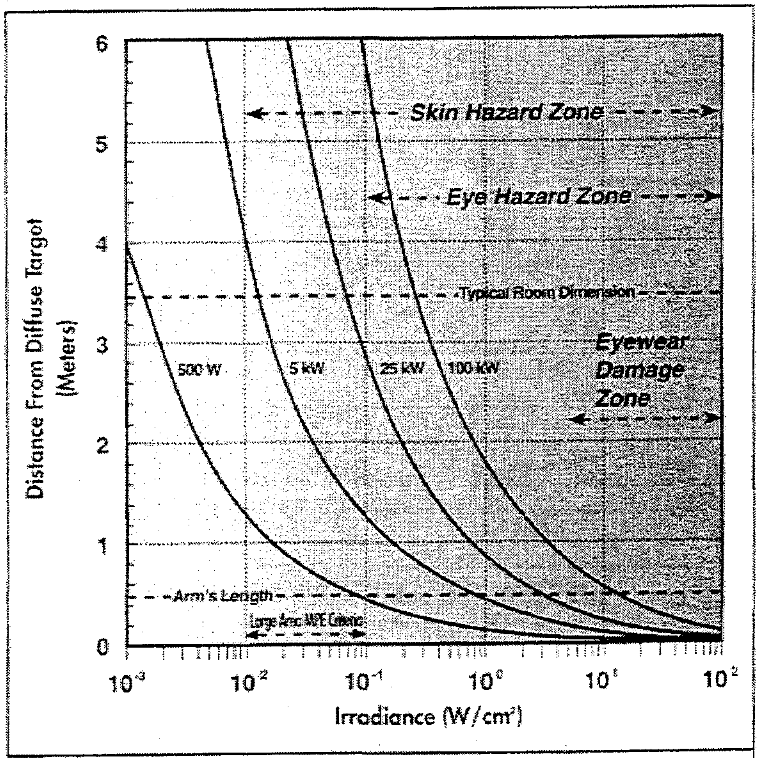


Figure 6. *Eye and skin nominal hazard zones and laser eyewear damage zones for scattered laser radiation with100 percent diffuse reflection from a CO_2 laser.*

a laser would be exposed to diffuse levels that exceed both the skin and eye exposure and the damage-threshold level of the protective eyewear when the laser powers approach 25 kW.

Thus, as continuous-wave laser powers increase in the range from 20 to 100 kW — as they now are for some heavy-industry welding and cutting applications — laser safety practices and procedures must begin by excluding the worker from the nominal hazard zone. In some of these cases, laser eye protective devices and/or simple laser barriers are not an alternative control measure, and personnel working in the same room as the laser-target interaction will almost always be exposed to laser-radiation levels exceeding the MPE for skin.

This raises many questions on the procedures for adjustment and alignment of lasers during setup and servicing. Previous discussions of laser accidents have shown that these are the situations most often associated with laser accidents.[7]

In the high-power laser environments of today's industrial facilities, most industrial lasers do not produce significantly unsafe conditions except during infrequent conditions of service. Nevertheless, some specific controls commonly need attention.

It is certain that new approaches will be introduced. It seems very possible that as humans are further removed from material-processing equipment, remote-sensing and multiple-beam-path concepts will become a significant factor in tomorrow's high-power laser environments.

(Editor's note: Readers who wish to discuss these and other laser safety topics may participate in a "chat" on the Internet sponsored by the authors at 4 p.m. EST on May 10. Obtain details at http://www.rli.com.) ☐

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2. American National Standards Institute (1993). *American National Standard for the Safe Use of Lasers: ANSI Z-136.1.* Laser Institute of America, Orlando, Fla.
3. KoKosa, J.M. (June 1994). Hazardous chemicals produced by laser materials processing. *JOURNAL OF LASER APPLICATIONS.* 6:4:195-201.
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Meet the authors

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- *The section numbers in layout below refer to the Federal Register, Vol 50, No 161, August 20,1985.*

Aperture Labels

Aperture labels: Section 1040.10(g)(4) pg. 32254 applicable for all lasers

AVOID EXPOSURE
LASER RADIATION IS EMITTED
FROM THIS APERTURE

E

AVOID EXPOSURE
INVISIBLE LASER RADIATION
EMITTED FROM THIS APERTURE

EE

AVOID EXPOSURE
VISIBLE and/or INVISIBLE
LASER RADIATION IS EMITTED
FROM THIS APERTURE

EEE

AVOID EXPOSURE
HAZARDOUS ELECTROMAGNETIC
RADIATION IS EMITTED
FROM THIS APERTURE

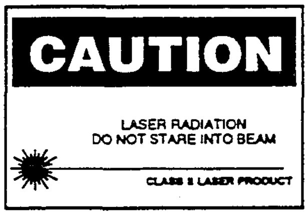
F

AVOID EXPOSURE
HAZARDOUS X-RAYS
ARE EMITTED FROM
THIS APERTURE

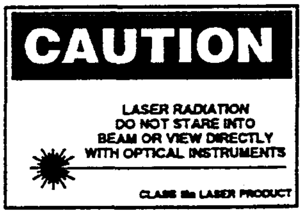
G

Class II / IIIa Lasers

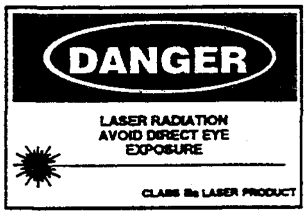
Logotype Labels: Section 1040.10, paragraph(g)(1-3) pg. 32264



A



B



BD

Labels for noninterlocking protective housing: Section 1040.10(g)(6) pg 32254

CAUTION
LASER RADIATION WHEN OPEN
DO NOT STARE INTO BEAM

H

CAUTION
LASER RADIATION WHEN OPEN
DO NOT STARE INTO BEAM OR
VIEW DIRECTLY WITH OPTICAL
INSTRUMENTS

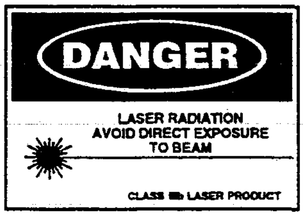
I

DANGER
LASER RADIATION WHEN OPEN
AVOID DIRECT EYE EXPOSURE

ID

Class IIIb Lasers

Logotype labels: Section1040.10(g)(1-3) pg. 32264



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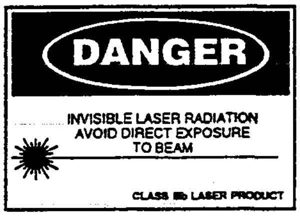
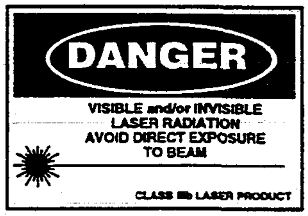


CC



CCC

Labels for noninterlocked protective housings: Section 1040.10 (g)(6) pg. 32254

DANGER
LASER RADIATION WHEN OPEN
AVOID DIRECT EXPOSURE TO BEAM

J

DANGER
INVISIBLE LASER RADIATION WHEN OPEN
AVOID DIRECT EXPOSURE TO BEAM

JJ

Labels for defeatably interlocked protective housings : Section 1040.10(g)(7) pg. 32254

DANGER
LASER RADIATION WHEN OPEN
AND INTERLOCK FAILED OR DEFEATED
AVOID EXPOSURE TO BEAM

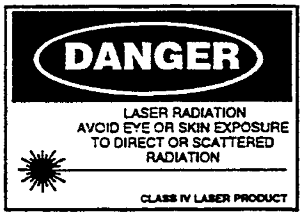
NF

DANGER
INVISIBLE LASER RADIATION WHEN OPEN
AND INTERLOCK FAILED OR DEFEATED
AVOID DIRECT EXPOSURE TO BEAM

NNF

Class IV Lasers

Logotype labels : Section1040.10(g)(1-3} pg. 32254



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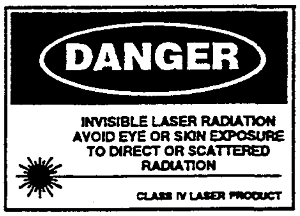

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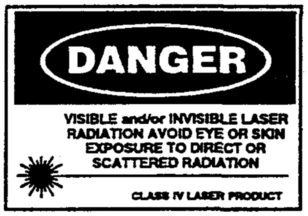

DDD

Labels for noninterlocked protective housings: Section1040.10 (g)(6) pg. 32254

DANGER
LASER RADIATION WHEN OPEN
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION

K

DANGER
INVISIBLE LASER RADIATION WHEN OPEN
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION

KK

DANGER
VISIBLE and/or INVISIBLE LASER RADIATION
WHEN OPEN AVOID EYE OR SKIN EXPOSURE
TO DIRECT OR SCATTERED RADIATION

KKK

Labels for defeatably interlocked protective housings: Section 1040.10 (g)(7) pg. 32254

DANGER
LASER RADIATION WHEN OPEN
AND INTERLOCK DEFEATED
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION

O

DANGER
INVISIBLE LASER RADIATION WHEN OPEN
AND INTERLOCK DEFEATED
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION

OO

DANGER
VISIBLE and/or INVISIBLE LASER RADIATION
WHEN OPEN AND INTERLOCK DEFEATED
AVOID EYE OR SKIN EXPOSURE
TO DIRECT OR SCATTERED RADIATION

OOO

DANGER
LASER RADIATION WHEN OPEN
AND INTERLOCK FAILED OR DEFEATED
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION

OF

DANGER
INVISIBLE LASER RADIATION WHEN OPEN
AND INTERLOCK FAILED OR DEFEATED
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION

OOF

DANGER
VISIBLE and/or INVISIBLE LASER RADIATION
WHEN OPEN AND INTERLOCK FAILED OR
DEFEATED AVOID EYE OR SKIN EXPOSURE
TO DIRECT OR SCATTERED RADIATION

OOOF

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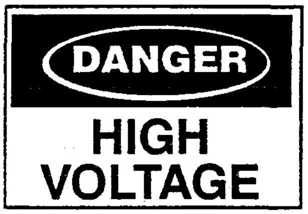

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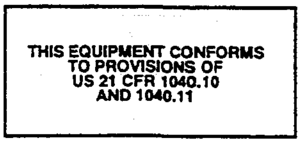

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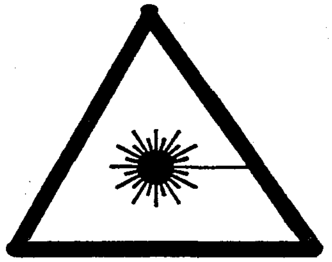

IN

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L

M

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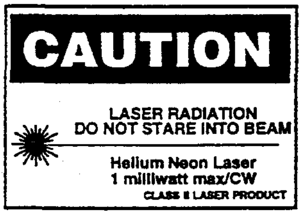

A-HN ImW

C-HN 15mW

C-HN 40 mW

Special Label Printing

Special printing of labels is also available when: 1. Label is not a stock item 2. The label is not listed in this brochure. Further information concerning special printing can be obtained by calling RLI. The most requested special printing is the addition of laser specifications on logotype labels. However, other labels are also available and a representative selection is shown above. A minimum order of 500 is required for special printing of labels. Call for price quote.

Rockwell Laser Industries
P.O. Box 43010
Cincinnati, Ohio 45243
(513)271-1568 Fax (513)271-1598

Bulk Rate
U.S. Postage Paid
Cincinnati, OH

Permit No. 6461

Postmaster: Address Correction Requested

Now available in Four Materials from Rockwell Laser Industries

LASER WARNING SIGNS

Following the recommendations of ANSI Z136.1

ROCKWELL LASER INDUSTRIES can provide laser warning signs for almost any laser application. All signs follow the recommendations of the ANSI Z136.1 Standard, and the "standard laser warning placards" as required by OSHA (CFR 1518.54). Laser warning signs are available for all classes of lasers. Wording on each sign is in accordance with FDA/CDRH, ANSI Z136, and OSHA requirements.

RLI offer standard blank caution, danger and signs, temporary controlled area notice signs, standard pre-printed, and special print signs are available for an additional cost.

NOTE: Specific laser specifications can be added to any standard sign contact **RLI** for more information. For special print signs contact **RLI** for information and pricing

The ANSI Z136.1 (1993) Standard indicates:

An area which contains a Class 3a laser or laser system should be posted with the appropriate sign as described in 4.7 except as noted in 4.5.1.10. An area which contains a Class 3b or Class 4 laser or laser system shall be posted with the appropriate sign as described in 4.7. (See 4.3.10.1 and 4.3.10.2). The NHZ shall be identified and the NHZ demarcated as a laser hazard area. A notice sign, as described in 4.7, shall be posted outside a temporary laser controlled area.

QUICK MOUNT

For installation that is quick and easy we have a new product called the **Quick Mount**, which can be used with any standard laser warning sign. This holder is made of durable clear plastic and allows for quick removal and placement of signs in a controlled laser area. Contact **RLI** today for more information on warning signs or the **Quick Mount**.

Materials Available!!!

- **Plastic 10" x 14" x 0.125"**
- **Magnetic 10" x 14" x 0.125"**
- **PVC 10" x 14" x 0.125"**
- **Paper**

Laser Warning **Signs** can be obtained from **ROCKWELL LASER INDUSTRIES**. Call or FAX today for more detailed information or a specific laser or application.

Rockwell Laser Industries

Business Office/Product Sales	P. O. Box 43010 Cincinnati, Ohio 45243	(513) 271-1568	Fax (513) 271-1598
South West Regional Office	1605 Propps N.E. Albuquerque, New Mexico 87112	(505) 293-2519	Fax (505) 293-2519
South East Regional Office	3 So. Wrenn Place / Foxfire Jackson Springs, NC 27281	(910) 673-4746	Fax (910) 673-4745
THE LASER ZONE	Computer Bulletin Board System	(513) 271-1579	Available 24 hrs/day

ROCKWELL LASER INDUSTRIES
1996 INDUSTRIAL COURSE CALENDAR

Basics of Lasers and Optics (L-110) 2 ABIH CM Credits Awarded	February 6-7, 1996	Orlando	$595.00
	April 23-24	Cincinnati	
	May 28-29	San Diego	
	June 11-12	Cincinnati	
	August 6-7	Albuquerque	
	October 1-2	Cincinnati	
	November 5-6	San Diego	
	December 3-4	Detroit	
Industrial Laser Safety (L-120) 2 ABIH CM Credits Awarded	February 8-9, 1996	Orlando	$595.00
	April 25-26	Cincinnati	
	May 30-31	San Diego	
	June 13-14	Cincinnati	
	August 8-9	Albuquerque	
	October 3-4	Cincinnati	
	November 7-8	San Diego	
	December 5-6	Detroit	
Laser Safety Officer (L220) 5 ABIH CM Credits Awarded	March 25-29, 1996	Cincinnati	$1095.00
	July 8-12	Cincinnati	
	November 11-15	Cincinnati	
Advanced Laser Safety Officer (L-320) 4 ABIH CM Credits Awarded	June 25-28, 1996	Cincinnati	$1495.00 Includes LAZAN 4.1
	September 10-13	Cincinnati	
The Safety of Lasers In Airspace (A-220) Meets ILDA requirements	TBA	Cincinnati	$795.00

- *All courses subject to cancellation and Locations subject to change. Call to reconfirm date and time.*