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ARMSTRONG LABORATORY

BASE-LEVEL MANAGEMENT OF LASER RADIATION PROTECTION PROGRAM

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This report has been developed to assist Air Force units in the application of Air Force Occupational Safety and Health (AFOSH) Standard 161-10, "Health Hazards Control of Laser Radiation." The report provides supplementary material not contained in AFOSH Standard 161-10 and should be of assistance in evaluation of some unique laser hazards and exposure situations. This report is not meant to replace AFOSH Standard 161-10; if policy conflicts arise between this document and the AFOSH Standard, the AFOSH Standard should take precedence.

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I. Introduction

A. Purpose. The purpose of this guide is to assist base-level medical authorities in application of Air Force Occupational Safety and Health Standard (AFOSH Std) 161-10, "Health Hazards Control of Laser Radiation" (Ref 1), for use of lasers in Air Force operations. Use of lasers in the Air Force is becoming increasingly widespread. Virtually every Air Force workplace contains a laser of some type. Offices may contain lasers in computer printers, compact disc players for databases, and facsimile machines. Base exchanges, commissaries, and supply units have bar code readers that contain lasers; survey instruments used by civil engineering squadrons typically contain lasers. Lasers are also frequently found in our medical centers, research laboratories, weather squadrons, and industrial workplaces. Some of the more hazardous lasers are contained within advanced weapons systems and used for infrared mapping, rangefinding, and target designation.

B. Content. This guide contains supplementary material not contained in the AFOSH like background material on laser fundamentals, biological effects of laser radiation, detailed examples of laser hazard evaluations, discussion of laser safety eyewear, special considerations for medical lasers and optical fibers, and summary evaluations of common Air Force laser systems. Much of the information provided in this guide was obtained from articles published in technical journals, texts on laser basics and laser safety, and other Department of Defense (DoD) published reports or documents. References are made where necessary so the reader may obtain more detailed information. Appendix C, "Common Air Force Laser Systems," and Appendix B, "Laser Safety Eyewear Listing," of this document will be updated periodically as new information becomes available. This is a first generation document; comments and suggestions from the field for improvements to this document are necessary for periodic updates as well as a possible second version in the future.

C. Use. This guide should not be used as a replacement for the AFOSH; the AFOSH is the primary document used to regulate the safe use of lasers in the Air Force. Any recommendations made in this guidebook were made within the spirit and intentions of the AFOSH; apparent conflicts between the documents should be resolved by use of the AFOSH. The information provided in the AFOSH is sufficient for evaluation and control of the hazards from the majority of the lasers used in the Air Force. The information provided in this guide may be useful in evaluation of laser systems more complex than those described in AFOSH Std 161-10 or developmental systems that have not been previously classified according to the procedures in the AFOSH, ANSI Z136.1, or Title 21 Code of Federal Regulations, Subchapter J, Part 1040 (21 CFR 1040). The user of this document is expected to have some fundamental mathematical skills and a prior knowledge of the information provided in the AFOSH. Appendix A provides definitions for some terms used in this document and also those used and defined in the AFOSH. In most cases, terms or acronyms used in the text of this document will be defined only the first occasion of their use. To aid the user of this document, some of the tables contained in the AFOSH are reproduced in Appendix F. These tables are not in numerical sequence with tables provided in the text of this report, rather, they are numbered and referenced as they appear in the AFOSH.

D. Other standards and guides. Other Air Force documents provide supplementary material in support of the AFOSH. The following is a list of the most important material.

1. USAFOEHL Report 87-091RC0111GLA, "Laser Range Evaluation Guide for Bioenvironmental Engineers," July 1987. This guide provides descriptions of potentially hazardous situations and needed range safety controls for use of lasers on ranges. Evaluations of airborne and ground based systems currently being used throughout the DoD are included. Distribution is authorized to U.S. Government agencies only for administrative or operational use. Original distribution was made to all Bioenvironmental Engineering Sections (BES). Copies of this report can be obtained from Armstrong Laboratory/OEPP, Brooks AFB TX 78235-5000.

2. USAFSAM Technical Report 88-21, "Medical Management of Combat Laser Eye Injuries," October 1988. This report was written to aid medical personnel in handling patients with suspected laser exposures. The report provides background information on lasers, symptoms, diagnostic tests, clinical findings, treatment recommendations, and return to duty and evacuation criteria. Distribution is unlimited and approved for public release. Original distribution was made to all Aerospace Medicine Sections. Copies of this report can be ordered from the National Technical Information Service, 5285 Port Royal Road, Springfield VA 22161-2103 or can be requested from Armstrong Laboratory, Brooks AFB TX 78235-5000.

3. Joint U.S. Navy/U.S. Air Force laser training videotape,"Lasers in Military Operations," Part I (803562DN). Subjects of the videotape include: laser physics, bioeffects, and eye protection. Available from HQ AAVS, Norton AFB CA 92409.

4. USAF Flight Surgeon's Flying Safety Kit, "Lasers and Aircrews: A Flying Safety Kit for Flight Surgeons." This kit contains 35mm transparencies intended for laser safety briefings on safety with lasers used in flying operations. Some of the material in the slides is general in nature with respect to laser safety and may be useful for briefings to personnel that use other types of lasers as well. Available from HQ AAVS, Norton AFB CA 92409.

The following is a list of other documents that pertain to laser safety.

5. United States Navy, Space and Naval Warfare Systems Command Manual E0410-BA-GYD-010\7034 LASER, "Technical Manual - Laser Safety." Distribution authorized to U.S. Government Agencies and their contractors. Copies may be obtained from Naval Warfare Systems Command, Safety Office (SPAWAR 00F), Washington D.C. 20363-5100.

6. Department of the Army Technical Bulletin TB MED 524, "Control of Hazards to Health from Laser Radiation."

7. American National Standard for the Safe Use of Lasers, ANSI Z136.1-1986. Laser Institute of America, Orlando FL.

8. American National Standard for the Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources, ANSI Z136.2-1988. Same as item 7.

9. American National Standard for the Safe Use of Lasers in Health Care Facilities, ANSI Z136.3-1988. Same as item 7.

10. Military Standard 1425, 13 Dec 1983, "Safety Design Requirements for Military Lasers and Associated Support Equipment." Applicable to military lasers exempt from 21 CFR, Subchapter J, under FDA Exemption No 76 EL-01 DoD. Currently under revision.

E. Practical comments on laser safety. Despite the emphasis on radiation hazards from lasers, a high incidence of serious injury or death to individuals that work with lasers results from electrocution from equipment power supplies. This type of hazard is often overlooked and in many cases should be emphasized to a greater degree than the hazards from intrabeam viewing. Furthermore, for many of the eye injuries that have been reported in the Air Force (and the civilian community), the cause of injury was not a result of improper hazard identification or insufficient safety equipment (safety eyewear), rather, the injuries were a result of neglect to wear the specified eye protection. In many cases, the eyewear was present in the vicinity of the accident site. Testimonials of individuals that received eye damage from exposures to lasers are provided at the end of Section IV. These testimonials are very convincing and should be relayed to laser workers that doubt the ability and/or possibility of a laser to cause eye damage.

II. Fundamental Characteristics of Lasers

A. Laser radiation.

1. Electromagnetic spectrum. Radiation is often referred to as the movement of energy. Radiation is commonly described by two different theories: the wave and particle theories. The first, referred to as the electromagnetic (E-M) theory, is very successful in the explanation of diffraction, propagation, interference, refraction, and many other phenomena. The particle theory is useful in describing the photoelectric effect, photon emission and absorption, exposure of film, photon-electron interactions, and other effects. The particle theory is useful in describing some forms of radiation such as x- and gamma radiation, but has limited application in describing the emissions from a laser, and will not be discussed in detail. On the other hand, E-M theory is often used to describe laser emissions. An electromagnetic wave is characterized by a combination of time-varying electric and magnetic fields propagating through space as shown in Figure 1.

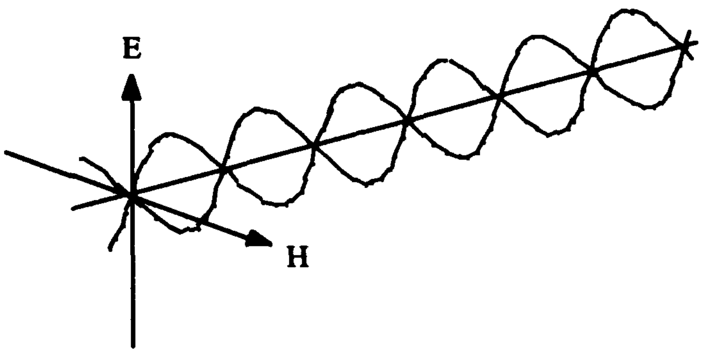


Figure 1. Electromagnetic wave.

It was first shown by James Clerk-Maxwell in 1873 that light (visible radiation) is electromagnetic radiation that propagates at approximately 3 x 10^8 meters/second (m/s). Albert Einstein later predicted that the velocity of light in a vacuum was constant throughout the universe and was the highest speed at which energy could be transmitted. The frequency, ν, of the oscillation and wavelength, λ, of the fields are related through Equation 1,

$$\lambda \cdot \nu = c, \quad (1)$$

where c is the speed of light in a vacuum, approximately 3 x 10^8 meters/second (m/s). For transmission of radiation in matter, c is replaced with the velocity of light in that material. Humans have made use of almost the entire E-M spectrum from 0 Hertz (Hz), direct current, to 10^{24} Hz, hard x-rays. Optical radiation as defined by the Committee on Photobiology of the International Commission on Illumination (CIE) extends from 0.100 to 10^3 µm (Ref 24). Many other schemes have been formulated to define the limits of the optical radiation band, but, the CIE specifications are by far the most universally accepted (Ref 24). Laser radiation is a part of the optical radiation band. For the purposes of AFOSH 161-10, laser radiation emissions are defined for wavelengths in the range: 0.2 - 10^3 micrometers (µm), or 200 - 10^6 nanometers (nm). This definition is not totally inclusive as the emission wavelength of some lasers is below the 0.2 µm lower limit. For example, a

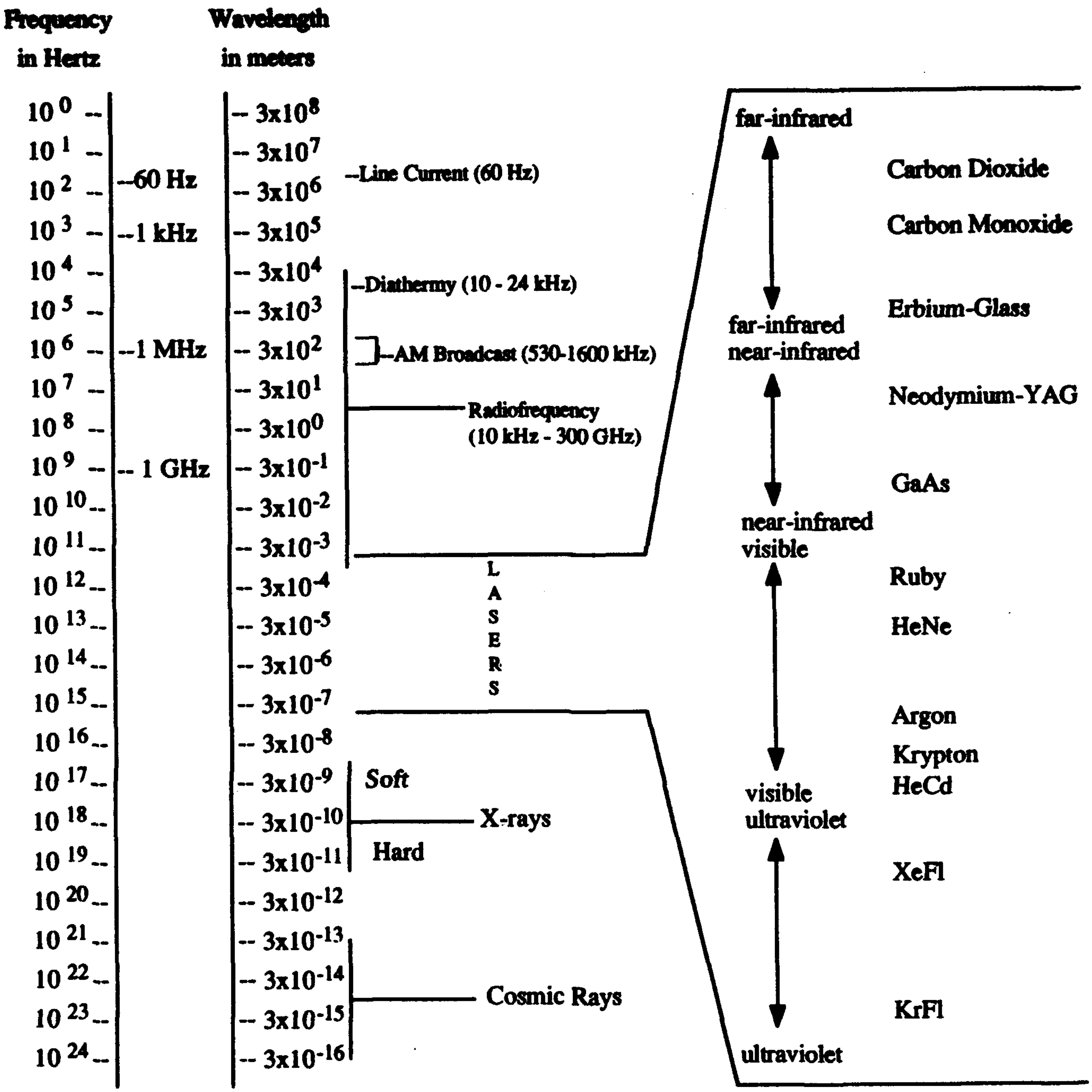


Figure 2. Electromagnetic spectrum.

laser with xenon as its active medium has an emission line at 172 nm. The emission spectrum for lasers can be broken down into four distinct regions based on emission wavelength:

a. ultraviolet (UV): 0.200 - 0.400 µm (200 - 400 nm),

b. visible (light): 0.400 - 0.700 µm (400 - 700 nm),

c. near-infrared (near-IR): 0.700 µm (700 - 1400 nm), and

d. far-infrared (far-IR): 1.4 - 10^3 μm (1400 - 10^6 nm).

The definitions of the regions given above are unique to the laser safety discipline and are based in part on the properties of the human eye. Figure 2 provides a brief summary of the E-M spectrum with expanded detail for the laser radiation band. Also provided are examples of some common lasers that emit in each distinct region.

While laser radiation is a part on the E-M spectrum, laser radiation has many unique properties that are not exhibited to the same extent by any other radiation source. These unique properties are described below.

2. Monochromaticity. Radiation waves from the laser are extremely monochromatic; that is, the electric field vector is closely defined by a single frequency. Though the laser approaches this ideal condition, no radiation source is capable of absolute monochromaticity. Depending on the source of optical radiation, the linewidth (also called bandwidth) of the emission or spread in wavelength, $\Delta\lambda$, can vary greatly. For example, the linewidth for a white-light source is typically about 300 nm, while the spectral lines from the emission of a mercury vapor lamp are on the order of a few to tens of nm. The bandwidth for some laser discharge lines are on the order of 0.01 nm (Ref 22). Bandwidth is an important property in the transmission of microwave and radio signals because it limits the amount of information being transmitted by the signal. For many laser uses, this property is not important, except in the case of fiber optic communication applications.

3. Directionality. The directionality of lasers is one of its most important qualities. Directionality of a laser beam is normally expressed in terms of the full-angle beam divergence, ϕ, twice the angle that the outer edge of the beam makes with the center of the beam, as shown in Figure 3.

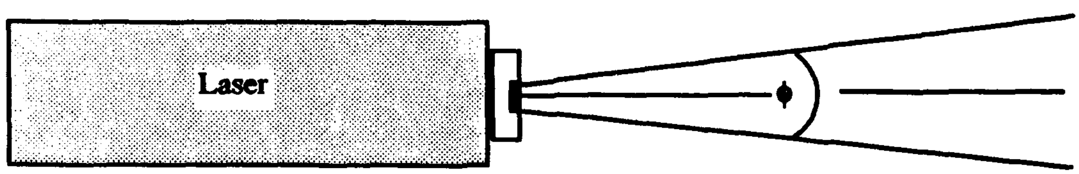
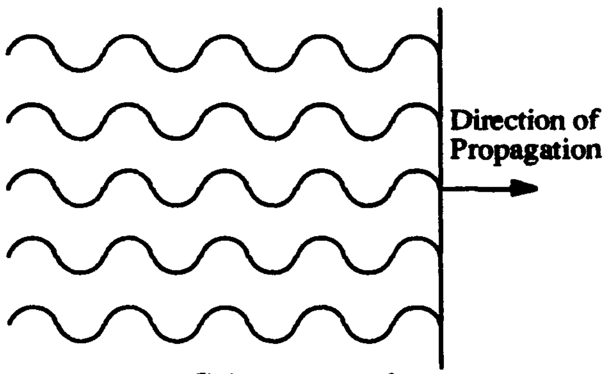


Figure 3. Full-angle beam divergence.

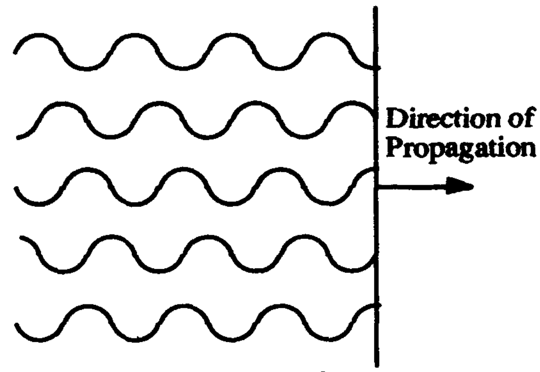
For the purposes of the AFOSH, the beam width is defined as the point where the beam irradiance has dropped to a value 1/e (0.368) of the value at the center of the beam. Again, as was the case of monochromaticity, highly collimated beams of energy are not attainable from other radiation sources like those of a laser beam. Microwave radar beams, for example, can achieve a high degree of collimation, but not to the extent of a laser beam. A radar with an antenna gain of 50 decibels (dB) will produce a circular beam with a full-angle beam width equal to ~8 milliradians (mrad), while for a typical small laser, the full-angle beam width (divergence) is about 1 mrad. With an appropriate beam expander, the laser beam divergence can be made many times smaller, on the order of tens of μrad (See Section IIC9e for a description of a beam expander).

4. Brightness. Lasers are intense light sources. O'Shea in Introduction to Lasers and Their Applications (Ref 22), performed a comparison of a 1 milliwatt (mW) helium-neon (He-Ne) laser and the sun to their effect on the human eye. O'Shea determined that the brightness of the sun is 1.5 x 10^5 lumens/cm^2-steradian, while the brightness of the He-Ne laser is 2.04 x 10^7 lumens/cm^2-steradian (assuming a beam divergence of 1 mrad), more than 200 times greater. From this comparison, it is easy to understand why lasers have great potential for damage to the human eye.

5. Coherence. The last important property of lasers to describe is coherence. Coherence refers to the relative organization of the radiation waves emitted from the laser. When a radiation wave exhibits complete coherence, there is a correlation between the amplitude and phase at any point in the radiation field to any other point in the field. There are two types of coherence: spatial and temporal. In a spatially coherent laser beam, every point on the wavefront will have the same phase. This characteristic is displayed in Figure 4 along with an example of an incoherent wavefront. Note from the figure that the peaks all occur at the same location in the wavefront at all times.



a. Coherent wavefront



b. Incoherent wavefront

Figure 4. Spâtial coherence.

Temporal coherence, on the other hand, is a measure of the constancy of phase in time of the wavefront at a given point. For a given point, the phase at a given time is predictable from the phase at another time. If phase at a given point is random, the radiation source is characterized as being temporally incoherent. An incandescent light bulb is an example of an incoherent radiation source. Among light sources, lasers provide the highest degree of coherence.

B. Basics of lasers.

1. General. The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. Operation of most lasers is dependent on three necessary conditions: 1) an active medium: a collection of atoms, molecules, or ions that emit radiation in the optical region of the E-M spectrum, 2) a population inversion, and 3) optical feedback.

2. Active medium. The first operational laser built used a ruby crystal rod as its active medium. Since that time, many other materials have been used. Lasers that use gases as an active medium perhaps constitute the greatest number and variety of lasers in use today. A helium-neon mixture was the first gas used as an active medium; other gases used commonly are carbon dioxide, argon, and hydrogen fluoride. Solid materials are also used as active materials, for example, neodymium:yttrium-aluminum-garnet (Nd:YAG), erbium glass, and semiconductors like gallium-aluminum-arsenide (GaAlAs), or alexandrite. Liquid materials that are used as active mediums include: rhodamine dye and coumarin. Section D provides a summary of lasers according to the type of active medium.

3. Electron energy levels. To understand how a laser operates, it is necessary to understand the process from the atomic level. Atoms of all materials are composed of a small, dense nucleus of protons and neutrons surrounded by a field of electrons, where the number of electrons equals the number of protons in an electronically neutral atom. Molecules are composed of two or more atoms that are held together by the bonding forces of the atom's electrons. For simplicity, it is assumed that the electrons of an atom travel in orbits around the nucleus of an atom. Figure 5 describes a simple atom with one orbital electron.

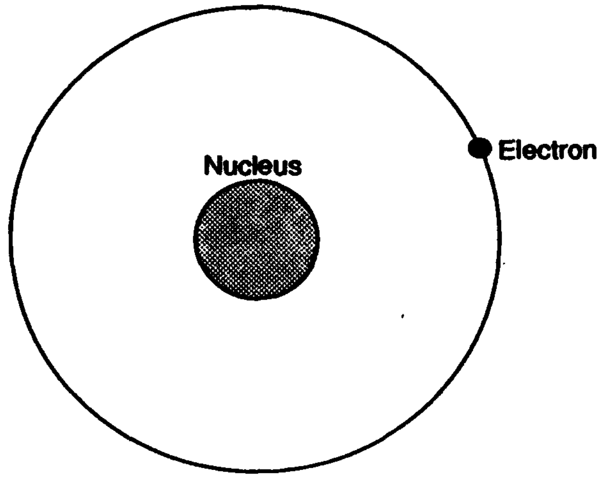
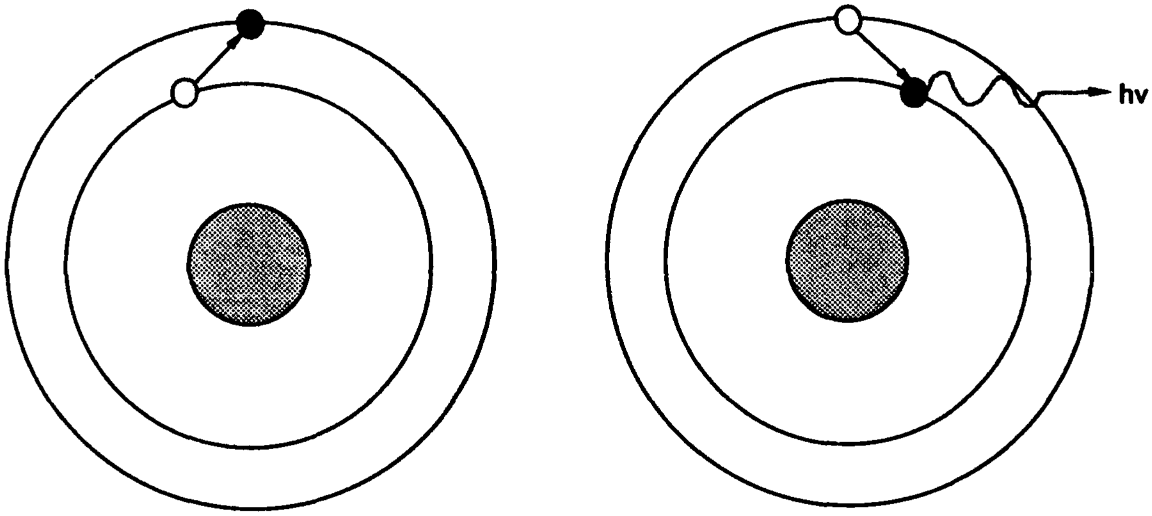


Figure 5. Simple atomic model.



a. Absorption of energy in atom. b. Release of energy from atom as photon.

Figure 6. Energy transitions of a simple atom.

In atoms with many electrons, the electrons fit systematically into sets of energy levels that are specific for that atom. The separation in energy between two adjacent energy levels in an atom is called the energy gap. Through the absorption of energy, an electron can move from a lower energy level to a higher energy level, where the atom is left in an excited state. This process is referred to as a transition and is depicted in Figure 6a. Transitions can also occur in the opposite manner. An atom in an excited state can have one of its electrons transition from a higher energy level to a lower energy level. In this transition, energy can be absorbed, or released as the energy of a photon as shown in Figure 6b. The energy released per transition is equal to hv, where h is Plank's constant, 6.625 x 10^{-34} joule-second. Therefore, the frequency (and wavelength as well) are determined by the energy gap between the two energy levels. There are two methods in which electrons can transition from a lower energy level to that of a higher level. Brownian motion leads to collisions among the atoms in which sufficient energy is transferred to an atom to cause the atom to become excited. The other method is caused by an input of energy from an external source. Heating is used to excite atoms in an incandescent lamp, while electron collisions are used to initiate absorption and subsequent fluorescent discharge from a fluorescent lamp or television picture tube. In lasers, as will be seen later, excitation can be provided from a multitude of sources. The simple atomic model presented above is useful in understanding the production of radiation in an active medium. For many lasing mediums, however, the process is not as simple as that described by the simple atomic model. For example, molecular lasers can use the transition from various vibrational and rotational energy levels that exist in the molecule as a whole.

4. Spontaneous and stimulated emission. The preceding section provides a mechanism for the conversion of energy into a different form. The excitation process shown can occur either spontaneously or can occur as a result of an external source of energy. The second process is referred to as stimulated absorption because an input of energy was required. Transitions of electrons from an excited energy level to a lower energy shell can occur through two processes as well: spontaneous or stimulated emission. Spontaneous emissions occur without any outside stimulation and occur randomly in time. For spontaneous emissions, the amount of time an electron spends in a higher energy level is dependent on the stability of the atom in the excited state. If an atom is unstable in an excited state, the average lifetime of the atom in this state is approximately 10 nanoseconds (ns), but could be longer in some cases (Ref 15). Stimulated emission, on the other hand, occurs when an atom interacts with radiated energy of the same frequency as its own transition frequency, ν.

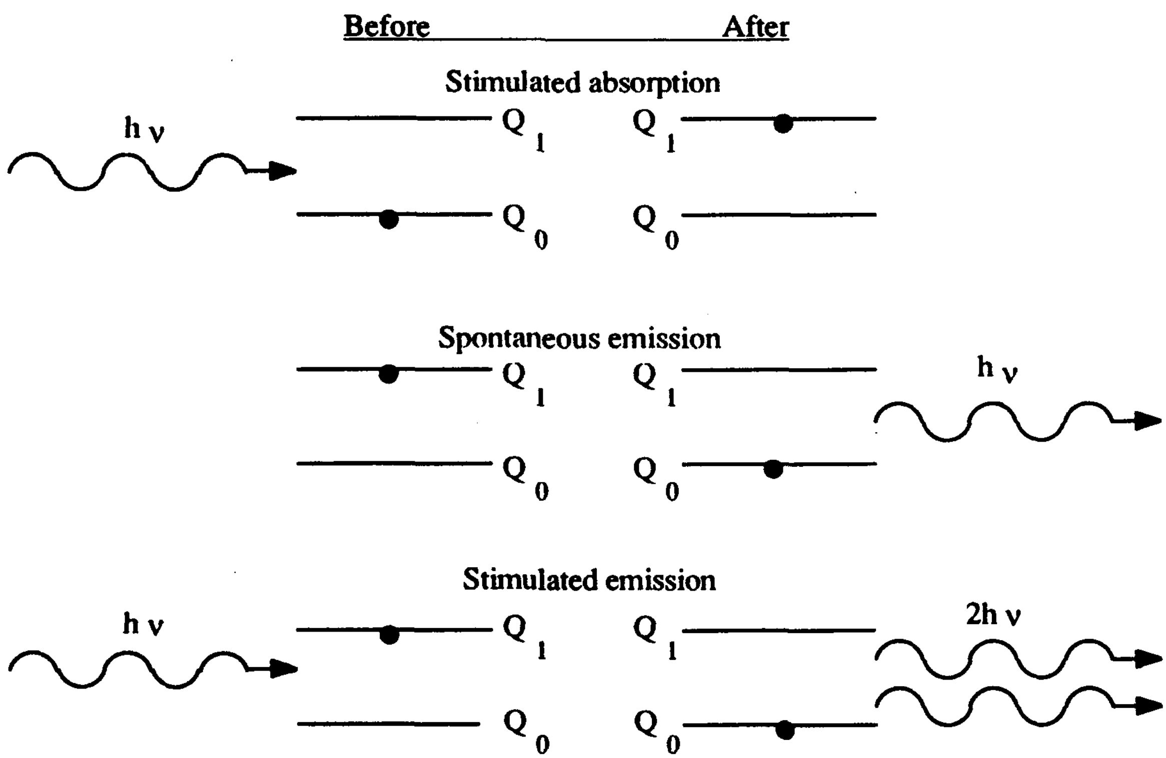


Figure 7. Energy-state-transition diagram describing stimulated absorption, spontaneous emission, and stimulated emission. Diagram adapted from O'Shea (Ref 22).

Representations of the two processes along with stimulated absorption are shown in Figure 7, where Q_0 and Q_1 represent the lower and higher energy levels, respectively. The stimulated emission process shown in the lower section of Figure 7 is necessary for the operation of a laser. Thus, if an atom in a given medium is stimulated to emit radiation by a radiation wave already existing in the medium, the emission will be in phase with the pre-existing wave and will add constructively to the wave. This process is fundamental to the coherent nature of laser radiation emissions. The spontaneous emission process described in the middle section of Figure 7 is characteristic of the random emissions from other radiation sources like an incandescent lamp or a fluorescent tube. Actually, some of the emissions from an incandescent lamp are caused from the stimulated emissions, but the major portion of the energy released is from spontaneous emissions.

5. Population inversion. The previous two sections described the first necessary ingredient for a laser: an active medium. The second principal requirement for a laser is a population inversion or a condition where the number of atoms (or molecules, ions, etc.) in an excited state exceeds the number of atoms (or molecules, ions, etc.) in the ground energy state. A population inversion is necessary for light amplification. A source of energy external to the active medium is necessary to create an inversion. To understand the process, it is necessary to first consider the normal distribution of atoms in a medium. Boltzmann's principle defines the fraction of atoms, on average, in any energy state for any given equilibrium temperature accordingly,

$$N_i/N_0 = e^{-Ei/kT}, \tag{2}$$

where N_i is the number of atoms in an excited state, N_0 is the number of atoms in ground energy state, $k = 1.38 \times 10^{-23}$ joule/K (Boltzmann's Constant), Ei is the energy gap between excited state and the ground state, and T is the absolute temperature in degrees Kelvin. From the equation, it is apparent that the probability of an atom existing in an excited state is smaller than its probability of existing in a ground state. As T in Equation 2 is increased, the probability of an atom existing in an excited state increases, but the population in a higher energy state can never exceed that in a lower energy state unless an external source of energy is applied, often called "pumping" the medium. There are many methods of pumping an active medium; some of these methods will be described in Section D.

6. Metastable energy levels. For a material to operate as an active medium of a laser, it must have at least one excited state where electrons are trapped and do not immediately drop to a lower energy level spontaneously. The electrons may remain in a metastable energy level for a few microseconds to a few milliseconds. If the medium is excited by an external source of energy, the electrons will remain in the metastable energy level for a period of time long enough to achieve a population inversion between the metastable energy level and next lower energy level. On the other hand, if the trapping time is not sufficiently long, spontaneous energy decay will predominate and lasing will not occur. Figure 8 describes a simple three-level pumping scheme. In this scheme, the upper state of transition, Q_m, is achieved indirectly by pumping atoms from the ground energy level, Q_0, to a level, Q_1. For a population inversion to occur, the transition from Q_1 to Q_m must be sufficiently fast and energy level Q_m must be relatively stable. Under these conditions, the population of atoms at energy level Q_m will exceed the population at the ground energy level. Many other energy level schemes are possible.

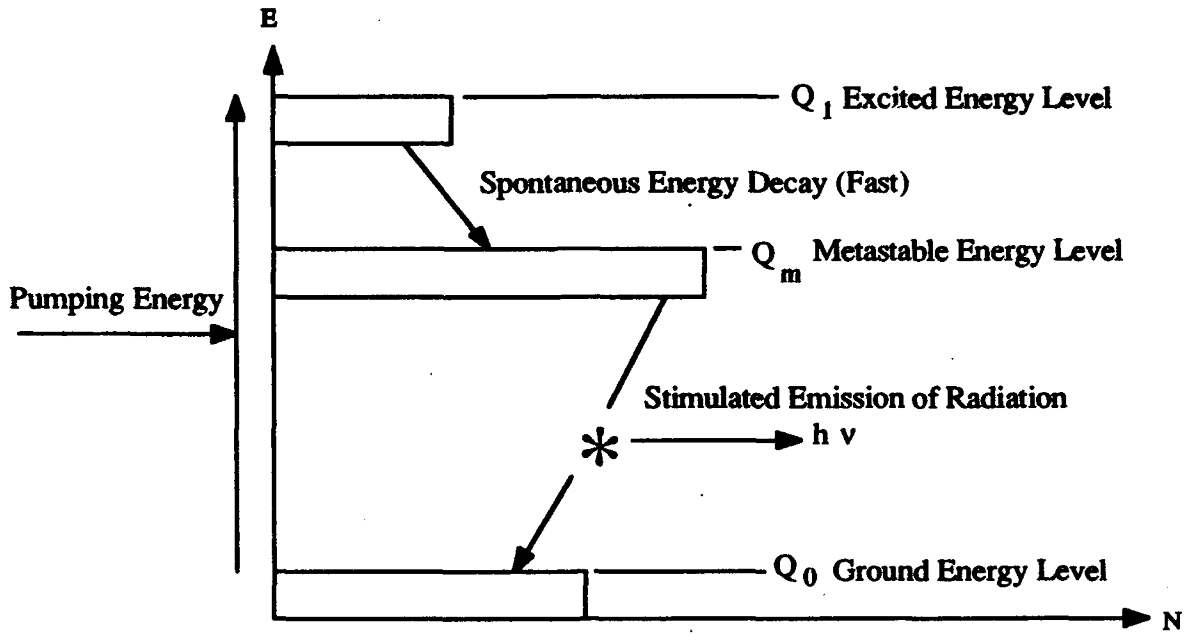


Figure 8. Population energy levels by pumping in a three-level scheme. Adapted from O'Shea (Ref 22).

7. Optical feedback. The optical feedback component of a laser is commonly referred to as an optical cavity. Although the process of stimulated emission is in itself a form of gain or amplification, for most lasers an optical cavity is necessary to provide the greatest amount of amplification. The first laser, the ruby laser provided amplification by coating each end of the ruby rod with silver. Most lasers, today, employ a system of mirrors. Figure 9 shows a simple flat mirror optical feedback system. In this example, one mirror has a totally reflective surface while the other is 98% reflective, in effect permitting release of a small portion of the energy contained in the medium. Amplification is provided by simply reflecting the beam through the active medium many times and as a result stimulating the emission of excited atoms at a rate many times that of a single pass. This type of system has an effective length roughly 50 times the separation distance between the mirrors (Ref 22). Figure 10 shows some example mirror configurations. Note that some of the designs are more stable than others.

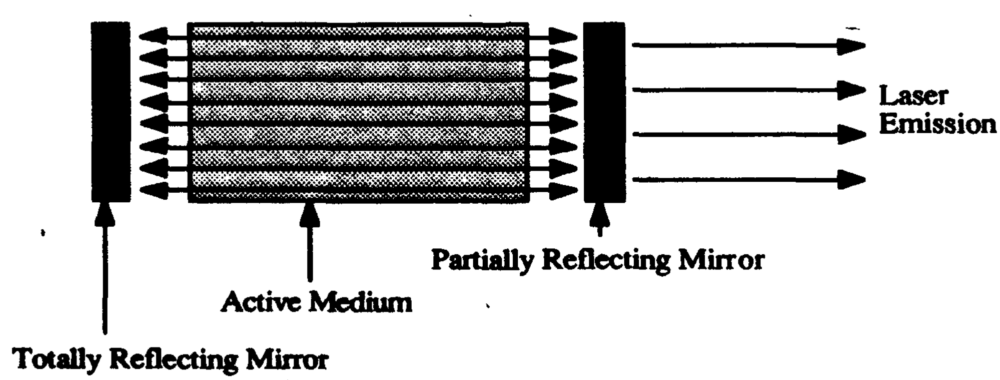


Figure 9. Simple flat mirror optical feedback system.

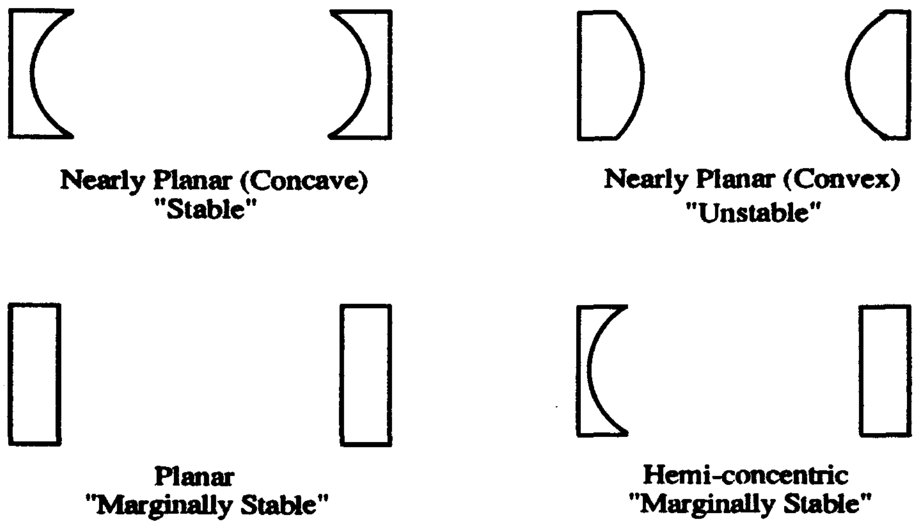


Figure 10. Possible laser cavity mirror configurations. Adapted from Laurence (Ref 15).

C. Laser output.

1. Axial modes of operation. The output of a laser is not nearly as perfect as one would be led to believe from the previous discussion. Earlier in the text it was noted that the typical linewidth, $\Delta\lambda$, of a laser is approximately 0.01 nm. Rather, a typical laser output consists of a series of more narrow lines corresponding to the high-Q frequencies of the laser cavity. These narrow lines are referred to as the axial modes of a laser. Q, or quality factor, refers to the ability of the resonating ability to store energy. Q is defined as follows:

$$Q = \frac{2\pi \text{ x energy stored}}{\text{energy dissipated per cycle}}$$

A high Q-cavity stores energy well, while a low-Q cavity does not. Cavities having high-Q values have relatively small linewidth. There are many mechanisms that contribute to the broadening of the linewidth. Some broadening is a result of imperfections in the energy level transition. For gas lasers at low pressure, the atoms or molecules are in constant random motion. The frequency of the emission is subject to variations caused by Doppler broadening or a change in frequency depending on the relative velocity of an atom of molecule undergoing transition. Collision broadening is more predominant in high-pressure gas lasers and is a result of collisions among the atoms of the medium. The number of axial modes present is dependent on the linewidth, because the separation frequency between adjacent axial modes is fixed. The separation frequency between adjacent lines is defined below as:

$$\Delta v = c/2L, \tag{3}$$

where c is the speed of light and L is the distance between the mirrors. Figure 11 provides a description of the axial modes of a laser. The graph in Figure 11a shows the "apparent" linewidth one would expect for a typical laser. The width of the curve at the half intensity point is equal to $\Delta\lambda$. The graph in Figure 11b shows the axial modes with the frequency separation between adjacent modes equal to c/2L, and the graph in Figure 11c is a combination of the first two graphs and represents the resultant output of the laser. In all graphs, I represents the intensity of the beam and v is the frequency. Axial modes are a result of the limitations the cavity places on which wavelengths are permitted to oscillate. Only the wavelengths within the transition linewidth that are multiples of one-half the distance between the mirrors can oscillate. While the axial mode structure of a laser determines the spectral quality of the output, it does not have a significant impact on the hazards of a laser.

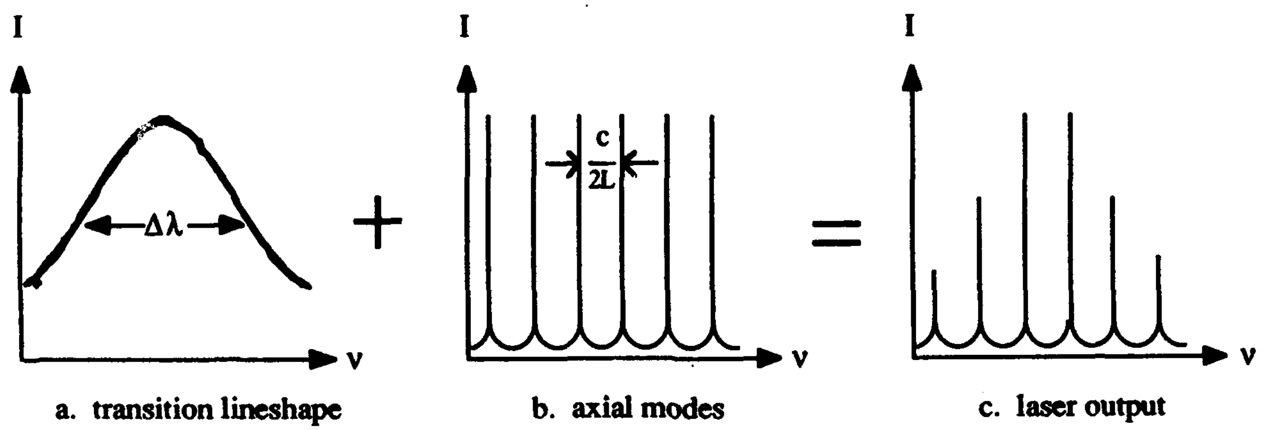


Figure 11. Combination of laser transition linewidth and the axial modes provides the laser output. Adapted from O'Shea (Ref 22).

2. Transverse electromagnetic (TEM) modes. While the axial mode structure of a laser describes the spectral broadness of a laser beam in terms of frequency, the transverse electromagnetic mode of a laser beam describes its spatial structure perpendicular to its direction of travel. As is the case with axial modes, TEM modes are caused by limitations of the optical cavity. There are a limited number of possible TEM modes for a given laser, dependent on those modes supported by the cavity. The most common pattern is the TEM_{00} mode as shown in Figure 12. TEM_{00} produces a beam with the smallest possible beam divergence and diameter.

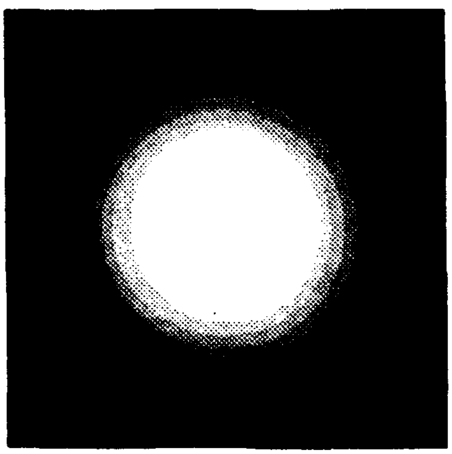
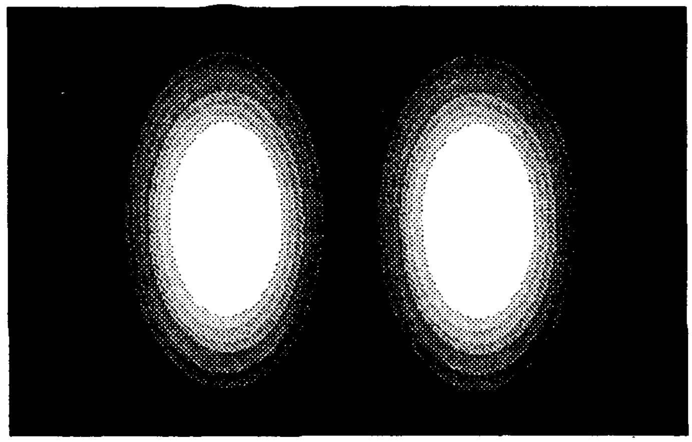
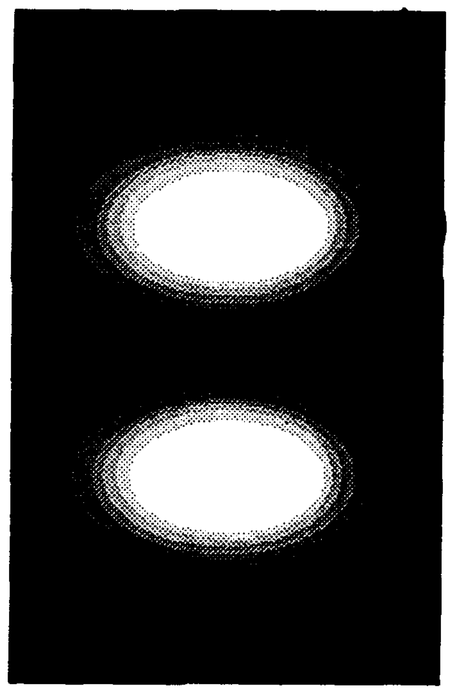


Figure 12. TEM_{00}.



a. TEM_{10}.



b. TEM_{01}

Figure 13. Other common TEM modes.

Two other common TEM modes are shown in Figure 13. The patterns shown are considered to be two lasers side-by-side, with each side possessing one-half the power as the TEM_{00} mode beam.

3. Multimode vs. single-mode operation. It is possible for a laser to operate in more than one TEM transverse and axial mode at one time. When a laser supports many modes of operation, the laser is referred to as operating multimode. The number of modes a laser can support is dependent on the transition linewidth and the distance between the mirrors of the cavity. It is often desirable (or necessary for some applications) that a laser provide only a single-mode output. There are many

methods of achieving single-mode operation. One method involves use of an intracavity prism, or other optical element, that provides a high degree of selectivity for the wavelengths permitted to oscillate. This method reduces the number of axial modes. Figure 14 below provides a simple diagram of a prism placed in the cavity of a laser. Assume that the three rays shown: λ_a, λ_b, and λ_c represent three separate potential axial modes where the wavelength of the modes is as follows, $\lambda_a < \lambda_b < \lambda_c$. The axial modes with wavelengths smaller than λ_b, like λ_a, will have a greater amount of refraction in the prism and will not oscillate in the cavity. The wavelengths greater than λ_b will undergo refraction to a lesser degree than λ_b. These wavelengths are represented as λ_c and will not oscillate in the cavity.

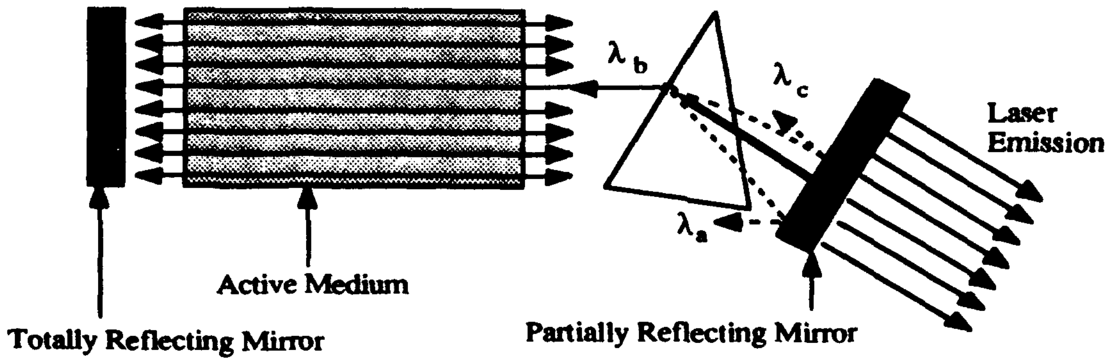


Figure 14. Intracavity prism for selective oscillation of one axial mode.

Two other methods are commonly used to achieve a single-axial-mode of operation. The first method involves simply reducing the distance between the mirrors of the cavity. With a smaller distance between the mirrors, the separation frequency between adjacent axial modes, c/2L, will increase. As a result, only one mode will be sufficiently supported by the cavity. However, because of a shorter cavity length, the active medium must be shorter, and the power output will be less. The other method involves placing an etalon in the cavity. An etalon is a special piece of glass that has two faces with a high degree of parallelism. The etalon provides additional constraint on the number of frequencies permitted to oscillate in the cavity. Figure 15 provides the layout of a laser with an etalon as an intracavity device. The figure attempts to show that by introduction of the etalon in the cavity, some of the axial modes will not oscillate and the laser will have a decreased output power. For some typical lasers, reduction in power output as a result of introduction of an etalon in the cavity is 25% (Ref 22).

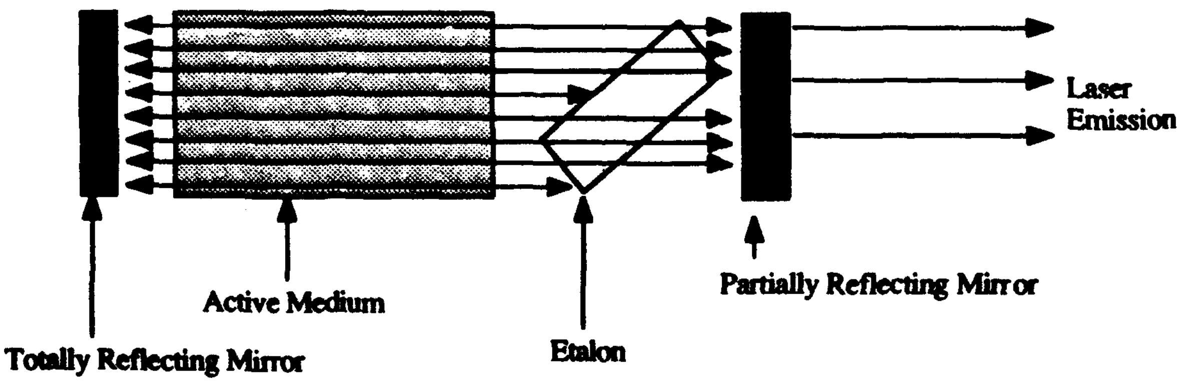


Figure 15. Etalon as intracavity device for single-axial-mode operation.

While the three methods described above are useful for providing only a single axial mode, other methods are available to reduce all TEM modes, except the TEM_{00} mode. Many of the methods accomplish this by placing an adjustable diaphragm (limiting aperture) in the cavity. The diaphragm causes significantly higher losses to higher TEM modes than to the TEM_{00} mode. As a result, the output beam is predominantly TEM_{00}. Figure 16 shows the use of a limiting aperture in the cavity.

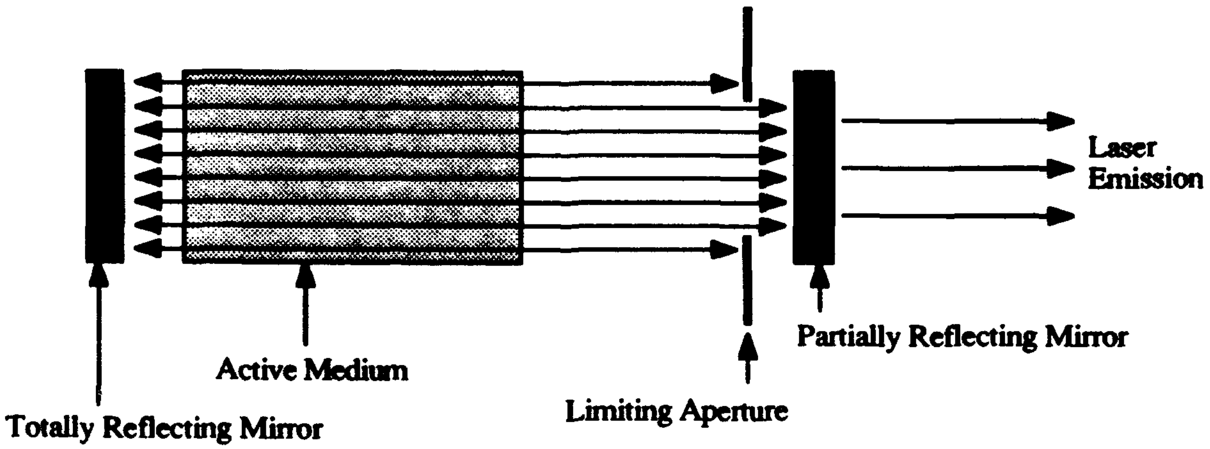


Figure 16. Intracavity diaphragm for reducing higher order TEM modes.

In some cases, operating a laser in multimode is advantageous to its operation in single-mode. Heat treating is one example. The total power or energy in a laser operating in multimode is greater than its operation in single-mode.

4. Temporal modes of operation.

a. Continuous wave (CW). Temporal mode of operation refers to the rate at which energy is produced. Lasers that produce energy continuously are continuous wave lasers or simply CW. The helium-neon (He-Ne) laser is perhaps the best example of a CW laser. By strict definition of AFOSH 161-10 and ANSI Z136.1, a CW laser operates continuously for a period ≥ 0.25 second. Lasers that operate continuously for periods of time < 0.25 second are considered single pulse lasers provided that the rate at which pulses are delivered is less than 1 hertz (Hz). For lasers with pulse durations (also called pulse width, τ) less than 0.25 second, but have pulse repetition frequencies ≥ 1 hertz are considered repetitively pulsed lasers. Figure 17 provides a summary.

b. Normal-pulse. The pulse duration of a normal-pulsed laser is typically a few tenths of μs to a few ms. For this type of laser, the pulse repetition frequency (prf) and pulse duration are normally the same as that of the energy source, whether it be a flashlamp or otherwise. The ruby and a pulsed Nd:YAG are good examples of this type of pulsed laser.

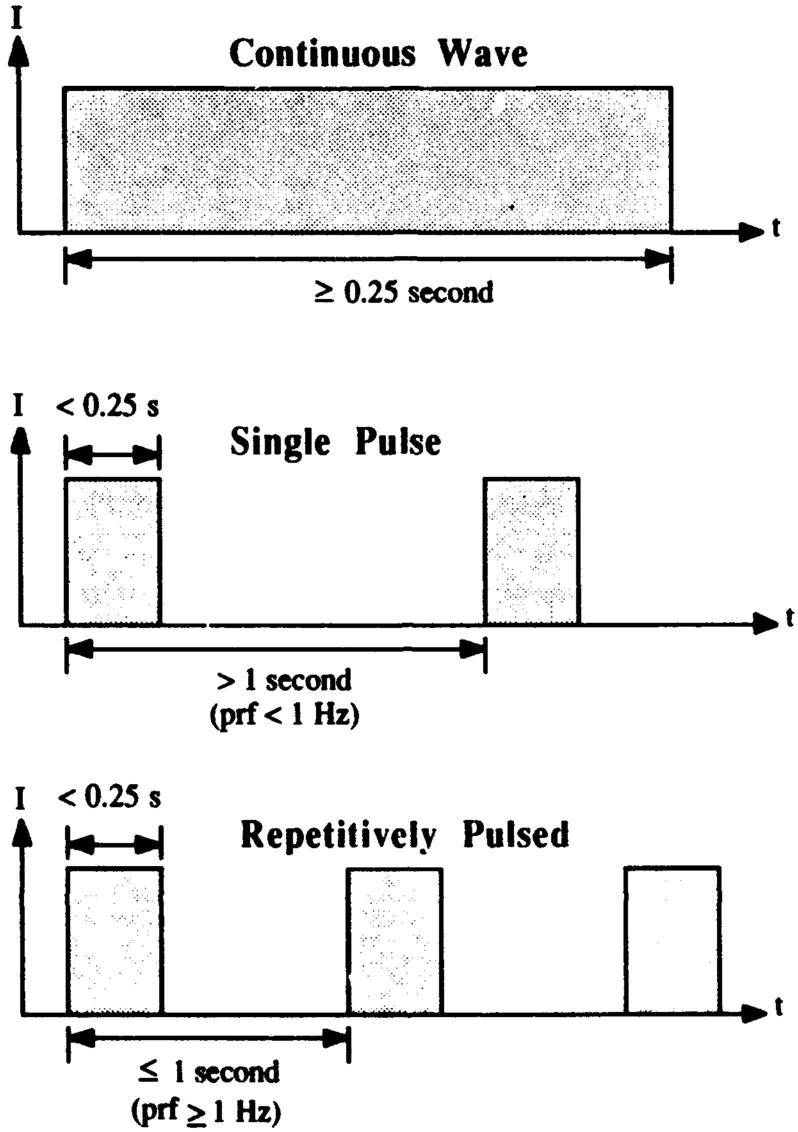


Figure 17. CW, single pulse, and repetitively pulsed lasers as defined by AFOSH Std 161-10.

c. Q-switched. The pulse duration of Q-switched laser is considerably smaller than that of a normal-pulse laser. Typically, for a Q-switched laser, pulse durations are a few tenths of a nanosecond to few tenths of a μs. As is the case of a normal-pulse laser, the prf of a Q-switched laser is normally the same as that of the energy source; however, for the Q-switched laser, the pulse duration is considerably less than that of its energy source. A Q-switch laser essentially compresses the energy delivered in a normal-pulse into a time frame considerably smaller than the duration of the excitation. Q-switched lasers accomplish this task by changing the quality factor, Q, of the cavity during the period of time excitation energy is delivered to the active medium. There are many methods of changing the quality factor of a cavity during its operation. Figure 18 provides a schematic diagram of a laser that uses the rotating mirror method. In the rotating mirror method, the rapidly rotating mirror is the element that changes the quality factor of the cavity. During a majority of time within a complete cycle of rotation, the rotating mirror is out of alignment with the cavity and does not reflect incident waves back through the cavity. During these times, if an input of power is provided to the cavity by the power supply, lasing cannot occur because the amplification of the cavity is small. As a result, a population inversion within the active medium will grow. During other times within the mirror rotational cycle, the rotating mirror is favorably aligned with the cavity, amplification within the cavity is high, and lasing can occur. Therefore, during periods of low amplification, the cavity stores a large amount of energy, and during times of high amplification, there is a great release of this stored energy within a very short period of time. The amount of energy in a single pulse is dependent on the intensity and duration of the excitation provided by the energy source, while the output pulse duration is dependent on the angular velocity of the rotating mirror and the mechanical configuration of the cavity. The peak power of some Q-switched lasers is on the order of several megawatts (MW) or gigawatts (GW). From Figure 18, it must be understood that the velocity of the rotating mirror does not determine pulse repetition frequency of the output. Electronic circuits on the flashlamp determine pulse rate. The triggering laser initiates the pulse sequence by sending a pulse of laser radiation to the rotating mirror. When in alignment, the pulse is received by the detector as a reflection from the mirror. The trigger circuit sends an impulse to the flashlamp power supply to initiate a pulse. Note the feedback loop to the trigger from the flashlamp. Feedback from the flashlamp controls the trigger and thereby limits overheating of the flashlamp of laser medium.

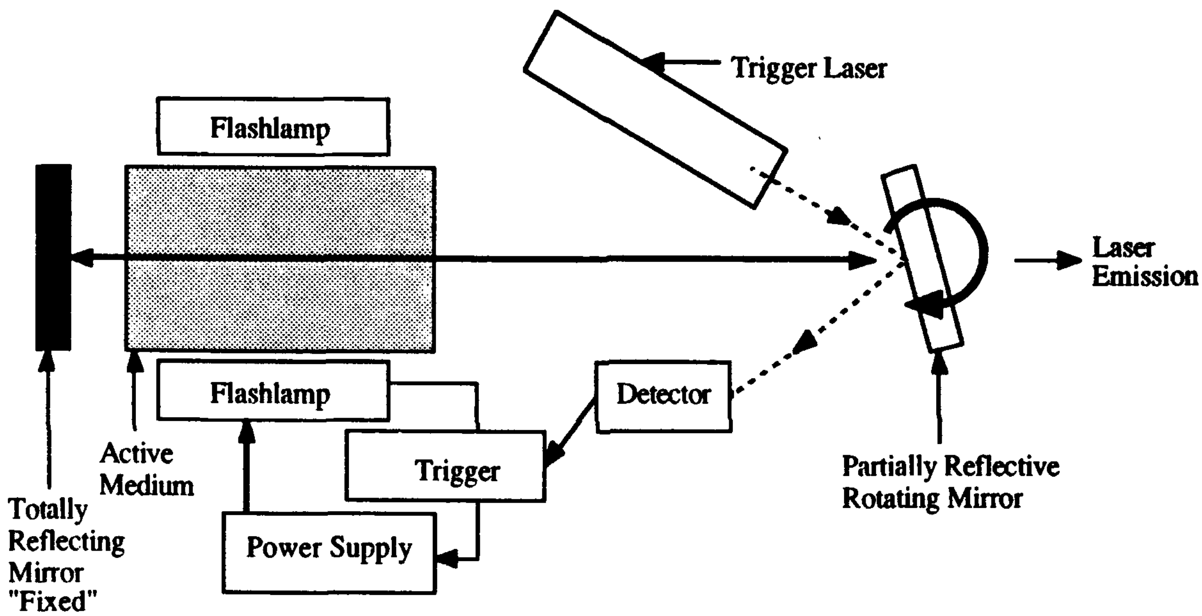


Figure 18. Schematic diagram of a Q-switched laser that uses a rotating mirror.

Other devices are used for Q-switching. Some of the more common ones use electro-optical, magneto-optical and acousto-optical materials. These devices will not be described here.

d. Mode-locked lasers. Q-switching can be used to convert a laser with a long pulse duration into a laser with high-power and short pulse-duration. Mode-locking a laser can perform the same task, but can create pulses of smaller duration and higher power. Pulse widths as small as a few hundred femtoseconds are possible with mode-locking (Ref 15). As was shown earlier, most laser cavities are capable of supporting many axial modes within the frequency limits defined by the transition linewidth. The larger the transition linewidth, the greater number of axial modes. Also, the frequency separation between any adjacent lines is c/2L, where L is the distance between the mirrors. Under · ..nal operation, the axial modes are random in phase with respect to each other. Mode-locking imposes a constant phase between the axial modes and causes a temporal interference pattern to form in the output. Figure 19 illustrates the basic foundation of this technique. In the lower section of the diagram, four axial modes are shown. In this example, the amplitude of each mode is equal. The separation frequency between each adjacent mode is assumed to be c/2L. The resultant output is shown in the upper section of the figure. The intensity of the output for a mode-locked laser is the squared sum of the amplitudes, while for a non-mode-locked laser, intensity is the sum of the amplitudes squared. The pulse width, τ, for mode-locked lasers, is approximately the inverse of the linewidth of the laser (Ref 22). This relationship is shown in Equation 4,

$$\tau = 2L/Nc, \tag{4}$$

where N is the number of axial modes. Mode-locking is accomplished by placing a modulator (shutter) in the cavity and switching this device at a frequency equal to 2L/c, the round-trip transit time of a pulse in the cavity. The shutter is open for a short period of time every 2L/c. Thus, only axial modes that are in-phase with the modulator are permitted to oscillate, while those out-of-phase with the modulator are absorbed by the shutter. Electro-optic and acousto-optic shutters are frequently used as modulators.

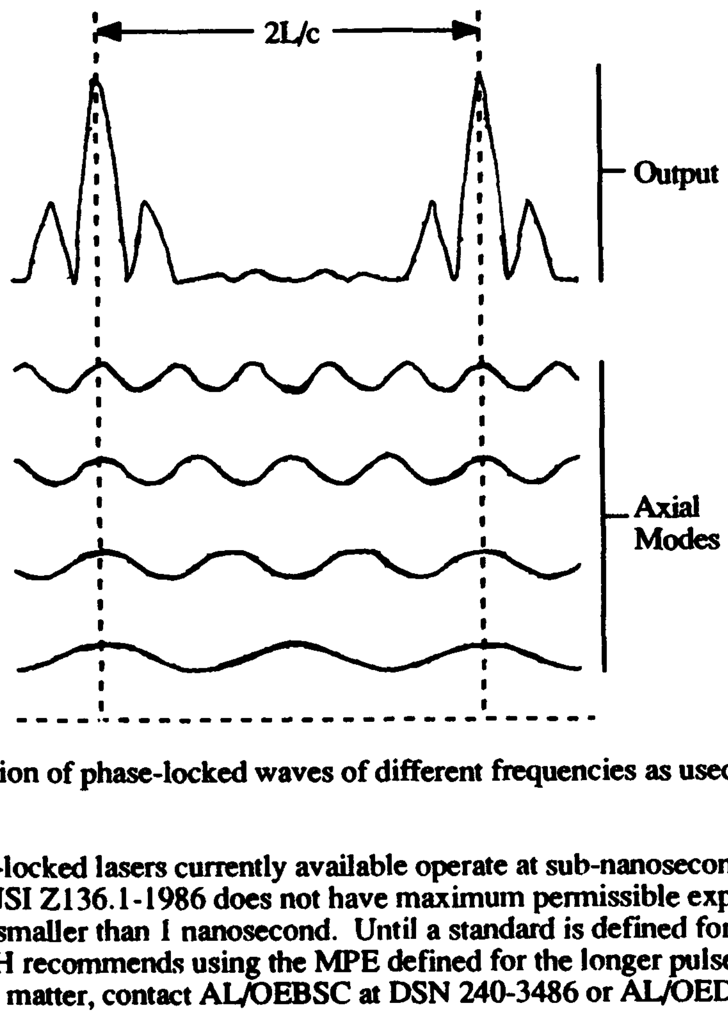


Figure 19. Addition of phase-locked waves of different frequencies as used in a mode-locked laser.

Some of the mode-locked lasers currently available operate at sub-nanosecond pulse widths. Unfortunately, ANSI Z136.1-1986 does not have maximum permissible exposures (MPE's) for lasers with pulse widths smaller than 1 nanosecond. Until a standard is defined for sub-nanosecond pulse widths, the AFOSH recommends using the MPE defined for the longer pulse widths. For additional clarification on the matter, contact AL/OEBSC at DSN 240-3486 or AL/OEDL at DSN 240-3622.

5. Laser power and energy. For the purpose of classifying and analyzing the relative hazards of a laser it is necessary to define the average power emitted by a CW laser, or the peak power or energy emitted per pulse for a pulsed laser. Two systems exist to describe these parameters for optical radiation. The photometric system is used to describe the sensation of radiation by the human eye and is limited to those radiations in the visible spectrum, 400 - 700 nm; this system has limited use in describing the output of lasers. The radiometric system is used to describe the output of lasers. There are six terms in the radiometric system that are of primary importance in describing the output of lasers

and its application to the maximum permissible exposure levels given in the AFOSH. The solid angle concept is also described since it is used in the description of some laser outputs.

a. Solid angle. The concept of the term solid angle is often difficult to understand. Figure 20 is provided to assist. The solid angle is the area, A, of a sphere subtending the solid angle, Ω, divided by the square of the sphere's radius as given by Equation 5.

$$\Omega = A/r^2. \qquad (5)$$

The unit of the solid angle is the steradian, a unitless quantity. An entire sphere has a solid angle equal to $4\pi r^2$ divided by r^2 or 4π steradians.

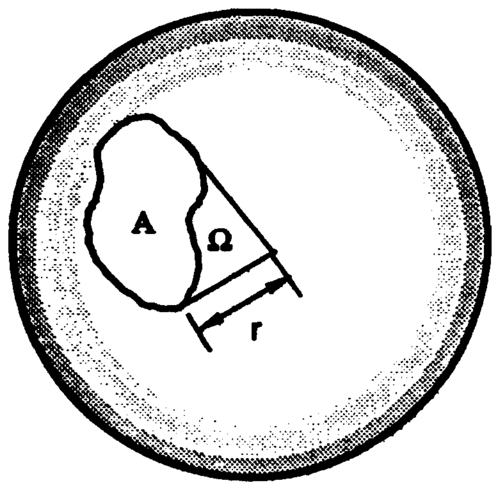


Figure 20. Solid angle.

b. Describing source output. Of the six terms to be described, four of these terms are useful in describing the output of a source of radiation.

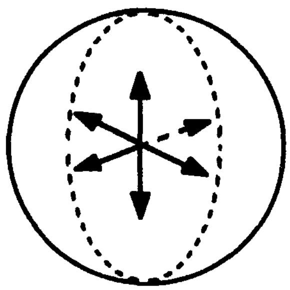
(1) Power, Φ, is the amount of energy per unit time emitted from a source. Normally, power is used to describe the output from continuous wave laser. Periodically, a pulsed laser is described by the peak power of a pulse. The units for power are joules/second or watts (W).

(2) Energy, Q, is commonly used to characterize the output from pulsed lased lasers. The unit used for energy is joules (J).

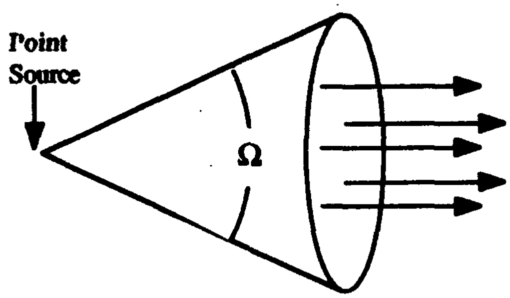
(3) Radiant intensity, I, is used to describe the spatial distribution of the power emitted from a source with respect to a uniform distribution in space. The unit used for power per unit solid angle is watts/steradian (W/sr).

(4) Radiance, L, is used to describe the spatial distribution of the power emitted from an area source with respect to a uniform distribution in space. The unit used for power per unit solid angle and per unit area is watts/steradian-cm^2 (W/sr-cm^2).

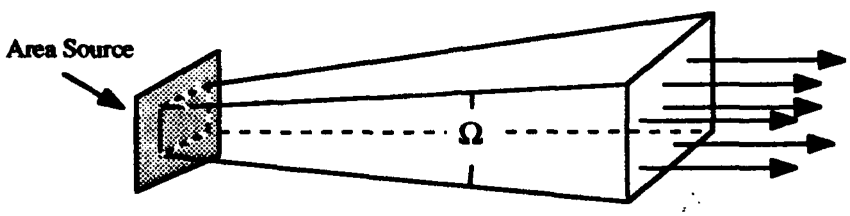
Figure 21 shows the use of these four terms. Figure 21a shows the use of power or energy as the total power or energy collected in an integrating sphere. Figure 21b illustrates the application of the term radiant intensity to the radiation emission of a point source. In this figure, Ω, represents the solid angle subtended by the source. Figure 21c shows the use of the term radiance as applied to the power emission from an area source.



a. Total power or energy of source (watts or joules).



b. Radiant intensity of source (watts/steradian).



c. Radiance for area source (watt/sr-cm^2).

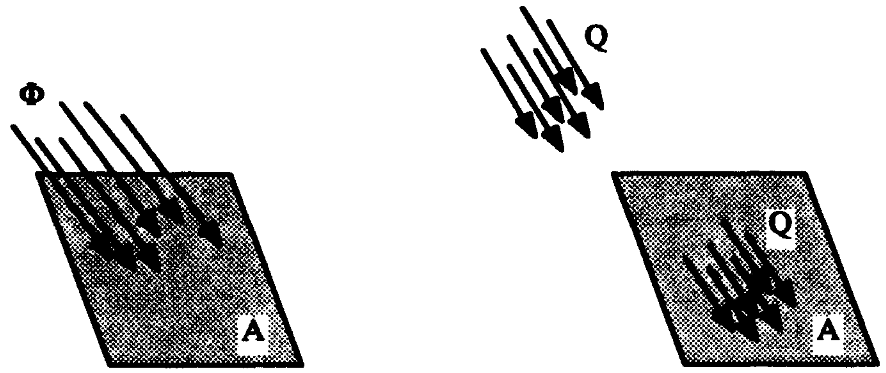
Figure 21. Terms used to describe the output of radiation sources.

c. The remaining terms are commonly used to describe the irradiation of a surface by a source. These terms are very important, since the MPE limits given in the AFOSH are listed in these terms.

(1) Irradiance, E, is the power intersecting a surface of unit area. The unit for irradiance is watts/cm^2 (W/cm^2).

(2) Radiant exposure, H, is the energy intersecting a surface of unit area. The unit for radiant exposure is joules/cm^2 (J/cm^2).

Figure 22 shows the use of these terms. Figure 22a depicts the continuous power, Φ, incident on surface A, while Figure 22b shows two pulses of energy, Q, incident on surface A.



a. Irradiance (W/cm^2).

b. Radiant exposure (J/cm^2).

Figure 22. Terms useful for describing the irradiation of a surface.

6. Beam diameter. The beam diameter of a laser beam is measured at the exit aperture of the laser cavity. Most commonly, the laser output of a TEM_{00} mode is assumed to follow a Gaussian profile where the irradiance at any point is defined as follows:

$$E = E(0)e^{-r^2/r_1^2}, \tag{6}$$

where E(0) is the peak irradiance in the beam center, r is the radial distance from the beam center, and r_1 is the radius at which the irradiance is 1/e times the peak. Figure 23 provides an example.

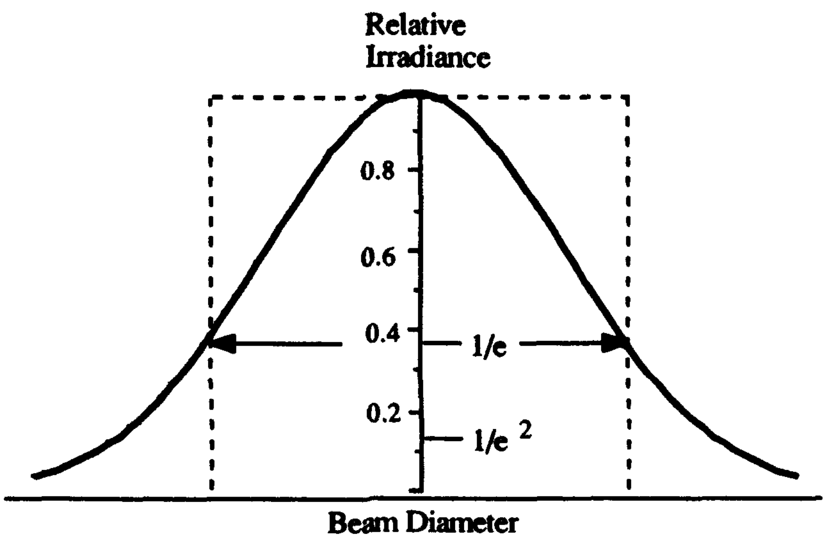


Figure 23. Irradiance at various points in a cross-section of a Gaussian beam.

For the TEM_{00} transverse mode, the edge of the beam is defined at a various points along the beam. Laser manufacturers commonly define the beamwidth or diameter at the $1/e^2$ point. The beam defined within this region carries 86.5% of the total power of the beam. For persons performing safety analysis of a laser beam, the beam diameter is normally expressed at the 1/e point, where the relative intensity of the beam is 0.37 of the irradiance at the center of the beam. The beam defined within this area comprises 63% of the total power in the beam. Defining a beam in this manner is very useful because the peak irradiance in the beam can be calculated by the quotient of the total beam power and the beam area (as defined by the 1/e beam diameter points). This relationship is shown in Figure 23 by the dashed lines. The dashed lines define the beam in a manner assuming all the beam power is uniformly distributed within the region defined by the beam diameter. AFOSH 161-10 defines beam diameter at the 1/e points. For Gaussian beams there is a constant relationship between the beam diameter values as specified at the 1/e and $1/e^2$ points. The relationship is defined by Equation 7.

$$\text{Diameter } (1/e^2) = \sqrt{2}\ \text{Diameter } (1/e). \tag{7}$$

7. Beam divergence. No source of radiation provides a perfectly collimated beam. Divergence, the increase in beam diameter with distance from the laser, is used to define the collimation of a laser beam. Again, as was the case in the definition of beam diameter, divergence is defined for the simplest transverse mode of the laser, TEM_{00}. As defined in the AFOSH, the beam divergence is defined as the full angle spread of the beam as measured at the 1/e irradiance point. For Gaussian beams, there is a constant relationship between the beam divergence values as specified at the 1/e and $1/e^2$ points. The relationship is the same as that defined for beam diameters in Equation 7. Figure 24 shows the beam divergence, ϕ, of an example laser beam.

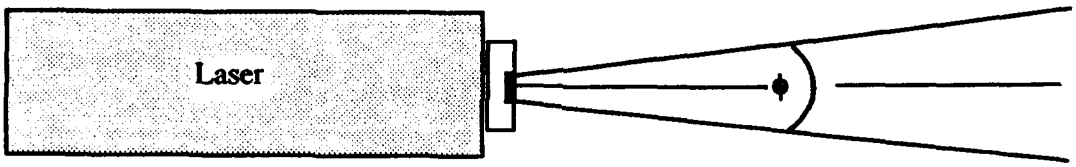


Figure 24. Beam divergence.

8. Polarization. Electromagnetic radiation is composed of oscillating electric and magnetic fields. Polarization refers to the orientation of these fields in space. The electric and magnetic fields are both polarized perpendicular to the direction of propagation as shown earlier in Figure 1. If the electric field is polarized in one direction, the radiation is considered to be linearly polarized in that direction. Radiation emissions with a random combination of polarizations are referred to as unpolarized. An ordinary incandescent bulb emits unpolarized radiation. The emission from many lasers are unpolarized. Many methods are used to polarize the emissions from lasers. A birefringent crystal, as shown in Figure 25, is sometimes used to polarize laser emissions. In this example, the polarizing material is external to the laser. In birefringent crystals, there are two separate indices of refraction. The index of refraction in the vertical direction is small as compared to that in the direction perpendicular to the page. As a result, radiation vertically polarized travels at a greater velocity than radiation polarized in the direction vertical to the page. In Figure 25, the radiation incident on the crystal is polarized in two directions: vertical and perpendicular to the page. The radiation polarized vertically will pass through the space between the crystals that is filled with air, oil, or cement provided the angle the prism is cut is less than the critical angle. The critical angle is defined by Equation 8.

$$\theta_{critical} = \sin^{-1} (n/n_{crystal\text{-}vertical}), \tag{8}$$

where n is the index of refraction of the material and $n_{crystal\text{-}vertical}$ is the index of refraction of the crystal in the vertical plane. The radiation polarized perpendicular to the page will not pass through the interface provided the angle of incidence is greater than the critical angle.

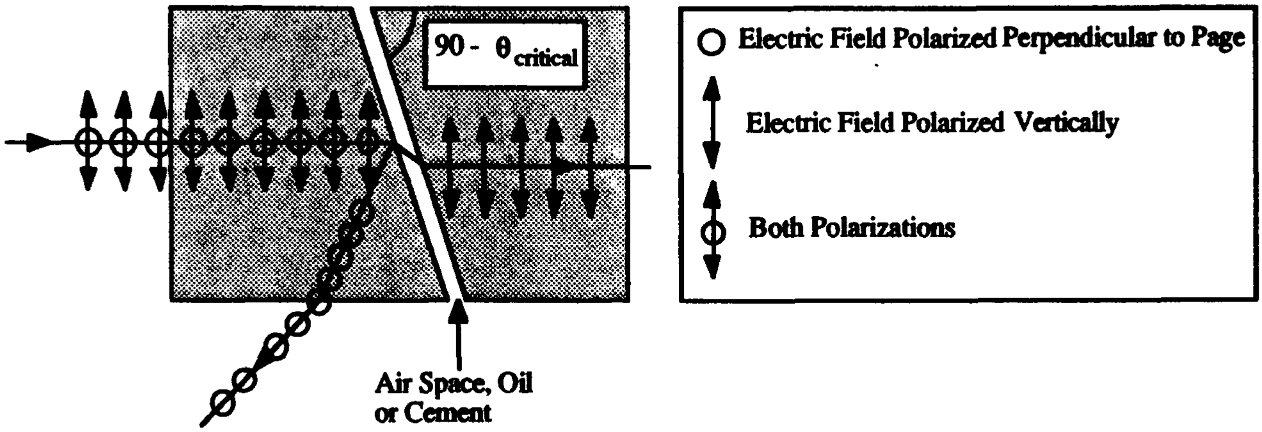


Figure 25. Polarization of radiation by a birefringent crystal. Adapted from O'Shea (Ref 22).

The use of Brewster windows is another technique used to polarize laser radiation, but this technique is internal to the device. Brewster windows are often used for gas lasers. The Brewster window is a flat piece of glass placed at each end of the gas tube. The Brewster window selectively transmits radiation parallel to the windows surface, while reflecting radiation orthogonal to its surface. The angle the Brewster window is set is called the Brewster angle. Figure 26 provides a diagram of a gas tube and one of its Brewster windows.

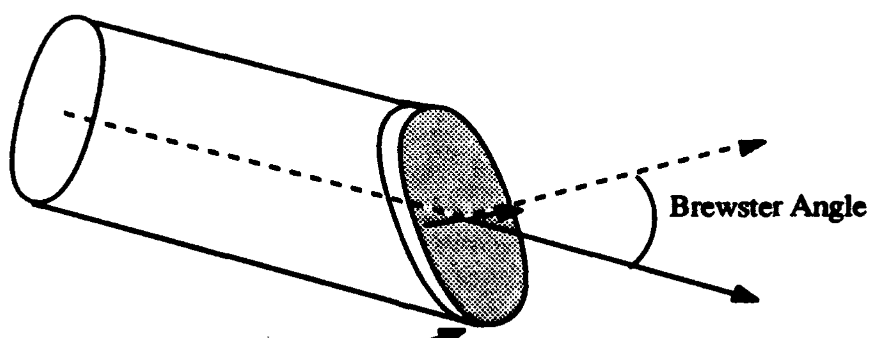


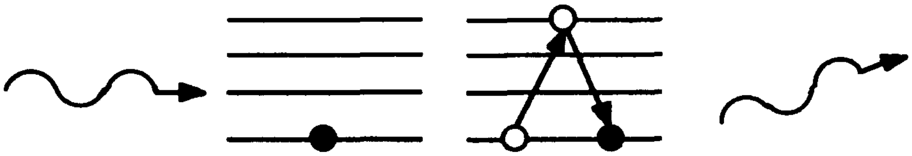
Figure 26. Brewster window.

9. Modifying the laser output.

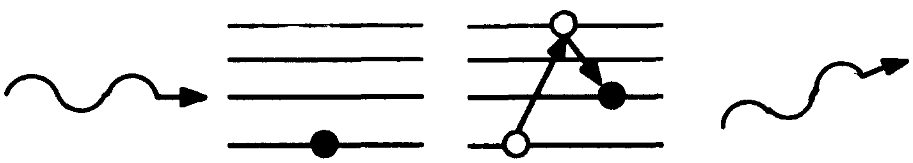
a. General. The output beam of a laser is often modified. Earlier in this report, some of the techniques for altering the temporal output of a laser were given. This section will provide two techniques that are used to alter the wavelength of the laser output: frequency doubling and Raman shifting. Also, a discussion of beam expanders will be provided. Beam expanders are used to alter the spatial charateristics of a laser beam.

b. Frequency doubling. Frequency doubling or second harmonic generation is a technique of altering the output wavelength of a laser. The production of secondary or multiple harmonics is theoretically possible by passing the primary beam through any material. However, the conversion efficiency is typically very small unless the material has nonlinear optical qualities. One of the most commonly frequency doubled laser beams is that produced from the Nd:YAG laser. The primary wavelength of the laser is 1064 nm, while the wavelength of the secondary harmonic is 532 nm. Some of the crystals commonly used for wavelength doubling are: KDP (KH_4PO_4), CDA (CsH_2), RDA (RbH_2AsO_4), and $LiNbO_3$. The conversion efficiency of a crystal is dependent on the wavelength of the radiation; efficiencies typically range from 5 - 30 %. Tripling or quadrupling the primary wavelength can also be accomplished, but the conversion efficiency is very small in comparison to frequency doubling.

c. Raman shifting. Raman shifting is another useful technique for changing the wavelength of a laser beam. Raman shifting or Raman scattering is an inelastic scattering process in contrast to Rayleigh (elastic scattering). Figure 27 provides a description of these two processes. Figure 27a illustrates Rayleigh scattering where a photon is absorbed by a material and emitted in a one-step process. The atom or molecule in this case returns to its original energy state. Figure 27b depicts the Raman scattering phenomenon where the photon emission is at an energy smaller than the energy of the photon absorbed. Like Rayleigh scattering, Raman scattering is a one-step process.



a. Rayleigh (elastic) scattering



b. Raman (inelastic) scattering

Figure 27. Rayleigh and Raman scattering.

The shift in wavelength is dependent on the material being irradiated by a laser beam and is characteristic of the energy level differences of the material in use. Many lines are possible for a given material. The energy level of the lines are dependent on initial energy level of an atom or molecule, the energy of the incident photon, and the final energy of the atom or molecule. The lines are referred to as the Stokes lines. Figure 28 shows the Stokes lines for Raman scattering in an example material and the frequency of the incident photon, ν_i. A methane-gas filled Raman cell is used for the Low Altitude Navigational and Targeting Infrared System for Night (LANTIRN). For this system, the incident wavelength is at 1064 nm, while the primary Stokes line selectively transmitted is at 1540 nm. Other materials commonly used for Raman cells are H_2, D_2, N_2, and O_2.

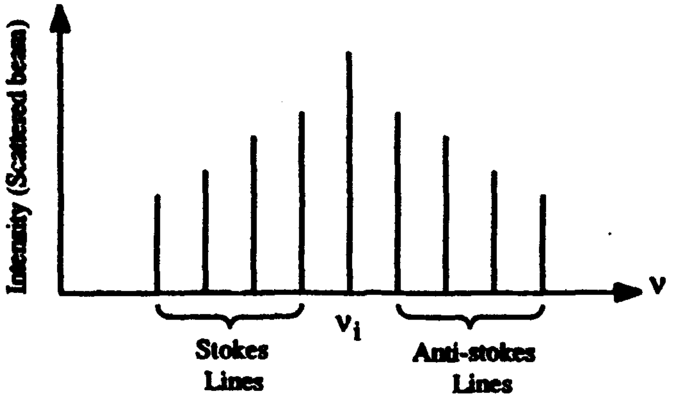


Figure 28. Stokes lines for a Raman scattered beam.

d. Multiple wavelength lasers: safety concerns. The specification of the wavelength or wavelengths of a laser is often done by the manufacturer. The manufacturer will normally list the emissions of primary importance, but may neglect to list other emissions that are low in power or considered unimportant to the function of the device. For example, in the case of a frequency doubled Nd:YAG laser, the secondary harmonic has a wavelength of 532 nm (in the visible spectrum), while the primary beam has a wavelength of 1064 nm. If the laser user is interested only in using the 532 nm emission, it is necessary to use a beam block or filter to absorb the 1064 nm line. For a contained system, this function may be performed internal to the device. But, for laser systems built on bench tops, the 1064 nm line may be accessible to personnel. Problems could arise in this type of set-up. Operators may become complacent in concern and protect against only the 532 nm line; small changes to the system set-up may produce an invisible hazard to the operators from the 1064 nm line. In most cases where Raman shifting or frequency doubling is used, the wavelength of the primary beam retains the greatest amount of the primary beam energy or power. In evaluation of laser systems, consideration should be given to exposure hazards from secondary beams.

e. Beam expanders. Beam expanders are useful for modifying the diameter and divergence of a laser beam. Commonly, Air Force weapon systems use beam expanders to produce a beam with a smaller divergence than that produced by the laser. These modifications can be performed by lenses, mirrors, or prisms. This report uses a simple Galilean telescope to explain the basic principles of a beam expander. Figure 29 illustrates a Galilean telescope. In the figure, d_0 represents the initial beam diameter, d_1 represents the exit beam diameter, f_e is focal length of the smaller lens, and f_0 is the focal length of the larger lens. For this example, magnification (M) of the telescope is given in Equation 9.

$$M = f_0/f_e. \tag{9}$$

The exit beam diameter and divergence are defined in Equations 10 and 11 where θ_e and θ_0 are the initial and exit beam divergences, respectively.

$$\theta_0 = \theta_e / M. \tag{10}$$

$$d_1 = d_e \times M. \tag{11}$$

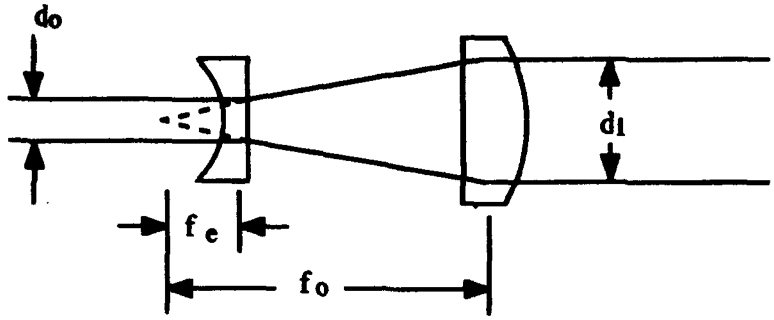


Figure 29. Galilean telescope used as a beam expander.

D. Types of lasers.

1. General. There are many types of lasers commercially available. This section of the report provides a brief summary of these lasers according to the type of material used for an active medium.

2. Gas lasers. Gas lasers by far constitute the vast majority of lasers in use today. Of these, the helium-neon laser is the most common, while the carbon dioxide laser is the most powerful.

a. Atomic lasers. Atomic lasers utilize a transition between energy levels of nonionized atoms. The helium-neon laser is the most common of this group. The 632.8 nm transition in the helium-neon laser is the most commonly used output, while other emission wavelengths exist at 1150 and 3390 nm. Of the noble gases, neon is the only one that will effectively lase in the neutral state. Figure 30 shows a simplified diagram of a gas laser. The laser requires a larger potential to start the laser than it requires to operate. The starting voltage is $V_s + V_r$, while the running voltage is V_r.

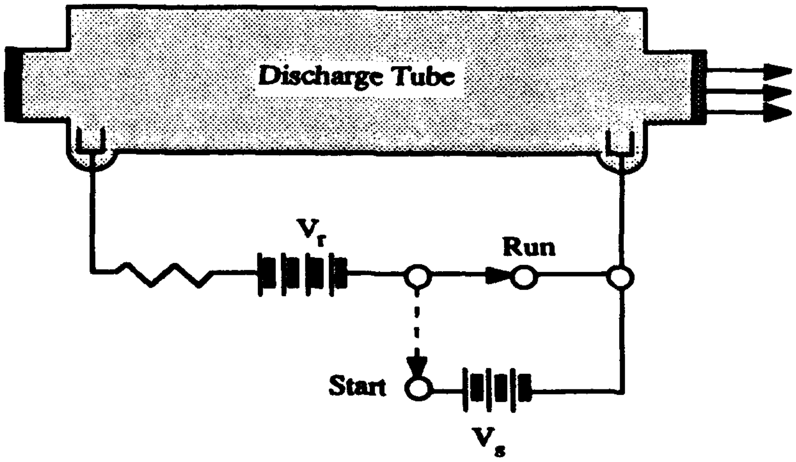


Figure 30. Simplified diagram of a gas laser.

b. Noble gas ion lasers. The noble gas ion lasers are the most powerful visible lasers. Of the noble gases, helium, argon, xenon, and krypton are effective ion lasers. To ionize the gases, a high current in the range of 15 - 50 amps is required. Argon is the most common of the noble gas ion lasers. The two strongest lines of the argon laser are the 488 nm and 514.5 nm that occur in the blue and green portions of the visible spectrum, respectively. Krypton gas ion lasers have strong lines at 350.7 nm and 356.4 nm in the ultraviolet region; and 520 nm, 530.9 nm, 647.1 nm, and 676.4 nm in the visible region.

c. Metal vapor lasers. Metal vapor lasers combine features of operation from the atomic lasers and noble gas ion lasers. Two common examples of this laser are the helium-cadmium and helium-selenium. For both of these lasers, the metal atoms are heated to form a vapor. The excited helium atoms collide with the metal atoms to bring the metal atoms into an excited state. From the excited state, the metal atoms undergo complex decay patterns. The helium-cadmium laser provides two lines: 325 nm and 442 nm. The helium-selenium laser has 30 lines within the 460.4 - 700 nm wavelength range (Ref 4).

d. Molecular lasers. The CO_2 laser is the best example of a molecular laser. The CO_2 laser has high power and efficiency. The laser is used in many industrial applications including welding and metal cutting, and medical applications involving tissue ablation. The strongest line from the CO_2 laser is at 10,600 nm, while a weaker line exists at 9,600 nm. The carbon monoxide laser is also a molecular laser that operates in the far-infrared region. The CO laser has many lines of emission in the wavelength region 5000 - 5500 nm. Excimer lasers are also in the class of molecular lasers. The active media for these lasers are commonly a rare gas dimer (Ar_2, Kr_2, or Xe_2), a rare gas oxide (ArO, KrO, or XeO), or a halogenated rare gas (ArF, KrF, or XeF). The emissions of many of the excimer lasers are in the ultraviolet region. Excimer lasers have been pumped by high energy electron beams with energies as high as 1 MeV (Ref 22).

e. Chemical lasers. The lasers discussed in the above paragraphs were separated according to the type of active medium. Chemical lasers are so designated according to the method of excitation. For most lasers, an electrical current or potential, or radiative type of stimulation (i.e., arc lamp) is used for excitation, while chemical lasers use the energy released from a chemical reaction as a source of excitation. Chemical lasers have the potential for extremely high peak powers. Pulses with peak powers exceeding 2×10^{11} watts have been achieved with hydrogen fluoride lasers. Most of the chemical lasers operate in the far-IR spectrum. For example the HF laser emits in the 2600 - 3300 nm region and the HCN has emission lines at 33700, 311000, and 337000 nm.

3. Doped insulator lasers (crystal solid-state). The first laser, the ruby laser, is a doped insulator laser. Doped insulator lasers are simple, rugged, and easy to maintain. A flashlamp is generally used to excite doped insulator lasers. These lasers are commonly used to generate high peak powers within very small pulse durations. Applications of this type of laser in the Air Force are numerous, but most notable is the use of the Nd:YAG laser in many of the Air Force's laser weapons systems. The primary output of the Nd:YAG laser is at 1064 nm. Other solid-state crystal lasers include: dysprosium, erbium, europium, holmium, and thulium.

4. Semiconductor lasers. Semiconductor lasers are the smallest and most inexpensive lasers. Many applications for the devices exist, but due to their small size there is an overwhelming use in fiberoptic communication systems. The semiconductor laser diode is similar in many respects to that of a simple diode. A representation of a laser diode is given in Figure 31.

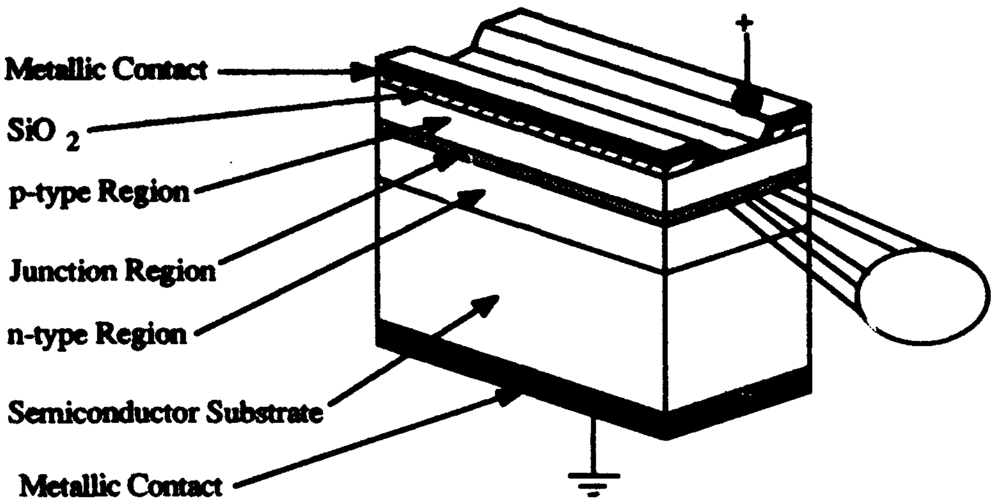


Figure 31. Semiconductor laser diode.

Semiconductor laser diodes require that both holes and electrons exist in the junction region. To provide for both holes and electrons to exist in the junction region requires heavy doping of impurities in the p- and n-type regions. When the diode is forward biased, i.e., p-type material has a positive potential with respect to the n-type material, the emission of optical radiation is possible when recombination of an electron and hole occurs. At high bias potentials, the electric field across the junction region is sufficient to create a population inversion, a condition where there is a greater number of electrons in the conduction band than holes in the valence band. A population inversion is a necessary condition for the diode to operate as a laser. At lower bias potentials, stimulated emission does not occur and the device operates as a light-emitting diode (LED). Figure 32 illustrates the differences in emission spectrum of a laser diode and an LED operating lasing threshold. Note that the laser diode has a considerably smaller emission spectrum.

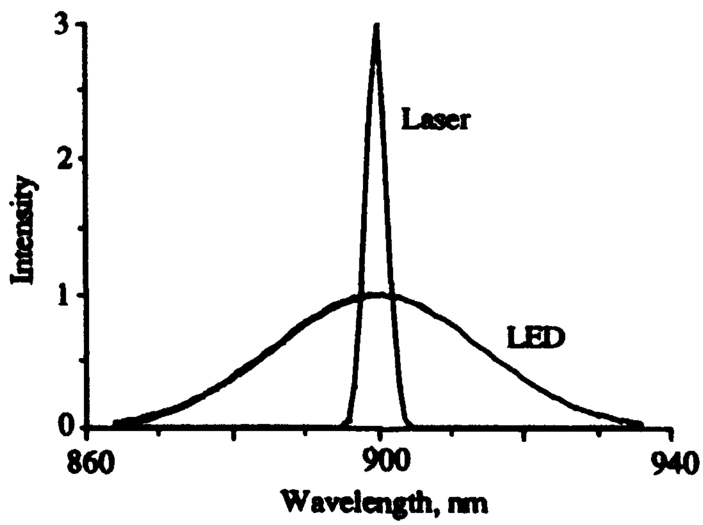


Figure 32. Emission spectrum of a laser diode and an LED. Adapted from O'Shea (Ref 22).

The most common laser diodes are formed with gallium-arsenide (GaAs) or gallium-aluminum-arsenide (GaAlAs) substrate materials. The output wavelength of these devices at room temperature is 850 nm and 905 nm for GaAs and GaAlAs, respectively. Cooling the devices increases the efficiency and maximum output power, and decreases the wavelength of emission. At the temperature of liquid nitrogen (77 °K), the GaAs emits at 825 nm.

5. Dye lasers. The laser types described above have narrow limits of wavelength tunability. Liquid dye lasers, on the other hand, are able to be tuned across relatively wide wavelength regions. The active medium of dye lasers are organic dyes. Dyes are excited by a source of radiation and the dye emits radiation at a longer wavelength. Coumarin dyes are useful as active media for emissions in the blue to green region of the visible spectrum, rhodamine dyes cover the green to red region of the spectrum, and perchlorite dyes are used in the red to near-IR region.

6. Summary. A summary of lasers, their emission wavelength, and laser type is provided in Appendix E.

III. Biological Effects of Laser Radiation

A. General. The eye is normally the most vulnerable organ to damage from laser radiation. The vulnerable tissues of the eye are highly wavelength dependent. Generally, the retina is susceptible to damage from radiation in the visible and near-IR band (400 - 1400 nm). The lens and cornea are susceptible to damage from UV-A, while the cornea is prone to damage from UV and far-IR. Most higher energy x-rays and gamma rays pass through the eye with little absorption. Though the skin is normally of smaller concern than the eye, the skin is susceptible to damage from the entire laser emission spectrum. However, emissions in the UV and IR bands typically raise more concern.

B. Anatomy of the eye. The human eye is approximately 2.5 cm in diameter. Figure 33 provides a horizontal cross-section diagram of the eye. The wall of the eye is composed of three layers: the cornea-sclera, a tough outer connective tissue; an intermediate vascular-connective tissue layer that is comprised of the iris, ciliary body, and choroid; and the retina, a fragile inner neurosensory layer.

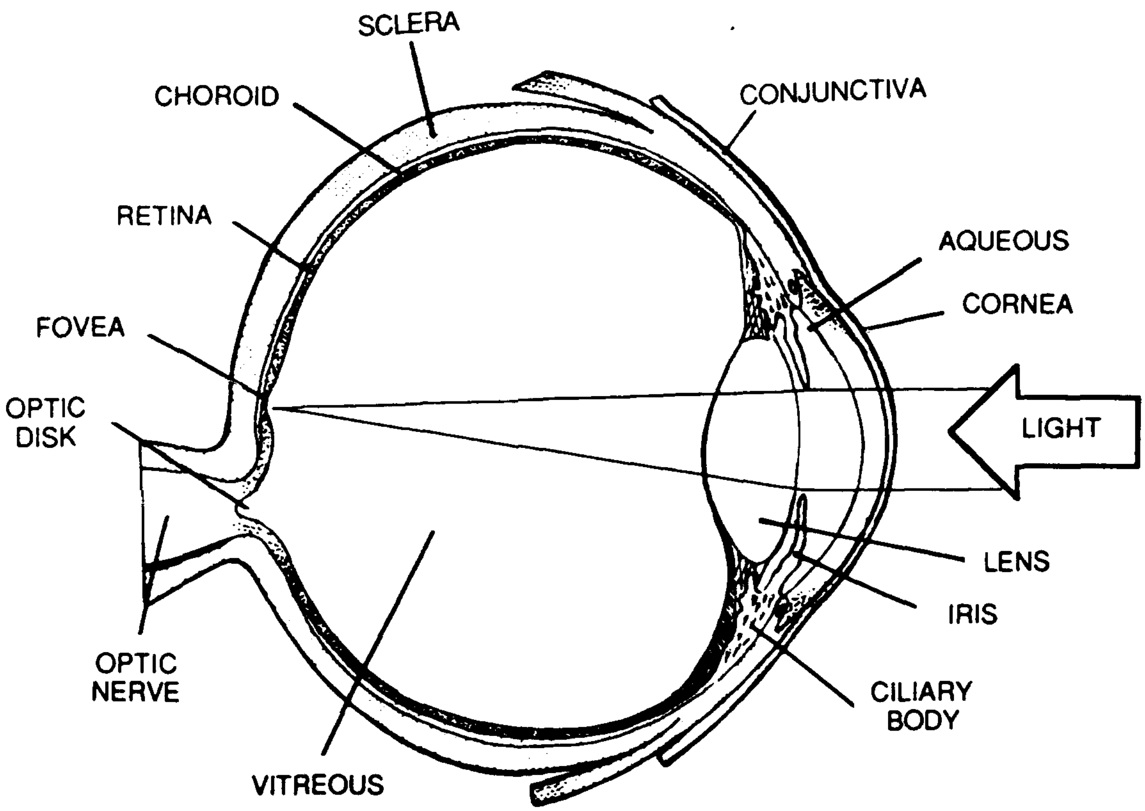


Figure 33. Horizontal cross-section of the human eye. Diagram reproduced from USAFSAM-TR-88-21 (Ref 13).

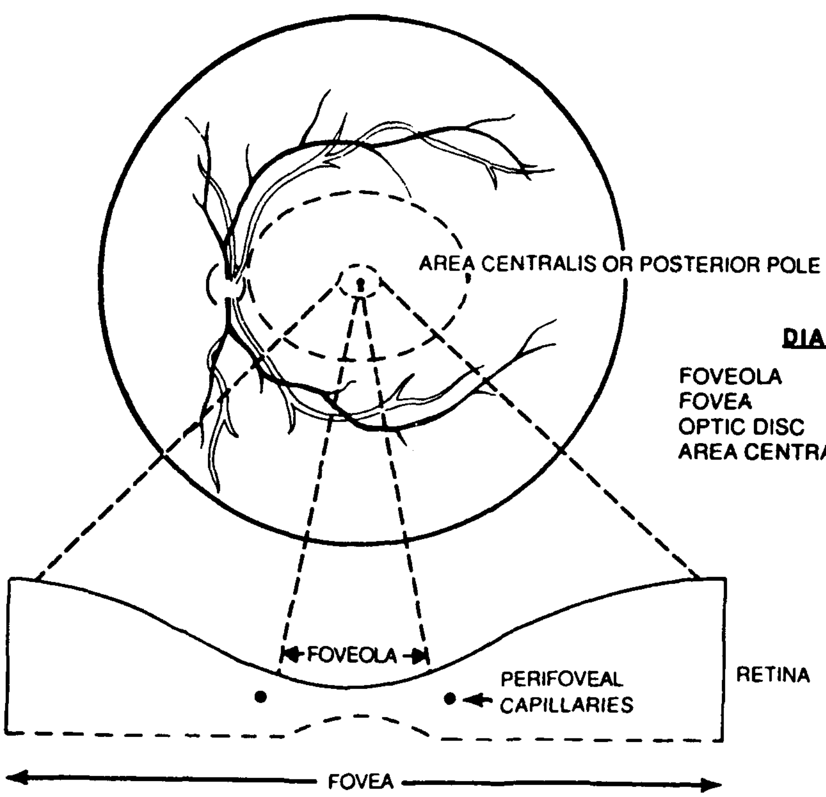
The rear cavity of the eye (posterior cavity) is filled by the vitreous humor, a colorless gel, that is attached to the retina and the ciliary body (Ref 24). The front cavity of the eye (anterior cavity) is filled with the aqueous humor. The aqueous humor is slowly drained through a filtration bed at the base of the ciliary body and is replenished by secretions from the same body.

1. Lens. The cornea and lens are the focusing elements of the eye. The lens of the eye is an inhomogeneous material, but is clear in the visible spectrum and a portion of the near-IR spectrum. The lens is supported in place by fine ligaments that are connected to the ciliary body. The lens is the

fine-focusing element of the eye. The ciliary muscles control the focus of the lens. The iris is a pigmented layer of muscular tissue that adjusts to form the pupil of the eye. The pupil of the eye determines the amount of radiant energy reaching the retina. The amount of energy reaching the retina is proportional to the area of the pupil opening. Typically, the range of pupil diameters varies from 1.6 mm (outdoor daylight) to 8 mm (dark adapted) depending on the average brightness of the subject. The ratio of areas for these two diameters is 1:25.

2. Cornea. The cornea is the outermost covering on the front of the eye. The entire structure is living, in contrast to the dead layer of cells on the exterior of the epithelium. The cornea is the main focussing element of the eye. For point sources of light, the magnification factor for the entire eye could be higher than 100,000 for a 7 mm pupil diameter (Ref 24). For smaller pupil diameters, the magnification factor is lower. The cornea effectively absorbs UV-B and C and if the levels absorbed are sufficiently large, damage may result. Self repair of the cornea normally occurs within a couple days post exposure provided damage to the stroma does not occur.

3. Retina. The retina is the imaging element of the eye. The retina consists of several layers of complex nerve cells that transmit sensory information to the brain. The photoreceptor cells absorb light and convert it to an electrical signal. There are two types of photoreceptor cells: rods and cones. The retina contains approximately 120 million rods and 6 million cones. Rods are important in night vision because they have a sensitivity much lower than that of a cone. Rods do not have the ability to differentiate between light of different wavelengths, which explains why night vision is usually black and white. There are three types of cone cells; each type responds preferentially to different wavelengths of light: blue, green, and red. The fovea is a small region of the retina that contains only cones and is responsible for our acute vision. Figure 34 provides a diagram of the fovea and surrounding structures. The regions of the retina exterior to the area centralis contains only rods.



DIAMETERS

FOVEOLA	0.35 mm
FOVEA	1.50 mm
OPTIC DISC	1.50 mm
AREA CENTRALIS	5.50 mm

Figure 34. Diagram of posterior pole. Reproduced from USAFSAM-TR-88-21 (Ref 13).

Figure 35 shows spectral response of the human eye for both night vision (scotopic) and day vision (photopic). The peak response wavelength of the eye for scotopic vision is approximately 500 nm, while for photopic it is 560 nm.

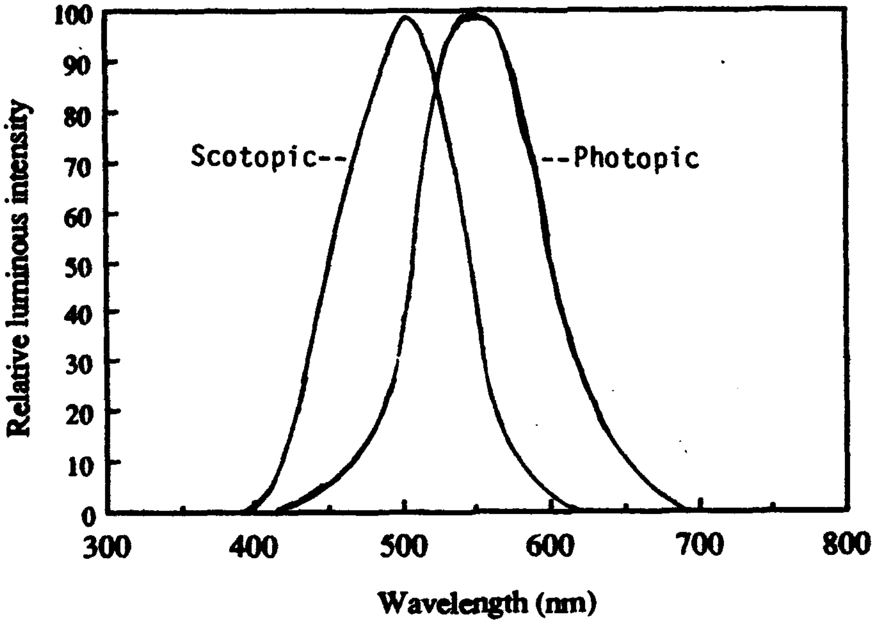


Figure 35. Scotopic (night) and photopic (day) responses of the human eye. Adapted from USAFSAM-TR-78-30 (Ref 21).

C. Absorption of radiation by the eye. Pigments and other tissue constituents determine the absorption characteristics of eye tissue. The cornea and lens will absorb most of the radiation in the ultraviolet region with wavelength less than 400 nm. Some of the incident radiation in the 315 - 340 nm region, however, will be transmitted and absorbed by the retina (Ref 13). Radiation in the range of 400 -1400 nm is almost completely transmitted through the cornea and lens. The retina and choroid absorb most of the radiation in this range with the longer wavelengths penetrating to deeper tissues. Radiations in the far-infrared region, 1400 - 10^6 nm, are almost completely absorbed by the cornea. From 1200 -1400 nm, radiation is absorbed by the retina, cornea, and lens. Maher measured the transmission of the elements of the rhesus monkey eye (Ref 17) which is similiar to the human eye. Figure 36 contains reconstructed transmission curves based on the data produced by Maher. The curves contain in order the transmission of the cornea, aqueous humor, lens, vitreous humor, and the entire ocular media. The plot for the entire ocular media is a summation of the former elements of the eye and represents the percent radiation incident on the eye that reaches the retina.

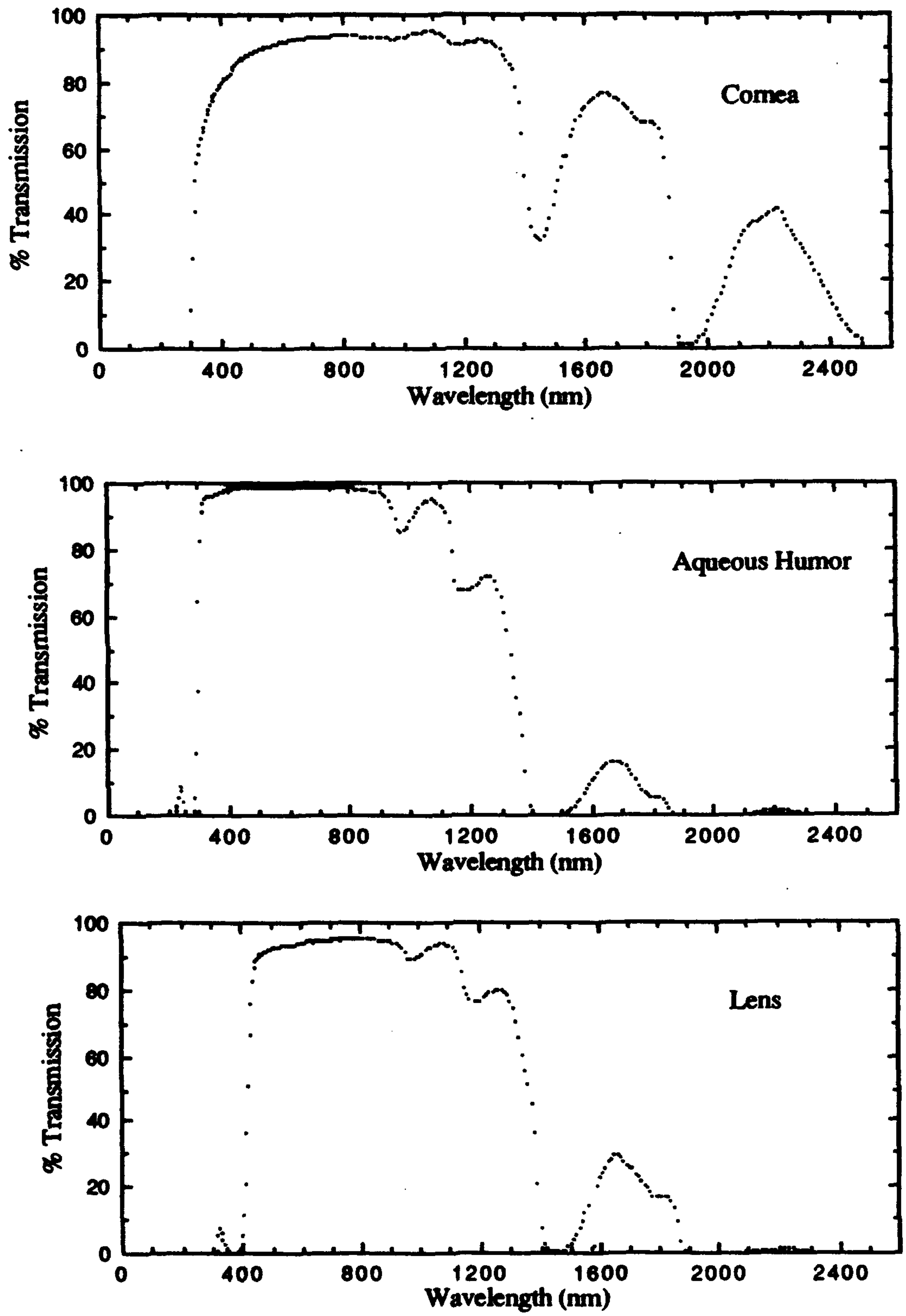
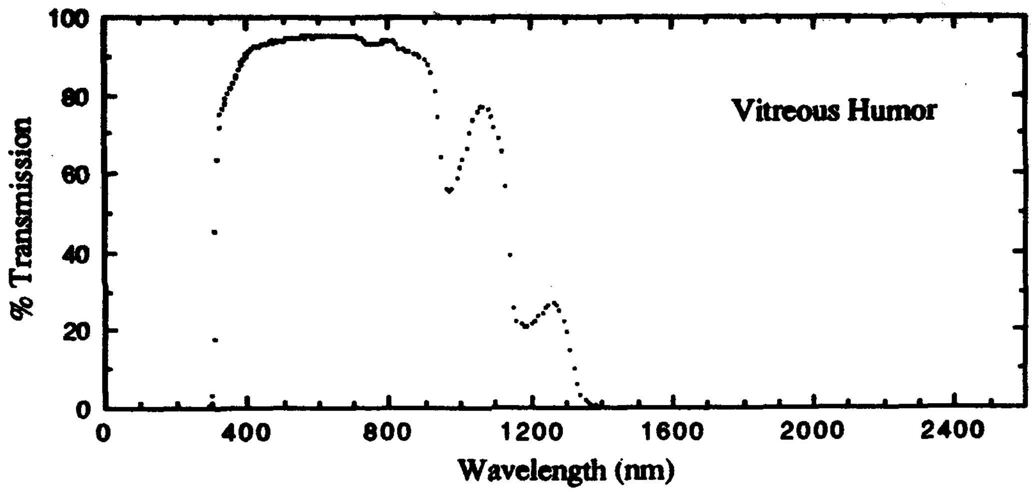


Figure 36. Transmission curves for various elements of the rhesus monkey eye (Ref 17).



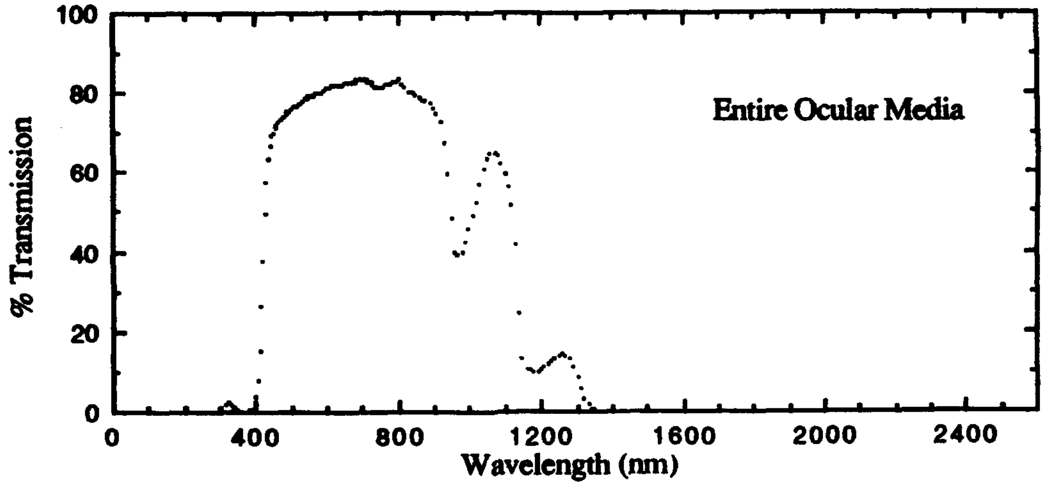


Figure 36 continued. Transmission curves for various elements of the rhesus monkey eye (Ref 17).

D. The skin. The skin is the largest organ of the body. For laser radiation, the concerns for damage to the skin are usually small compared to that of the eye because in many cases damage to the skin is only temporary while eye damage can be permanent or can significantly limit visual capabilities for temporary periods. The skin is an inhomogeneous tissue that consists of a variety of cells and structures including: sweat glands, sebaceous glands, hair follicles, nerves, blood vessels, etc. The stratum corneum is the outermost layer that is composed of dead, epidermal cells. Epidermal cells originate in the basal layer of the epidermis and are gradually pushed to the surface where they die. Through normal activities, the epidermal cells are worn off and replaced by other cells that are pushed to the surface. The stratum corneum is the body's first line of defense from external agents. In addition to the stratum corneum, the epidermis also contains melanocytes, specialized cells that produce melanin pigment granules. Underneath the epidermal layer is the dermis. The dermis is normally much thicker than the epidermis and is much stronger because it is composed primarily of connective tissue.

E. Tissue damage.

1. Damage mechanisms.

a. General. Damage to tissue is primarily the result of three mechanisms: thermal effects, photochemical effects, and acoustic effects. The mechanism of injury is dependent on many factors including: the wavelength of the laser radiation, the exposure duration, the rate at which energy is deposited, and the intensity of the radiation. The severity of the damage as well is dependent on the same factors. For some injuries, a combination of many mechanisms may exist. For example, in the case of ultraviolet exposure to the cornea, the primary damage mechanism is photochemical, but, at high intensities and short pulse durations, thermal damage mechanisms may contribute to the injury as well.

b. Thermal effects. The thermal model depends on absorption of energy by melanin granules contained within tissue and release of the energy in the form of heat. Ultimately this energy is distributed to other cells in the tissue. Damage results from steam generation and denaturation (or inactivation) of proteins and other essential cellular components (Ref 29). Damage to retinal tissue is primarily the result of a thermal damage mechanism for exposure durations in the microsecond to 10 second range from radiations in the 400 to 1400 nm spectral range. For exposures of this type, damage is highly dependent on the dose rate. Thermal damage to skin and components of the eye is possible from ultraviolet radiation, but, normally is a concern for exposure durations less than 10 seconds; for exposure durations greater than 10 seconds, the photochemical effect is a greater concern. Far-IR radiations damage tissues primarily from a thermal mechanism. Many computer programs have been produced to model thermal damage to various tissues. The Illinois Institute of Technology Research Institute (IITRI) developed a program for evaluation of retinal damage from thermal mechanisms under contract with the USAFSAM (Ref 20). Currently, the USAFSAM and the Department of Physics of Trinity University are improving the model developed in 1976. This work has not yet been published. IITRI also developed a thermal model for damage to the skin (Ref 25 and 26).

c. Acoustic effects (mechanical). For short laser pulses, thermal equilibrium is not achieved in the tissue as is in the case of thermal effects. Pulse widths of duration near the thermal relaxation time of melanin granules can create high localized temperatures in the granules. The inhomogeneity of temperatures in the granules can cause photoacoustical shock waves. In contrast to thermal effects, photoacoustical effects are relatively dose rate independent, with damage severity dependent primarily on the total dose. Photoacoustical effects predominate for pulse widths in the subnanosecond range; but, for greater pulse widths thermal, photochemical, or a combination of these two effects are more likely (Ref 29).

d. Photochemical effects (actinic). Photochemical effects are limited to the ultraviolet and short wavelength visible (blue light) spectral bands. For short wavelength visible light, photochemical effects are of concern for exposure durations greater than 10 seconds; for exposure durations less than 10 seconds, the thermal damage mechanism is predominant. Corneal burns and sunburn of the skin are two examples of UV induced damage. For photochemical damage, a reciprocity relationship exists between the laser intensity and exposure time. Thus, damage severity is a function of total dose and is independent of the rate the energy is delivered. Repeated exposures have a cumulative effect provided there is no significant repair or replacement of damaged tissue. Zuclich et al. reported that damage from exposure to the cornea generally develops 12 - 24 hours after the exposure (Ref 30). They found that for exposures in the 315 - 400 nm spectrum,the exposures are cumulative in any 72-hour period. They also felt that these criteria may extend to the 200 - 315 nm spectrum as well. The ANSI Z-136.1-1986 recommends for the spectral region 315 - 400 nm, accumulation of exposures received within 24 hours and reduction of the MPE by a factor of 2.5 if exposures are anticipated in succeeding days.

2. **Damage by tissue type.**

a. Retina. The retina is susceptible to damage from radiations in the spectral band: 400 - 1400 nm. Radiations in this spectral band have fairly good transmission through the ocular media (see Fig. 36) and are sharply focused on the retina. Typically, damage to the retina will result in a scotoma or blind spot. The size of the blind spot is highly dependent on the extent of the retinal damage. If the scotoma results from a lesion located in the fovea, vision could be severely handicapped. However, if the scotoma is caused from a lesion on the periphery of the retina, the scotoma may go unnoticed and have little effect on vision. More severe damage to the retina can result in hemorrhage, retinal detachments, and wrinkles in the retina (Ref 13). While retinal damage is largely restricted to the spectral band: 400 - 1400 nm, Zuclich et al. found retinal damage from a mode-locked HeCd laser (325 nm) at considerably lower energy doses than required to produce corneal or lenticular damage (Ref 30). Rhesus monkeys were used for the study. From examination of the transmission curve for the entire ocular media as shown in Figure 36, it can be seen that there is a small window of increased transmittance in the UV region at 325 nm.

b. Cornea. Ultraviolet radiation absorbed by the cornea and the conjunctiva can produce epithelial damage. Damage of this type is also called keratoconjunctivitis or snow blindness and can be very painful. A latency period of many hours may exist between the exposure and manifestations of the damage. Minor damage to the cornea normally will self repair and heal within a few days (Ref 13). Damage to the stroma (deeper layers of the cornea) is normally followed by vascularization changes to the cornea that results in opacities that restrict normal vision. Tissue graft is normally the only successful treatment for this type of damage (Ref 24). The action spectrum is relatively flat for these effects from 200 - 300 nm. Far-infrared radiation is primarily absorbed by the cornea. Thermal damage to the cornea is produced at all corneal layers. At sufficiently high doses, damage can be permanent.

c. Lens. Damage to the lens results primarily from absorption of UV-A and -B. Effects from UV-C are considerably less since the cornea filters most of the radiation in this band. Damage to the lens is usually in the form of opacities or photokeratitis. At low thresholds, opacities formed may disappear, while for higher thresholds, the opacities may be permanent. The action spectrum for damage to the lens is relatively flat from 320 - 400 nm and decreases significantly from 300 - 320 nm.

d. Skin. For radiations in the far-infrared and UV spectral bands the thresholds for injury are very similar to that of the cornea. Damage to the skin can result from either thermal injury due to elevated temperature levels in the skin and photochemical effects from UV radiation. The absorption of energy by the skin is dependent on many factors. The most important factors include: blood flow rates, water content, and pigmentation of the skin.

3. Summary. The graphs contained in this section assist in describing the three primary damage mechanisms as they pertain to the tissue being irradiated, the exposure duration, and the wavelength of the irradiation. All of the graphs are based on the MPE limits specified in ANSI Z136.1.

a. Figure 37 contains a graph of the point source ocular MPE values as a function of exposure duration for wavelengths between 400 and 550 nm. The MPE values for this spectral region are based on damage to the retinal tissue. From the graph it is apparent that for exposure durations less than 1.8×10^{-5} seconds, the MPE is independent of the dose rate and is based primarily on a mechanical damage mechanism. For exposure durations between 1.8×10^{-5} and 10 seconds, the MPE is based primarily on a thermal damage mechanism that is dose rate dependent. For exposure durations greater than 10 seconds, the MPE is based on thermal and photochemical damage mechanisms. In this region of the graph, the MPE is based on dose rate and dose, dependent on the exposure duration.

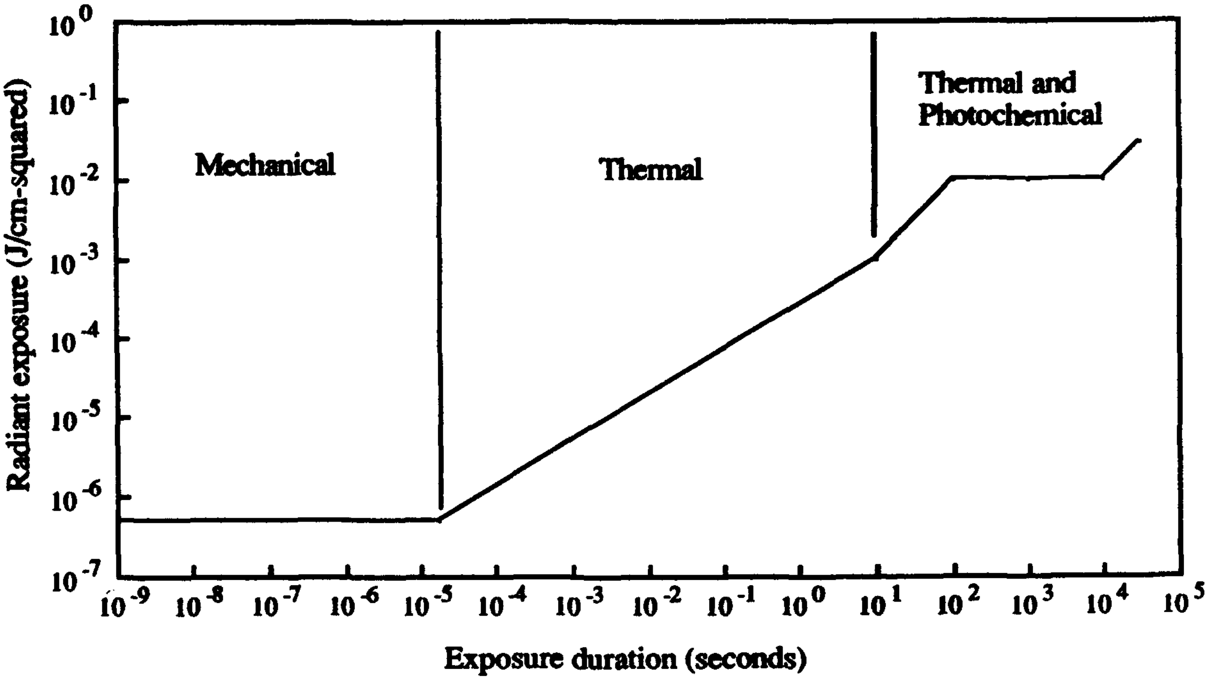


Figure 37. Ocular MPE for intrabeam viewing as a function of exposure duration for wavelengths between 400 and 550 nm (point sources).

b. Figure 38 contains a graph of the ocular MPE for point and extended sources as a function of exposure duration for wavelengths between 315 and 400 nm. From the graph, it is apparent that for exposure durations less than 10 seconds the MPE is based on a thermal damage mechanism that is dose rate dependent. On the other hand, for exposure durations greater than 10 seconds, the MPE is based on a photochemical damage mechanism that is dose rate independent.

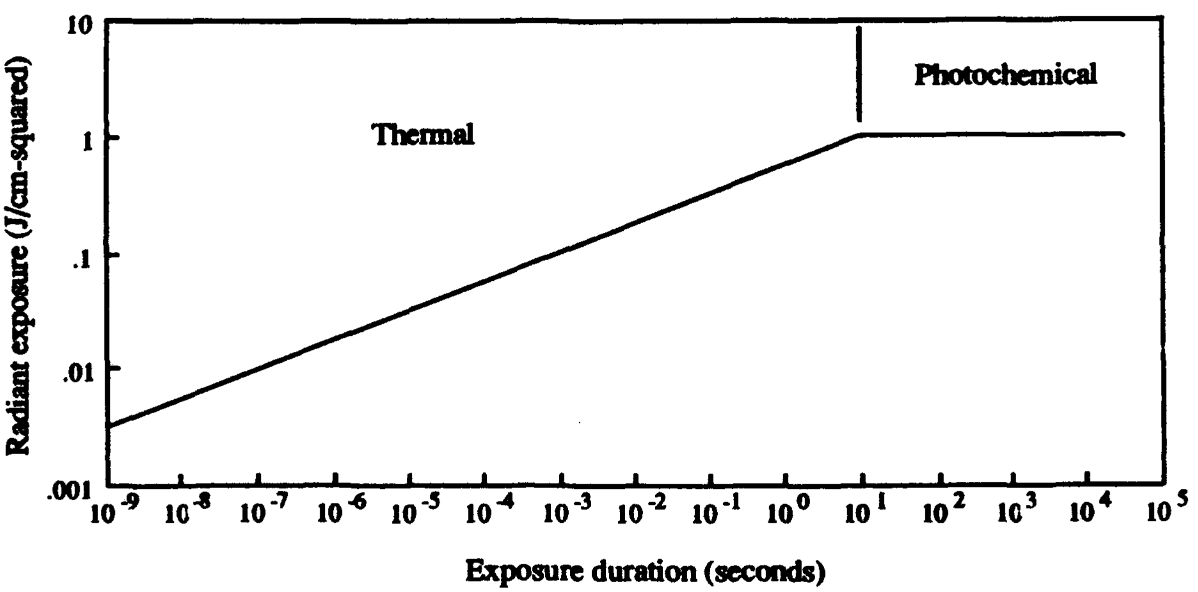


Figure 38. Ocular MPE for direct exposure to ultaviolet radiation as a function of exposure duration for wavelengths between 315 and 400 nm.

c. Figure 39 contains a graph of the point source ocular MPE values as a function of exposure duration for some wavelengths in the spectral region: 700 -1400 nm. The MPE for exposures in this spectral region are based on tissue damage to the retina as was the case described in paragraph a above. For exposures of short duration, the MPE is based primarily on a mechanical damage mechanism that is dose rate independent, while for longer exposures, the MPE is based purely on a thermal damage mechanism. One important difference between near-IR and visible exposures to the retina is that for near-IR exposures there is no photochemical effect at longer exposure durations. Also, apparent from the graph, is a gradual increase in attenuation of radiations from 700 - 1050 nm. This effect can be recalled from Figure 36 where a decrease in transmission of near-IR radiations occurs for the entire ocular media.

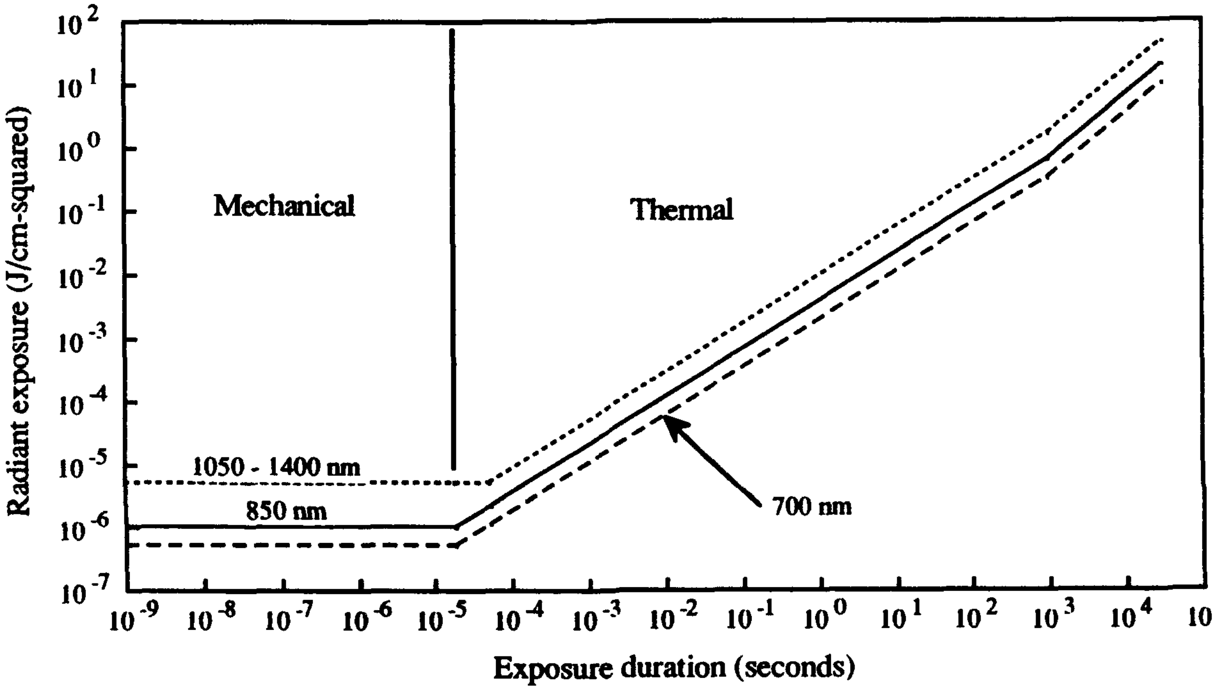


Figure 39. Ocular MPE for intrabeam viewing as a function of exposure duration and wavelength for wavelengths: 700 - 1400 nm.

F. Non-damage effects on vision from laser radiation. Permanent or temporary damage due to radiation exposure are two of the most severe effects from exposure to laser radiation. Laser safety standards are designed to limit exposure to levels below which these effects are realized. Three other effects from exposure to laser radiation - glare, flashblindness, and afterimage - can interfere with normal vision at exposure levels many orders of magnitude below that necessary to cause damage.

1. Glare. Exposure to continuous wave (CW) or pulsed lasers (pulse repetition frequency < 100 Hz) can produce glare similar to that experienced when viewing bright light sources like the sun or headlights of an automobile. Glare can cause reduction or total loss of visibility of objects. The effects of glare are more pronounced when the source of glare is near objects being viewed. Petherbridge and Hopkinson provided an equation for determining the luminance, L_g, required to produce glare (Ref 24). The equation is:

$$L_g \leq (816 \times L_o/\theta), \tag{12}$$

where θ is the angular subtense of the source in radians and L_0 is the background luminance. As an example, assume a helium-neon laser with an output at 632.8 nm is viewed with an angular subtense of 1° (0.0175 rad). Also, assume the beam divergence and diameter are 1 mrad and 0.7 mm, respectively. The laser power required to produce glare is 57×10^{-9} watts. ANSI Z136.1-1986 specifies a limit of 7×10^{-6} W for a similar exposure scenario and duration of 10^4 seconds. Therefore, in this case, glare is achieved at a beam intensity one-hundredth of the protection standard. Continuing studies of the effects of glare on the visual field are being performed by AL/OE for military unique applications.

2. Flashblindness. Much work has been performed on the effects of flashblindness and on developing devices to protect personnel from the effects. Some of the major efforts have been performed for the purpose of protecting military aviators from potential exposure to the flashes from atomic detonations and from exposure to offensive military laser weapons. Flashblindness is the inability to detect or resolve visual objects post exposure to a bright light and is the result of a temporary depletion of visual pigments. The effects can last a few seconds to minutes dependent on the intensity of the light source, ambient lighting, and the brightness of the object being viewed. The magnitude of the impairment is largely a function of the size and location of the area affected.

3. Afterimage. Afterimage is the perception of light, dark, or colored spots after exposure to a bright light (Ref 13). The images may persist for many days, but are unlikely to cause visual decrement.

G. Psychological effects of exposure to laser radiation. There are numerous potential psychological effects from exposure to laser radiation. Psychological effects can be divided into two categories: direct effects and indirect effects (Ref 18). Indirect (or suppressive) effects can include many factors. The most obvious effect is the fear of losing one's vision. Most persons would consider themselves helpless without their vision or even with a partial loss. Other suppressive effects may be caused by the wearing of protective equipment. Protective equipment degrades performance, especially for a pilot and aircrew. Protective equipment can also distort a soldier's view of the world in the same way full chemical gear can to a foot soldier. The direct psychological effects from exposure to laser radiation can be more devastating than the direct biological effects. Exposure to a glaring light source or a source that causes temporary flashblindness may have serious psychological effects on a person even after all effects are gone. Startled reaction and hysteria are two effects that could significantly hinder performance.

H. Military incidents involving or suspecting the use of lasers. Aircrews involved in incidents where the use of lasers are suspect should be referred to the Flight Surgeon. Appropriate questions for the debriefing of such incidents are included in Appendix G of this report as given in USAFSAM-TR-88-21 (Ref 13).

I. Example case histories.

1. General. The incidence of laser injuries is very small compared to the number of lasers in use. Nevertheless, there remains an attitude among some laser workers that: "it can't happen to me; the chance of a laser beam striking my eye is so small, it is not worth the time to wear protection; or I've been working with lasers for the past __ years, I know what I am doing." The case histories reported in this section are given to illustrate the fact that laser injuries do occur and that the effects can cause permanent damage. One common theme throughout some of these histories is that laser protective eyewear was available, but it was not worn.

2. Case history #1. This case history was published in the Comment section of the August 1977 issue of *Laser Focus* (Ref 8).

The necessity for safety precautions with high power-lasers was forcibly brought home to me last January when I was partially blinded by a reflection from a relatively weak neodymium-yag laserbeam. Retinal damage resulted from a 6-millijoule, 10-nanosecond pulse of invisible 1064-nanometer radiation. I was not wearing protective goggles at the time, although they were available in the laboratory. As any experienced laser researcher knows, goggles not only cause tunnel vision and become fogged, they become very uncomfortable after several hours in the laboratory.

When the laser beam struck my eye I heard a distinct popping sound, caused by laser-induced explosion at the back of my eyeball. My vision was obscured almost immediately by streams of blood floating in the vitreous humor, and by what appeared to be particulate matter suspended in the vitreous humor. It was like viewing the world through a round fishbowl full of glycerol into which a quart of blood and a handful of black pepper have been partially mixed. There was local pain within a few minutes of the accident, but it did not become excruciating. The most immediate response after such an accident is horror. As a Vietnam War Veteran, I have seen several terrible scenes of human carnage, but none affected me more than viewing the world through my bloodfilled eyeball. In the aftermath of the accident I went into shock, as is typical in personal injury accidents.

As it turns out, my injury was severe but not nearly as bad as it might have been. I was looking directly at the prism from which the beam had reflected, so the retinal damage is not in the fovea. The beam struck my retina between the fovea and the optic nerve, missing the optic nerve by about three millimeters. Had the focused beam struck the fovea, I should have sustained a blind spot in the center of my field of vision. Had it struck the optic nerve, I probably would have lost the sight of that eye.

The beam did strike so close to the optic nerve, however, that it severed nerve-bundles radiating from the optic nerve. This has resulted in a cresent-shaped blind spot many times the size of the lesion. . . . . Also, I still have numerous floating objects in the field of view of my damaged eye, although the blood streamers have disappeared. These 'floaters' are more a daily hindrance than the blind areas, because the brain tries to integrate out the blind area when the undamaged eye is open. There is also recurrent pain in the eye, especially when I have been reading too long or when I get tired.

The moral of all this is to be careful and to wear protective goggles when using highpower lasers. The temporary discomfort is far less than the permanent discomfort of eye damage. The type of reflected beam which injured me also is produced by polarizers used in q-switches, by intracavity diffraction gratings, and by all beam splitters or polarizers used in optical chains.

3. Case history #2. This article, like Case History #1, appeared in the Comment section of *Laser Focus* (Ref 5). It is similar in many respects to the above case history except that the exposure was from a visible laser.

As I read my November issue of Laser Focus, I took note of the eye injury report, curious about the particulars of this novel accident. Even though I have been working with lasers for five years in the presence of many of the same hazards pointed to in this article, I didn't think while reading it, "This could happen to me." But it did.

On January 22, 1982, I spent several hours aligning a low-power, frequency-doubled Nd:YAG beam through a dye laser set-up. In order to see the 532-nm pump beam propagation I was not wearing goggles. I had also removed a beam block intended to absorb a Brewster's angle reflection, to observe end pumping of an amplifier cell. The green power was increased to determine the extent of dye lasing without replacing the beam block. I did not put on my goggles. While placing a power meter at the dye laser output I leaned over the uncovered amplifier and caught a reflection in my right eye. Because I was in continuous motion looking at the meter and not the beam, I doubt that more than one 10-15 nsec pulse of ~ 20 microjoules was focused onto the fovea. While I do remember seeing a green flash there was no pain. I was not immediately aware of any significant eye damage. It wasn't until I shut the lasers off and returned to my desk to record the day's activity that I realized I had a blind spot comparable to a camera flash, but only in my right eye. It was almost 5:00 p.m. on a Friday, and I didn't report the incident because I couldn't believe that any serious damage was done.

By Saturday afternoon I knew I had a problem. Monday the 25th I notified our safety division and started my visits to an ophthalmologist. The initial examination supported the probability of permanent damage although hemorrhaging in the affected area obstructed detail. By the end of the first week, peripheral vision around the spot was improving (due to decreased swelling), and the actual contact point was observed to be on the right side of the macula. (That corresponds to a blind spot slightly center left.) I was encouraged and felt fortunate, considering the negative potential of this careless mistake. But by week two peripheral vision had declined. Distortion (curving) of resolution around the spot became more noticeable due to additional blood pooling under the retina. If this hemorrhaging were to persist, laser cauterization would be necessary. But for now, "treatment" consists of waiting, observing, and photographing.

Although recovery has not been straightforward, and my vision may get worse before it gets better, I still feel lucky in that one eye totally escaped injury. So while reading was difficult at first, my daily life has remained largely unaffected because the brain and stereo vision compensate the anomaly.

But more important than the actual event is the idea that this incident could have been avoided. Don't let it happen to you or a coworker. Take time to assess safety conditions, and do it again in 6 months or a year; additionally, hazards arise in an ever-changing research environment. Safety deserves your thoughtful consideration, now, before *your* accident. If even one injury can be prevented by publication of this accident account, then more positive than negative outcome may result from the mistake.

4. Case history #3. Reported from the November 1981 issue of *Laser Focus* (Ref 7).

A Naval Research Laboratory chemist who was struck in the eye with a laser beam this summer is still suffering from the injury. The victim, who requested his name not be printed, was hit by 585-nanometer dye laser light that had reflected off an angle-tuned frequency doubler when he bent over to adjust a stepper-motor drive. Although his vision has gradually improved, he told Laser Focus he lost much of the high-resolution capability in his eye.

The chemist, who has worked with lasers for the past five years and considers himself a "laser jock," was "amazed" by how little laser energy it took to do so much harm. Measurements made after the accident showed that the pulse back-reflected off the frequency doubler carried only about 25 microjoules. But that was enough to punch a hole through multiple layers of eye tissue and to cause hemorrhaging. The result was a blood blister over the macula lutea, the part of the eye that provides visual acuity and which is necessary for tasks such as reading. The pulse energy would have been much higher - close to two millijoules - if the NRL group had not earlier taken steps to suppress amplified spontaneous emission in the dye amplifier chain, the victim said.

A surprising - and unsettling - discovery after the accident was how little the doctors knew about laser eye injuries. According to the injured, even retinal specialists were often reduced to guessing during treatment.

The NRL researcher said he never saw a flash when the laser beam struck the eye. "I bent over and all of a sudden I couldn't see," he recalled. He wasn't wearing safety glasses at the time, which he said was common practice in the lab. One reason was that the laser - a YAG-pumped dye system - was run by computer and seldom needed adjustments which required close eye proximity to the beam. Also, he pointed out, laser systems that simultaneously produce numerous beams at wavelengths from the ultraviolet to the infrared are difficult to guard against. Since no single pair of goggles will block out all the beams, many lab workers choose to wear none at all. And in a darkened laser room, glasses that protect the wearer from laser light also obscure vision enough to raise the possibility of other hazards, such as hitting your head or tripping over cable.

The injured chemist criticized laser manufacturers for their method of compliance with Bureau of Radiological Health safety rules. Lasers are built in such a way "that to use one you've usually got to partly disassemble it," he said. "Laser companies should design their product so that it can actually be adjusted and used while complying with BRH rules." He also had harsh words for the maker of the frequency doubler that reflected the light into his eye. "A $10 beam-stop on the doubler could have prevented this whole thing from happening," he said.

5. Case history #4. This case history does not involve an actual injury, but rather a purported case of temporary blindness caused by a laser exposure. This article is from the January 1982 issue of *Laser Focus* (Ref 6).

In what may be the worst reported incident of its kind, the Los Angeles Police Department said last October that a laser beam was flashed into the cockpit of a police helicopter, temporarily blinding both the pilot and the co-pilot. While the pilots escaped serious injury, they said that their brief disorientation could have caused them to lose control of the aircraft.

According to the pilot, Jim Van Bibber, the chopper was assisting ground units on a night call when suddenly an intense blue light hit him and his co-pilot in the eyes. Van Bibber said they both experienced a temporary "flash blindness," which apparently was severe enough to jeopardize their safety. "I briefly lost sight of my instruments," he said. "A situation like that could have been fatal in a machine as unstable as a helicopter."

Other officers near the scene arrested Michael Archer, a 21-year-old laser engineer, in connection with the incident; also seized was an argon laser manufactured by Spectra-Physics Inc. Archer was charged with interfering with a police officer, a misdemeanor.

In an interview with Laser Focus, Archer said that he did indeed project a laser beam into the night sky where it was intercepted by a helicopter. He claimed, however, that the incident was "greatly exaggerated" by the police. In support of his claim, Archer said that the small argon laser was operating on its blue line with only 10 milliwatts of output power. What's more, he continued, the beam would have spread to at least 12 inches in diameter at a distance of 600 feet, the height at which the helicopter was flying. "The beam was weak," he said. "The photon density would not have been great enough to cause something like flashblindness...."

IV. Interactions of Laser Radiation with Matter

A. General. Materials will either reflect, absorb, or transmit electromagnetic radiation. The process of interaction is dependent on the wavelength of the radiation, the properties of the material, the angle of incidence, and the geometry of the material. In most cases, one of the effects dominates, but all of the effects are present to some extent.

B. Reflections. There are two types of reflections: specular and diffuse.

1. Specular reflections. Specular reflections are best illustrated by the interaction of a mirror and light, although the effect can be observed with any other smooth surface. When E-M radiation is specularly reflected from the surface of a material it obeys the law of reflection where the angle of incidence equals the angle of reflection as shown in Figure 40. A surface is specular if the size of the surface imperfections and variations are smaller than the wavelength of the incident E-M radiation. For this reason, lasers that have emissions at long wavelengths are more likely to produce specular reflections than lasers with emissions at shorter wavelengths. For example, in the case of the CO_2 laser with an emission at 10,600 nm, the incident radiation specularly reflects from surfaces that normally produce diffuse reflections from visible lasers. As a result, in the evaluation of IR lasers, one must carefully examine the surfaces in the vicinity of the beam.

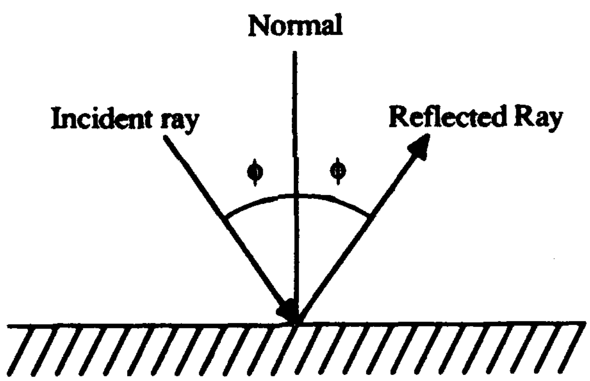


Figure 40. Specular reflection.

While a specular reflection from a flat surface can be considered simply a change in direction of the laser beam without a change in the beam characteristics, the energy of the reflected beam is dependent on the reflectivity of the surface. The reflectivity is dependent on the material and the wavelength of the radiation. Reflectivity, also called the coefficient of reflection, is the fraction of the incident radiation that is reflected. Table 1 provides coefficients of reflection for some common materials.

Table 1. **Coefficients of reflection for some common materials (normal incidence).**

Material	300-400 nm	400-800 nm	800-2600 nm	2600-7000 nm
Sand (very white)	0.15	0.40	0.50	0.30
Sand (yellowish/white)	0.08	0.25	0.33	0.31
Snow	0.35	0.40	0.15	0.18
White paper	0.8	0.30	0.30	0.15
NaCl	0.38	0.49	0.54	0.55
White cotton cloth	0.26	0.42	0.40	0.20

	500 nm	610 nm	840 nm	1780 nm
Red brick	0.15	0.41	0.48	0.56
Concrete	0.27	0.36	0.38	0.37
Asphalt	0.11	0.11	0.12	0.10

	250 nm	300 nm	350 nm	400 nm	500 nm	600 nm
Stainless steel	0.4	0.47	0.52	0.56	0.59	0.6
Aluminum	0.43	0.45	0.54	0.62	0.72	0.74

Source: Fowle, F.E. Smithsonian Physical Tables, Eight Revised Edition, 1934 (Ref 12).

It is a general physical property of transparent materials that when E-M radiation is incident on a boundary between two materials with different indices of refraction, a certain amount of radiation will be reflected from the surface, while the difference will pass through. This phenomenon is referred to as Fresnel reflection and is governed by the following equations:

$$R_{\parallel} = \tan^2\{\phi-\sin^{-1}[(\sin\phi)/n]\}/\tan^2\{\phi+\sin^{-1}[(\sin\phi)/n]\} \text{ and} \tag{13}$$

$$R_{\perp} = \sin^2\{\phi-\sin^{-1}[(\sin\phi)/n]\}/\sin^2\{\phi-\sin^{-1}[(\sin\phi)/n]\}, \tag{14}$$

where ϕ is the angle of incidence (and reflection) in radians, $R_{\parallel}$ and $R_{\perp}$ are the reflection coefficients for the parallel and perpendicularly polarized components, and n is the ratio of the indices of refraction for the two materials. In the ratio n_1/n_2, n_1 is the index of refraction for the denser material. Figure 41 provides a graphical depiction of the two equations. In the figure, a value of 1.6 is used for n and is representative of the interface between glass and air. The curve representing unpolarized light is an average of the specular reflectance from both polarizations. Note from the figure that for light perpendicular to the surface ($\phi = 0°$), about 5% of the incident light is reflected. For unpolarized light and for small angles of incidence, the average of the two equations reduces to the relationship described by Equation 15.

$$R_{unpolarized} = (n_1 - n_2)^2/(n_1 + n_2)^2. \tag{15}$$

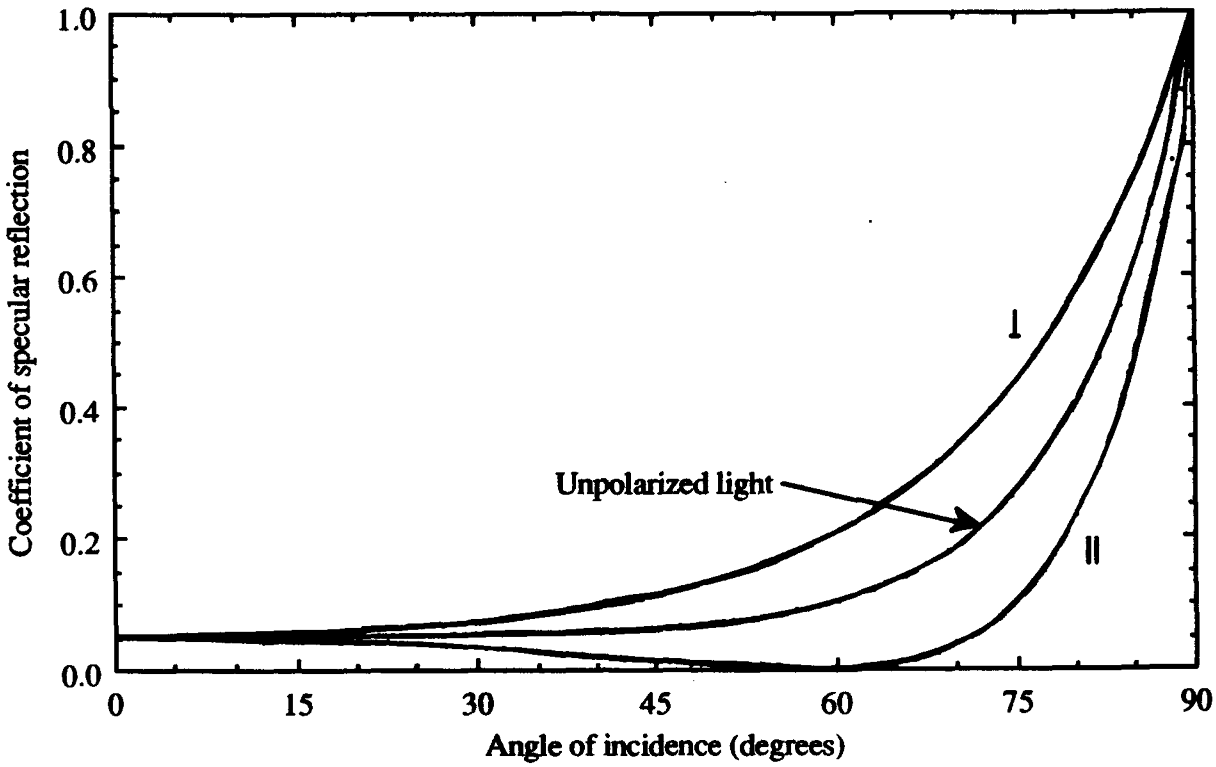


Figure 41. Specular reflectance for light incident on the boundary between two materials of different indices of refraction where the ratio of the indices is 1.6.

2. Diffuse reflections. If surface irregularities are randomly oriented and much larger than the wavelength of the incident radiation, the surface is considered diffuse. Consider a ray incident on the surface of a flat material as shown in Figure 42. The brightness of the reflection is the same for all angles of viewing. Surfaces obeying this relationship are called Lambertian surfaces and are perfect diffuse reflectors. The intensity of a diffuse reflection follows Lambert's Law as given by Equation 16.

$$H = (\rho \cdot Q \cdot \cos\theta)/(\pi \cdot r^2). \tag{16}$$

In the equation, H is the radiant exposure reflected from the surface, Q is the energy of the laser radiation on the surface, θ is the angle of observation with respect to the normal, ρ is the coefficient of reflection for the surface (wavelength dependent), and r is the distance from the surface. The length of the rays in Figure 42 represent the intensity of the diffuse reflection in the direction given.

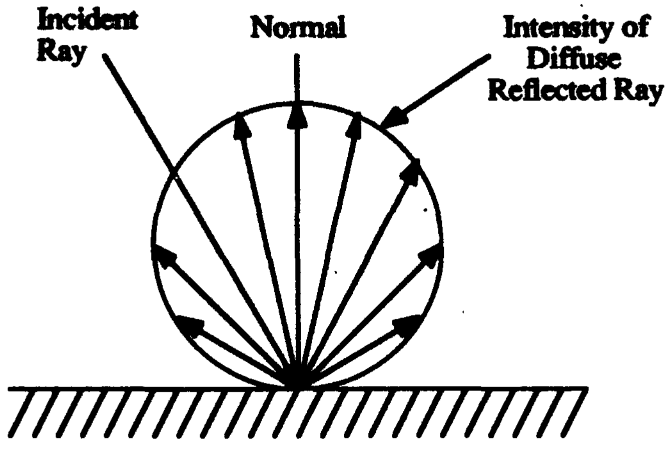


Figure 42. Intensity curve for a diffuse reflection.

3. Semi-diffuse (or semi-specular) reflections. For cases where the wavelength of the incident radiation is near that of the size of the imperfections, the surface is semi-diffuse or semi-specular. For these surfaces, the diffuse and specular components must be evaluated separately. Figure 43 provides an intensity plot of an example semi-diffuse surface. In the figure, the intensity of the diffuse reflected rays are the same as that for the totally diffuse surface except for a difference in the diffuse reflection coefficient, ρ. The intensity of the ray in the direction of the specularly reflected beam is equal to the sum of the intensity of the specularly and diffusely reflected energy.

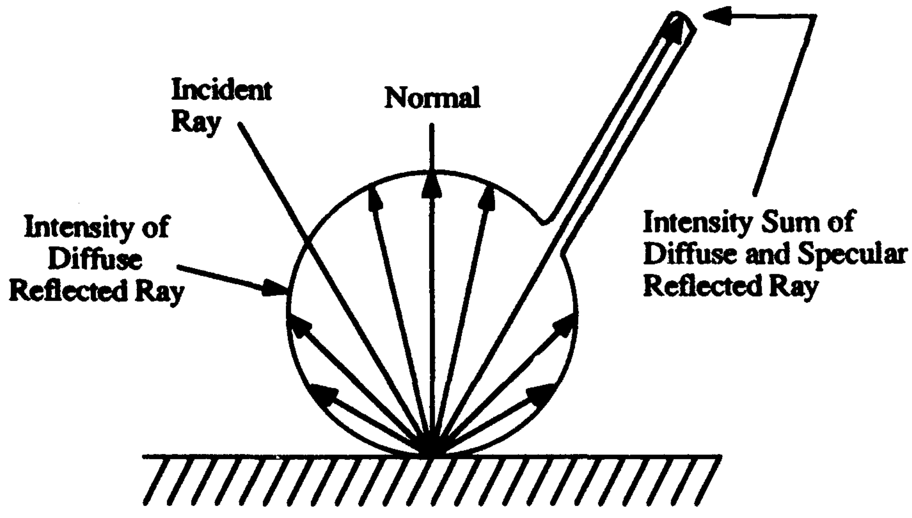


Figure 43. Intensity plot for reflection of incident ray from a semi-diffuse surface.

C. Refraction. The ratio of the velocity of E-M radiation in free space to its velocity in a given material is called the index of refraction for that material. When radiation passes between media of different index of refraction, the direction of travel changes. Refraction follows Snell's Law as given in Equation 17:

$$n_1 \cdot \sin \phi_1 = n_2 \cdot \sin \phi_2, \tag{17}$$

where n_1 and n_2 are the indices of refraction for the two materials, ϕ_1 is the angle of incidence with respect to the normal, and ϕ_2 is the angle of refraction. Figure 44 provides a graphical description of Snell's Law where $n_2 > n_1$.

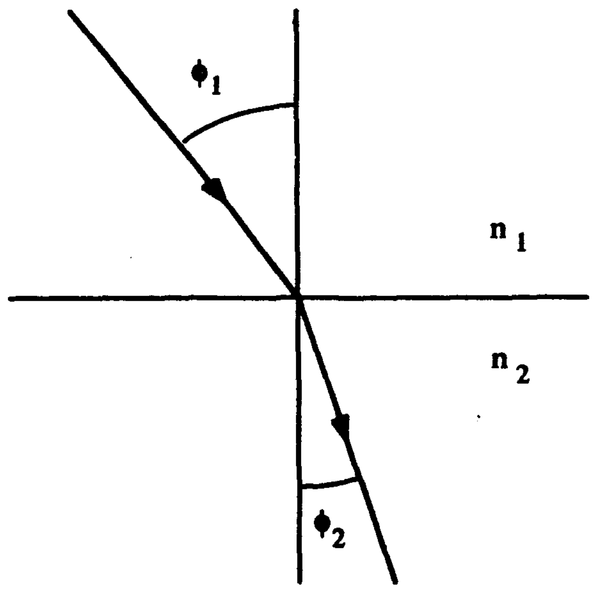


Figure 44. Refraction between two media with different indices of refraction where $n_2 > n_1$.

D. Absorption. When radiation is transmitted through a material, it loses energy to the medium through various attenuation processes. Absorption is one process of attenuation where the lost energy remains in the medium. If the material is homogeneous, the transmitted energy is described by the Lambert-Beer Law as shown in Equation 18:

$$Q = Q_0 \, e^{-kx}, \tag{18}$$

where Q_0 is the energy entering the medium, Q is the energy leaving the medium (provided absorption is the only attenuation process), k is the absorption coefficient, and x is the thickness of the medium. The Lambert-Beer Law adheres to an exponential decrease in beam energy with distance in the material. For example, if 10% of the beam is absorbed per cm, the beam energy remaining after the first centimeter of distance is $0.90 \cdot Q$. The beam energy remaining after the second centimeter is $0.81 \cdot Q$, and after the third centimeter, $0.729 \cdot Q$.

E. Scattering. Atoms, molecules, and particles in the atmosphere have the ability to scatter E-M radiation. Rayleigh scattering occurs when the particle, atom, or molecule size is much smaller than the wavelength of the radiation. Rayleigh scattering is inversely proportional to the fourth power of the wavelength of the radiation. For this reason, Rayleigh scattering is most prominent for radiation of shorter wavelengths. Rayleigh scattered radiation is scattered uniformly in all directions. Mie scattering, on the other hand, occurs when the size of the particles are on the order of or greater than the wavelength of the radiation. Mie scattered radiation is highly directional; the forward scattered radiation is normally much greater in magnitude than the backscattered radiation. As in the case of absorption, scattering follows the Lambert-Beer Law of exponential decrease over distance. The total transmission of radiation through a media of distance, x, is given in Equation 19:

$$Q = Q_0 e^{-(\sigma_M + \sigma_R + k)x}, \quad (19)$$

where Q, Q_0, x, and k are defined as in Equation 18; σ_M is the Rayleigh scattering coefficient; and σ_R is the Mie scattering coefficient. Commonly, the sum of σ_M, σ_R, and k is replaced by μ, the total attenuation coefficient.

F. Atmospheric effects: transmission of laser beams over long distances. When laser beams are transmitted over long distances, attenuation from both scatter and absorption can significantly decrease the energy or power of a laser beam. The AF Geophysics Laboratory (AFGL), formerly the AF Cambridge Research Laboratories, has developed models that predict the transmission of laser radiation in the terrestrial atmosphere. The earlier models developed by AFGL considered four atmospheric attenuation components: molecular scattering, σ_m; molecular absorption, k_m; aerosol scattering, σ_a; and aerosol absorption, k_a. The major components in the atmosphere responsible for molecular absorption are given in the order of importance: H_2O, CO_2, O_3, N_2O, CO, O_2, CH_4, and N_2. Molecular absorption is a function of gas density, temperature, and pressure. Molecular scattering, although, is dependent solely on the number density of molecules in the radiation path. Aerosol absorption and scatter are a function of the number density, size distribution, and index of refraction of the aerosol. Appendix D contains atmospheric attenuation coefficients for the four components defined above as reported in AFCRL-TR-72-0497, "Optical Properties of the Atmosphere (Third Edition)" (Ref 19). Coefficients are given for 12 discrete wavelengths from 337.1 - 337,000 nm under five different atmospheric models: tropical, midlatitude summer, midlatitude winter, subarctic summer, and subarctic winter. Aerosol attenuation coefficients are given for two models: clear, 23 km visibility and hazy, 5 km visibility. Examples of the use of atmospheric attenuation coefficients is provided in Section VII of this report. Recent Geophysics Laboratory (GL) models consider more atmospheric transmission factors. The GL developed a series of codes under the "LOWTRAN" designation in the 1970s and the 1980s. The latest version of this code is LOWTRAN 7. In the mid-1980s the GL developed a new series of codes under the FASCOD designation. This series of computer codes is most applicable to the transmission of laser radiation through the atmosphere. FASCOD2, the latest version, is written in FORTRAN for operation on VAX computer systems. FASCOD3 is currently under development. Questions on the FASCOD programs should be directed to Dr. Frank Kneizys at DSN 478-3654 or Commercial (617) 377-3654. Operational Air Force units can request copies of the code from Ms Gail P. Anderson at DSN 478-2335 or Commercial (617) 337-2335, or write:

GL/OPE
Hanscom AFB MA 01731

V. Laser Hazards

A. Beam exposure hazards: classification of lasers by ANSI Z136.1-1986. The classification scheme developed by the ANSI Standard separates lasers into classes based on the relative hazard of each laser. Class 1 lasers are the lowest class and represents lasers that do not create an intrabeam viewing hazard. Class 4 lasers are the highest laser class and represents lasers that create direct viewing hazards as well as hazards from viewing the diffuse reflection of a laser.

1. General. The AFOSH follows the same criteria for classification of lasers as does the ANSI. The different classes of lasers are described below. Class 1, 3b, and 4 lasers can include single pulse, continuous wave (CW), and repetitively pulsed lasers. The Class 2a and 2 designations include only visible CW or repetitively pulsed lasers. The Class 3a designation is allowed only for continuous wave systems. The standard does not explicitly state this; however, it can be inferred from keynotes of Tables 1 and 2 of the ANSI Z136.1-1986. For the majority of lasers, determination of the laser Class is sufficient for evaluation of the system. From the Class designation, required control measures and specifications for protective equipment can often be made.

2. Class 1 lasers. Class 1 lasers cannot emit accessible laser radiation in excess of the applicable exposure limits specified in Tables 2 and 3 of the AFOSH. Normally, 3×10^4 seconds (8 hours) is used as the maximum exposure duration for classification purposes. However, shorter durations can be used if they correspond to the maximum possible duration inherent in the design or intended use of the laser.

3. Class 2a lasers. A Class 2a laser has visible emissions with accessible output below the applicable exposure limit for a 1000 second exposure duration. Additionally, these systems must be designed for a specific purpose where the output beam is not intended to be viewed. This classification was initially proposed for bar code scanners.

4. Class 2 lasers. A Class 2 laser has visible emissions with accessible output above the applicable exposure limit for the maximum possible exposure duration, but below the applicable exposure limit for 0.25 seconds. For CW systems, the limit is 1 mW.

5. Class 3a lasers. A continuous wave laser that has an output emission level 1 to 5 times the

a. Class 2 limit for visible lasers, or

b. Class 1 limit for wavelengths less than 400 nm or greater than 700 nm.

6. Class 3b lasers.

a. Ultraviolet (200 - 400 nm) and far-IR (1400 nm - 1 mm). UV and far-IR lasers that have output emissions in excess of the Class 3a limits (CW) or the Class 1 limits (single pulse or repetitively pulsed) but cannot

(1) emit an average radiant power in excess of 0.5 watts for ≥ 0.25 seconds, or

(2) produce a radiant exposure of 10 J/cm^2 within an exposure time < 0.25 seconds.

b. Visible (400 - 700 nm) CW or repetitively pulsed. Visible CW or repetitively pulsed lasers that have emissions in excess of the Class 3a limits (CW) or the Class 2 limits (repetitively pulsed) but cannot emit an average radiant power greater than 0.5 watts.

c. Visible (400 - 700 nm) and near-IR (700 - 1400 nm) single pulsed. Visible and near-IR single pulsed lasers that have output emissions in excess of the Class 1 limits but cannot produce a radiant exposure in excess of 10 J/cm^2 or produce a hazardous diffuse reflection as given in Table 8 of the AFOSH.

d. Near-IR (700 - 1400 nm) CW or repetitively pulsed, Near-IR CW or repetitively pulsed lasers that have output emissions in excess of the Class 3a limits (CW) or Class 1 limits (repetitively pulsed) but cannot emit an average power of 0.5 watts for periods > 0.25 seconds.

7. Class 4 lasers. Lasers that have emissions in excess of the Class 3b limits.

B. Point sources/extended sources. Intrabeam viewing and viewing a specular reflection are the most common exposure conditions evaluated. When optical radiation sources are small with respect to the distance between the eye and source, the image formed on the retina is small, typically, about 5 - 10 μm in diameter (Ref 24). Under these exposure conditions, the source is considered a point source and the size of the image formed on the retina is relatively independent of source size. Point sources are evaluated with respect to MPE limits specified in Table 2 of AFOSH 161-10 (Appendix F). Sources that do not meet the criteria of a point source are extended-sources. The criteria for extended sources are given in paragraph VIIC2 with example calculations. The image formed on the retina by an extended-source is dependent on the size of the image and the distance between the eye and the source. The diffuse reflections of point sources can be considered extended-sources provided the eye is sufficiently close to the image formed on the diffuse reflector. Extended-source exposures are evaluated with respect to the MPEs in Table 3 of the AFOSH (Appendix F).

C. Computer-based laser hazard evaluation and classification. Many computer codes have been developed by commercial vendors and the military to perform laser hazard evaluations and classifications. The USAF School of Aerospace Medicine (USAFSAM) in the 1970s developed a code that performed laser classifications and evaluations. In the early 1980s, USAFSAM developed a PC-based code using the MPEs specified by the 1980 version of AFOSH Standard 161-10. In 1988, the Air Force Occupational and Environmental Health Laboratory (AFOEHL) distributed a PC-based code to the field. This code was an updated version of the USAFSAM PC-based code that included the MPE values from ANSI Standard Z136.1-1986. In 1990, USAFSAM developed a PC-based code using the same MPE values. The code was written in a spread sheet type of format and has proven to be easier to use than the AFOEHL code that was written in 1988. Copies of this code will be available to operational Air Force units once verification of the code is complete.

D. Associated hazards. Hazards from interactions of the laser beam with human tissue are normally the most highly emphasized hazards from operation of lasers. Other hazards like those associated with electrical systems and chemicals can create hazards greater than those caused by the laser beam.

1. Electrical hazards. The potential for electrocution can be high in some laser labs because many lasers require high voltage supplies. In research and development laboratories, the risks are even higher since many of the components used are not packaged in insulated cases. Manufacturers of off-the-shelf lasers, on the other hand, must meet electrical safety standards. Inspection of electrical systems is not the responsibility of Bioenvironmental Engineering Services (BES), but observations of the electrical systems can be performed during a workplace visit to detect electrical safety hazards. The following items can be evaluated. Insure distribution lines have been installed by a trained electrician and insure that the power supply is adequate for the devices being supplied; in some workplaces, workers may perform some of the electrical work to save the time and hassle of requesting trained personnel. Capacitors are commonly found in association with laser systems and present an electrical shock hazard if they have an impulse capability of 0.25 J or more. Those with an impulse capability of 50 J or more can be lethal. Electronic instrumentation used in laboratories may use high voltage power supplies. Components of electronic instrumentation should be shielded and instrumentation cases should be properly grounded.

2. Chemical hazards. Many of the work areas that contain lasers also have chemical hazards that may be related to the use of lasers. Personnel responsible for storing and handling chemicals should be aware of proper storage and handling techniques. Safety devices like eyewashes and showers (as necessary) should be installed in laboratories that use acids, strong oxidizing (or reducing) agents, or caustics. Necessary precautions should be taken to preclude personal exposure to airborne toxins like dusts, fumes, gases, and volatile solvents. Some precautions may include: hoods, ventilation systems, and respirators. Fluorine is used as an active medium for some laser systems. Hydrofluoric acid and fluorine gas are two of the most active chemicals known. All operations requiring the use of fluorine and chlorine should be performed with at least two personnel. Fluorine containers should be maintained in a ventilated area like a hood. Dye lasers also contain hazardous chemicals. Many of the dyes contain dimethyl sulfoxide (DMSO), a chemical that can aid in the transport of chemicals through skin. Some dyes that contain DMSO also contain cyanides.

3. Fire hazards. Along with the high intensity of energy (or power) contained by laser beams is the potential for fires. The interaction of laser beams with chemicals and other materials like paper may be sufficient for ignition to occur. High power CO_2 lasers can easily burn through paper, wood, and other materials.

VI. Control Measures

A. General. Control measures are used to limit or reduce the exposure of personnel to laser radiation and/or reduce or eliminate health and safety hazards from the associated hazards of lasers. Control measures generally take one of two forms: engineering controls or administrative controls. Normally, engineering controls are considered and evaluated before consideration is given to the application of administrative controls. Controls are generally considered in the following order: design to eliminate or reduce hazards, engineer control through use of safety devices, use warning devices, and apply procedures and training. For lasers, the use of protective equipment is considered a procedure. Laser safety eyewear is the most common form of protective equipment. AFOSH 161-10 and ANSI Z136.1 provide an exhaustive list of required engineering and administrative controls for each Class of laser. Therefore, the discussion in this report will focus on design considerations and laser safety eyewear.

B. Engineering controls. Engineering design controls are the first type of control that should be considered to reduce or eliminate the hazards of laser and laser radiation. Design controls are normally one of two types: those dealing directly with the laser and those with the environment that the laser is used. A listing and discussion of some design controls are given. A complete listing of required engineering controls is provided in AFOSH 161-10.

1. Laser type. The choice of the laser used for a particular application is a design consideration. The output power or energy should be reduced to the lowest practical level that provides sufficient performance. For cases where a laser is already part of an organization's equipment inventory and a need exists for a laser of that type, but, at a lower output, consideration should be given to the use of attenuation filters or operation at a lower output level (if possible). In other cases, lasers that operate at less hazardous wavelengths can be substituted for particular functions. A good example of this was in the design of the training mode of the Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) system. For this system, the training mode used a 1540 nm output instead of the 1064 nm output provided by the operational mode. For equal irradiances, the 1540 nm wavelength is less hazardous to the eye than the 1064 nm wavelength. The use of low power lasers for alignment purposes is recommended.

2. Facilities design. Many design considerations should be made in the layout and design of facilities that contain lasers. Often facilities are constructed and used for other purposes prior to their use with laser systems. For these situations, modifications may be necessary. Some design considerations are given:

a. Entrances. Shielding the entrance of a room from the nominal hazard zone of a laser may be recommended for some facilities that do not use remote interlock connectors. The use of remote interlock connectors is required for facilities that contain a Class 4 laser. The interlock is normally connected to a room entryway or the floor through use of a switch embedded in a floor mat. However, for the use of medical lasers, interlocks can sometimes interfere with critical procedures. Figure 45 shows a diagram of a facility entrance that is shielded from the nominal hazard zone (NHZ).

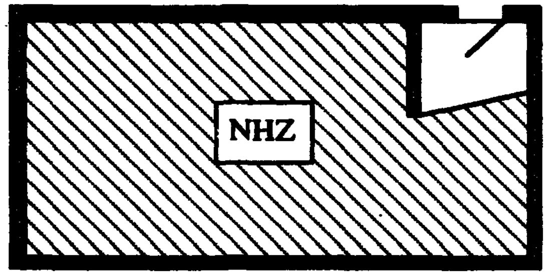


Figure 45. Facility design with entrance shielded from the nominal hazard zone.

b. Remote operation. Whenever possible Class 4 laser should be remote fired. Monitoring can be accomplished through the use of closed-circuit TV or shielded viewing portals. Monitoring of CO_2 laser emissions can be performed through plate glass. Special filtering films that can be adhered to glass can be acquired to reduce hazardous emissions to levels that are considered safe. Several of the laser protective eyewear suppliers manufacture such films. Never use a material that has not been specially tested and certified for use with lasers. Some materials may appear to provide adequate protection, but they may not be able to withstand the radiant energy of pulsed lasers and may suffer from degradation in the attenuation capabilities over time.

c. Materials. The choice of materials to construct a facility and to use with lasers is very important. The walls of a facility should be finished to provide a diffuse surface to laser radiation. For visible radiations, plaster, wood, and concrete are diffuse surfaces if unfinished and if coated with flat finish coatings. Flat black paint is not recommended for the walls since it reduces the ambient light in the room. Most materials, including water, are poor reflectors of UV radiation. Radiations in the far-IR can be a problem, since they are specularly reflected from materials that are diffuse surfaces to visible radiations. Tools, benchtops, or other equipment that are used in laser facilities should also be coated with diffusely reflective materials. Tools constructed of black anodized steel are normally recommended for use around lasers. Laser facilities with hazardous lasers should not contain windows unless the material chosen for the window reduces the laser radiation to safe levels. Most common glass materials effectively attenuate UV and far-IR emissions, but the attenuation afforded should be confirmed through proper testing. The flammability of materials should be evaluated when high power continuous wave or high energy pulsed lasers are used.

d. Beam orientation. Laser beams should be maintained at elevations that are not commonly at eye level. In this evaluation, one should consider all normal postures of personnel, i.e. sitting, standing, etc.

C. Administrative controls (laser safety eyewear). A complete listing of required administrative controls is given in AFOSH 161-10; this section will focus on laser safety eyewear.

1. Design parameters. Many design parameters for laser protective eyewear must be assessed to assure adequate protection. The various parameters are discussed here.

a. Wavelength. The laser wavelength (s) that the protective eyewear was designed for should be specified. Most commercially available eyewear is designed to attenuate the transmission of specific wavelengths. All of the wavelengths that the eyewear protects against should be clearly marked on the device. Some eyewear may list a range of wavelengths for which protection is afforded, commonly, for the range of wavelengths, the minimum protection factor for the range will be specified.

b. Optical density. Optical density (D_λ) is a parameter that defines the protection factor or the attenuation for a particular filter. The optical density is a logarithmic notation and is described by Equation 20.

$$D_\lambda = \log_{10} [E_0/E], \tag{20}$$

where E_0 is the incident beam irradiance and E is the irradiance of the transmitted beam. From the relationship given: a filter that has an attenuation factor of 10^2 has an optical density of 2. Laser safety eyewear should have the optical density clearly marked for all wavelengths for which the eyewear provides protection.

c. Luminous transmittance (photopic vs. scotopic). While laser safety eyewear provides protection from laser radiation, eyewear can in most cases decrease the amount of visible light that passes through the filter. Luminous transmittance is a measure of the decreased visible light transmittance weighted against the spectral response of the eye. Luminous transmittance is normally specified for both scotopic and photopic vision (see Figure 35 of this report). Decreased luminous transmittance can help create eye fatigue and/or severely degrade the ability to perform tasks. For some laser protective eyewear, luminous transmittance can be high; for example, some eyewear designed to protect against 1064 nm radiation may have an optical density of 6 with luminous transmittance as high as 80 %. However, for other cases, luminous transmittance can be low; for protective eyewear designed for the 488 and 514.5 nm emissions from argon ion lasers, luminous transmittance can be as low as 20 %. Some operational conditions may require engineering modifications to allow the use of laser protective eyewear. For example, if He-Ne lasers with 632.8 nm emissions are used in a lab, personnel will have significant difficulties observing red LED's on lab instruments. Green LED's may be an appropriate substitution. Reduced luminous transmittance of eyewear can also lead to serious laboratory accidents like electrocution. Clearly adequate optical density at the wavelength of interest must be carefully weighted with the need for sufficient luminous transmittance. For most applications, luminous transmittance should not be lower than 20 %. At lower levels, vision can be severely impaired.

d. Damage threshold. All filters have a limit to the amount of radiation the material can absorb before the material is subject to cracking, melting, or other types of damage. The damage threshold of a filter is dependent on the characteristics of the laser beam and the filter material. Pulsed lasers have a considerably lower threshold for damage (based on the average power emitted) than a CW laser. The damage threshold for pulses from Q-switched and mode-locked lasers is between 10 and 100 J/cm^2 for absorbing glass and is between 1 and 100 J/cm^2 for plastic and dielectric coatings (Ref 24). In the selection of eyewear for high power CW and high energy pulsed lasers, always consult the manufacturer for damage threshold data.

e. Bleaching and other effects. Laser eye protection should also be evaluated for other stresses that may degrade the ability to provide adequate protection. Bleaching, or reduction in optical density, can be caused by many environmental factors including solar exposure, heat stress, and excessive humidity. Effects of this type have been noted for plastics by the USAF School of Aerospace Medicine, but according to Sliney and Wolbarsht (Ref 24), these effects have not been identified for any glass laser eye protection. Destruction of the filters surface by mechanical abrasions or by acids, bases, the oxidation effect of salt spray, etc., can cause optical distortions and haze. These potential stresses should be considered in the selection of laser protective eyewear. Glass materials generally are more resistant to environmental stresses.

f. Eyewear for UV, visible and near-IR, and far-IR.

(1) UV protection (200 - 400 nm). Many clear materials absorb ultraviolet radiation with little attenuation of visible light. For ultraviolet radiation levels less than 10 times the MPE limit, plate glass and some clear plastics may be sufficient protection. Schott Glass GG-9 is one type of filter that is specifically designed for ultraviolet protection. For a 3 mm thick piece of the material, the optical density is greater than 5 for wavelengths in the region 200 - 400 nm and the luminous transmittance is about 90 % (Ref 28).

(2) Visible and near-IR (400 - 1400 nm). Selection of appropriate eyewear for lasers that emit in the visible region is much more critical than for any other region since the attenuation afforded will affect the luminous transmission. Many companies manufacture protective eyewear for the visible and near-IR region. Filters are generally one of three types: high-pass, low-pass, or notch filters. High-pass filters attenuate radiation in a particular spectral region while transmitting radiations of higher wavelengths. Low-pass filters do just the opposite - they attenuate a particular spectral region while transmitting radiations of lower wavelength. Notch filters are generally designed to attenuate specific wavelength(s) while transmitting all other visible wavelengths. Notch filters can be designed to attenuate only one spectral region or many (multiwavelength filters).

(3) Infrared (1400 - 10^6 nm). The same filters that are effective for attenuation of the near-IR wavelengths are also effective for absorption of radiations in the far-IR region. Almost all glass and plastic materials absorb infrared emissions above 3000 to 4000 nm (Ref 28). For 10,600 nm emissions from CO_2 lasers, plastics or glass are usually recommended. For high power lasers, where damage is of concern, it is preferable to use a filter material that has a known damage threshold. The damage threshold for KG-5 is about 30 W/cm^2 (Ref 28).

(4) A list of available laser safety eyewear is provided in Appendix B. The list is not comprehensive, but represents some of the major commercial suppliers.

g. Style. The factors given above are most important to proper selection of protective eyewear. Other factors that are important are given here.

(1) Frame design: safety and comfort. Though other factors are most important to the design of protective eyewear, comfort is important since in some cases it is the dividing line between whether workers wear the eyewear or not. Workers are more inclined to wear eyewear that is light, comfortable, and easily stored in a pocket case. Laser safety eyewear comes in many different frame styles as explained below.

(a) Dual-lens frame holder. The dual lens frame holder design is one of the most common designs. The advantage of this type of design is that it will accept prescription lenses. Most of the designs are comfortable and allow sufficient ventilation to preclude fogging of the lenses. Some of the designs have side shields. The side shields can be totally opaque or constructed of the same material as the lenses. Side shields are useful for protection from stray debris or other forms of radiation, but, reduce peripheral vision. Winburn claims that the possibility of side entrance or back reflection from properly worn spectacles is very remote (Ref 28). Furthermore, he claims that peripheral vision by the worker is overwhelmingly preferred over side shields. To support his claim, he performed an optical analysis of a specular reflection from the interior of the spectacles lens surface and determined that the opportunity for a reflection to focus on the retina is remote. The analysis performed by Winburn was for flat lenses; for the case of curved lenses, the analysis of specular reflections may be more complex and have to be accomplished on a case by case basis. Furthermore, for Class 4 lasers, the opportunity for a hazardous diffuse reflection from the interior surface of the lens exists if the laser is sufficiently powerful and the interior lens surface has a sufficient coefficient for diffuse reflections. For Class 3 or lower lasers, the potential of diffuse reflections does not exist. The need for side shield protection must be evaluated based on many factors:

1 the potential for side or rear entrance of laser beams (in most cases the potential for side or rear entrance of beams is significantly lower than the potential for front entrance),

2 the need for peripheral vision, and

3 the potential for diffuse reflections from the interior surface of the eyewear.

Currently, the Directed Energy Division of the Armstrong Laboratory is evaluating the potential for intrabeam exposures from side and rear entrance of laser beams for spectacles designed for flight crews.

(b) Eye shield. This type of eyewear is similar to the dual lens holder style except that the entire device is normally constructed of the same type of material. One disadvantage of this type of device is that it may be inadequate for some persons requiring corrections for vision problems. Most of the devices of this design have side shields.

(c) Goggles. The goggles style for laser protective eyewear is also common. The disadvantages of this type of protection are: fogging of the interior of the goggles is common, especially if worn in hot environments and/or for long periods of time; for most persons goggles are uncomfortable; and, for some persons, goggles cause feelings of claustrophobia and decreased peripheral vision (greater in magnitude than that caused by spectacles with side shields). On the positive note, most goggles allow persons to wear prescription glasses at the same time. This can reduce costs for shops that have many persons sharing eye protection. Additionally, goggles afford excellent protection from foreign debris entering the eye zone, especially liquids.

(d) Full-face shield. Of the designs noted, the full-face shield by far is the most bulky. This type of protection may be recommended for applications using far-IR lasers where skin damage is of concern. The face shield may also be recommended for other safety concerns like flying debris or the splashing of toxic or caustic liquids. Of the devices described, the full-face shield is the least desirable if full-face protection is not required.

h. Other factors: impact resistance and resistance from non-beam caustic agents. The operational environment may dictate additional design considerations for protective eyewear other than those required for protection from laser hazards. Impact resistance is important if the eyewear is being used in an environment that has the potential for flying debris. Some types of glass or plastics may shatter and have the potential for serious mechanical damage to the eye or other parts of the face. Resistance of the materials to caustic agents may also be necessary if these materials are used in the work environment. The protective eyewear should provide for protection of the individual from accidental releases of the caustic agent, but should be resistant to continual contact with caustic agents if continual contact is anticipated. Caustic agents can cause damage to eyewear materials and may degrade the ability of the eyewear to provide adequate protection over time.

2. Eyewear for military applications. Many unique military operations require personnel to wear laser safety eyewear. The common wavelength for which protection is required is the 1064 nm line from Nd:YAG lasers. AFOEHL Report 87-091RC0111GLA, "Laser Range Evaluation Guide for Bioenvironmental Engineers," July 1987 (Ref 9), contains on page 85 a listing of commercially available eyewear that affords protection for the 1064 nm line. Many of the spectacles listed there are also listed in Appendix B of this guide. The Glendale Model LGS-NDGA spectacles have been recommended for ground crew for protection against 1064 nm radiation. The National Stock Number (NSN) listing for these spectacles is 4240-00-620-0054. Schott Optical Glass Company's KG-3 lenses are recommended for aircrews for protection against 1064 nm radiation (NSN 1680-01-169-3151). Recent advances in military laser weapons have created a need for eyewear to provide protection to aircrews from a variety of wavelengths in the visible and near-IR spectrum. The Armstrong Laboratory has contracted commercial vendors to develop eyewear that can provide protection for

many lines in the visible and near-IR spectrum while retaining adequate luminous transmittance. A description of some of the most recent eyewear is provided.

a. Glendale FV-2. The Glendale Model FV-2 is a multiwavelength filter that provides protection from 4 wavelengths of radiation. A plot of the optical density across the wavelength spectrum: 200 - 1200 nm is given in Figure 46. The luminous transmission of the FV-2 filter is 15.8 % for photopic (day) vision and 3.1 % for scotopic (night) vision. Due to the low scotopic transmittance of the FV-2, it is not recommended for night training or operations.

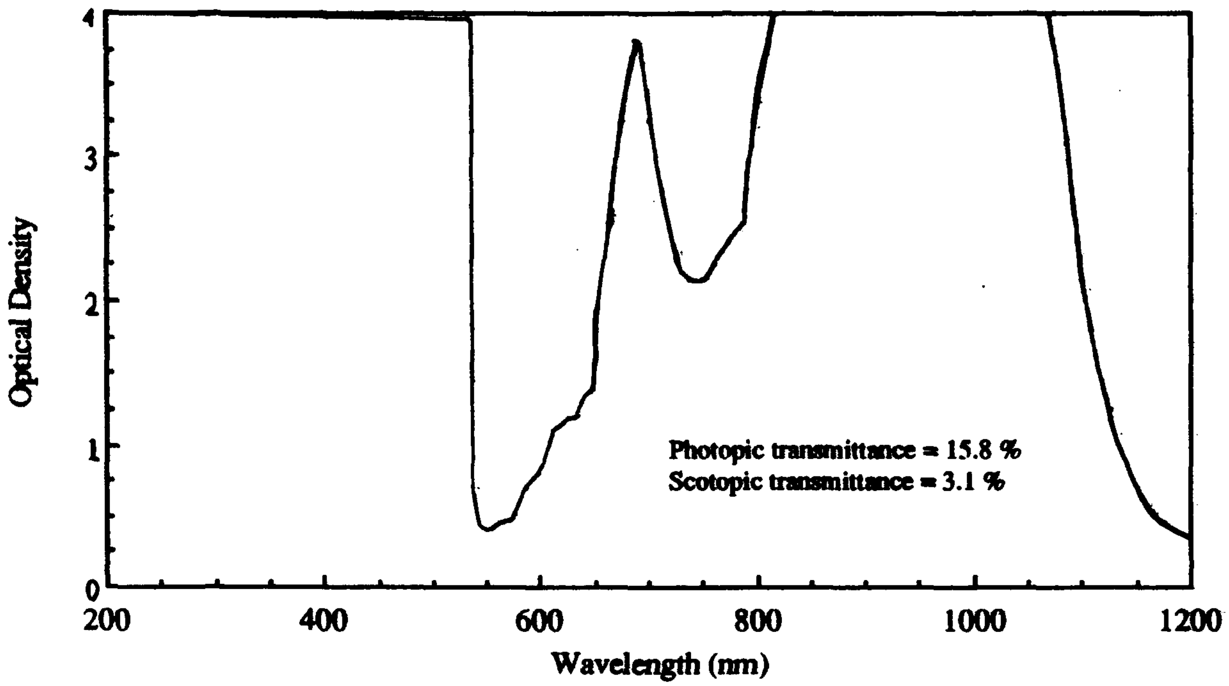


Figure 46. Optical density vs. wavelength for the Glendale Model FV-2 spectacles. Source: USAFSAM, "Lasers and Aircrews: A Flying Safety Kit for Flight Surgeons" (Ref 14).

The FV-2 spectacles have noticeable color distortion with light in the blue and green spectrum severely attenuated. The FV-2 is recommended for aircrews that don't wear headgear. The FV-2 is used commonly by Navy units and by some Air Force units. The NSN for the 52 mm and 58 mm spectacles are given:

52 mm	NSN 1680-01-287-0121
58 mm	NSN 1680-01-287-0122.

b. Barnes 3λ. The Barnes 3λ visor is also available to aviators for protection from multiwavelength threats for both operations and training. As the name implies, the Barnes 3λ provides protection from radiations of three wavelengths. The Barnes 3λ has less color distortion than the Glendale FV-2 spectacle. The Barnes 3λ is available in three visor styles: one for Tactical Air Command (TAC) aircrews, one for Strategic Air Command (SAC) aircrews, and one for the dual visor helmet design. The NSN listings for these visors are as follows:

Model MBU-12/P (TAC) NSN 8475-01-295-4011

Model MBU-05/P (SAC) NSN 8475-01-295-4012

Dual visor helmet design NSN 8475-01-294-5469.

This visor is the most commonly used multiwavelength visor in the Air Force.

c. Glendale FV-4. Glendale is currently manufacturing prototype spectacles under the model designation FV-4. The FV-4 will have larger spectacles than the FV-2 and enhanced protection in the red to near-IR region.

Air Force units having questions on the application of protective eyewear to military training or operational missions should contact:

Armstrong Laboratory
Occupational and Environmental Health Directorate/OEDL
Brooks AFB TX 78235-5000
DSN 240-3622 Comm. (512) 536-3622

or

Armstrong Laboratory
Occupational and Environmental Health Directorate/OEBSC
Brooks AFB TX 78235-5000
DSN 240-3486 Comm. (512) 536-3486.

3. Laser safety eyewear inspections. Laser safety eyewear inspections should be performed during routine visits to shops where their use is required. The following items should be checked.

a. Optical density (OD) and wavelength. Insure that the optical density for the eyewear is sufficient for emission wavelength(s) of the lasers in use in the shop. Be aware of the potential for multiple wavelength emissions, especially in labs that use frequency doublers or other wavelength shifting components.

b. Light leaks. Insure that the eyewear doesn't have light leaks in areas of the device that protection is usually afforded, i.e., separation of the frame from the filter material, etc. Note: In the specification for some spectacles, the need for peripheral vision may override the requirement for side shields.

c. Lens condition. Check the lenses for pitting, surface cracks, or discoloration. All of these defects may reduce the attenuation capabilities of the filter. If the device has been subjected to environmental stresses such as high humidity, ultraviolet radiation, high temperatures, caustic agents, etc., one should consider replacement or testing of the filter.

d. Frame condition. Check side shield, vent caps, filter supports, and hinges where applicable to insure their function is adequate.

e. Storage of eyewear. Inspect the storage area of the eyewear. Eyewear should be stored in an area that protects the eyewear from damage during times of non-use, but should be easily accessible to lab personnel. Be leery of shops that store their protective eyewear in the manufacturer's original box or of eyewear that doesn't show signs of normal wear; in both of these cases, one would suspect that eyewear was not being used. Undisturbed dust on eyewear may lead one to the same conclusion as well.

VII. Example Calculations Used for Laser Classification and Evaluation

A. General. In many cases, calculations are not necessary for the evaluation and classification of laser systems. However, in some cases it is necessary to perform calculations to classify and/or evaluate a laser. The sample calculations are similar to some of the examples provided in the ANSI Standard Z136.1. The symbols are defined as in the ANSI Standards (Ref 2, 3, 4), except for a few cases where it seemed better to apply symbols that were contained in the AFOSH (Ref 1).

B. Symbols. The following symbols are used in the sample calculations.

a = diameter of emergent laser beam

b_0 = diameter of laser beam incident on a focusing lens

b = major axis of elliptical cross-section beam

c = minor axis of elliptical cross-section beam

b_1 = width of rectangular beam

c_1 = height of rectangular beam

d_1 = emergent beam divergence of the major cross-sectional dimension of a rectangular or elliptical beam

d_2 = emergent beam divergence of the minor cross-sectional dimension of a rectangular or elliptical beam

d_e = diameter of the eye pupil (normally varies between 2 - 7 mm)

d_{min} = limiting size of an extended object

D_e = diameter of the exit pupil of an optical system

D_L = diameter of laser beam at range r

D_0 = diameter of the objective lens of an optical system

e = base of natural logarithm (2.71828)

f = focal length of lens

G = ratio of retinal irradiance of radiant exposure received by optically aided eye to that received by the unaided eye

H, E = radiant exposure (H) or irradiance (E) at range r, measured in J/cm^2 for pulsed lasers and W/cm^2

H_0, E_0 = emergent beam radiant exposure (H_0) or irradiance (E_0) at zero range (units the same as for H, E)

H_p = the potential eye exposure, in the appropriate units, utilized in the determination of the optical density of protective eyewear

L = radiance of an extended source

L_p = integrated irradiance of an extended source

M = magnification power of an optical system

NA = numerical aperture of optical fiber

PRF = pulse repetition frequency

Q = total radiant energy output of a pulsed laser

r = range from the laser to the viewer or to a diffuse target

r_1 = range from the laser target to the viewer

$r_{1\,(max)}$ = maximum range from the laser target to the viewer where extended-source MPE apply

R = radius of curvature of a specular surface

r_{NOHD} = the distance along the axis of the unobstructed beam from the laser beyond which the irradiance or radiant exposure is not expected to exceed the appropriate MPE

S = scan rate of a laser (number of scans across the eye per second)

t = duration of a single pulse

T = total exposure duration of a train of pulses

α = viewing angle subtended by an extended-source

α_{min} = minimum angle subtended by a source for which extended-source MPE applies

μ = atmospheric attenuation coefficient at a particular wavelength

ϕ = emergent beam divergence

Φ = total radiant power of a CW laser, or the average power (W) of a repetitively pulsed laser

ρ = reflectivity of a material or object at a specific wavelength

θ_s = maximum angular sweep of a scanning beam

ω_0 = mode field diameter of a single mode optical fiber

θ_v = viewing angle

C. Examples of maximum permissible exposure (MPE) determination and laser classification.

1. MPE for intrabeam viewing.

a. Single-pulse MPEs. The single-pulse MPEs are calculated from the information provided in Tables 2, 3, and 4 of the AFOSH (ANSI Tables 5, 6, and 7). The tables from the AFOSH are in Appendix F.

Example 1. Calculating the MPE for single pulse visible laser. Determine the MPEs for a direct intrabeam exposure to a 694.3 nm ruby laser pulse having durations of 1×10^{-5} and 1×10^{-2} seconds. The MPE for the shorter pulse is given from Table 2:

MPE: $H = 5 \times 10^{-7}\ J/cm^2$.

The MPE for the longer pulse is given from Table 2:

MPE: $H = 1.8 \cdot t^{3/4} \cdot 10^{-3} = (1.8 \times 10^{-3})(1 \times 10^{-2})^{3/4}\ J/cm$
$= 5.7 \times 10^{-5}\ J/cm^2$.

Example 2. Calculating the MPE for single pulse near-IR laser. Determine the MPEs for a direct intrabeam exposure to a 1060 nm neodymium-glass laser having pulse durations of 1×10^{-5} and 1×10^{-2} seconds. The MPE for the shorter pulse is given from Table 2 of the AFOSH.

MPE: $H = 5 \cdot C_A \cdot 10^{-7}\ J/cm^2 = 5 \times 5 \times 10^{-7}\ J/cm^2$, where $C_A = 5$ (λ: 1050 - 1400 nm
$= 2.5 \times 10^{-6}\ J/cm^2$.

The MPE for the longer pulse is given from Table 2.

MPE: $H = 1.8 \cdot C_A \cdot t^{3/4} \cdot 10^{-3} = (9 \times 10^{-3})(1 \times 10^{-2})^{3/4}\ J/cm^2 = 2.8 \times 10^{-4}\ J/cm^2$.

b. Repetitively pulsed lasers. For repetitively pulsed lasers, the MPE is based on the PRF, wavelength, duration of a single pulse, and the total exposure duration, T. The MPE per pulse for repetitively pulsed lasers with wavelength greater than 700 nm is $n^{-1/4}$ times the MPE for a single pulse laser where n is the total number of pulses in the total exposure duration, T. For wavelengths between 400 and 700 nm, the $n^{-1/4}$ criteria applies except that the calculated single pulse MPE must not exceed the MPE calculated for nt second when nt is greater than 10 seconds. The MPE for lasers with PRFs greater than 15 kHz is calculated as follows: the average irradiance or radiant exposure (radiance or integrated radiance) for the total exposure duration, T, is limited to the MPE for a pulse equal to the total exposure duration, T.

Example 3. Calculating the MPE for a repetitively pulsed visible laser with high PRF. Determine the direct intrabeam MPE of a 632.8 nm He-Ne laser operating at a PRF of 30 kHz, pulse width of 1 µs, and a total exposure duration of 0.25 seconds. Since the PRF is greater than 15 kHz, the MPE is based on the average radiant exposure. From Table 2 of the AFOSH, the average radiant exposure is:

MPE (avg): $H = 1.8 \cdot t^{3/4} \cdot 10^{-3} = (1.8 \times 10^{-3})(0.25)^{3/4}\ J/cm^2$
$= 6.4 \times 10^{-4}\ J/cm^2$.

Expressed in terms of the average irradiance,

MPE: $E = H/T = (6.4 \times 10^{-4}\ J/cm^2)/0.25$ second
$= 2.5 \times 10^{-3}\ W/cm^2$.

Expressed in terms of the radiant exposure for a single pulse, the MPE is:

MPE (single pulse) = $H/n = 6.4 \times 10^{-4}/7500$ J/cm^2, where $n = 30{,}000 \times 0.25 = 7500$
$= 8.5 \times 10^{-8}$ J/cm^2.

Example 4. Calculating the MPE for a repetitively pulsed near-IR laser with moderate PRF. Determine the intrabeam direct viewing MPE for a 905 nm GaAs laser that has a pulse width of 1×10^{-4} second and a PRF of 1 kHz. Assume a 10 second exposure duration. The single pulse MPE is calculated from Table 2 of the AFOSH.

MPE (single pulse): $H = 1.8 \cdot C_A \cdot t^{3/4} \cdot 10^{-3}$ J/cm^2, $C_A = 10^{0.002(\lambda - 700)}$
$= (1.8 \times 10^{-3})(10^{0.002(905-700)})(1 \times 10^{-6})^{3/4} = 1.5 \times 10^{-7}$ J/cm^2.

For a 10-second exposure, the total number of pulses is $10 \times 1000 = 10{,}000 = n$ and $n^{-1/4} = 0.1$. The MPE/pulse is:

MPE/pulse: H = MPE (single pulse) $\times\, n^{-1/4} = (1.5 \times 10^{-7})(0.1)$ J/cm^2
$= 1.5 \times 10^{-8}$ J/cm^2.

Example 5. Calculating the MPE for a repetitively pulsed visible laser. Determine the MPE for a 514.5 nm argon laser where the pulse width is 1 ms, PRF is 100 Hz, and exposure duration is 0.25 second. The per pulse MPE is the product of $n^{-1/4}$ and the single pulse MPE. Also, the per pulse MPE must not exceed the MPE calculated for nt when nt is greater than 10 seconds. $nt = 100 \times 0.25 \times 1 \times 10^{-3}$ s $= 2.5 \times 10^{-2}$ second and therefore the latter criterion does not apply. The MPE is from Table 2 of the AFOSH:

MPE/Pulse: $H = 1.8 \cdot t^{3/4} \cdot 10^{-3} \cdot n^{-1/4} = (1.8 \times 10^{-3})(1 \times 10^{-3})^{3/4} \cdot (25)^{-1/4}$ J/cm^2
$= 4.5 \times 10^{-6}$ J/cm^2.

Example 6. Calculating the MPE for a repetitively pulsed far-IR laser. Determine the MPE for a 1540 nm erbium-glass laser where the pulse width is 10 ns, the PRF is 10 Hz, and the exposure duration is 10 seconds. The per pulse MPE is the product of the single pulse MPE and $n^{-1/4}$. For the 1540 nm wavelength, assessment of the single pulse MPE is not a clear-cut task. As given in Table 2 of the AFOSH Std, there are two MPE values specified: one for lasers of wavelength 1400 - 10^6 nm and one for "1540 nm only." The difference between the two MPEs is 100 fold with the MPE specified for "1540 nm only" case being the higher. For the case of the "1540 nm only" specification, the exposure duration must be between 10^{-9} and 10^{-6} seconds, while for the 1400 - 10^6 nm specification, the MPEs are defined for exposure durations from 10^{-9} to 3×10^4 seconds. In the text of the ANSI Std, it does not explain which MPE to use for the case of repetitively pulsed lasers with parameters as given in this example. USAFSAM/RZ, based on their thermal damage model, recommended application of the "1540 nm only" MPE for repetitively pulsed lasers with pulse duration 10^{-9} to 10^{-6} seconds (Ref 16). This issue has been discussed previously in USAFSAM TR-78-29, "Format of Revised Safety Standards for Infrared Laser Exposures" (Ref 23). Reed recommended a wavelength-dependent standard for far-IR lasers based on the absorption characteristics of the cornea. The recommendations provided for less restrictive MPEs for lasers of lower wavelength and lower MPEs for longer wavelengths where the absorption coefficients for the eye are much greater than the lower wavelengths. These recommendations were made for exposure durations less than 100 seconds, while for exposure durations greater than 100 seconds, the MPEs converge for all wavelengths greater than 1400 nm.

The per pulse MPE is given where $n = 100$ and the single pulse MPE is 1 J/cm^2.

MPE/pulse: $H = 1 \cdot n^{-1/4} = (100)^{-1/4}$ J/cm^2
$= 0.32$ J/cm^2.

Example 7. Calculating the MPE for repetitively pulsed, pulse groups. Find the MPE for a 532.1 frequency doubled Nd:YAG laser used for pulse-code-modulated communications. The laser provides 1 million words per minute with each word consisting of five pulses with pulse durations of 20 ns. The period for each word is less than or equal to 0.5 μs. Figure 47 provides an example pulse train. The maximum exposure duration anticipated is 0.25 seconds.

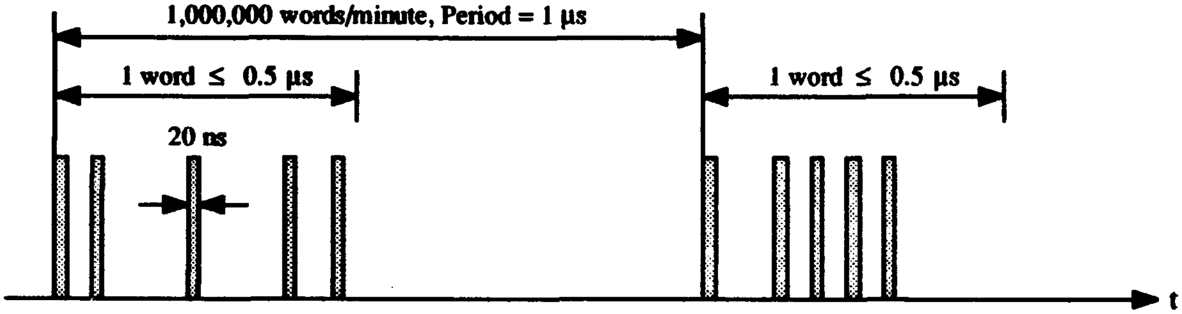


Figure 47. Example laser output used for pulse-code-communications.

The effective PRF of the pulse train is equal to the product of the number of words per second, 1 million, and the number of pulses per word, 5. The product is 5 MHz. Since the effective PRF is greater than 15 kHZ, the laser is evaluated as a CW laser. The MPE from Table 2 of the AFOSH is:

MPE: $H = 1.8 \cdot t^{3/4} \cdot 10^{-3} = (1.8 \times 10^{-3})(0.25)^{3/4}$ J/cm^2
$= 6.4 \times 10^{-4}$ J/cm^2.

The MPE on a per pulse basis is calculated by dividing the MPE above by the number of pulses within a 0.25 second period.

MPE/pulse: $H = (6.4 \times 10^{-4})/1.25 \times 10^{6}) = 5.1 \times 10^{-10}$ J/cm^2.

Example 8. Calculating the MPE for a pulsed UV laser. Determine the MPE for a 337.1 nm pulsed N_2 excimer laser. The pulse width of the laser is 10 ns, the PRF is 500 Hz, and the exposure duration is 8 hours (28,800 seconds). For pulsed ultraviolet lasers, the energy emitted per pulse is integrated over the entire exposure duration. The MPE is calculated from Table 2 of the AFOSH.

MPE: $H = 1$ J/cm^2.

The per pulse MPE is calculated by dividing the MPE for the entire exposure duration by the total number of pulses in the pulse train, (28,800 x 500) or 1.44×10^7 pulses.

MPE/pulse: $H = 1/ 1.44 \times 10^7 = 6.9 \times 10^{-8}$ J/cm^2.

2. Determining when to use extended-source MPEs. Intrabeam MPEs are applied to direct viewing of the beam or its specular reflection, except for close viewing of laser diodes or an array of diodes. Intrabeam MPEs are also used when viewing an extended-source at a distance greater than $r_{1\ (max)}$ (Ref 4).

a. Extended-source MPE application. Extended-source MPEs are applied only in the spectral region of 400 - 1400 nm where the source size is significantly larger than a point and where the retinal image in the viewer's eye is not a minimal spot (Ref 4). Diffuse reflections can be considered extended-sources, provided the viewing distance is small. Class 1 and 2 lasers are not capable of producing hazardous diffuse reflections and as a result only the direct ocular intrabeam-viewing MPEs are applied, except in the case of intrabeam viewing of semiconductor diode lasers and laser arrays. Class 3 lasers are not capable of producing hazardous diffuse reflections for exposure times ≤ 0.25 seconds unless focused; direct beam MPEs are normally used for Class 3 lasers, except for diode arrays. Class 4 lasers are always capable of producing hazardous diffuse reflections; the degree of the hazard is dependent on the viewing distance.

b. Applying the limiting angle, α_{min}. The angle, α_{min}, is used to determine if r_1, the distance between the viewer and target, is small enough for extended-source viewing criteria to apply. Figure 48 provides a physical description of this exposure scenario. In the figure, a laser beam is normally incident on a diffuse reflecting surface (assume the surface is Lambertian) where the beam diameter (also called target size) is D_L at the surface of the reflector. D_L is the longest dimension of the beam for cases where the beam is not circular. The angle, α, is the apparent visual size as calculated from the source size and distance from the source, r_1.

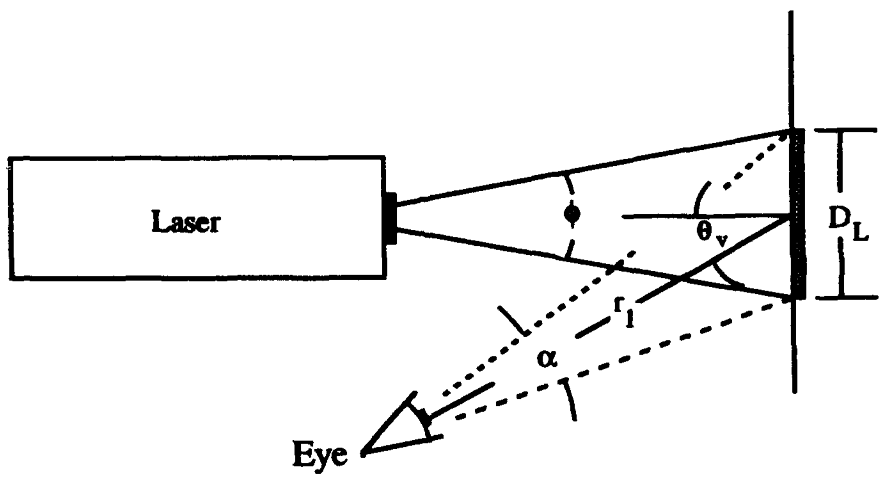


Figure 48. Extended-source viewing from a diffuse reflection (laser incident normal to surface).

Based on Figure 48, $\alpha = (D_L \cdot \cos \theta_v)/r_1$, where

$$\alpha_{min} = (D_L \cdot \cos \theta_v)/r_{1(max)}. \tag{21}$$

The graph in Figure 49 contains values for α_{min}. The graph was constructed from data in ANSI Z136.1-1986 (Ref 4). Values of α_{min} can be taken from the graph or calculated from the equations provided in the figure. For exposure durations greater than 10 seconds, α_{min} is 24 mrad.

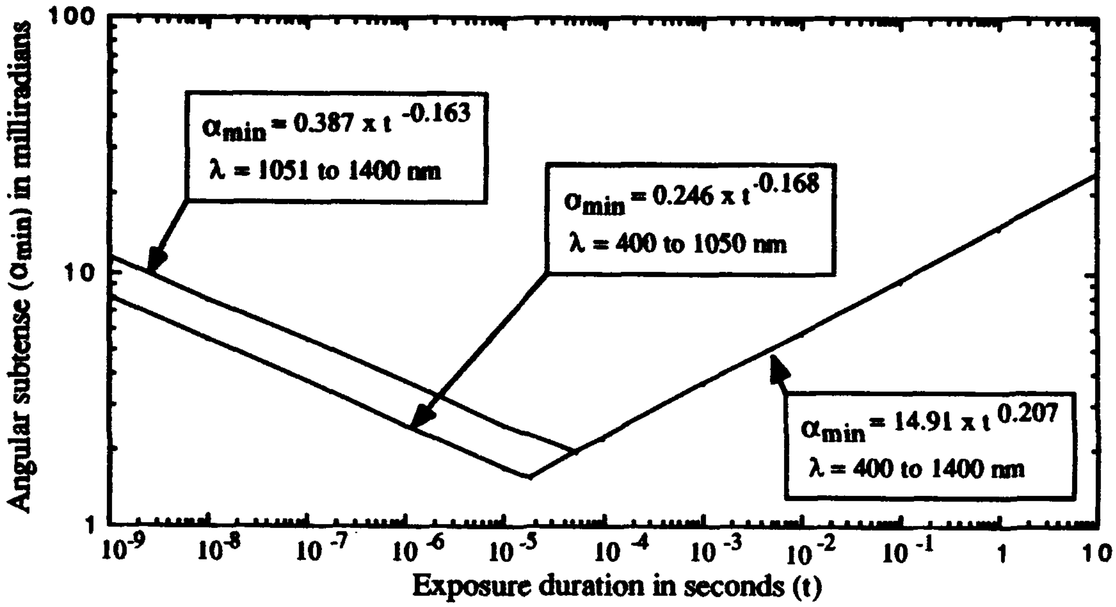


Figure 49. Limiting angular subtense, α_{min}, for extended-source viewing conditions (Ref 4).

Example 9. Finding the maximum distance where the extended-source MPE applies. Find the maximum distance, $r_{1(max)}$, for a visible laser that forms a 1 cm diameter image on a diffuse matte surface. The viewing angle, θ_v, is 10° and the pulse duration is 10 µs. From Figure 49, α_{min} is calculated.

$\alpha_{min} = 0.246 \times t^{-0.186} = 0.246 \times (10 \times 10^{-6})^{-0.186} = 1.7$ mrad.

The limiting angular subtense calculated is independent of PRF and the train length of a repetitively pulsed laser. The maximum distance $r_{1(max)}$ is calculated by rearranging Equation 21.

$r_{1(max)} = (D_L \cdot \cos\theta_v)/\alpha_{min} = (1 \text{ cm} \cdot \cos 10°)/1.7 \times 10^{-3}$ radians = 580 cm.

Therefore, for viewing distances less than 580 cm, MPE values are taken from Table 3 of the AFOSH. For viewing distances greater than 580 cm, the intrabeam viewing conditions exist and the MPE values are taken from Table 2 of the standard.

Example 10. Finding the maximum distance where the extended-source MPE applies for a CW visible laser. Find $r_{1(max)}$ for identical viewing conditions as in Example 9 except that the laser is CW and the exposure duration is 0.25 seconds. The limiting angular subtense, α_{min}, is calculated from the equation in Figure 49.

$\alpha_{min} = 14.91 \times t^{0.207} = 14.91 \times (0.25)^{0.207} = 11.2$ mrad.

and

$r_{1(max)} = (D_L \cdot \cos\theta_v)/\alpha_{min} = (1 \text{ cm} \cdot \cos 10°)/11.2 \times 10^{-3}$ rad = 88 cm.

Therefore, for viewing distances less than 88 cm, the MPE is taken from Table 3 of the AFOSH. From Table 3:

MPE: $L = 10 \cdot t^{1/3} = 10 \times (0.25)^{1/3}$ J/cm²·sr = 6.3 J/cm²·sr.

3. **Determining the irradiance and radiant exposure at a surface.** Often in the evaluation and classification of lasers it is necessary to determine the maximum irradiance, E, and the maximum radiant exposure, H, at some range, r, from the aperture of a laser. For circular beams, the maximum irradiance and radiant exposure are calculated by dividing the beam power and energy, respectively, by the area of the beam as measured at the 1/e point. Equations 22 and 23 describe these relationships where D_L is the beam diameter as measured at the 1/e point, Φ is beam power, and Q is beam energy.

$$E = 4\Phi/(\pi \cdot D_L{}^2). \tag{22}$$

$$H = 4Q/(\pi \cdot D_L{}^2). \tag{23}$$

The magnitude of the beam diameter, D_L, is dependent on the distance from the laser. For lasers with diverging beam characteristics, the beam diameter is calculated by Equation 24 where a is the beam diameter at the aperture, ϕ is the beam divergence (in radians) as measured at the 1/e point, and r is the distance from the laser.

$$D_L \cong a + (r \cdot \phi),\ \phi \text{ in rad.} \tag{24}$$

Equation 24 is an approximation and is accurate provided $\sin \phi \cong \phi$. For divergences equal to 30.85° (0.5384 radians), the error is 5 %. For divergences less than 13.98° (0.244 radians), the error is less than 1 %.

Example 11. Determining the irradiance, E, at a distance, r, from the aperture of a laser. Find the irradiance for a 1 mW laser at a distance of 32 cm from the aperture. The beam divergence, ϕ, is 0.1875 radians and the beam diameter at the aperture, a, is 1 cm. Figure 50 provides a graphical description of the conditions.

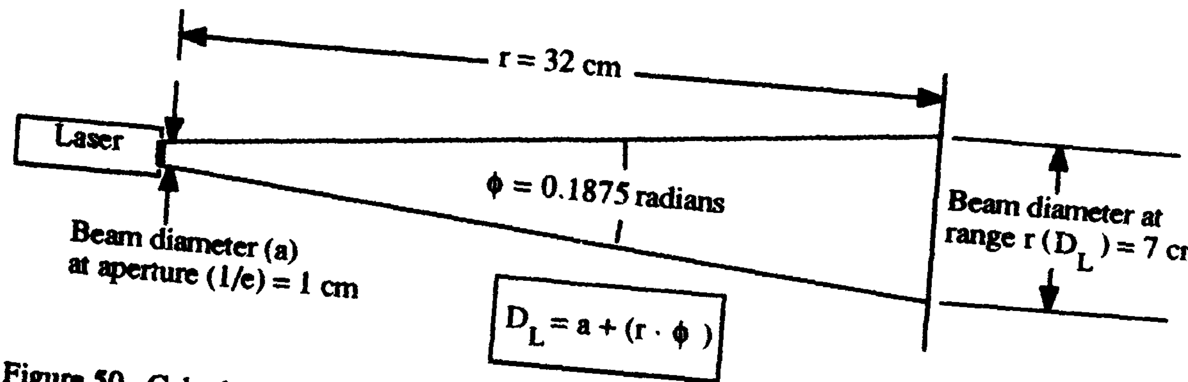


Figure 50. Calculation of beam diameter, D_L, at distance, r, from the aperture of a laser.

The beam diameter is calculated from Equation 24.

$D_L \cong a + (r \cdot \phi) = 1 \text{ cm} + (32 \text{ cm} \cdot 0.1875 \text{ rad}) = 7 \text{ cm}.$

And, from Equation 22, the irradiance is calculated.

$E = \Phi/(\pi \cdot D_L^2) = 1 \text{ mW}/[(\pi \cdot (7 \text{ cm})^2] = 6.5 \times 10^{-3} \text{ mW/cm}^2$.

4. Determining the radiant exposure, H, and the irradiance, E, from extended-sources or reflections from diffuse surfaces. Often it is necessary to determine the irradiance or radiant exposure from a reflection from a diffuse surface or an extended-source like an array of diodes. Equations 16 and 25 define the radiant exposure and irradiance, respectively, for distances, r, from the source.

$$H = (\rho \cdot Q \cdot \cos \theta)/(\pi \cdot r^2) \text{ and} \tag{16}$$

$$E = (\rho \cdot \Phi \cdot \cos \theta)/(\pi \cdot r^2), \tag{25}$$

where Φ is the radiant power, Q is the radiant energy, θ is the angle from the normal, and ρ is the coefficient of reflection. From the equations, it is evident that the intensity of the reflection is independent of source size. These equations hold, provided the distance from the source is large compared to the largest dimension of the source. Commonly, a factor of 10 is acceptable. For distances close to the source, the radiant exposure and irradiance are approximately equal to the values reflected from the source. Typically, this relationship holds for distances within one-tenth of the smallest dimension of the source.

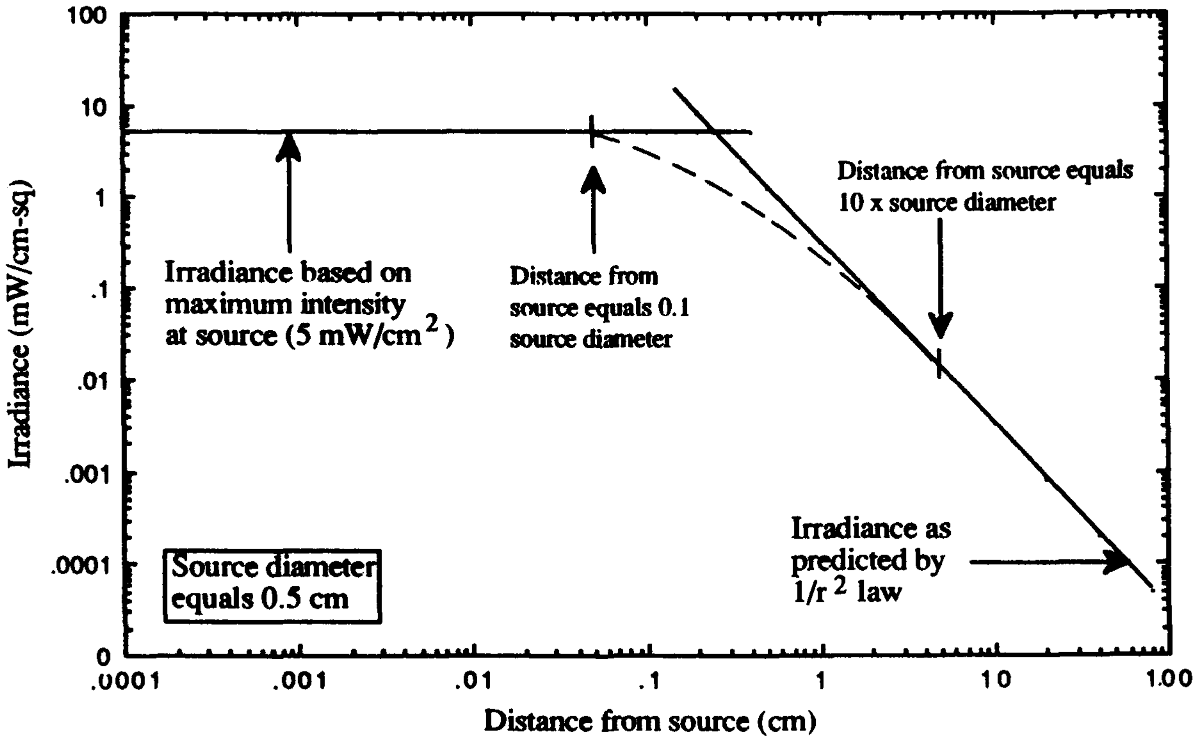


Figure 51. Irradiance values at various distances from an extended-source on the normal.

The graph in Figure 51 provides irradiance values for distances from a circular source with a diameter equal to 0.5 cm and total radiant power equal to 1 mW. All distances are on the normal. The line in the right section of the graph is based on Lambert's law where irradiance is inversely proportional to the distance from the source. The line on the left section of the graph shows the irradiance to be constant for distances close to the source. The dashed line represents an approximation of the irradiance for distances from the source: (0.1 · source diameter) > distance from source < (10 · source diameter).

Radiance and integrated radiance are two parameters used to describe the output of extended-sources. Equations 26 and 27 define the radiance and integrated radiance, where E and H are the respective irradiance and radiant energy incident on a diffuse surface, and ρ is the reflectance of the surface.

$$L = (E \cdot \rho)/\pi \tag{26}$$

$$L_p = (H \,.\, \rho)/\pi \tag{27}$$

Example 12. Finding the radiant exposure at various distances from a 256 element near-IR laser diode array. Determine the irradiance at the surface, at 50 cm, and at 1 meter from a 256-element laser diode array. For each range, assume the measurement is on the normal. Figure 52 provides a graphical representation of the array. Each element has a circular aperture with diameter equal to 1 mm, CW output power of 5 mW, and output wavelength of 820 nm. The array is 4.8 cm x 4.8 cm and has a 2 mm spacing between each element in a row.

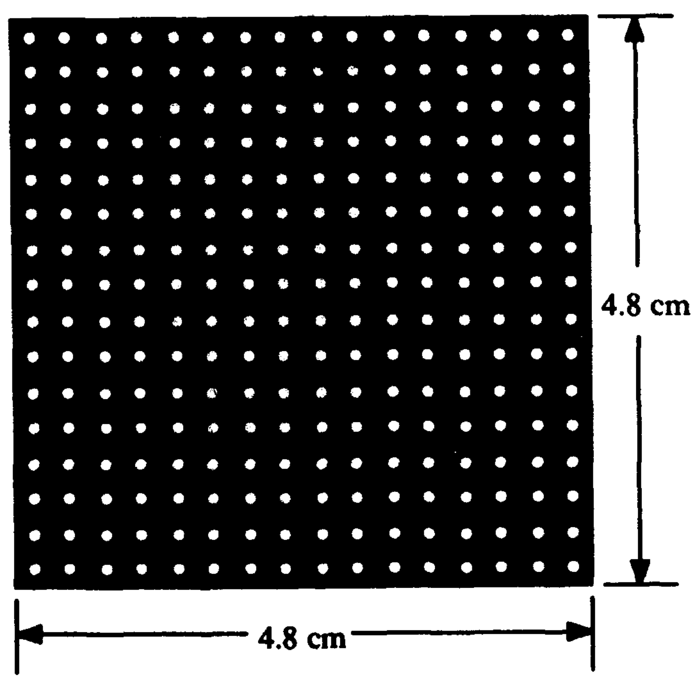


Figure 52. Two-hundred fifty-six element laser diode array.

To assess the irradiance at a distance of 1 meter, Equation 25 applies. The radiant power is calculated by summing the output of the individual elements. The radiant power is (256 · 5 mW) = 1.28 watts. The irradiance at 1 meter from the source is:

$E = (\rho \cdot \Phi \cdot \cos\theta)/(\pi \cdot r^2) = (1 \cdot 1.28 \text{ watts} \cdot \cos 0°)/[\pi \cdot (100 \text{ cm})^2]$
$= 4.1 \times 10^{-2}\ \text{mW/cm}^2.$

The longest dimension of the source is (4.8 cm · $\sqrt{2}$) = 6.8 cm. For measurements at a distance of 50 cm from the source, Equation 24 does not apply since the longest dimension of the source is greater than one-tenth the distance from the source. Therefore, to approximate the irradiance, Equation 25 will be applied and corrections will be made based on the dashed line in Figure 50. From Equation 25:

$$E = (\rho \cdot \Phi \cdot \cos\theta)/(\pi \cdot r^2) = (1 \cdot 1.28 \text{ watts} \cdot \cos 0°)/[\pi \cdot (50 \text{ cm})^2] = 0.163 \text{ mW/cm}^2.$$

From Figure 50, for distances 7.4 times the size of the source, Equation 25 overestimates the irradiance by about 5 %. The corrected irradiance is:

$$E = (0.163 \text{ mW/cm}^2)/1.05 = 0.155 \text{ mW/cm}^2.$$

The irradiance at the surface is approximated by averaging the radiant power of the source over the source area. However, for the array under study, averaging the total radiant power over the total source area will underestimate the irradiance at some locations over the array, in particular if the measurement location is directly over an element. The maximum irradiance at the surface of the array is estimated by averaging the radiant power of one element over the area of the element. The maximum irradiance is:

$$E = \Phi / \text{source area} = 5 \text{ mW}/[(\pi \cdot (0.05 \text{ cm})^2] = 637 \text{ mW/cm}^2.$$

5. Laser classification. The following examples show the methods used for classifying lasers in accordance with the limits specified in the AFOSH, Paragraph C2b(3).

Example 13. Classifying a single pulse visible laser. Classify a single pulse (PRF < 1 Hz) 694 nm ruby laser with a pulse energy of 1 joule, a pulse width of 1 ms, and a beam diameter of 1 cm (as measured at the 1/e point). For single pulse lasers, the only possible classifications are 1, 3, and 4 as specified by the AFOSH. The MPE for direct ocular exposure is calculated from Table 2 of the AFOSH.

MPE: $H = 1.8 \cdot t^{3/4} \cdot 10^{-3} \text{ J/cm}^2 = (1.8 \cdot 10^{-3})(10^{-3})^{3/4} = 1 \times 10^{-5} \text{ J/cm}^2.$

And, the emergent radiant exposure, H_o, is calculated.

$$H_o = Q/(\pi \cdot r^2) = 1 \text{ J}/[\pi(0.7 \text{ cm}/2)^2] = 2.6 \text{ J/cm}^2.$$

Since the emergent radiant exposure exceeds the MPE, the laser is not a Class 1 laser. Note that in calculation of the emergent radiant exposure, the limiting aperture of 7 mm (0.7 cm) is used as the beam diameter. The limiting aperture is used for most laser classification cases whether the laser beam is lesser or greater than the limiting aperture. In some cases, it is permissible to use a larger aperture; for example, if the laser is used indoors and/or viewing the beam with the aid of optical instruments (i.e., binoculars) is not anticipated, then the actual beam diameter may be used. Often for near-IR lasers this assumption may be used. If viewing the beam is possible, then a practical limit on the diameter of the collection optics is 50 mm (5 cm). To determine whether the laser is a Class 3 or 4, the criteria given in Table 8 of the AFOSH must be applied. Table 8 defines the maximum radiant exposure incident on a surface that will not produce a hazardous diffuse reflection. From Table 8, the maximum radiant exposure for a Class 3 laser is:

$$H = 10 \cdot \pi \cdot t^{1/3} \text{ J/cm}^2 = 31.4(10^{-3})^{1/3} \text{ J/cm}^2 = 3.14 \text{ J/cm}^2.$$

Since the radiant exposure does not exceed this limit, the laser is a Class 3 laser. For visible beams where the beam diameter is greater than 50 mm, the beam power or energy used for classification is determined by calculating the maximum beam power or energy that can be collected by a 50 mm aperture. Example 14 will provide an example of this type of calculation.

Example 14. Classifying a repetitively pulsed visible laser. Classify a repetitively pulsed 694.3 nm ruby laser with a pulse width of 1 ms, PRF of 2 Hz, maximum exposure duration of 5 seconds, a beam width of 10 cm (1/e), and a pulse energy of 2 joules. To compare the output of this laser to the limits specified for Class 1, 2a, and 2, the maximum energy that is captured by a 50 mm diameter circle must be determined. For the Class 3b limit, the average beam energy must be determined, independent of spatial parameters. A method for determining the energy collected by an aperture is given here. The method is applicable to Gaussian beams. Equation 6 can be used to determine the irradiance at any distance from the center of a Gaussian beam. Integrating Equation 6 over a circle of radius, x, and dividing by the total irradiance, provides the ratio of total energy or power of the beam captured by the circle of radius, x. This function is simplified in Equations 28 and 29 for power and energy, respectively.

$$\text{Beam power} = \Phi\,(1 - e^{-x^2/r_1^2}). \tag{28}$$

$$\text{Beam energy} = Q\,(1 - e^{-x^2/r_1^2}). \tag{29}$$

In the equations, x is the radius of the circle collecting the beam power or energy, r_1 is the radius of the beam specified at the 1/e point, and Φ and Q are the total beam power and energy, respectively. Applying Equation 29 to the problem gives the fraction of the total beam energy collected by a circle of radius equal to 25 mm.

$$\text{Beam energy} = Q\,(1 - e^{-x^2/r_1^2}) = 2\text{ J}\,[1 - e^{-(2.5\text{ cm})^2/(5\text{ cm})^2}] = 0.44\text{ J}.$$

The radiant exposure for a single pulse is based on this energy averaged over the limiting aperture, 7 mm.

$$H = Q/(\pi \cdot r^2) = 0.44\text{ J}/[\pi \cdot (0.35\text{ cm})^2] = 1.1\text{ J/cm}^2.$$

The per pulse MPE is calculated from Table 2 of the AFOSH with n = (2 Hz · 5 seconds) = 10.

$$\text{MPE/pulse (5 seconds)} = 1.8 \cdot t^{3/4} \cdot 10^{-3} \cdot n^{-1/4}\text{ J/cm}^2 = (1.8 \cdot 10^{-3})(1 \cdot 10^{-3})^{3/4}(10)^{-1/4}\text{ J/cm}^2$$
$$= 5.7 \times 10^{-6}\text{ J/cm}^2.$$

Since the radiant exposure for a single pulse exceeds the MPE/pulse (5 seconds), the laser is not a Class 1 laser. The Class 2 limit is based on an exposure duration of 0.25 seconds or a single pulse.

$$\text{MPE/pulse (0.25 seconds)} = 1.8 \cdot t^{3/4} \cdot 10^{-3} \cdot n^{-1/4}\text{ J/cm}^2 = (1.8 \cdot 10^{-3})(1 \cdot 10^{-3})^{3/4}(1)^{-1/4}\text{ J/cm}^2$$
$$= 1.0 \times 10^{-5}\text{ J/cm}^2.$$

Since the radiant exposure for a single pulse exceeds the MPE/pulse (0.25 seconds), the laser is not a Class 2 laser. The Class 3b limit is 0.5 watts averaged over the exposure duration. The average irradiance is:

$$H = (2\text{ J/pulse} \cdot 10\text{ pulses})/5\text{ seconds} = 4\text{ watts}.$$

Therefore, the laser is classified as a Class 4 laser.

Example 15. Classifying a CW visible laser. Classify an argon laser that has a CW output of 3 watts at 488 nm, 5 watts at 514.5 nm, and an emergent beam diameter of 4 mm (1/e). For classification purposes, an exposure time of 3×10^4 seconds is assumed. The maximum permissible exposure for direct intrabeam viewing is calculated from Table 2 of the AFOSH.

MPE: $E = C_B \cdot 10^{-6}$ W/cm^2 = $1 \cdot 10^{-6}$ W/cm^2.

The emergent irradiance is calculated with the limiting aperture, 7 mm. The total power, Φ, is the sum of the power from each of the beams.

$E_o = \Phi/(\pi \cdot r^2) = 8$ watts/$[\pi(0.7 \text{ cm}/2)^2] = 20.8$ W/cm^2.

Since the irradiance is greater than the Class 1 limit, the laser is Class 2a, 2, 3a, 3b, or 4. In order for the laser to meet the requirements of a Class 2 laser, the irradiance must not exceed the MPE for an exposure time of 0.25 seconds, the blink reflex response.

MPE (0.25 s): $E = [1.8 \cdot t^{3/4} \cdot 10^{-3}]/(0.25)$ W/cm^2 = $(7.2 \cdot 10^{-3})(0.25)^{3/4} = 2.6 \times 10^{-3}$ W/cm^2.

The irradiance exceeds this level and therefore is not Class 2 or 2a. The irradiance of 20.8 W/cm^2 exceeds 5 times the 0.25s MPE, and therefore, the laser is not a Class 3a laser. Since the laser power is greater than 0.5 watts, the laser is a Class 4 laser. For this example, the classification of the system could have been accomplished by simply noting that the average power exceeded the 0.5 watt Class 3b limit; the additional calculations were provided to illustrate the steps necessary for classification of visible lasers with lower output powers.

Example 16. Classifying a far-IR CW laser. Classify a 10,600 nm (10.6 µm) CO_2 laser with an output power of 10 watts (CW) and a beam diameter of 1/2 in (1/e). Since the average power of the laser is greater than 0.5 watts, the laser is a Class 4.

6. The laser range equation. Often it is necessary to determine the maximum irradiance or radiant exposure at a range, r, from the aperture of a laser. Equations 30 and 31 define the irradiance and radiant exposure of circular beams at a distance, r, from the aperture. The beam divergence, ϕ, and a, the beam diameter at the aperture, are defined at the 1/e point. In the equations, μ, is the total atmospheric attenuation coefficient, Φ is the beam power, and Q is the beam energy.

$$E = 4 \cdot (\Phi \cdot e^{-\mu r})/\{\pi \cdot [a + (r \cdot \phi)]^2\}. \tag{30}$$

$$H = 4 \cdot (Q \cdot e^{-\mu r})/\{\pi \cdot [a + (r \cdot \phi)]^2\}. \tag{31}$$

The irradiance and radiant exposure of rectangular or elliptical laser beams can be determined through simple modifications of Equations 30 and 31. Equations 32 and 33 are for elliptical beams.

$$E = 4 \cdot (\Phi \cdot e^{-\mu r})/\{\pi \cdot [b + (r \cdot \phi_1)] \cdot [c + (r \cdot \phi_2)]\}. \tag{32}$$

$$H = 4 \cdot (Q \cdot e^{-\mu r})/\{\pi \cdot [b + (r \cdot \phi_1)] \cdot [c + (r \cdot \phi_2)]\}. \tag{33}$$

And Equations 34 and 35 are for rectangular beams.

$$E = 4 \cdot (\Phi \cdot e^{-\mu r})/\{\pi \cdot [b_1 + (r \cdot \phi_1)] \cdot [c_1 + (r \cdot \phi_2)]\}. \tag{34}$$

$$H = 4 \cdot (Q \cdot e^{-\mu r})/\{\pi \cdot [b_1 + (r \cdot \phi_1)] \cdot [c_1 + (r \cdot \phi_2)]\}. \tag{35}$$

Example 17. Determining the radiant exposure of a near-IR laser at a range, r, from the aperture. Determine the radiant exposure of a 1064 nm Nd:YAG laser at a range of 2 km from the aperture. The beam diameter at the aperture of the circular beam is 9 mm (1/e), the beam divergence is 0.1 mrad, and the per pulse energy is 0.1 joule. From Appendix D, the atmospheric attenuation coefficient can be calculated. Assume the laser is located at ground level, the laser is directed horizontally, and the atmospheric conditions are: midlatitude summer with a hazy aerosol. Under these assumptions, the total atmospheric attenuation coefficient is (8.20E-4 km^{-1} + 9.63E-2 km^{-1} + 3.31E-1 km^{-1}) = 0.43 km^{-1}. Using Equation 31, the radiant exposure at 2 km is:

$$H = 4 \cdot (Q \cdot e^{-\mu r})/\{\pi \cdot [a + (r \cdot \phi)]^2\} = 4 \cdot (2\ J \cdot e^{-(0.43 \times 2)})/\{\pi \cdot [0.9\ cm + (2 \times 10^5\ cm \cdot 0.1 \times 10^{-3}\ rad)]^2\} = 2.4 \times 10^{-3}\ J/cm^2.$$

7. Nominal ocular hazard distance (NOHD). Ignoring atmospheric attenuation and solving for range, r, Equation 36 can be solved for the NOHD.

$$r_{NOHD} = (1/\phi) \cdot [\sqrt{(4 \cdot \Phi)/(\pi \cdot MPE)} - a]. \qquad (36)$$

If atmospheric attenuation is needed in a calculation of NOHD,then Equation 36 must be modified. Equation 37 includes a modification for atmospheric attenuation, but use of this equation requires an iterative process to determine a solution.

$$r_{NOHD} = (1/\phi) \cdot [\sqrt{(4 \cdot \Phi \cdot e^{-\mu r})/(\pi \cdot MPE)} - a]. \qquad (37)$$

Example 18. Calculating the NOHD for a CW visible laser. Calculate the NOHD for a 632.8 nm visible laser with a circular beam. The beam diameter is 0.7 cm at the aperture (1/e), the beam divergence is 0.7 mrad (1/e), and the beam power is 10 mW. Use the MPE for a 0.25 second exposure and ignore atmospheric attenuation. The MPE for a 0.25 second exposure is 2.5 x 10^{-3} W/cm^2. Using Equation 36, the NOHD is:

$$r_{NOHD} = (1/\phi) \cdot [\sqrt{(4 \cdot \Phi)/(\pi \cdot MPE)} - a]$$
$$= (1/7 \cdot 10^{-4}) \cdot [\sqrt{(4 \cdot 0.01\ watts)/(\pi \cdot 2.5 \cdot 10^{-3}\ W/cm^2)} - 0.7] = 2.2 \times 10^3\ cm \text{ or } 2.2\ km.$$

Example 19. Calculating the NOHD for a laser including atmospheric attenuation. Calculate the NOHD for a 514.5 nm argon laser with a CW power of 1 watt, aperture beam diameter of 1 cm, and beam divergence of 0.1 mrad. Assume the beam is directed horizontally across ground level, the atmospheric conditions are midlatitude summer with a clear aerosol, and the exposure duration is 0.25 seconds. From Table 2 of the AFOSH, the MPE is:

MPE: $H = 1.8 \cdot t^{3/4} \cdot 10^{-3}\ J/cm^2 = (1.8 \times 10^{-3})(0.25)^{3/4} = 6.36 \times 10^{-4}\ J/cm^2$ or $2.55 \times 10^{-3}\ W/cm^2$.

For the atmospheric conditions given, the atmospheric attenuation coefficient is (0.015 + 0.168)km^{-1} = 0.183 km^{-1}. Using Equation 37, a first estimate of the NOHD will be made assuming no atmospheric attenuation.

$$r_{NOHD} = (1/\phi) \cdot [\sqrt{(4 \cdot \Phi \cdot e^{-\mu r})/(\pi \cdot MPE)} - a]$$
$$= (1/1 \times 10^{-4})[\sqrt{(4 \cdot 1\ W \cdot 1)/(\pi \cdot 2.55 \times 10^{-3}\ W/cm^2)} - 1\ cm] = 2.13\ km.$$

For the second estimate, the value from the first estimate of NOHD will be used in the equation.

$$r_{NOHD} = (1/\phi) \cdot [\sqrt{(4 \cdot \Phi \cdot e^{-\mu r})/(\pi \cdot MPE)} - a]$$
$$= (1 \times 10^4)[\sqrt{(4\ W \cdot e^{-(2.13 \times 0.183)})/(8 \times 10^{-3}\ W/cm^2)} - 1\ cm] = 1.74\ km.$$

For the third estimate, this value will be used in the equation.

$$r_{NOHD} = (1 \times 10^4) \cdot [\sqrt{(4\ W \cdot e^{-(1.75 \times 0.183)})/(8 \times 10^{-3}\ W/cm^2)} - 1\ cm] = 1.81\ km.$$

And the fourth estimate is given.

$$r_{NOHD} = (1 \times 10^4) \cdot [\sqrt{(4\ W \cdot e^{-(1.81 \times 0.183)})/(8 \times 10^{-3}\ W/cm^2)} - 1\ cm] = 1.80\ km.$$

The fourth estimate provided only a small increase in the accuracy of the estimate. In this case, the value obtained from the third estimate would have been sufficient. The number of iterations needed is dependent on the accuracy required and the degree to which atmospheric attenuation affects the calculation.

8. Optically aided viewing. The use of optical viewing instruments may increase the radiant exposure or irradiance received by biological tissues. The ratio, G, defines the increase in radiant exposure or irradiance. In hazard evaluation equations, radiant exposure or irradiance should be increased by the factor G. For viewing conditions that require use of extended-source MPEs, radiant exposure of irradiance values should be increased by the factor, M, the magnification of the optical instrument in use. The relationship between the factors M and G are defined below. For the discussion below, d_o is the diameter of the beam at the entrance of the optical system.

a. For intrabeam viewing, specular reflections, or a diffuse spot unresolved by the eye and an optical system:

(1) Wavelengths between 400 and 1400 nm.

(a) $D_e \geq 0.7$ cm: $G = M^2$.

(b) $D_e < 0.7$ cm and $d_o > 0.7$ cm: $G = (d_o/0.7\ cm)^2$.

(c) $D_e < 0.7$ cm and $d_o < 0.7$ cm: $G=1$.

(2) Wavelengths: 200 to 400 nm and 1400 to 10^6 nm, $G = M^2$.

b. For indirect viewing of a diffuse reflection and extended objects (only wavelengths between 400 and 1400 nm):

(1) $D_e \geq 0.7$ cm: $G = 1$.

(2) $D_e < 0.7$ cm and $d_o > 0.7$ cm: $G = (d_o/(0.7\ cm \cdot M))^2$.

(3) $D_e < 0.7$ cm and $d_o < 0.7$ cm: $G = (1/M)^2$.

The ratio, G, is directly affected by the optical transmission of the viewing instrument. For viewing visible and near-IR radiation, this factor is usually insignificant. For viewing UV radiation, the attenuation of the instrument could be great unless the instrument is specifically designed to transmit UV. As well, most optical glasses have poor transmission of infrared radiation of wavelengths greater than 3000 nm. If the transmission characteristics of an instrument are not known, the conservative approach is to assume that transmission is 100 %.

Example 20. Calculating the factor, G, for viewing a visible laser with 7 x 50 mm binoculars. Calculate the gain factor, G, for viewing a 632.8 nm laser with 7 x 50 mm binoculars. Assuming intrabeam viewing, G is calculated based on paragraph VIIC8a(1)(a) of this report.

$G = M^2 = 7^2 = 49.$

Example 21. Calculating the NOHD for a near-IR laser aided by 8 x 40 mm binoculars. Calculate the NOHD for a 1064 nm pulsed Nd:YAG laser assuming the beam is viewed with the aid of 8 x 40 binoculars for an exposure duration of 10 seconds. The output parameters for the laser are the following: energy/pulse = 0.1 J, aperture beam diameter = 0.9 cm, beam divergence = 1 mrad, PRF = 20 pps, and pulse width = 20×10^{-9} seconds. The MPE is calculated from Table 2 of the AFOSH where $n = (10 \cdot 20) = 200$.

MPE/pulse: $H = 5 \cdot 10^{-6} \cdot n^{-1/4} = (5 \times 10^{-6})(200)^{-1/4} = 2.26 \times 10^{-6}\ \mathrm{J/cm^2}$.

Ignoring atmospheric attenuation, Equation 36 is used to calculate the NOHD. The gain factor, G, is $(d_o/0.7\ \mathrm{cm})^2$ from paragraph VIIC8a(1)(b) of this report and is inserted into the equation. For the calculation, d_o will be set to 40 mm, the maximum diameter of the objective lens of the binoculars which gives a value of $G = (4\ \mathrm{cm}/0.7\ \mathrm{cm})^2 = 32.65$. After the calculation of the NOHD, it will be necessary to calculate the beam diameter at a range equal to the NOHD to confirm the assumption that the beam completely covers the objective lens of the binoculars.

$$r_{NOHD} = (1/\phi) \cdot [\sqrt{(4 \cdot G\Phi)/(\pi \cdot MPE)} - a]$$
$$= (1/10^{-4}) \cdot [\sqrt{(4 \cdot 32.65 \cdot 0.1\ \mathrm{J})/(\pi \cdot 2.26 \times 10^{-6}\ \mathrm{J/cm^2})} - 0.9\ \mathrm{cm}] = 1.36 \times 10^7\ \mathrm{cm}\ (136\ \mathrm{km}).$$

From Figure 50, the beam diameter is $D_L = [a + (r \cdot \phi)] = [0.9\ \mathrm{cm} + (1.36 \times 10^7\ \mathrm{cm} \cdot 10^{-4}) = 1356$ cm; therefore, the initial assumption that the beam completely covered the objective lens was valid. If the beam did not completely cover the objective lens, then the diameter of the beam would be substituted for d_o in the equation above.

9. Simultaneous exposure to multiple wavelengths of radiation. Many situations occur in which multiple wavelengths of radiation are emitted from a laser. Addition of the energy or power for each of the wavelengths is permitted if all of the wavelengths are within one of the following ranges: 200 - 400 nm, 400 - 1400 nm, and 1400 - 10^6 nm. In many cases, multiple lines from a laser system do fall within a single wavelength region like the argon laser that has discrete emission lines from 457.9 to 514.5 nm and the doubled Nd:YAG laser with a primary emission line at 1064 nm and a frequency-doubled line at 532.1 nm. For the argon laser, calculation of parameters like the NOHD and the NOHD with atmospheric attenuation are relatively easy because the MPE is the same for all of the lines assuming exposure duration is less than 10^4 seconds and atmospheric attenuation effects do not vary significantly across the emission wavelengths of interest. For the doubled Nd:YAG laser, the MPEs for the two lines vary by a factor of 10 for some exposure durations and the atmospheric attenuation factor varies by a factor of about 2 for most of the atmospheric conditions listed in Appendix D. For this situation, calculations become more complicated. For cases where multiple wavelengths exist but the wavelengths fall into two or more categories, more careful consideration must be given. For example, if the emissions of two different wavelength regions affect a different tissue, the exposures can be considered separately. This occurs for exposures to the eye from an emission in the 400 to 1400 nm region and an emission in either the 200 to 400 nm or 1400 to 10^6 nm region, where the visible or near-IR exposure is to the retina and the other exposure is to the cornea. However, if both UV and IR exposures are involved to the same tissue, synergistic effects may occur. MPE values for this type of exposure have not been determined.

Example 22. Calculating NOHD for two simultaneous wavelengths including atmospheric attenuation effects. Calculate the NOHD for a Nd:YAG laser with an output of 5 mJ at the 532.1 nm frequency-doubled line and 25 mJ at the 1064 nm primary emission line. Assume for both emissions, a pulse width of 20×10^{-9} seconds, a PRF of 20 pps, a beam divergence of 0.1 mrad, and an aperture beam diameter of 0.9 cm. The exposure duration is 10 seconds and the atmospheric conditions are subarctic summer with a clear aerosol. Assume the laser beam is directed parallel to the ground at ground level. Since the pulse train characteristics of this laser are the same as that in Example 21, the 1064 nm MPE of 2.26×10^{-6} J/cm^2/pulse will be quoted from that example. From Table 2 of the AFOSH, the 532.1 nm MPE is simply a factor of 10 lower than the 1064 nm MPE. From Appendix D, the atmospheric attenuation coefficients are: (8.38E-4 + 0.0198 + 0.0679) km^{-1} = 0.0885 km^{-1} and (0.0153 + 0.168) km^{-1} = 0.183 km^{-1} for 1064 and 514.5 nm, respectively. Since the 532.1 nm wavelength is not covered in Appendix D, the atmospheric attenuation coefficient for 514.5 was used as an approximation. To calculate the NOHD, Equation 37 will be used through a series of iterative approximations. To simpify use of Equation 37, only one MPE will be specified in the equation: that of the 1064 nm wavelength; the energy/pulse for the 532.1 nm line will simply be normalized to the 1064 nm MPE by multiplying by a factor of 10, or 50 mJ/pulse. However, atmospheric attenuation must be considered separately for each wavelength as their atmospheric attenuation coefficients are significantly different. The first estimate of NOHD is calculated ignoring atmospheric attenuation.

$$r_{NOHD} = (1/\phi) \cdot [\sqrt{(4 \cdot (Q_1 e^{-\mu_1 r} + Q_2 e^{-\mu_1 r}))/(\pi \cdot MPE)} - a] = (10^4)[\sqrt{(4 \cdot (50\text{ mJ} + 25\text{ mJ}))/(\pi \cdot 2.26 \times 10^{-6}\text{ J/cm}^2)} - 0.9\text{ cm}] = 2.05 \times 10^6\text{ cm (20.5 km)}.$$

For the second estimate, this value will be used for calculation of atmospheric attenuation.

$$r_{NOHD} = (10^4)[\sqrt{(4 \cdot (50e^{-(0.183 \times 20.5)} + 25e^{-(0.0885 \times 20.5)})\text{mJ})/(\pi \cdot 2.26 \times 10^{-6}\text{ J/cm}^2)} - 0.9\text{ cm}] = 5.36 \times 10^5\text{cm (5.36 km)}.$$

For the third estimate, this value will be used for calculation of atmospheric attenuation.

$$r_{NOHD} = (10^4)[\sqrt{(4 \cdot (50e^{-(0.183 \times 5.36)} + 25e^{-(0.0885 \times 5.36)})\text{mJ})/(\pi \cdot 2.26 \times 10^{-6}\text{ J/cm}^2)} - 0.9\text{ cm}] = 1.38 \times 10^6\text{ cm (13.8 km)}.$$

The fourth estimate is given.

$$r_{NOHD} = (10^4)[\sqrt{(4 \cdot (50e^{-(0.183 \times 13.8)} + 25e^{-(0.0885 \times 13.8)})\text{mJ})/(\pi \cdot 2.26 \times 10^{-6}\text{ J/cm}^2)} - 0.9\text{ cm}] = 7.91 \times 10^5\text{ cm (7.91 km)}.$$

The fifth estimate is given.

$$r_{NOHD} = (10^4)[\sqrt{(4 \cdot (50e^{-(0.183 \times 7.91)} + 25e^{-(0.0885 \times 7.91)})\text{mJ})/(\pi \cdot 2.26 \times 10^{-6}\text{ J/cm}^2)} - 0.9\text{ cm}] = 1.16 \times 10^6\text{ cm (11.6 km)}.$$

The sixth estimate is given.

$$r_{NOHD} = (10^4)[\sqrt{(4 \cdot (50e^{-(0.183 \times 11.6)} + 25e^{-(0.0885 \times 11.6)})\text{mJ})/(\pi \cdot 2.26 \times 10^{-6}\text{ J/cm}^2)} - 0.9\text{ cm}] = 9.10 \times 10^5\text{ cm (9.10 km)}.$$

The seventh estimate is given.

$$r_{NOHD} = (10^4)[\sqrt{(4 \cdot (50e^{-(0.183 \times 9.10)} + 25e^{-(0.0885 \times 9.10)})\text{mJ})/(\pi \cdot 2.26 \times 10^{-6}\text{ J/cm}^2)} - 0.9\text{ cm}] = 1.07 \times 10^6\text{ cm (10.7 km)}.$$

The final estimate is given.

$$r_{NOHD} = (10^4)[\sqrt{(4 \cdot (50e^{-(0.183 \times 10.7)} + 25e^{-(0.0885 \times 10.7)})mJ)/(\pi \cdot 2.26 \times 10^{-6}\ J/cm^2)} - 0.9\ cm] = 9.6 \times 10^5\ cm\ (9.5\ km).$$

10. Optical density of protective eyewear. The optical density required for laser safety eyewear is dependent on the irradiance or radiant exposure of the incident radiation and the MPE. For cases where the beam diameter of the incident radiation is less than the limiting aperture, the irradiance or radiant intensity of the incident beam is normalized to the limiting aperture. The limiting apertures are: 200 - 400 nm and 1400 - 10^5 nm, 1 mm; 400 - 1400 nm, 7 mm; and 10^5 - 10^6, 11 mm. Equation 20 defines the optical density for laser safety eyewear. In the equation, E is replaced by the MPE. The MPE should be based on an exposure duration that is wavelength and/or system specific. For example, for UV and far-IR lasers it is permissible to use the maximum time of anticipated direct exposure. If this time is not known, it is appropriate to use 8 hours. Eyewear designed for these wavelengths typically has high luminous transmission independent of the optical density. For eyewear designed for the visible and near-IR region, this is not the case, especially for the visible region where luminous transmission is highly dependent on the optical density of the filter. For these wavelengths, one must be careful not to overspecify optical density requirements because it can greatly reduce the luminous transmission. For near-IR lasers, a maximum exposure duration of 10 seconds provides an adequate hazard criterion for either unintended or purposeful staring into the beam; eye movements will provide a natural exposure limitation eliminating the need for exposure durations greater than 10 seconds. For visible wavelengths, if purposeful staring into the beam is not anticipated, the aversion response of 0.25 seconds may be used. For single-pulse lasers, the pulse width is the exposure duration.

Example 23. Calculating the optical density for a visible laser. Calculate the optical density needed for direct ocular exposure to a 632.8 nm He-Ne laser with a power output of 8 mW and a beam diameter of 0.9 mm. From Table 2 of the AFOSH, the MPE for a 0.25 second exposure is:

MPE: $E = 1.8t^{3/4} \cdot 10^{-3}\ J/cm^2/0.25\ s = (1.8 \times 10^{-3})(0.25)^{3/4}\ J/cm^2/0.25\ s = 2.55 \times 10^{-3}\ W/cm^2$.

The beam irradiance at the aperture is: $E_0 = (8 \times 10^{-3}\ W)/(\pi \cdot (0.35\ cm)^2) = 2.08 \times 10^{-2}\ W/cm^2$. From Equation 20, the optical density is calculated.

$D_\lambda = \log_{10} E_0/MPE = \log_{10} [2.08 \times 10^{-2}\ W/cm^2/2.55 \times 10^{-3}\ W/cm^2] = 0.91$

Example 24. Calculating the optical density for a far-IR laser. Calculate the optical density needed for direct ocular exposure to a 10,600 nm CO_2 laser with a power output of 10 watts and a beam diameter of 1 cm. Assume a maximum exposure duration of 1 minute. From Table 2 of the AFOSH, the MPE for a 60-second exposure is:

MPE: $E = 0.1\ W/cm^2$.

The beam irradiance at the aperture is: $E_0 = (10\ W)/(\pi \cdot (0.5\ cm)^2) = 12.7\ W/cm^2$. From Equation 20, the optical density is calculated.

$D_\lambda = \log_{10} E_0/MPE = \log_{10} [12.7\ W/cm^2/0.1\ W/cm^2] = 2.1$.

VIII. Special Considerations: Optical Fibers and Medical Lasers

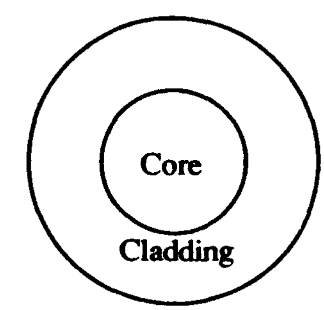
A. General. Medical lasers and the use of optical fibers are two of the fastest growing areas of laser use. The use of lasers in these applications has prompted the ANSI Z136 committee to develop separate standards for each of these laser application types. This section provides background information for both of these applications with additional information from ANSI Standards: Z136.2, "for the Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources" (Ref 3) and Z136.3, "for the Safe Use of Lasers in Health Care Facilities" (Ref 2). Presently, neither of these standards has been adopted by the Air Force and the comments made here are recommendations only.

B. Optical fibers.

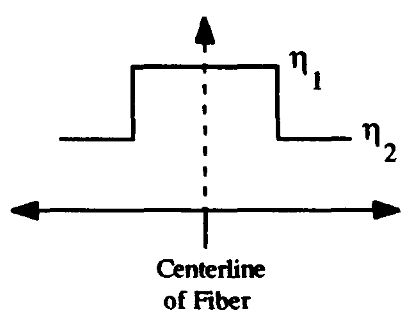
1. Introduction. Laser waveguides are light pipes that transmit laser radiation from its source to its destination. These waveguides are normally made of fibers of glass, plastic, or quartz. Optical fibers have found uses in many areas including: industrial laser welding; medical surgery; dental work; product-code scanners; communications systems like telephones, television signals, and computer links; and in military applications.

2. Fundamentals of fiber optics. The diameter of individual optical fiber varies dependent on the material of composition and application. Optical fibers used for communication systems are typically from about 2 μm to 250 μm, while those used for medical applications range from about 0.2 mm to 1 mm. For some applications, fibers are bundled together to form a fiber-optic bundle or conduit. There are two types of fiber-optic conduits: coherent and noncoherent. The fibers in a coherent conduit are arranged the same along the entire length of the conduit such that an optical image introduced at one end of the bundle will be transmitted without change to the other end. Noncoherent bundles, on the other hand, are arranged randomly. Individual fibers are manufactured to form fibers of two different types: stepped index fibers and graded index fibers.

a. Stepped index fibers. Figure 53 shows an example of the cross-section of a stepped index fiber. The central material is called the core and the outer material is called the cladding. The index of refraction of the core, η_1, is always higher than the index of the cladding, η_2.



a. Stepped index fiber



b. Index of refraction vs. distance from centerline

Figure 53. Cross-section of stepped index fiber.

From Snell's Law, optical radiation cannot be transmitted across the core/cladding interface for angles greater than α as defined by Equation 38 and shown in Figure 54.

$$\alpha = \sin^{-1} [\eta_2/\eta_1]. \quad (38)$$

For angles of incidence less than α, the ray escapes the core.

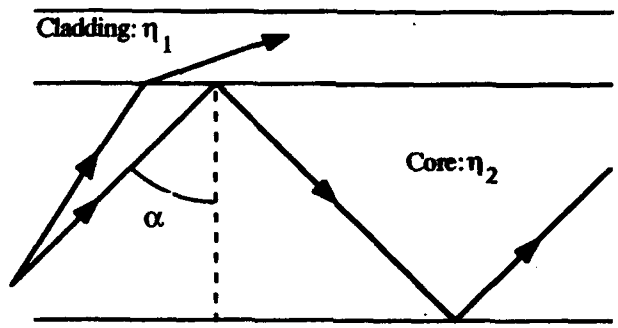


Figure 54. Internal reflection for a stepped index fiber.

Also, from Figure 54 another property of optical fibers can be realized. For rays of angle less than α, the amount of time it takes for a ray to traverse from one end of the fiber to the other end is less than that for a ray incident at an angle equal to α. For data being transferred by pulses, the width of a pulse is enlarged by the difference in time between a ray transmitted at an angle equal to α and a ray transmitted parallel to the fiber axis. The time lag created by this phenomenon limits the bandwidth of the conduit. The number of modes a fiber is capable of propagating is given by:

$$N = (\pi^2 d^2/2\lambda^2)(\eta_1^2 - \eta_2^2), \quad (39)$$

where d is the diameter of the core and λ is the wavelength of the radiation. Fibers with values of $N < 2.89$ (neglecting polarization moding) are capable of supporting only a single mode and are called single mode fibers. Unfortunately, single-mode fibers have very small core diameters that make alignment a problem. The normalized frequency of a fiber, V, is equivalent to $\sqrt{N/2}$. Fibers that are capable of supporting more than one mode are called multimode fibers. The maximum light admitting measure of an optical fiber is the numerical aperture (NA). The numerical aperture is defined by Equation 40.

$$NA = \sqrt{\eta_1^2 - \eta_2^2}. \quad (40)$$

where η_1 and η_2 are the indices of refraction for the core and cladding, respectively. For an air/core interface, the maximum acceptance angle (Θ) with respect to the axis of the fiber is given by Equation 41.

$$\Theta = \sin^{-1} NA . \quad (41)$$

For core and cladding indices of refraction of 1.48 and 1.46, respectively, yields a NA of 0.2425 and a maximum acceptance angle of 14.03°. This value is typical for a low-loss stepped index fiber (Ref 3).

b. Graded index fibers. Graded index fibers are formed of one continuous material as compared to stepped index fibers that are composed of two materials. The index of refraction for a graded index fiber is shown in Figure 55. The maximum index of refraction for the fiber is on the centerline of the fiber. The index decreases as shown in the figure to a minimum at the outer surface of the fiber.

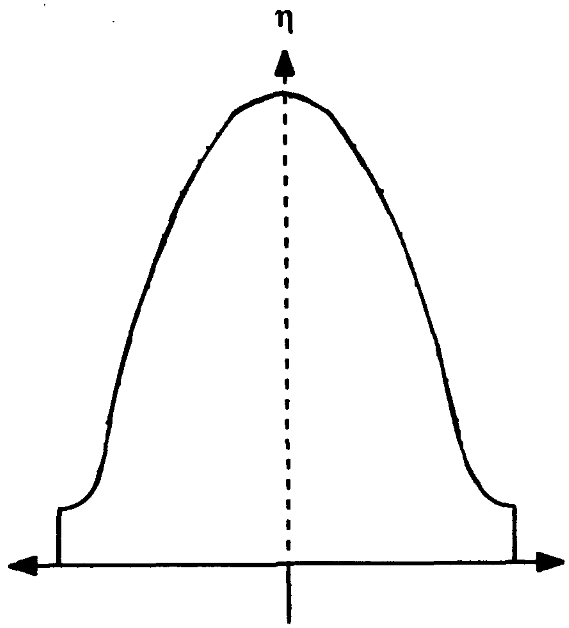


Figure 55. Index of refraction for a graded index fiber.

The travel of a ray through the graded index fiber follows a sinusoidal function. This unique property of the graded index fiber provides an advantage over the stepped graded fiber. Rays that take a wider path through the fiber must by necessity travel a greater distance through the fiber than rays that follow a more narrow path. However, wider rays gain in speed of travel since the rays spend a greater period of time in regions of lower indices of refraction than regions of higher indices. As a result, wide rays and narrow rays have identical average travel speeds with respect to the axis of the fiber. For this reason, graded index fibers can have bandwidths more than ten times that of an equivalent stepped index fiber. Graded index fibers typically are lower in attenuation than stepped fibers. Graded index fibers generally have lower numerical apertures than stepped index fibers of the same diameter. For graded fibers, single-mode operation occurs for normalized frequency values, V, less than $2.405\sqrt{(g+2)/g}$, where g is the profile parameter of the fiber.

3. Hazard evaluation. The hazard potential of fiber optics is dependent on the specific laser with which it is used, the viewing conditions, and the characteristics of the fiber.

a. Beam characteristics. The beam emanating from an optical fiber has a divergence much greater than that of a conventional laser beam. For circular beams, the beam divergence is the angle subtended by the far-field beam diameter. This definition assumes that the beam diameter is small and the source is essentially a point source. For hazard analysis purposes, it is generally assumed that emissions from a multimode fiber are Gaussian and the beam divergence (in radians) is:

$$\phi \approx NA/1.7 \text{ (multimode)}, \tag{42}$$

where NA is the numerical aperture of the fiber and is measured at the 5%-of-peak irradiance point. For single mode fibers, the divergence is defined by Equation 43.

$$\phi = 2\lambda/\pi \cdot \omega_0 \text{ (single mode)}. \tag{43}$$

where ω_0 is the core diameter of the fiber and λ is the wavelength of the radiation. From Equations 42 and 43, the beam diameter is approximated in Equations 44 and 45, respectively, for multimode and single-mode fibers.

$$\text{beam diameter} \approx 2 \cdot l \cdot (NA)/1.7 \text{ (multimode) and} \tag{44}$$

$$\text{beam diameter} = 2\lambda \cdot l/\pi \cdot \omega_0 \text{ (single mode)}, \tag{45}$$

where l is the distance from the exit aperture of the fiber.

b. Classification and evaluation of optical fiber communication systems per ANSI Z136.2-1988.

(1) General. ANSI Z136.2 applies to optical fiber communication systems (OFCS). Applications using optical fibers for purposes other than OFCS must meet the requirements of ANSI Z136.1 Since the current AFOSH does not specifically address ANSI Z136.2, Air Force OFCS must meet the requirements of the AFOSH which is consistent with ANSI Z136.1. ANSI Z136.2 is briefly described here since information and recommendations contained in the standard are useful for application to OFCS while not contradicting any recommendations made in the AFOSH . Also, it is prudent to provide this information here as future revisions made to the AFOSH may incorporate recommendations from ANSI Z136.2.

(2) Background. During normal system operation, OFCS are completely enclosed and there is no accessible radiation. But, during service, when connectors are removed, there is the potential for hazardous exposure to the unaided eye and/or for optically aided viewing using instruments like eye-loupes, hand magnifiers, or microscopes. Inadvertent viewing of a disconnected -energized fiber at distances greater than 10 cm will normally not cause injury to the unaided eye. However, damage is possible if optical aids are used. Presently, no OFCS operate at wavelengths greater than 1700 nm nor with power levels in excess of 10 mW. Current OFCS that use lasers use Class 1 or 3B devices. Light-emitting diode (LED) sources emit incoherent radiation at wavelengths typically over 700 nm as appied to OFCS. LEDs have lower hazards than a laser diode due to differences in emission characteristics involving: power, coherence, wavelength, and beam divergence. However, the ANSI Std (Z136.1 and .2) treat LEDs as laser diodes for the purpose of uniformity.

(3) Service group classification. ANSI Z136.2 assigns OFCS into one of four service groups: SG1, SG2, SG3a, and SG3b.

(a) SG1. An OFCS is classified SG1 if the total output power is less than the accessible emission limit (AEL) for Class 1 and there is not risk of exceeding the maximum permissible irradiance (MPI) when viewing the end of a fiber with a microscope, an eye loupe or with the unaided eye. The limiting aperture and AEL measurement distance for SG1 are 5 mm and 2.5 cm (the focal length of a 10X eye loupe), respectively, for wavelengths between 400 nm and 1400 nm; the exposure duration is 100 seconds. For wavelengths between 1400 and 10^6 nm, the limiting aperture is 1 mm, the measurement distance is 2.5 cm, and the exposure duration is 10 seconds. SG1 OFCSs do not present a hazard for unaided viewing or for viewing with the aid of optical instruments.

(b) SG2. An OFCS is classified SG2 if it emits at wavelengths between 400 and 700 nm (visible) and is potentially hazardous for viewing times greater than 0.25 seconds. The limiting aperture and AEL measurement distance are 5 mm and 2.5 cm, respectively. SG2 OFCSs do not present a hazard for unaided viewing or for viewing with the aid of optical instruments for exposure durations $\leq$ 0.25 seconds.

(c) SG3a. An OFCS is classified SG3a if it is hazardous when viewed with a microscope or an eye loupe but is not hazardous when viewed with the unaided eye. For wavelengths between 400 and 1400 nm, the limiting aperture and AEL measurement distance are 5 mm and 10 cm, respectively; the exposure duration is 100 seconds. For wavelengths between 1400 and 10^6 nm, the limiting aperture is 1 mm, the measurement distance is 10 cm, and the exposure duration is 10 seconds. SG3a OFCSs do not present a hazard for unaided viewing, but are potentially hazardous for optically aided viewing.

(d) SG3b. An OFCS is classified SG3b if it does not meet any of the criteria above, but the total power is less than 0.5 watts. SG3b OFCSs present potential hazards for unaided viewing and optically aided viewing.

(e) Multiple pulsed signals are evaluated in the same manner as they are in ANSI Z136.1. For PRF values greater than 15 kHz, the average power is calculated and the OFCS is evaluated as a CW system. For PRF values less than 15 kHz, the $n^{-1/4}$ criterion is applied as defined in ANSI Z136.1.

(4) Maximum permissible irradiance (MPI) values for direct ocular exposure. The MPIs from Table 3 of ANSI Z136.2 are given for wavelengths between 400 and 1400 nm. For other wavelengths, Table 2 of the AFOSH is identical.

Table 2. MPIs for Direct Ocular Exposure from ANSI Z136.2-1988.

Wavelength, λ (nm)	Exposure Duration, t (s)	Maximum Permissible Irradiance (MPI)
400 to 700	10^{-9} to $1.8 \cdot 10^{-5}$	$1 \cdot 10^{-6}$ J/cm^2
400 to 700	$1.8 \cdot 10^{-5}$ to 10	$3.6t^{3/4} \cdot 10^{-3}$ J/cm^2
400 to 550	10 to 10^4	$20 \cdot 10^{-3}$ J/cm^2
550 to 700	10 to T_1	$3.6t^{3/4} \cdot 10^{-3}$ J/cm^2
550 to 700	T_1 to 10^4	$20C_B \cdot 10^{-3}$ J/cm^2
400 to 700	10^4 to $3 \cdot 10^4$	$2\,C_B \cdot 10^{-6}$ W/cm^2
700 to 1050	10^{-9} to $1.8 \cdot 10^{-5}$	$10C_A \cdot 10^{-7}$ J/cm^2
700 to 1050	$1.8 \cdot 10^{-5}$ to 10^3	$3.6C_At^{3/4} \cdot 10^{-3}$ J/cm^2
1051 to 1400	10^{-9} to $5 \cdot 10^{-5}$	$1 \cdot 10^{-5}$ J/cm^2
1051 to 1400	$5 \cdot 10^{-5}$ to 10^3	$1.8t^{3/4} \cdot 10^{-3}$ J/cm^2
700 to 1400	10^3 to $3 \cdot 10^4$	$640C_A \cdot 10^{-6}$ W/cm^2 *

* NOTES: 5 mm limiting aperture

$C_A = 1$ for $\lambda = 400$ to 700 nm

$C_A = 10^{0.002(\lambda-700)}$ for $\lambda = 700$ to 1050 nm

$C_A = 5$ for $\lambda = 1050$ to 1400 nm

$C_B = 1$ for $\lambda = 400$ to 550 nm

$C_B = 10^{0.015(\lambda-550)}$ for $\lambda = 550$ to 700 nm

$T_1 = 10 \cdot 10^{0.02(\lambda-550)}$ for $\lambda = 550$ to 700 nm

(5) Warning labels. ANSI Z136.2 recommends use of warning labels on OFCS where safety connectors are not used. The recommended wording for the labels is given below.

For SG2 OFCS: CAUTION-
DISCONNECTED OPTICAL CONNECTORS
MAY EMIT OPTICAL RADIATION
DO NOT STARE INTO BEAM

For SG3a OFCS: CAUTION-
DISCONNECTED OPTICAL CONNECTORS
MAY EMIT OPTICAL RADIATION
DO NOT VIEW BEAM WITH
OPTICAL INSTRUMENTS

For SG3b OFCS: DANGER-
DISCONNECTED OPTICAL CONNECTORS
MAY EMIT OPTICAL RADIATION
AVOID DIRECT EYE EXPOSURE
TO THE BEAM

For infrared systems, the words INVISIBLE OPTICAL RADIATION should be used in place of OPTICAL RADIATION. For visible systems, it is permissible to replace OPTICAL RADIATION with OPTICAL ENERGY.

(6) Example classifications to determine service groups. A procedure for determining the appropriate service group is given below.

(a) Determine the power, Φ, through the limiting aperture at the shortest distance specified for service group SG1. Calculate the average irradiance through the aperture.

(b) Determine the MPI for SG1.

(c) Compare the irradiance to the MPI, if greater, apply the criteria for the next service group.

(d) If the irradiance exceeds the MPI for the next service group, apply the criteria for the next higher service group, etc.

Example 25. Determining the Service Group for an OFCS energized by a visible laser. Determine the service group classification for a multimode optical fiber with a numerical aperture of 0.24 that is energized by 632.8 nm radiation. The total average power emitted by the fiber is 3 mW. The criteria for a visible SG1 OFCS is based on calculation of the power captured by a 5 mm diameter circle at a distance of 2.5 cm from the end of the fiber. An exposure duration of 100 seconds is used. The beam diameter (1/e) at a distance of 2.5 cm is calculated by Equation 44.

beam diameter $\approx 2 \cdot l \cdot (NA)/1.7 = (2)(2.5\text{ cm})(0.24)/1.7 = 0.706\text{ cm}$.

Using Equation 28, the power through a limiting aperture of 5 mm can be calculated where x is the limiting aperture and r_1 is the beam diameter.

beam power $= \Phi\,(1 - e^{-x^2/r_1^2}) = 3\text{ mW}(1 - e^{-(5\text{ mm})^2/(7.06\text{ mm})^2}) = 1.18\text{ mW}$.

And the irradiance is $1.18\text{ mW}/\pi(0.25\text{ cm})^2 = 6 \times 10^{-3}\text{ W/cm}^2$. From Table 2, the MPI is calculated.

MPI: $E = 3.6t^{3/4} \cdot 10^{-3}\text{ J/cm}^2/100\text{ s} = (3.6 \times 10^{-3})(100)^{3/4}\text{ J/cm}^2/100\text{ s} = 1.14 \times 10^{-3}\text{ W/cm}^2$.

Since the irradiance exceeds the MPI for a SG1 OFCS, the criteria for a SG2 will be tested. The only difference between the criteria for a SG1 and SG2 OFCS is the exposure duration. For a SG2, an exposure duration of 0.25 seconds is used. Again, from Table 2, the MPI is calculated.

MPI: $E = 3.6t^{3/4} \cdot 10^{-3}\text{ J/cm}^2/0.25\text{ s} = (3.6 \times 10^{-3})(0.25)^{3/4}\text{ J/cm}^2/0.25\text{ s} = 5 \times 10^{-3}\text{ W/cm}^2$.

Since the irradiance exceeds the MPI for a SG2 OFCS, the criteria for a SG3a will be tested. The SG3a criteria are calculation of the total power through a 5 mm limiting aperture at a distance of 10 cm from the fiber end. The comparison is made with the MPI for a 100 second exposure duration. As calculated earlier, the MPI is $1.14 \times 10^{-3}\text{ W/cm}^2$. From Equation 44, the beam diameter is calculated.

beam diameter $\approx 2 \cdot l \cdot (NA)/1.7 = (2)(10\text{ cm})(0.24)/1.7 = 2.82\text{ cm}$.

From Equation 28, the irradiance is calculated.

Beam power $= \Phi\,(1 - e^{-x^2/r_1^2}) = 3\text{ mW}(1 - e^{-(5\text{ mm})^2/(28.2\text{ mm})^2}) = 0.093\text{ mW}$.

And the irradiance is $0.093\text{ mW}/\pi(0.25\text{ cm})^2 = 4.7 \times 10^{-4}\text{ W/cm}^2$. The irradiance is below the MPI and the OFCS is a SG3a OFCS.

c. Hazard calculations. Optical fibers are used for many applications other than for communications. Generally, for OFCSs, the categorization system described above is a sufficient hazard evaluation, not requiring additional calculations. The discussion provided here is for non-OFCS optical fibers.

(1) NOHD. As in the case of conventional laser sources, the nominal ocular hazard distance (NOHD) can be calculated for the emissions from optical fibers. The viewing scenario for unaided viewing is shown in Figure 56. Equations 46 and 47 define the NOHD for multimode and single mode fibers, respectively.

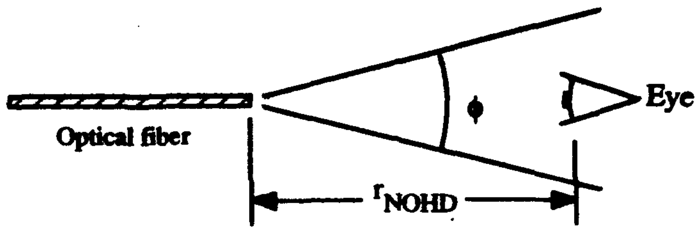


Figure 56. NOHD for emissions from a fiber optic.

$$r_{NOHD} = 1.7/NA[\Phi/\pi \cdot MPE]^{1/2} \text{ (multimode).} \quad (46)$$

$$r_{NOHD} = \omega_0/\lambda[\Phi/\pi \cdot MPE]^{1/2} \text{ (single mode).} \quad (47)$$

Example 26. Calculating the NOHD for a multimode optical fiber with near-IR emissions. Calculate the NOHD for a multimode optical fiber with a numerical aperture of 0.25 and energized with a 5 mW, 840 nm GaAlAs laser diode. The exposure duration is 10 seconds. The MPE is calculated from Table 2 of the AFOSH.

MPE: $E = 1.8C_At^{3/4} \cdot 10^{-3}/10 \text{ s} = (1.8 \cdot 10^{-3})(1.905)(10)^{3/4} \text{J/cm}^2/10 \text{ s} = 1.93 \times 10^{-3} \text{ W/cm}^2$.

From Equation 46, NOHD is calculated.

$r_{NOHD} = 1.7/NA[\Phi/\pi \cdot MPE]^{1/2} = 1.7/0.25[5 \cdot 10^{-3} \text{ W}/\pi \cdot 1.93 \times 10^{-3} \text{ W/cm}^2]^{1/2} = 6.2 \text{ cm}$.

Example 27. Calculating the NOHD for a multimode optical fiber with visible emissions. Calculate the NOHD for a multimode optical fiber with a numerical aperture of 0.26 and energized with a single pulse 694.3 nm ruby laser. The energy per pulse is 0.01 joule and the pulse width is 1 msec. The MPE is calculated from Table 2 of the AFOSH.

MPE: $H = 1.8t^{3/4} \cdot 10^{-3} = (1.8 \times 10^{-3})(1 \times 10^{-3})^{3/4} \text{ J/cm}^2 = 1.0 \times 10^{-5} \text{ J/cm}^2$.

The NOHD is calculated from Equation 46.

$r_{NOHD} = 1.7/NA[\Phi/\pi \cdot MPE]^{1/2} = 1.7/0.26[0.01 \text{ J}/\pi \cdot 1.0 \times 10^{-5} \text{ J/cm}^2]^{1/2} = 117 \text{ cm } (1.17 \text{ m})$.

Figures 57 and 58 show NOHD as a function of power for various numerical apertures of a multimode fiber at two wavelengths commonly used for OFCS.

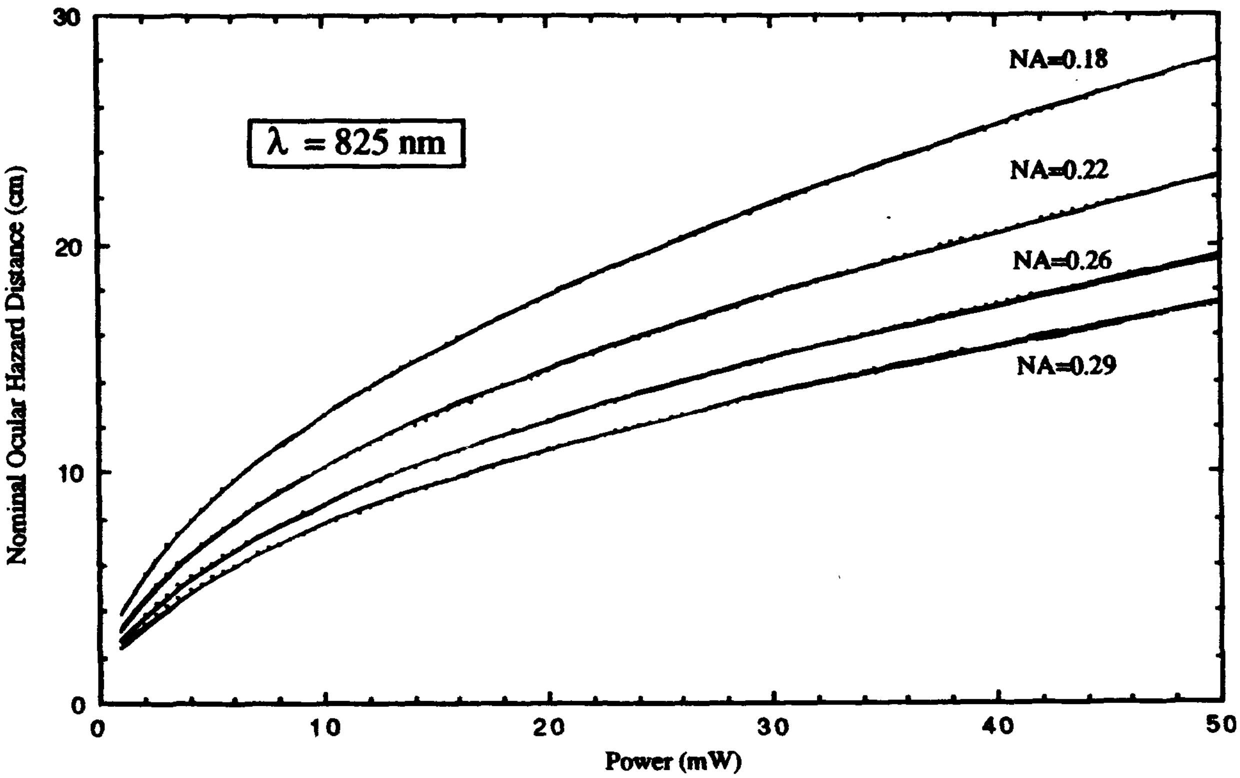


Figure 57. Plot of NOHD vs output power of a multimode optical fiber at 825 nm.

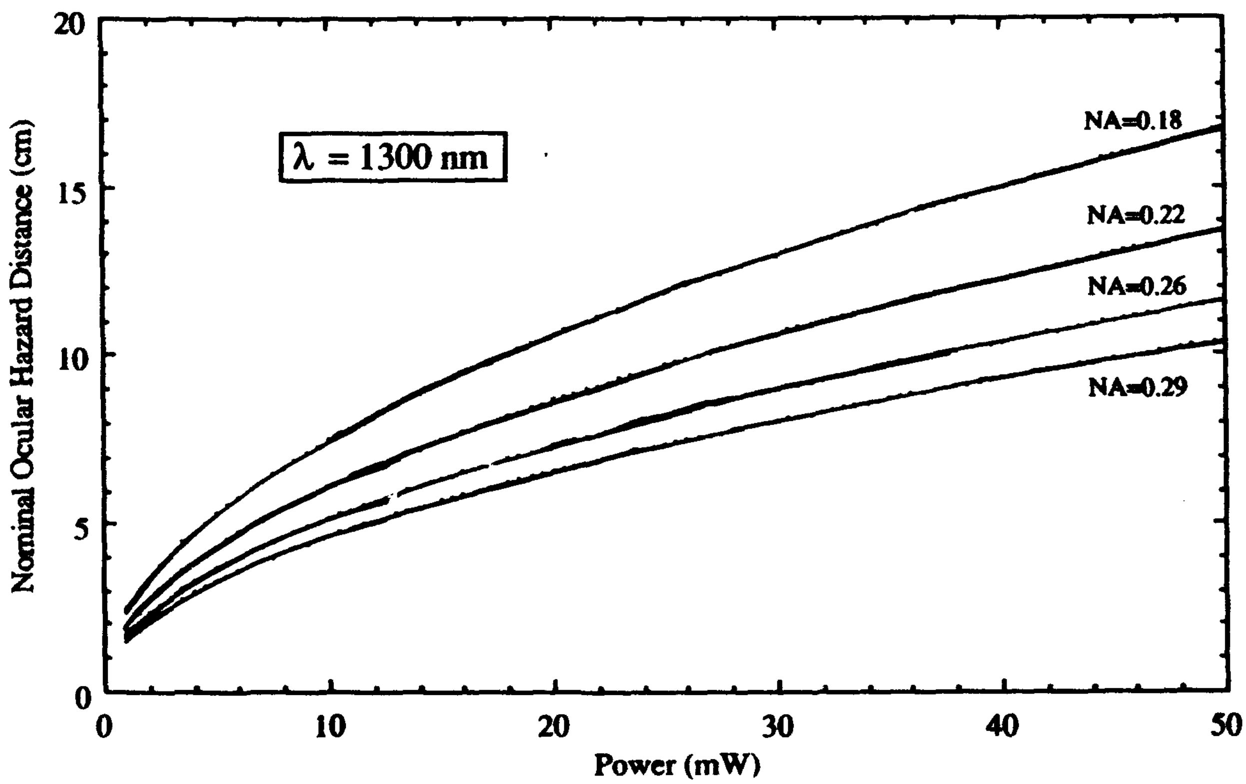


Figure 58. Plot of NOHD vs output power of a multimode optical fiber at 1300 nm.

(2) Commonly, technicians view the ends of fiber optics with the aid of optical instruments like an eye loupe or microscope during fiber splicing operations. Viewing an optical fiber while it is energized is a hazardous practice even if the levels of radiation are below levels that are considered hazardous, because the habit can be carried over to activities where the emissions from fibers are hazardous. Figure 59 illustrates the viewing of emissions from an optical fiber with the aid of a simple lens. For this case, the amount of energy that impinges on the eye is greater than for the corresponding case of unaided viewing.

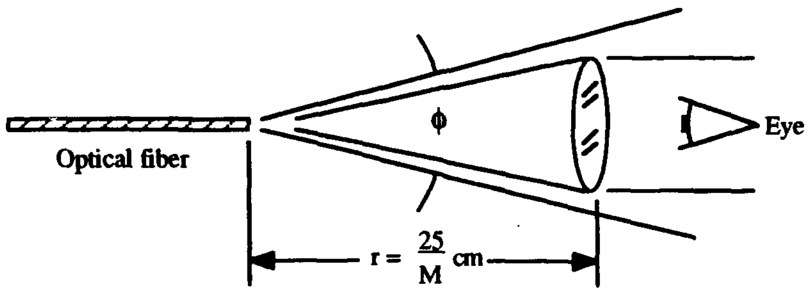


Figure 59. Viewing emissions of optical fiber with the aid of a simple lens.

Simple lenses tend to collimate the beam as shown in the figure. If the lens is placed at a distance from the fiber equal to the focal distance of the lens, the effective viewing distance is reduced to that value. The focal length of a simple lens (e.g., an eye loupe) is related to the magnification power of the lens as shown in Figure 59 where r = 25/M cm and M is the magnification power of the lens.

Example 28. Calculating the maximum permissible emission power of a multimode fiber viewed with the aid of a 7.5x eye loupe. Calculate the maximum permissible emission power of a multimode fiber with a numerical aperture of 0.25 and energized by a 905 nm GaAs laser diode. The exposure duration is 10 seconds. For a 7.5x eye loupe, the focal length of the lens is 25/M cm = 3.3 cm, where in this case is the distance the lens is from the optical fiber. The beam diameter at this distance from the fiber is estimated by Equation 43: $2 \cdot 1 \cdot (NA)/1.7 = (2 \cdot 3.3 \text{ cm} \cdot 0.25)/1.7 = 0.98$ cm. Since this laser is used for a non-OFCS application, the limiting aperture and MPE from the AFOSH are used. The fraction of the total power emitted through the limiting aperture of 7 mm is calculated with Equation 28, where d_e is the limiting aperture and D is the beam diameter.

$$(1 - e^{-d_e^2/D^2}) = (1 - e^{-0.7 \text{ cm}^2/0.98 \text{ cm}^2}) = 0.40.$$

The MPE is calculated from Table 2 of the AFOSH.

$$\text{MPE: } E = 1.8 \cdot C_A \cdot t^{3/4} \cdot 10^{-3} \text{ J/cm}^2/10 \text{ s} = (1.8 \times 10^{-3} \text{ J/cm}^2)(2.57)(10)^{3/4}/10 \text{ s}) = 2.6 \times 10^{-3} \text{ W/cm}^2.$$

Therefore, using a limiting aperture of 7 mm, the maximum permissible emission power is:

$$\Phi_{max} = \text{MPE} \cdot \pi \cdot (0.7 \text{ cm}/2)^2/0.4 = 2.6 \times 10^{-3} \text{ W/cm}^2 \cdot \pi \cdot (0.7 \text{ cm}/2)^2/0.4 = 2.5 \text{ mW}.$$

C. Medical lasers.

1. Introduction. Lasers are being used with increasing frequency in Air Force medical care facilities. Virtually all surgical specialties use lasers in some of their procedures. The highest concentration of use is in the fields of ophthalmology, cardiology, radiology, gastroenterology, and oncology (Ref 27).

2. **Laser/tissue interactions.** There are currently five laser/tissue interaction mechanisms associated with laser treatment. Three of the mechanisms are combined under the photochemical mechanism heading. The mechanisms are dependent primarily on the wavelength, power (or energy) and spot size of the incident radiation, and the absorption characteristics of the tissue. These factors determine the penetration depth of the laser effect.

a. Thermal. Thermal mechanisms are based on the volumetric rate of heat production that occurs when laser radiation is absorbed by tissue chromophores like blood, pigments, etc. Heat production is used to damage tissue irreversibly, and through normal healing processes a scar is formed. A scar can stop uncontrolled bleeding and can be useful for attaching separated tissues. The effects normally observed within the affected zones are:

(1) coagulation, sealing or cauterizing with minimal necrosis (tissue temperatures above 45 °C) and

(2) vaporization for incising or excising (tissue temperatures above 100 °C).

Both of these effects are used in many surgical applications.

b. Acoustical. Acoustical interactions use shockwaves to fragment or disrupt tissues. The acoustical effects are commonly used in ophthalmology and urology. In ophthalmology, short Q-switched pulses are used in cataract treatment. In urology, pulsed dye lasers are used to fragment impacted ureter stones.

c. Photochemical. Photochemical effects are divided into three categories.

(1) Photoablation. Photoablation requires sufficient heat generation within irradiated tissue so that vaporization occurs. Short-pulses of ultraviolet radiation are used to yield fine cuts with no visible necrosis. The depth of ablation is a function of the penetration depth of the laser radiation and pulse width.

(2) Photodynamic. In photodynamic therapy, a photosensitizer agent is administered intravenously and becomes concentrated in metabolically active tumor tissues. Post injection, laser radiation is applied to the tumor tissue which promotes formation of cytotoxic free radicals that selectively destroy the tissue containing the sensitizing agent. One agent that is commonly used is hematoporphyrin derivative (HpD). He-Ne radiation (632.8 nm) is used with HpD.

(3) Photobiostimulation. The mechanisms underlying photobiostimulation are not well known and have caused much controversy as to whether a mechanism does exist. Low-power lasers like the He-Ne and GaAs have been used in the studies.

d. Absoption coefficient and penetration depth. The absorption coefficient is an important parameter that defines the penetration depth of the laser radiation. Tissue penetration varies from about one cell thickness (200 nm radiation) to about 1 cm (700 nm radiation). The difference in absorption characteristics is due to the different absorption mechanisms: proteins and water absorb UV, chromophores absorb in the visible and near-IR region, and water absorbs for wavelengths greater than 1300 nm (Ref 27). Table 3 provides absorption coefficients for four biological tissues as a function of the wavelength of four common medical lasers.

Table 3. Absorption coefficients (relative units) for selected biological tissues at the wavelengths of four common medical lasers (Ref 10).

Tissue	KrF (249 nm)	Argon (488 nm)	Nd:YAG (1060 nm)	CO_2 (10,600 nm)
Water	--	0.00025	0.363	1106
Skin	1650	55	15	911
Liver	--	50	12.5	200
Blood	--	105	9.9	--

The absorption coefficient of a tissue at a specific wavelength determines which lasers are used for certain applications. For example, UV and IR (CO_2) lasers have high absorption coefficients in tissue and are effectively absorbed at the surface of tissues, making them effective for cutting tissue. The CO_2 laser, however, is not a good choice for cauterization since it doesn't penetrate well into tissue. The argon laser is absorbed well by blood, making it effective in treatment of "port wine" birthmarks.

e. Spot size. Spot size is also an important beam parameter that must be controlled for each laser application. Small spot sizes are used for procedures like cutting where high irradiance is needed to vaporize tissue. On the other hand, larger spot sizes are used for cauterization.

3. Equipment.

a. Lasers. The CO_2, argon, and Nd:YAG are the primary lasers used in medical/surgical applications. Recently, other lasers have gained more widespread use due in part to advances in fiber optics and research efforts. Some of the most common lasers used in medicine are described below with their routine clinical use.

(1) Excimer. The principal applications of the pulsed-excimer laser is photoablation due to the high absorption of UV in tissue. The most commonly used eximer lasers are the XeCl and XeF with respective emissions at 308 and 351 nm. Two other excimer lasers under study for potential uses are the ArF and KrF lasers. One study is investigating their use for photoablation techniques that require smaller penetration depths than those available from the more common eximer lasers. Both of these lasers have absorption coefficients about three times that of the XeCl laser and about ten times that of the XeF laser.

(2) Dye-tunable. Continuous-wave dye-tunable lasers are used principally for photodynamic therapy, dermatology, and plastic surgery. The tunability of the output wavelength is an asset for photodynamic therapy applications where the use of dyes with different absorption spectra is common. Pulsed dye-tunable lasers can be used for pulsed laser applications; but normally, other visible lasers are more economically feasible.

(3) Argon. The 488 and 514.5 nm emissions from the argon laser are used for superficial photocoagulation, retinal surgery, and plastic surgery.

(4) Gold vapor. The principal application of the 628 nm pulsed gold vapor laser is in photodynamic therapy.

(5) He-Ne. The 632.8 nm He-Ne laser is used for aiming and alignment of other invisible or more powerful lasers used in medical applications. He-Ne lasers are also being used in photobiostimulation research.

(6) Ruby. The 694.3 nm pulsed output of the ruby laser is used principally in dermatology and plastic surgery where vaporization of tissue is required.

(7) Laser diodes. The principal application of diodes is in photobiostimulation.

(8) Nd:YAG. The principal application of the pulsed Nd:YAG laser is for cauterization. As with the argon laser, the Nd:YAG laser is used for retinal surgery.

(9) HF and Er:YAG. The HF laser has an output wavelength band of 2600 - 3000 nm while the Er:YAG laser has an output at 2940 nm. The spectral output of both of these lasers is advantageous for cutting operations that demand high absorption coefficients in tissue. Prior to the development of zirconium and sapphire fibers, transmission through optical fibers was not satisfactory and endoscopic applications with these lasers were not possible.

(10) CO_2. Due to the high absorption is tissue, the 10,600 nm output from the CO_2 laser makes it useful for cutting and vaporization of tissue. Unfortunately, at this time, optical fibers do not effectively transmit radiation with wavelengths > 5000 nm, but first generation fibers are being tested at this time (Ref 27).

b. Delivery systems. Four major beam delivery systems are used in clinical procedures.

(1) Articulated arms. The articulated arm is a series of hollow tubes with a mirror at the connection point of each tube. Laser radiation is directed down the first tube, reflected through the second tube, and so on until the beam reaches the handpiece where, typically, the beam is focused by a lens at the end. Figure 60 shows an example of an articulated arm and its component parts.

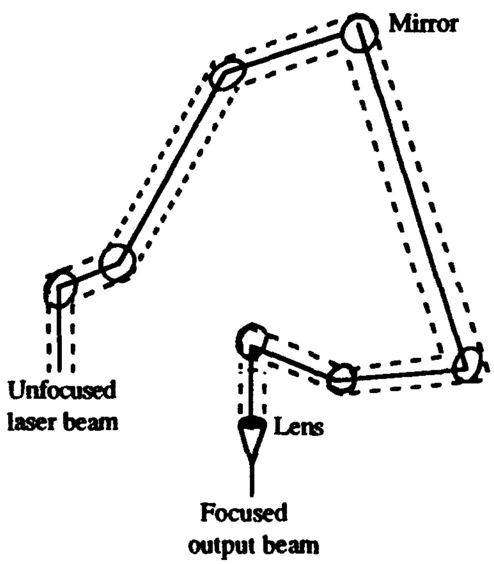


Figure 60. Articulated arm and its associated parts.

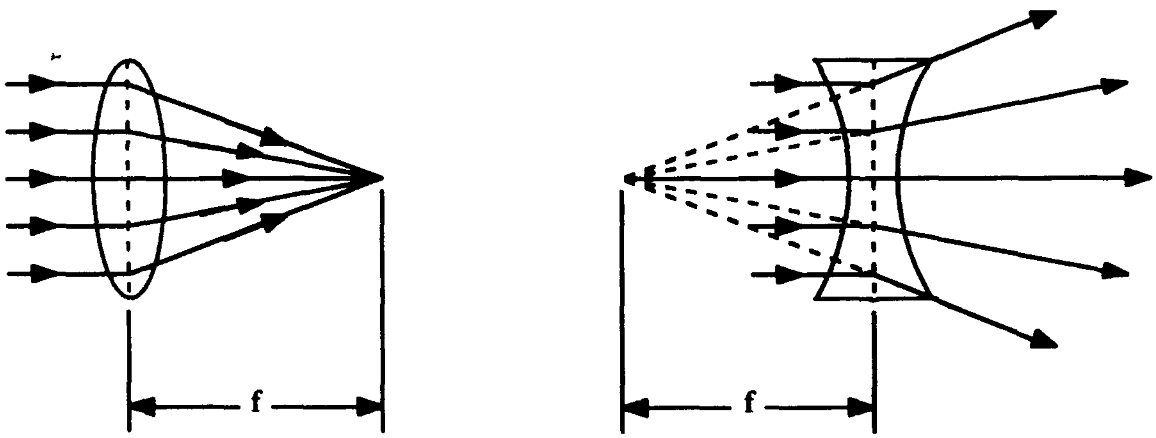
(2) Microscope. Some microsurgical procedures require the focused spot from a laser beam to be delivered to the visual field of an operating microscope. Gynecological and neurological procedures are two fields requiring the use of microscopes. Placement of the beam within the visual field is often aided with a "joy stick" and a low-power visible laser that is coaligned with the primary beam.

(3) Fiber optics. Fiber optics used for medical procedures have diameters typically in the range: 0.2 - 1 mm. Fiber optic systems that implement the bare end of the fiber are often used to cut and cauterize. For other applications where there is a requirement for high power (or energy)

density, the output of the fiber is often delivered through a lens, where the beam can be focused to small beam spots. For CW laser systems, the fibers available today are sufficient for transmission of radiations with wavelengths extending from the UV region to about 2500 nm according to van Gemert and Welch (Ref 27). They claim that the recent development of zirconium and sapphire fibers should allow transmission of radiations with wavelengths as high as 5000 nm. Problems exist in finding suitable fibers to transmit the high power, short pulse width emissions from Q-switched lasers, but some success has been made with transmission of pulses from some Q-switched excimer and Nd:YAG lasers. Van Gemert and Welch note that the electric breakthrough problem associated with the transmission of high intensity pulses should be overcome in the future.

(4) Sapphire tips. Optic fibers with specially designed sapphire tips have been used in place of the conventional fiber/lens combination delivery system. Properly designed, sapphire tips are capable of evenly distributing energy along a flat edge. When the edge is placed against tissue, the beam will cut tissue immediately adjacent to the edge. This type of delivery system has distinct advantages over the fiber/lens combination; for example, the contact with tissue gives surgeons the feel of a scalpel, while for the fiber/lens delivery system, the distance between the lens and tissue surface is critical in determining the spot size and irradiance.

c. Lenses. Simple lenses are used in many devices including binoculars, cameras, microscopes, etc. Convex (or positive) lenses are called converging lenses because they refract parallel light such that the rays converge to a point at the focal length of the lens as shown in Figure 61a. A concave (or negative) lens is called a diverging lens because incident parallel light is refracted such that the rays diverge from a virtual point on the side of the lens on which the rays originate. This type of lens is shown in Figure 61b.



a. Converging lens b. Diverging lens

Figure 61. Two common lenses.

Converging lenses are used in medical applications to focus beams. The ability to focus a laser beam onto a much smaller area than can the light from a conventional source is one of the greatest assets of the laser. But, diffraction-spreading does place limitations on the achievable diameter of the focused spot (also called beam waist). From diffraction theory, it can be shown that a (collimated) Gaussian beam from a laser can be focused to a spot of diameter:

$$w_0 = (\lambda \cdot f)/(\pi \cdot b_0). \qquad (48)$$

where f is the focal length of the lens, λ is the wavelength of the radiation, and b_0 is the diameter of the beam incident on the lens. Figure 62 shows the focusing of a Gaussian beam, noting that the minimum beam waist is at a distance from the lens equal to the focal length of the lens.

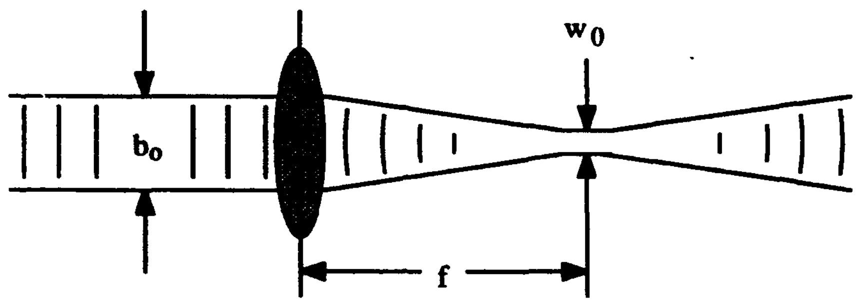


Figure 62. Beam waist for a collimated beam focused by a lens of focal length, f.

Equation 48 provides a theoretical limit on the minimum beam waist (spot size) and is applicable to beams with divergence $\leq$ 30 microradians (μrad). For beams with greater divergence, Equation 49 provides an estimate of the beam waist provided the lens is placed within the Rayleigh range of the laser.

$$w_0 = f \cdot \phi. \tag{49}$$

The Rayleigh range is equal to $(4 \cdot \lambda)/(\pi \cdot \phi^2)$, where ϕ is the beam divergence at the aperture, and λ is the wavelength of the radiation. Normally, for medical lasers, it is reasonable to assume that the lens is well within the Rayleigh range. Figure 63 provides a graphical description of Equation 49.

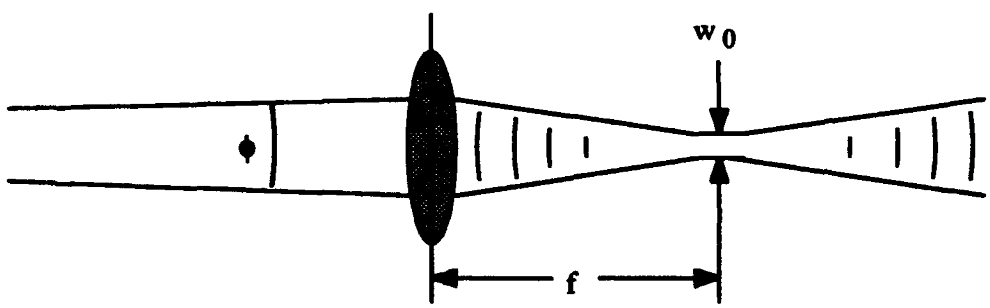


Figure 63. Beam waist defined by the beam divergence and the focal length of the focusing lens (for aperture to lens distances well within the Rayleigh range).

The focal length of a lens also determines the depth-of-focus of a beam. For short-focal-length lenses the depth-of-focus is short, while for long-focal-length lenses the opposite is the case.

4. Hazards evaluation.

a. General. ANSI Z136.3 describes four aspects that influence the hazard evaluation and control measures recommended for medical laser systems. The four aspects are:

(1) the capability of the radiant energy of the laser to injure health care providers (physicians, nurses, technicians, etc.) or the areas of the patient's body other than the intended treatment site(s),

(2) the environment in which the laser is used,

(3) the health care provider who may use, or be exposed to, laser radiation, and

(4) the non-emission hazards associated with medical lasers.

The medical environment provides for unique hazard control measures that separate them from lasers used for other applications even though the laser systems are essentially the same as those used for other applications. The use of focusing lenses on the majority of medical lasers deserves attention because it will modify two parameters that are commonly assessed in evaluation of the hazards from a laser: the maximum irradiance at the beam waist and the nominal ocular hazard distance (including the nominal hazard distance for skin hazards).

b. Hazards from the beam spot and optical density determination. The minimum beam waist is a parameter that is important to the application of a particular medical laser system. But, with respect to health care personnel in the vicinity of the beam, the beam waist is the region of the beam that has the greatest irradiance (or radiant exposure) and thus represents the greatest hazard to personnel. Though the focused beam may create greater hazards in some areas close to the focusing lens than an unfocused beam, the hazard distance of a focused beam is small in comparison to an unfocused beam. In the case of visible and near-IR lasers, eye hazards are independent of beam diameter if the beam diameter is less than the limiting aperture of 7 mm. Therefore, in specifying eye protection for these lasers the optical density is strictly dependent on the power or energy of the beam and the exposure duration. However, for skin hazards from visible and near-IR beams, and eye and skin hazards from UV and far-IR lasers, the minimum beam diameter (or beam waist) must normally be determined for focused beams since the value will normally be smaller than 1 mm, the limiting aperture for evaluation of the latter hazards.

Example 29. Calculating the optical density needed for eye protection from a CW far-IR laser. Calculate the necessary optical density required for a focused 10,600 nm CO_2 laser with a CW output power of 10 watts, an aperture beam diameter of 0.3 cm, and a beam divergence of 1 mrad. Assume the focal length of the lens is 100 mm, the lens is close to the aperture (within the Rayleigh range), and the exposure duration is 10 seconds. From Equation 49, the beam waist is calculated.

$w_0 = f \cdot \phi = 100 \text{ mm} \cdot 1 \text{ mrad} = 0.1 \text{ mm}.$

The maximum irradiance is 10 watts/($\pi \cdot (0.005 \text{ cm})^2$) = 1.3×10^5 W/cm^2. From Table 2 of the AFOSH, the MPE is 0.1 W/cm^2. From Equation 20, the optical density is calculated.

$D_\lambda = \log_{10} E_o/\text{MPE} = \log_{10}(1.3 \times 10^5 \text{ W/cm}^2/0.1 \text{ W/cm}^2) = 6.1.$

c. Nominal ocular hazard distance (NOHD) and nominal hazard distance (NHD) for skin hazards. Determination of the NOHD and NHD is often made in evaluation of a medical laser. To determine the NOHD and NHD for a laser focused by a lens, first, the divergence of the beam after refraction by the lens must be calculated. For small divergence (i.e., less than 0.244 rad), Equation 50 will provide an estimate of the divergence (in radians) with an error of less than 1 %.

$$\phi = f/b_o, \tag{50}$$

where f is the focal distance of the focusing lens and b_0 is the diameter of the beam incident on the lens. Equation 51 defines the NOHD or NHD for beams focused by lens.

$$r_{NOHD} \text{ (or } r_{NHD}) = (f/b_0)[(4 \cdot \Phi)/(\pi \cdot MPE)]^{1/2}. \quad (51)$$

Figure 64 graphically describes the NOHD or NHZ distance with respect to the lens and the laser.

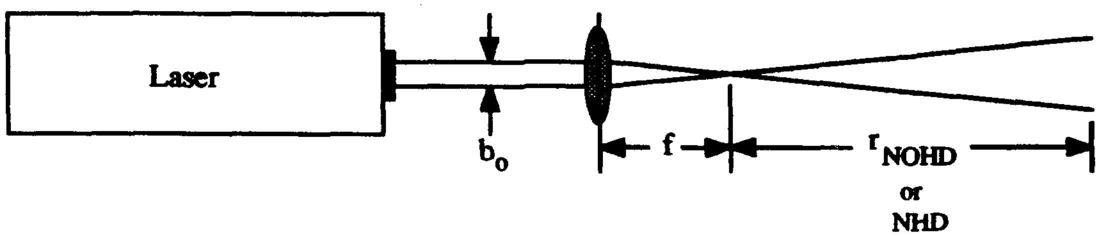


Figure 64. NOHD or NHD for laser beam focused by lens.

Example 30. Calculating the NOHD, NHD (skin), and optical density for a visible medical laser with a focusing lens. Calculate the optical density needed for eye protection, the NOHD, and the NHD for a 488 nm argon ion medical laser that has a CW output power of 1 watt, an aperture beam diameter of 1.5 mm, and an aperture beam divergence of 1 mrad. The lens is focused by a 50 mm lens that is well within the Rayleigh range of the laser. For calculations involving the eye, use a 0.25 second exposure duration, but for skin exposures assume a 10 second exposure duration. From Table 2 of the AFOSH, the MPE for direct ocular exposure is calculated.

MPE: $E = 1.8 \cdot t^{3/4} \cdot 10^{-3}$ J/cm²/0.25 s $= (1.8 \cdot 10^{-3})(0.25)^{3/4}$ J/cm²/0.25 s $= 2.55 \times 10^{-3}$ W/cm².

From Table 4 of the AFOSH, the skin MPE is calculated.

MPE(skin): $E = 1.1t^{1/4}$ J/cm²/10 s $= 1.1(10)^{1/4}$ J/cm²/10 s $= 0.2$ W/cm².

Using Equation 51, the NOHD and NHD for skin are calculated.

$r_{NOHD} = (f/b_0)[(4 \cdot \Phi)/(\pi \cdot MPE)]^{1/2} = (50 \text{ mm}/1.5 \text{ mm})[(4 \cdot 1 \text{ W})/(\pi \cdot 2.55 \times 10^{-3} \text{ W/cm}^2)]^{1/2} =$ 744 cm (7.44 m).

$r_{NHD}(\text{skin}) = (f/b_0)[(4 \cdot \Phi)/(\pi \cdot MPE)]^{1/2} = (50 \text{ mm}/1.5 \text{ mm})[(4 \cdot 1 \text{ W})/(\pi \cdot 0.2 \text{ W/cm}^2)]^{1/2} = 84$ cm.

To determine the necessary optical density for protective eyewear, the extent of the beam waist must be determined. Using Equation 49, the beam waist is calculated.

$w_0 = f \cdot \phi = 50 \text{ mm} \cdot 1 \times 10^{-3} \text{ rad} = 0.05$ mm.

Since, the beam waist is smaller than the limiting aperture of 1 mm, the limiting aperture will be used for calculation of the optical density. From Equation 20, the optical density is calculated.

$D_\lambda = \log_{10} E_0/MPE = \log_{10} [1 \text{ watt}/(\pi \cdot (0.05 \text{ cm})^2)]/2.55 \times 10^{-3} \text{ W/cm}^2 = 4.7.$

d. Ancillary hazards. Ancillary hazards for lasers used in research laboratories and industrial settings are described in the AFOSH and briefly in this document. The ancillary hazards described here are concerns that are more unique to medical lasers and their use. The hazards listed here are from ANSI Z136.3-1988.

(1) Electrical hazards.

(a) Shock hazard. Live parts of circuits and components with peak open-circuit potentials over 42.5 volts are considered hazardous, unless the current is limited to less than 0.5 mA. Such circuits require positive protection against contact. For equipment intended for general use, internal switches (and capacitor bleed resistors are applicable) or their equivalent shall be installed to remove the voltage from accessible live parts to permit servicing. Bleed resisters shall be of such size and rating as to carry the capacitor discharge current without burnout or mechanical injury. Circuits and components with peak open-circuit potentials of 2,500 volts or more shall be adequately covered or enclosed if an appreciable capacitance is associated with the circuits.

If servicing equipment requires entrance into an interlocked enclosure within 24 hours of the presence of high voltage within the unit, a solid metal grounding rod shall be utilized to ensure discharge of high-voltage capacitors. The grounding rod, e.g., a large-wattage ceramic resistor, may be used prior to application of the grounding rod to protect circuit components from overly rapid discharge, but shall not be used as a replacement.

(b) Grounding. The frames, enclosures, and other accessible non-current-carrying metallic parts of laser equipment shall be grounded. Grounding shall be accomplished by providing reliable continuous metallic connection between the part or parts to be grounded and the grounding conductor of the power wiring system.

(c) Electrical fire hazards. Components in electrical devices shall be evaluated with respect to fire hazards. Circuit components of combustible material, like transformers, that do not pass a short-circuit test without ignition shall be provided with individual noncombustible enclosures. Power supply circuit wiring shall be completely enclosed in noncombustible material.

(d) Electromagnetic interference. Electrical interference with monitoring equipment can be prevented by proper grounding or isolation techniques. However, new information suggests that implanted pacemakers may be altered by electric "plasma effect" if the tip of a Nd:YAG fiber is close to the pacemaker (thoracic implants).

(e) Marking. Lasers should be permanently marked with the primary electrical ratings in volts, frequency, and watts or amperes.

(2) Equipment explosion hazards. High-pressure arc lamps and filament lamps in laser equipment shall be enclosed in housings that can withstand the maximum explosive pressures resulting from lamp disintegration. The laser target and elements of the optical train that may shatter during laser operation shall also be enclosed or equivalently protected to prevent injury to operators and observers. Particular care must be taken if oxygen is used in the laser controlled area.

(3) Optical radiation hazards - excluding the laser beam. Ultraviolet radiation emitted from laser discharge tubes and pumping lamps, i.e., not part of the primary laser beam, shall be suitably shielded. In addition, laser beam interactions with hard tissues and bone can generate intense plasma emissions, thus requiring suitable filtering for direct viewing.

(4) Airborne contaminants. Airborne contaminants shall be controlled by the use of ventilation and respiratory protection. Airborne contaminants should be captured as near as practical to the point of evolution and vented outdoors. During surgery in or near respiratory passages, adequate

ventilation shall be provided for patient protection. In most Class 4 laser operations, the vaporization of target tissue produces noxious airborne contaminants that can cause lacrimation, nausea, abdominal cramping and vomiting. Such airborne contaminants shall be removed by localized exhaust ventilation. An alternative is the use of a portable smoke extractor using charcoal and/or high efficiency particulate for air (HEPA) type filters. Replaceable filters should be monitored on a regular basis following the manufacturer's recommendations and be considered a possible biohazard and disposed of accordingly.

Masks or other respiratory protectors shall be worn in the operating room during all procedures. A standard surgical mask filters out particulates down to 5 µm in size with a 99 % efficiency. However, laser plume particulates may be as small as 0.3 µm in size. Respiratory protection is available that will filter out particles as small as 0.3 µm with an efficiency of 99 %, but use of such masks may result in a decrease in the ease of breathing. If these masks become damp, they lose their efficiency.

(5) Explosion and fire hazards. The laser shall not be used in the presence of flammable materials, e.g., certain anesthetic preparation solutions, drying agents, ointments, plastic resins, anesthetics. Sponges, gauze pads and swabs located near the operating field shall be moistened with saline or sterilized water if Class 4 lasers are in use. Surgical drapes should be made of flame-retardant material and the region of the drape near the operating field shall be moistened with saline or sterilized water or be of an equivalent flame resistance or quenching ability if Class 4 medical lasers are used.

(a) Explosion hazards. Intra-anesthetic explosions, which occur primarily in laser surgery of the digestive tract, are associated with methane normally found in the tract. Nonexplosive anesthetics and localized ventilation should be considered.

(b) Fire hazards. Fire hazards related to endotracheal tubes, plastic adhesive tape, ointments and the like can be alleviated by careful choice of noncombustible instrumentation, use of a venturi ventilation technique, or shielding with wet substrates that will char rather than undergo a rapid combustion process (flame). This includes keeping the surrounding areas wet and using relatively noncombustible wet drapes.

(c) Oxygen and flammable gases. Since combustion may be initiated in the aerodigestive tract at high oxygen saturations or in the presence of methane, the lowest possible concentration of oxygen should be used in laryngotracheal procedures and adequate preparation should be provided for colonic procedures. The use of intravenous anesthetic techniques, rather than inhalation techniques, is recommended to prevent laser pyrolysis of anesthetic agents.

(6) Endotracheal and endobronchial tubes. Experience suggests that during surgery with an endoscope in the aerodigestive tract (oral, nasopharyngeal, or endobronchial) the endotracheal or other tubes shall require protection or special design to minimize laser beam penetration. Anesthesia personnel should use nonflammable endotracheal tubes or specially-wrapped red-rubber or 100 %-silicone tubes. Other plastics, portex, anode (wired or armored) tubes (even if wrapped) should not be used. The inflated cuff must be protected, e.g., with wet cotton towelettes.

(7) Endoscopic delivery systems. Care should be undertaken to avoid laser beam exposure on the sheaths of flexible-fiberoptic endoscopes since most of the sheaths are flammable in the presence of a high-oxygen environment. For metallic tubular delivery systems, e.g., bronchoscopes, laproscopes, avoid beam heating of the wall to preclude thermal damage of adjoining tissue.

5. Control measures. The AFOSH lists recommended and mandatory control measures for lasers by the ANSI Class and application of the laser. The presence of the patient in the medical environment creates the need for unique control measures. The control measures unique to medical

lasers explained here are from ANSI Z136 3-1988. The AFOSH provides a list of recommended control measures; therefore, this list may overlap that contained in the AFOSH. In many cases, control measures recommended for medical lasers are identical to those required for lasers in general; therefore, the AFOSH should be consulted for a complete list.

a. Laser use committee. For medical facilities that contain a number of different practitioners that use Class 3b or 4 medical lasers, a controlling body or laser use committee should be formed to govern laser activity and establish use criteria. A person from the BES staff should be a committee member.

b. Guarded switch. For Class 3b or 4 medical lasers, the switch that controls patient exposure shall be guarded, e.g., a guarded pedal switch or guarded finger-trigger switch. In environments with multiple-guarded foot pedal switches for different lasers or equipment, precautions should be taken to prevent inadvertent exposure.

c. Beam delivery disconnect safety features. Laser beam delivery systems for Class 3b or 4 medical lasers used in patient therapy, e.g., articulated arms or optical fibers, should be considered as an extension of the protective housing. Disconnection of the delivery system from the laser source shall not permit laser radiation in excess of the applicable MPE to directly exit from the laser.

d. Output calibration. Confirming power/energy measurements should be performed using an appropriate radiometer as specified by the manufacturer of the medical laser system, or deemed appropriate by BES to assure proper calibration of the power/energy monitor.

e. Laser treatment controlled areas (Class 3b). A Class 3b laser treatment controlled area should contain the nominal hazard zone, the extent of which is clearly designated. Some of the recommendations have similarities to the requirements for a laser controlled area as specified in the AFOSH. Similar items will be summarized rather than discussed. Controlled areas shall:

(1) be posted with appropriate warning signs, be supervised and occupied by authorized personnel, be under the direct supervision of an individual knowledgeable in laser safety, be located such that access to the area by spectators is limited and requires approval,

(2) have potentially hazardous beams terminated in a beam stop of an appropriate material,

(3) have only diffuse reflective materials in or near the beam path, where feasible (The use of anodized instruments should be considered.),

(4) have personnel who regularly require entry into a laser treatment controlled area adequately trained, provided with appropriate protective equipment and required to follow all applicable administrative and procedural controls,

(5) have all windows, doorways, open portals, etc., either covered or restricted in such a manner as to reduce the transmitted laser radiation to levels at or below the appropriate ocular

MPE. Windows need not be covered for wavelengths where the glazing is opaque (Window glass is opaque from 180 to 300 nm and from 4,000 to 10^6 nm.),

(6) require storage or disabling (removal of the key) of the laser when not in use to prevent unauthorized use,

(7) assure that the shutter mechanism is closed during stand-by periods, and

(8) provide an emergency shut-off switch to enable rapid shutdown of equipment.

f. Laser treatment controlled areas (Class 4). Class 4 laser treatment controlled areas shall be designed to fulfill all of the requirements of a Class 3b controlled area and the following:

(1) Entryway safety controls shall be employed for Class 4 laser treatment areas. Three options are recommended. The option chosen should be based on the training and knowledge of those routinely accessing the area, the extent of the NHZ, accessibility of the laser treatment controlled area by patients or the general public, accessibility by untrained staff, and availability of protective equipment. BES should consider options (a) or (b), for areas like out-patient clinics and some medical research laboratories that have possible access by untrained persons. Options (b) or (c), should be considered for areas like surgery and limited access out-patient, having a low probability of unrestricted access except by trained staff.

(a) Nondefeatable (nonoverride) area entry controls. Nondefeatable safety latches, entryway or area interlocks, e.g., electrical switches, pressure sensitive floor mats, infrared or sonic detectors, shall be used to deactivate the laser or reduce the output to the appropriate MPE levels in the event of unexpected entry into the laser controlled area.

(b) Defeatable area/entryway safety controls. Defeatable safety latches, entryway or area interlocks shall be used if nondefeatable area/entryway safety controls limit the intended use of the laser, e.g., during normal usage requiring operation without interruption such as during long-term testing, medical procedures or surgery. If it is clearly evident that there is no optical-radiation hazard at the point of entry, override of the safety controls shall be permitted to allow access to authorized personnel, provided that they have been adequately trained and provided with adequate personal protective equipment.

(c) Procedural area/entryway safety controls. Where safety latches or interlocks are not feasible or are inappropriate, e.g., during medical procedures, surgery, the following shall apply:

1 All authorized personnel shall be adequately trained and adequate personal protective equipment shall be provided upon entry.

2 A door, blocking barrier, screen, curtain, etc., shall be used to block, screen or attenuate the radiation at the entryway. The level of laser radiation at the exterior of these devices shall not exceed the applicable MPE, nor shall personnel experience any exposure above the MPE immediately upon entry.

3 At the entryway there shall be a visible or audible signal indicating that the laser is energized and operating at Class 4 levels. A lighted laser warning sign or flashing light are appropriate methods to accomplish this requirement.

(2) All Class 4 area/entryway safety controls shall be designed to allow both rapid egress and admittance to the laser treatment controlled area under emergency conditions.

(3) 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.

g. Optical fiber surgical probes. Backscattering from frosted probes used with some surgical optical fibers can be hazardous, as is demonstrated by the extensive NHZ required at sites utilizing such probes. BES should evaluate the application of such probes and implement personal and administrative controls commensurate with the potential hazard.

IX. Measurements

A. General. Measurement of the emissions from a laser may be desirable under certain circumstances where the output of a particular laser is not known or its output must be confirmed. The discussion in this section is focused primarily on measurements for the purpose of protection of health and safety. Analyses of laser output characteristics for other purposes may be beyond the scope of this discussion; if this is the case, other references should be consulted.

B. Parameters to measure. The parameters of a laser beam that need to be measured are dependent on the laser type and the parameters already known. Generally, the irradiance, E, and the radiant exposure, H, are two parameters that are of interest to the hazard assessment of a laser. Beam diameter is often of interest; several techniques are provided for determining the beam diameter. The measurement of beam diameter can be difficult for some lasers where the output is multimode. Often, the beam is assumed to be Gaussian, and the diameter where 63 % of the beam is captured is referred to as the beam divergence. Beam divergence can be estimated based on a series of beam diameter measurements at various distances from the laser. For pulsed lasers, it may be necessary to determine factors like the pulse width and the pulse repetition frequency. The pulse repetition frequency should be known based on manufacturer data or on design parameters of bench-top lasers. The pulse width may be given by the manufacturer, but normally, precise determination of the pulse width is not necessary, since MPE values for pulsed lasers have broad exposure duration criteria. For most pulsed lasers, approximate pulse width values of lasers are known simply based on the type: normal-pulse, Q-switched, mode-locked, etc. For classification of Class 1, 2a, 2, and 3a lasers, determination of the maximum energy or power captured by the limiting aperture (1 or 7 mm) is sufficient. To separate Class 3b and 4 pulsed lasers, determination of the maximum radiant exposure is sufficient.

C. Radiometric instruments and detectors. Radiometric instruments of interest are usually comprised of detectors that produce a voltage, a current, a resistance change, or a charge of which is measured by an electronic meter. No detector type is sufficient for measuring all types of laser radiation. All detectors have a limited range of wavelengths that the device has sufficient sensitivity. Some detectors are suitable for measurement of pulsed lasers, while others are suited for CW lasers.

1. Measurement of CW laser power. The output of a CW laser is usually specified in watts. Many commercially available devices are capable of measuring power from nanowatts to kilowatts (Ref 11). Power meters normally contain four elements: a radiation detector, an amplifier, a range switch that controls the gain of the amplifier, and a readout meter. Radiation incident on the detector creates a current flow proportional to the intensity of the radiation. Normally, the current must be significantly amplified to current levels required by meters or equivalent output devices. Three common detector types will be described.

a. Photodiodes. Photodiodes create current flow when excited by incident radiation. Within the operational range of the device, output current of the photodiode is proportional to the incident radiation. Two types of photodiodes are commonly used: vacuum photodiodes (high power CW and pulsed lasers) and semiconductor photodiodes (low power CW and pulsed lasers). Vacuum photodiodes normally require a bias potential of 600 - 1,200 volts. The spectral sensitivity of vacuum photodiodes is dependent on the photocathode material. Semiconductor photodiodes are made of silicon, gallium-arsenide, and germanium. Figure 65 shows one type of photodiode, a silicon photovoltaic cell. Response times of less than 1 ns are possible for some photodiodes and thus make them useful for measurement of pulsed beams as well.

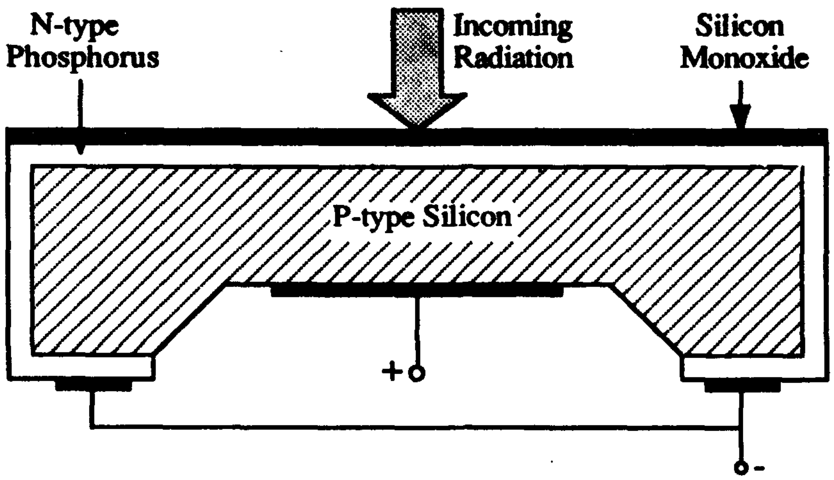


Figure 65. Silicon photovoltaic cell. Adapted from Reference 11.

b. Thermopiles. Thermopiles (also called disc calorimeters) are detectors that measure energy deposited by determining the temperature change in an absorbing material. Thermopiles normally measure the temperature change in a metallic material that is specially coated with compounds like gold black, carbon black, etc. The temperature rise in the metal is converted to an electrical potential or current which is then converted to a meter output of some type. Most thermopiles have a relatively flat response as a function of wavelength. Figure 66 shows a cutaway view of a thermopile. For CW measurements, the thermopile is ideal. But, the typical response time of a thermopile is greater than 2 seconds which limits the ability of the detector to measure rapid changes in the beam power and limits their use for pulsed lasers.

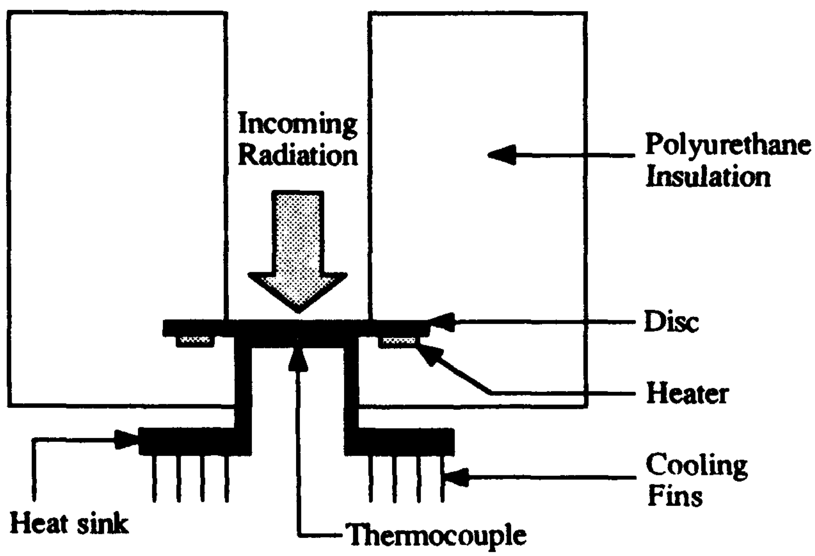


Figure 66. Cutaway view of a thermopile detector arrangement.

c. Photomultiplier tubes. Photomultiplier tubes can be used as detectors for laser radiation. Sensitivity of these detectors are from the UV to near-IR region of the spectrum. A negative potential of 300 - 1,000 volts is applied to the photocathode. In equal increments of potential, dynodes exist between the photocathode and the anode that is at ground potential. When radiation strikes the photocathode, an electron is freed and is accelerated to the first dynode. The kinetic energy of the electron incident on the second dynode is converted into the creation of many more excited electrons. These electrons are accelerated to the third dynode and so on with a multiplication of electron flow occurring for each successive dynode. The result is a current at the anode several orders of magnitude greater than the current possessed by the single electron that initiated the sequence. Photomultiplier tubes can be used for pulsed radiation as well.

d. Pyroelectric detectors. Pyroelectric detectors with the use of a suitable chopper can be used for measuring the output power of CW lasers. A discussion of this detector will be made in the next section.

2. Measurement of energy in a pulsed beam. Energy incident on a detector causes changes in the physical properties of the detector. When heat energy is added to a material, the temperature of the material increases. The temperature rise is dependent on the heat capacity of the material, the mass of the material, and the amount of energy deposited in the material. Calorimeters assess the temperature change in materials. Several common calorimeters will be discussed here.

a. Thermoelectric calorimeters. Thermoelectric calorimeters can be used to determine the temperature increase in an absorbing material. Thermocouple junctions are attached to the surface that absorbs the incident radiation and to a reference surface. The temperature change in a thermoelectric device causes a change in the impedance of the device. Impedance changes are detected by the change in current when a constant potential is applied across the device. The peak temperature difference between the detector and the reference is often recorded and assumed to be proportional to the energy of the pulse. Many styles of thermoelectric calorimeters are available; for the purpose of brevity, diagrams are not provided here.

b. Bolometer. A bolometer is a calorimeter that measures the temperature change in a detector due to a change in its electical impedance. A "rat's nest" bolometer uses hundreds of meters of randomly packed enameled copper wire. When radiation is absorbed by the wire, the temperature and impedance of the wire is increased. Impedance changes can be detected by placing a reference potential across the wire.

c. Pyroelectric calorimeters. Pyroelectric materials are nonconductors where the electrical polarization of the material is a function of temperature. Figure 67 shows a simple diagram of a pyroelectric device as used to measure temperature changes.

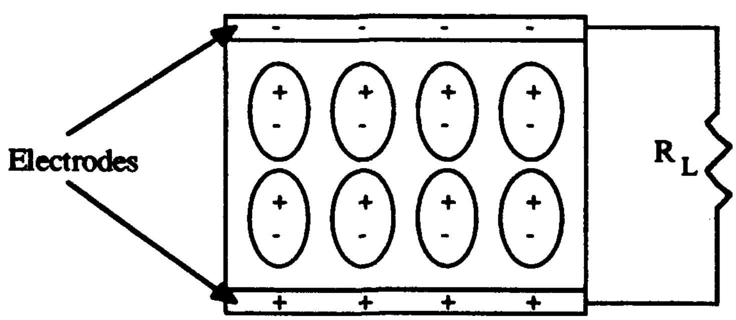


Figure 67. Simple diagram of a pyroelectric device.

The polarization of the material is shown in the diagram. When the material absorbs energy, the temperature of the material rises, the polarization of the material changes, and a current flows through the load impedance, R_L. The current flow can be related to the temperature change in the material. Unfortunately, since current flows only during times of temperature change in the material, pyroelectric materials are not suitable detectors for measurement of CW output beams unless a chopper is used. A chopper selectively transmits and absorbs temporal sections of a laser beam.

3. Measurement of pulse width. Often it is necessary to measure the pulse width of a laser beam. The most commonly used detectors for measuring pulse width of pulsed lasers are PIN photodiodes and pyroelectric detectors. The output signal of the detector is normally input to an oscilloscope for evaluation. To measure pulse width, the speed of the detector must be sufficient to respond to changes in the incident power. Often the speed of a detector is specified by its rise time. The rise time of a detector is the time for the electrical pulse amplitude to increase from 10 % of maximum to 90 % of maximum. Both the photodiode and pyroelectric detectors have rise times about 1 ns. Normally, for measurements of pulse width, the rise time of a detector should be no more than one-fifth of the length of the pulse. Often, however, the electronics associated with the detector limits the overall response time of the measurement system.

D. Control of beam characteristics. Often methods are necessary to alter the spatial characteristics of a beam prior to its measurement by the detector. For example, the active area of some detectors may be smaller than the area of the beam. For these cases, the use of a convex lens may be applied to reduce the beam diameter. Figure 68 provides an example of this scenario.

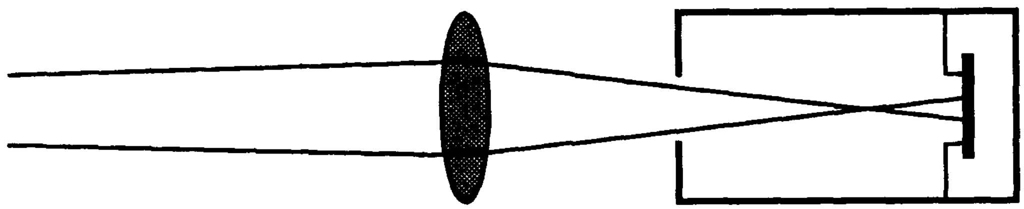


Figure 68. Convex lens converges beam to allow measurement with small area detector.

For some laser beams that have small beam diameters, the irradiance or radiant exposure may exceed the limits of the detector. In these cases, it may be acceptable to expand the beam to allow greater coverage over the surface area of the detector. Figure 69 shows the use of a concave lens to expand the beam.

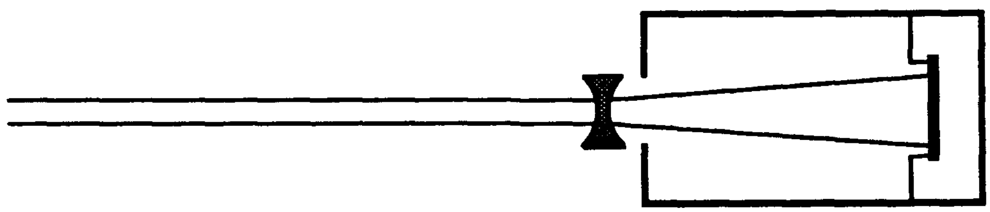


Figure 69. Concave lens expands beam to reduce irradiance (or radiant exposure) at the detector.

In some cases, expanding the beam will not reduce the irradiance at the detector to a level that is acceptable, and the use of an attenuator may be required.

E. Measuring beam diameter. The beam diameter is one of the fundamental laser parameters. For safety purposes, the beam diameter is usually specified at the 1/e point. From the measurement of beam diameter at different points, it is possible to determine the beam divergence. Normally, it is assumed for safety purposes that the beam follows a Gaussian distribution. Numerous methods for determining the beam diameter have been described. Sliney and Wolbarsht (Ref 24) list seven methods: by eye, the aperture method, the ribbon method, the knife edge method, the Rochi ruling method, photographic methods, and using damage profiles. The most common method used for safety purposes is the aperture method. The aperture method relies on two separate measurements: the first, a power or energy measurement of the entire beam and the second, a power or energy measurement with the beam passed through a circular aperture. Assuming a Gaussian distribution, the beam diameter can be determined by the ratio of the power (or energy) of the beam passed through the limiting aperture to the total power (or energy) of the beam, and comparison to the graph in Figure 70.

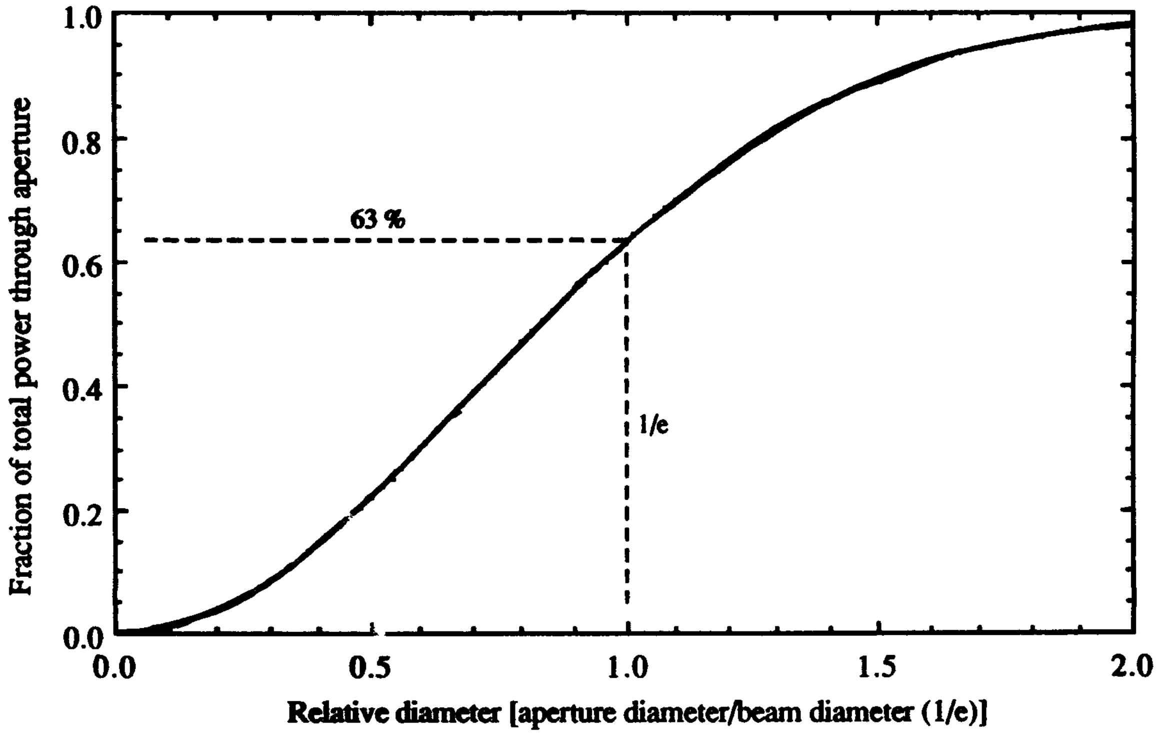


Figure 70. Fraction of power transmitted through a limiting aperture for Gaussian beams.

Example 31. Determining the beam diameter of a Gaussian beam based on power measurements. Determine the beam diameter of a Gaussian beam with a total beam power of 1 watt and a beam power of 0.4 watt as measured through a 2 mm diameter aperture. From Figure 70, the relative diameter is approximately 0.72 and the diameter of the beam is 0.72 x 2 mm or 1.44 mm.

F. Calculating beam divergence. Beam divergence can be calculated based on the measurement of beam diameter at two different distances from the aperture. Equation 52 defines the beam divergence, ϕ, in radians.

$$\phi = [D_{L2} - D_{L1}]/[r_2 - r_1], \tag{52}$$

where D_{L2} and D_{L1} are the beam diameters as measured at distances r_2 and r_1, respectively. Normally, this equation is applicable only to far-field measurements.

Example 32. Calculating the beam divergence for a laser beam with the beam diameter measured at two distances from the aperture. Calculate the beam divergence for a laser beam with beam diameters of 1.5 mm and 2.0 mm measured at distances from the aperture of 0.5 meter and 2 meters. From Equation 52 the beam divergence is calculated.

$\phi = [D_{L2} - D_{L1}]/[r_2 - r_1] = [0.002 - 0.0015 \text{ m}]/[2 - 0.5 \text{ m}] = 0.3$ mrad.

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APPENDIX A

Definitions

Definitions

absorption. Transformation of radiant energy to a different form of energy by interaction with matter.

accessible emission limit (AEL). The maximum accessible limit permitted within a particular class of laser.

accessible radiation. Radiation to which it is possible for the human eye or skin to be exposed in normal usage.

α_{min}. See *limiting angular subtense.*

angstrom (Å). A unit of length commonly used to measure the length of light waves; 1Å = 10^{-10} m.

aperture. An opening through which radiation can pass.

apparent visual angle. The angular subtense of the source as calculated from source size and distance from the eye. It is not the beam divergence of the source. (See section VIIC2b for an example calculation).

attenuation. The decrease in the radiant flux as it passes through an absorbing or scattering medium.

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 or bright light. It can occur with 0.25 s, including the blink reflex time.

beam. A collection of rays that may be parallel, divergent, or convergent.

beam diameter. The distance between diametrically opposed points in that cross-section of a beam where the power per unit area is 1/e (0.368) times that of the peak power per unit area.

birefringence. The splitting of a light ray, generally by a crystal, into two components which travel at different velocities and are polarized at right angles to each other. Birefringent crystals are commonly used to polarize laser beams.

blink reflex. See *aversion response.*

etalon. Special piece of glass that has two faces ground and polished to a higher degree of parallelism. Etalons can be introduced into the laser cavities to provide an output of only the highest Q mode (commonly the TEM_{00} mode).

calorimeter. A device for measuring the total amount of energy absorbed from a source of electromagnetic radiation.

carcinogen. An agent potentially capable of causing cancer.

cladding. The dielectric material surrounding the core of a stepped index optical fiber. The cladding must necessarily have a lower refractive index than the core.

coherent. A light beam is said to be coherent when the electric vector at any point in it is related to that at any other point by a definite, continuous function.

collimated beam. Effectively, a "parallel" beam of light with very low divergence or convergence.

conjunctival discharge (of the eye). Increased secretion of mucus from the surface of the eyeball.

continuous wave. The output of a laser which is operated in a continuous rather than a pulsed mode. In AFOSH Std 161-10, a laser operating with a continuous output for a period ≥ 0.25 s is regarded as a CW laser.

controlled area. An area where the occupancy and activity of those within is subject to control and supervision for the purpose of protection from radiation hazards.

core. The central region of an optical waveguide through which optical energy is transmitted.

cornea. The transparent outer coat of the human eye which covers the iris and the crystalline lens. The cornea is the main refracting element of the eye.

critical viewing distance. The distance from the end of an optical fiber to the point where the beam irradiance, averaged over the limiting aperture, falls below the applicable MPI.

cryogenics. The branch of physics dealing with very low temperatures.

depigmentation. The removal of the pigment of melanin granules from human tissue.

dermatology. A branch of medical science that deals with the skin, its structure, functions, and diseases.

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. Change of the spatial distribution of a beam of radiation when it is reflected in many directions by a surface or by a medium.

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 energy or irradiance is 1/e (36.8%) of the maximum value. For the purposes of AFOSH Std 161-10, divergence is taken as the full angle, expressed in radians, of the beam diameter measured between those points that include laser energy or irradiance equal to 1/e of the maximum value (the angular extent of a beam that contains all the radius vectors of the polar curve of radiant intensity that have length rated at 36.8% of the maximum). Sometimes this is also referred to as beam spread.

edema. The swelling of tissues in the human body due to the presence of abnormal amounts of fluid in the extracellular spaces.

electromagnetic radiation. The flow of energy consisting of orthogonally vibrating electric and magnetic fields lying transverse to the direction of propagation. X-ray, ultraviolet, visible, infrared, and radio waves occupy portions of the electromagnetic spectrum and differ only in frequency and wavelength.

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.

energy (Q). The capacity for doing work. Energy content is commonly used to characterize the output from pulsed lasers, and is generally expressed in joules (J).

epidemiology. A branch of medical science that deals with the incidence, distribution and control of disease in a population.

epithelium (of the cornea). The layer of cells forming the outer surface of the cornea.

erythema. Redness of the skin due to congestion of the capillaries.

extended source. A source of radiation that can be resolved by the eye into a geometrical image, in contrast to a point source of radiation, which cannot be resolved into a geometrical image.

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.

fiber optics. The branch of optical technology concerned with the transmission of radiant power through fibers made of transparent materials such as glass, fused silica, or plastic.

focal length. The distance from the secondary nodal point of a lens to the primary focal point. In a thin lens, the focal length is the distance between the lens and the focal point.

focal point. The point toward which radiation converges or from which radiation diverges or appears to diverge.

fundus. See *ocular fundus*.

funduscopic. Examination of the fundus (rear) of the eye.

graded index profile. Any refractive index profile that varies with core radius.

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.

hertz (Hz). The unit which expresses the frequency of a periodic oscillation in cycles per second. Typically, the hertz is also found in the following multiples:

kilohertz (kHz) = 10^3 Hz
megahertz (MHz) = 10^6 Hz
gigahertz (GHz) = 10^9 Hz

infrared radiation. Electromagnetic radiation with wavelengths which lie within the range 0.7 μm to 1 mm (700 nm - 10^6 nm).

integrated radiance (L). The integral of the radiance over the exposure duration. Also known as pulsed radiance. Units: joules per square centimeter per steradian ($J/cm^2/sr$).

intrabeam viewing. The viewing condition whereby the eye is exposed to all or part of a laser beam.

ionizing radiation. Electromagnetic radiation having sufficiently large photon energy to directly ionize atomic or molecular systems with a single quantum event.

iris. The circular pigmented membrane that lies behind the cornea of the human eye. The iris is perforated by the pupil.

irradiance (E) (at a point of a surface). Quotient of the radiant flux incident in an element of the surface containing the point at which irradiance is measured, by the area of that element. Unit: watt per square centimeter (W/cm^2).

Jaeger's test. Samples of type of various sizes printed on a card for testing close visual acuity. An analogue of the Snellen chart for distant visual acuity.

joule (J). A unit of energy. 1 joule = 1 watt · second.

Lambertian surface. An ideal surface whose emitted or reflected radiance is independent of the viewing angle.

laser. A device that produces an intense, coherent, directional beam of light by stimulating electronic or molecular transitions to lower energy levels. An acronym for Light Amplification by Stimulated Emission of Radiation.

laser diode. A laser employing a forward-biased semiconductor junction as the active medium.

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 that includes a laser.

lens connector. A connector which, by its design, decreases the divergence inherent in the optical fiber. Because of decreased divergence, the nominal hazard zone (NHZ) associated with lens connectors may be considerably greater than that of a conventional connector.

lesion. An abnormal change in the structure of an organ or part due to injury or disease.

light emitting diode (LED). A p-n junction semiconductor device that emits incoherent optical radiation when biased in the forward direction.

limiting angle subtense (α_{min}). The apparent visual angle that divides intrabeam viewing from extended-source viewing.

limiting aperture. The maximum diameter of a circle over which irradiance and radiant exposure can be averaged.

limiting exposure duration (τ_{max}). An exposure duration which is specifically limited by the design or intended use(s).

lossy medium. A medium that 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, that 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 section.

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.

maximum permissible irradiance (MPI). The level of a laser or LED radiation, associated with OFSC, to which a person may be exposed without hazardous effect or adverse biological changes in eye or skin. MPI values are unique for application to OFCS. MPI values are the same as MPE values specified in ANSI Z136.1 for the far-infrared region. For the visible and near-infrared region, the MPIs are derived from the ANSI Z136.1 MPEs and are related by the ratio of the area of a 5 mm diameter limiting aperture to a 7 mm diameter limiting aperture.

meter (m). A unit of length in the international system of units; currently defined as a fixed number of wavelengths, in vacuum, of the orange-red line of the spectrum of ^{86}Kr. Typically, the meter is subdivided into the following units:

centimeter (cm) = 10^{-2} m
millimeter (mm) = 10^{-3} m
micrometer (μm) = 10^{-6} m
nanometer (nm) = 10^{-9} m

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 distance along the axis of the unobstructed beam from the laser to the human eye beyond which the irradiance or radiant exposure during normal operation is not expected to exceed the appropriate MPE.

ocular fundus. The back of the eye. May be seen through the pupil with an ophthalmoscope.

operation. The performance of the laser (system) over the range of its intended functions (normal operation). It does not include *maintenance* or *service* as defined in this section.

ophthalmoscope. An instrument for examining the interior of the eye.

optical density (D_λ). Logarithm to the base ten of the reciprocal of the transmittance:
$D_\lambda = -\log_{10} \tau_\lambda$ is transmittance.

optical fiber. Any filament or fiber, made of dielectric materials, that guides light, whether or not it is used to transmit signals.

optical fiber communication system. A system consisting of one or more laser or LED transmitters, each of which is coupled to an individual fiber and which is used for the transmission of information, e.g., voice or data.

optically aided viewing. Viewing with an optical device like binoculars or for the case of an optical fiber an eye loupe, hand magnifier, microscope, etc. Optically aided viewing does not include viewing with corrective eyewear or with indirect image converters.

optically pumped laser. A laser in which the electrons are excited into an upper energy state by the absorption of light from an auxiliary light source.

optical time domain reflectometry (OTDR). A method for characterizing a fiber wherein an optical pulse is transmitted through the fiber and the resulting light scattered back to the input is measured as a function of time.

optical waveguide. Any structure capable of guiding optical power. In optical communications, generally a fiber designed to transmit optical signals.

photophobia. An unusual intolerance of light. Also, an aversion to light usually caused by physical discomfort upon exposure to light.

photosensitizer. Substances that increase the sensitivity of a material to irradiation by electromagnetic energy.

pigment epithelium (of the retina). The layer of cells that contain brown or black pigment granules next to and behind the rods and cones.

point source. A source of radiation whose dimensions are small enough, compared with the distance between source and receptor, to be neglected in calculations.

power (Φ). The rate at which energy is emitted, transferred, or received. Units: watts (joules per second).

prf. Abbreviation for pulse-repetition frequency.

protective housing. An enclosure that surrounds the laser or laser system that prevents access tò laser radiation above the applicable MPE level. The aperture through which the useful beam is emitted is not part of the protective housing. The protective housing may enclose associated optics and a work station and shall limit access to other associated radiant energy emissions and to electrical hazards associated with components and terminals.

pulse duration. The duration of a laser pulse; usually measured as the time interval between the half-power points on the leading and trailing edges of the pulse.

pulsed laser. A laser that delivers its energy in the form of a single pulse or a train of pulses. In AFOSH Std 161-10, the duration of a pulse < 0.25 s.

pupil. The variable aperture in the iris through which light travels to the interior of the eye.

Q-switch. A device for producing very short (≈30 ns), intense laser pulses by enhancing the storage and dumping of electronic energy in and out of the lasing medium, respectively.

Q-switched laser. A laser that emits short (≈30 ns), high-power pulses by means of a Q-switch.

radian (rad). A unit of angular measure equal to the angle subtended at the center of a circle by an arc whose length is equal to the radius of the circle. 1 radian ≈ 57.3 degrees; 2π radians = 360 degrees; 1 milliradian = 10^{-3} radians.

radiance (L). Radiant flux or power output per unit solid angle per unit area. Unit: watts per centimeter squared per steradian ($W/cm^2/sr$).

radiant energy (Q). Energy emitted, transferred, or received in the form of radiation. Units: joule (J).

radiant exposure (H). Surface density of the radiant energy received. Unit: joules per centimeter squared (J/cm^2).

radiant flux (Φ). Power emitted, transferred, or received in the form of radiation. Unit: watt (W). Also called *radiant power*.

radiant intensity (I) (of a source in a given direction). Quotient of the radiant flux leaving the source and propagated in an element of solid angle containing the given direction, by the element of solid angle. Units: watts per steradian (W/sr).

radiant power. See *radiant flux*.

radiometry. A branch of science that deals with the measurement of radiation. For the purposes of this guidebook and AFOSH Std 161-10, radiometry will be limited to the measurement of visible and ultraviolet radiation.

Rayleigh scattering. Scattering of radiation in the course of its passage through a medium containing particles whose sizes are small compared with the wavelength of the radiation.

reflectance (ρ). The ratio of total reflected radiant power to total incident power. Also called *reflectivity*.

reflection. Deviation of radiation following incidence on the surface.

retina. The sensory membrane that receives the incident image formed by the cornea and lens of the human eye. The retina lines the outside of the eye.

scanning laser. A laser having a time-varying direction, origin, or pattern of propagation with respect to stationary frame of reference.

scintillation. The rapid changes in irradiance levels in a cross-section of a laser beam.

second (s). A unit of time in the international system of units. Typically, the second is subdivided into the following units:

millisecond (ms) = 10^{-3} s
microsecond (μs) = 10^{-6} s
nanosecond (ns) = 10^{-9} s
picosecond (ps) = 10^{-12} s
femtosecond (fs) = 10^{-15} s

service. The performance of those procedures or adjustments described in the manufacturer's service instructions that may affect any aspect of the performance of the laser or laser system. It does not include *maintenance* or *operation* as defined in this section.

shall. The word "shall" is understood as mandatory.

should. The word "should" is to be understood as advisory.

single-mode in optical waveguide. An optical waveguide in which only the lowest-order bound mode or degenerate pairs of orthogonally polarized bound modes can propagate at the wavelength of interest.

solid angle (Ω). The three-dimensional angular spread at the vertex of a cone measured by the area intercepted by the cone on a unit sphere whose center is the vertex of the cone. It is expressed in steradians (sr).

source. A laser or a laser illuminated reflecting surface.

specular reflection. A mirrorlike reflection.

steradian (sr). The unit of measure for a solid angle. There are 4π steradians about any point in space.

stromal haze (of the cornea). Cloudiness in the connective tissue or main body of the cornea.

surface exfoliation (of the cornea). A stripping or peeling off of the surface layer of cells from the cornea.

tonometry. Measurement of the pressure (tension) of the eyeball.

transmission. Passage of radiation through a medium.

transmittance (τ). The ratio of total transmitted radiant power to total incident radiant power.

ultraviolet radiation. Electromagnetic radiation with wavelengths smaller than those of visible radiation; for the purposes of this guidebook, 0.2 to 0.4 μm (200 - 400 nm).

visible radiation (light). Electromagnetic radiation that can be detected by the human eye. This term is commonly used to describe wavelengths that lie in the range 0.4 to 0.7 μm (400 - 700 nm).

watt (W). The unit of power or radiant flux. 1 watt = 1 joule per second.

wavelength (λ). The distance between two successive points on a periodic wave that have the same phase.

APPENDIX B

Laser Safety Eyewear Listing

Laser Safety Eyewear Listing

This appendix contains a listing of commercially available laser safety eyewear. The listing is similar to a database of available laser safety eyewear maintained by the Armstrong Laboratory, Radiation Consultant Function (AL/OEBSC) and by no means is complete. AL/OEBSC maintains this list as a service to Air Force units to assist in maintenance of their occupational and safety programs, but does not endorse any of the devices.

Glendale Protective Technologies, Inc
130 Crossways Park Drive
Woodbury, N.Y. 11797
Com: (516) 921-5800

Glendale manufactures Laser-Gard goggles and spectacles. The Laser-Gard LGS series uses a variety of filters in its soft vinyl safety goggles. The goggles have four air vents to prevent fogging. The Laser-Gard 2500 series uses a variety of filters in its lightweight plastic spectacles frames. The Laser-Gard VL series is one-piece spectacles that have side protection. The optical density at various wavelengths and the costs are given below. The price quotes are from a December 1988 brochure.

	Optical Density for Wavelengths of Interest (λ in nanometers)								Luminous	
Model	λ	OD	λ	OD	λ	OD	λ	OD	Transmittance	Cost
LGA*	337	20	694	6	840	20	1060	20	20 %	$ 243.90
LGB*	200-400	14	488	11	515	7	530	4	45 %	$ 243.90
					840	4	1060	4		
LGS-A-NDGA**	353	20	530	7	1060	14			15 %	$ 271.10
VL-, LGS-, or 2500-										
A	488	15	514	11					45 %	$ 133.45
NN	332	15	337	16					70 %	$ 133.45
HN	633	6							20 %	$ 133.45
R	694	6							20 %	$ 133.45
K	647	5	676	5	694	5			25 %	$ 133.45
NDGA	840	6	1060	14					30 %	$ 133.45
CO2	10600	12							30 %	$ 133.45
LOD-ND CO2*	1060	4.5	10600	10					55 %	$ 140.50
LOD-CO2*	10600	10							55 %	$ 43.80
LOD-K*	647	1	676	2	694	1			45 %	$ 140.50
LOD-A*	488	2.6	515	2.1					60 %	$ 140.50
LOD-HN*	633	2							40 %	$ 140.50
Film (5 mils)***	200-400	5.5	332	5.5	337	5.5	633	0.3	60 %	$ 224.64
	694	1.3	840	10	1060	10	10600	3.8		per sq.ft.

* LGS or 2500 series
** LGS only
*** Lower cost for areas greater than 9 sq.ft.

LGS-NDGA: NSN = 4240-00-620-0054
LGA (LGS): NSN = 4240-00-258-2054
LGB(2500): NSN = 4240-00-188-3728

Lase-R Shield, Inc
P.O. Box 80245
Albuquerque, NM 87198-0245
Com: (505) 266-0222 Fax: (505) 260-1459

Lase-R Shield, Inc. offers custom spectacles and goggles designs and Laser-Gard products. Twelve spectacles style frames are available and 6 goggles style frames are available. Other products like laser-blocking film are also available. The specifications and pricing are from a December 1988 sales brochure.

a. Custom spectacles.

Type	Cost	Glass lenses					Frame styles		
Plano, flat glass	$ 165	KG-3	GG-9	GG-10	GG-400	GG-420	G74	G75	T10
Plano, 6 diopter curve	$ 197	GG-455	GG-475	GG-495	OG-515	OG-530	T70	M52	K44
Single vision correction	$ 213	OG-550	OG-570	OG-590	RG-610	RG-630	A38	A24	A98
Bifocal correction	$ 265	RG-645	RG-665	BG-1	BG-3		A91	A99	A92

Type	Cost	Plastic lenses	Frame styles
Plano, 6 diopter curve	$ 73	UV-4 (OD = 4, λ: 200 - 400 nm: lum. tr. = 95 %)	Same as above
Single vision correction	$ 86	UV-515 (OD = 4, λ: 200 - 515 nm; lum. tr. = 60 %; add $ 45)	
Bifocal correction	$ 101		

Type	Cost	Multiwavelength protection	Frame styles
Plano, flat glass	$ 310	Selection of two glass lenses as given above or use of the following: KG-5, BG-18, BG-39, or BG-40 (add $ 20 for each of these used) or use of the following: BG-15, BG-26, BG-36, BG-38, NG-1, NG-3, NG-4, NG-5, VG-10, or VG-14 (add $ 50 for each of these used)	Same as above
Cemented, flat glass	$ 315		
Plano, 6 diopter curve	$ 375		
Cemented, plano, curved	$ 380		
Single vision correction	$ 400		
Bifocal correction	$ 465		
Cemented, plano curved*	$ 270		
Cemented, single vision*	$ 285		

* UV-4 filter in place of one glass filter

b. Custom goggles.

Type	Cost	Glass lenses	Frame styles
Vinyl body w/vents for single filter	$ 160	Selection of glass lenses from single design or use of the following: KG-5, BG-18, BG-39, or BG-40 (add $ 20 for each of these used) or use of the following: BG-15, BG-26, BG-36, BG-38, NG-1, NG-3, NG-4, NG-5, VG-10, or VG-14 (add $ 50 for each of these used)	GU1
Vinyl body w/vents for two filters	$ 300		GU2

c. Laser-Gard products.

	Optical Density for Wavelengths of Interest (λ in nanometers)								Luminous	
Model	λ	OD	λ	OD	λ	OD	λ	OD	Transmittance	Cost
LGU-NDGA	840	14	1064	14					30 %	$ 120
LG-A	337	20	694	6	840	20	1060	20	20 %	$ 256
LG-B	200-400	14	488	11	515	7	530	4	45 %	$ 256
	840	4	1060	4						
LGS-A-NDGA	353	20	530	7	1060	14			15 %	$ 285
VL-, LGS-, and 2500-										$ 141
A	488	15	514	11					45 %	"
NN	332	15	337	16					70 %	"
HN	633	6							20 %	"
R	694	6							20 %	"
K	647	5	676	5	694	5			25 %	"
NDGA	840	6	1060	14					30 %	"
CO2	10600	12							30 %	"
LOD-ND CO2*	1060	4.5	10600	10					55 %	$ 148

	Optical Density for Wavelengths of Interest (λ in nanometers)								Luminous	
Model	λ	OD	λ	OD	λ	OD	λ	OD	Transmittance	Cost
LOD-CO2*	10600	10							55 %	$ 47
LOD-K*	647	1	676	2	694	1			45 %	$ 148
LOD-A*	488	2.6	515	2.1					60 %	$ 148
LOD-HN*	633	2							40 %	$ 148
AR-LEPD 11	488-515	4							60 %	
UVC-303	200-400	4 (spectacles)							95 %	$ 12
UVC-503	200-400	4 (goggles)							95 %	$ 15
LRS-1112A	10600	10 (spectacles)							95 %	$ 10
LRS-3202A	10600	10 (goggles)							95 %	$ 12

Laser-Gard Film: 5mil film with OD of 10 for 840 and 1060 nm, luminous transmittance = 60 %, cost = $ 23.40/lineal ft for 15" width and $ 46.80/lineal ft for 30" width.

Laser-Blocking Film: Optical density of 4 at 515 or 632.8 nm, cost = $17.40 for 24" x 21" sheet and $400.00 for 25' x 4' sheet.

* LGS and 3500 series only

Fred Reed Optical, Inc.
P.O. Box 27010
Albuquerque, N.M. 87125-7010
Com: (505) 265-3531

Fred Reed Optical offers a multitude of products from American Optical Corp, Schott Optical Glass Company, Glendale Optical Company, Titmus Optical Inc., and Ultra-violet Products Inc. Provided is a price list of their custom spectacles service. The prices are quoted from a March 1989 brochure.

Type	Cost	Glass lenses					Frame styles
Flat curve	$ 155			KG-3			GBS
Six diopter curve	$ 185			KG-3			GBS
Single vision prescr	$ 200			KG-3			GBS
Round bifocal prescr	$ 260			KG-3			Any
Flat-top trifocal prescr	$ 285			KG-3			Any
Flat curve	$ 170	BG-1	BG-3	BG-14	BG-26	GG-400	GBS
Six diopter curve	$ 195	GG-420	GG-435	GG-455	GG-475	GG-495	GBS
Single vision prescr	$ 215	OG-515	OG-530	OG-550	OG-570	OG-590	GBS
Round bifocal prescr	$ 270	RG-610	RG-630	RG-645	RG-665	VG-10	Any
Flat-top trifocal prescr	$ 295						Any
Flat curve	$ 175						GBS
Six diopter curve	$ 200						GBS
Single vision prescr	$ 220	BG-18	BG-39	BG-40	KG-5	GG-9	GBS
Round bifocal prescr	$ 275						Any
Flat-top trifocal prescr	$ 300						Any

CVI Laser Corp
P.O. Box 11308
200 Dorado Place SE
Albuquerque NM 87192-0308
Com: (505) 296-9541 Fax: (505) 298-9908

CVI manufactures laser goggles eye protection. There are two basic styles: goggles with separate filters for each eye (called "goggles" style) and a laser goggles shield with one solid filter for both eyes (called "shield" style). Each of these styles also has an optional hinge for the filter assembly to flip. This feature allows the protection to be temporarily removed without removing the goggles. Protection is available for single and double wavelengths as shown below. Prices are quoted from a January 1989 brochure.

Type	λ	OD	λ	OD	Style	Cost
Quadrupled YAG	266	6			Any	$ 168
Neon/Nitrogen	332	6	337	6	Any	$ 168
Tripled YAG	355	6			Any	$ 168
Argon	488	6	515	6	Any	$ 168
Argon	488	3	515	3	Any	$ 168
Doubled YAG	530	6			Any	$ 168
Doubled YAG	530	3			Any	$ 168
Helium-Neon	633	6			Any	$ 168
Helium-Neon	633	3			Any	$ 168
Ruby	694	6			Any	$ 168
Ruby	694	3			Any	$ 168
Gallium-Arsenide	780	6	905	6	Any	$ 168
YAG	1064	6			Any	$ 168
Carbon monoxide	5000	6			Any	$ 168
Carbon dioxide	10600	6			Any	$ 168
Quadrupled YAG/YAG	266	6	1064	6	Any but flip goggles*	$ 336
Tripled YAG/YAG	355	6	1064	6	Any but flip goggles*	$ 336
Doubled YAG/YAG	530	6	1064	6	Any but flip goggles*	$ 336
Helium-Neon/YAG	633	6	1064	6	Any but flip goggles*	$ 336
Ruby/YAG	694	6			Any but flip goggles*	$ 336

* Flip shields add $ 10

Laser-X
1760 Grand Avenue
Merrick, NY 11566
Com: (516) 379-1203

Laser-X offers a variety of products including laser safety glasses and goggles, and laser safety signs. Unfortunately, the August 1988 brochure did not specify optical densities or luminous transmission values for the safety glasses and goggles. The prices are given:

Description	Cost	Description	Cost
Planar glasses for Nd:YAG	$ 160	Prescription glasses for Nd:YAG	$ 250
Safety goggles for Nd:YAG	$ 145	Planar glasses for CO_2	$ 15
Planar glasses for argon	$ 170	Prescription glasses for argon	$ 260
Safety goggles for argon	$ 160	Planar glasses for Cu vapor (578 nm)	$ 260
Prescription glasses for Cu vapor	$ 370	Safety goggles for Cu vapor	$ 240

Phase-R Corp
Box G-2
New Durham, NH 03855
Com: (603) 859-3800

Phase-R is a manufacturer of laser components. The company has developed a pair of goggles for broadband protection against tunable dye lasers. The blue goggles have optical density values at the following wavelengths: 6 (300 nm), < 1 (350 - 515 nm), 2 (535 nm), 3 (555 nm), 4 (580 nm), 5 (600 nm), 6 (590 nm), and 4 (700 nm). The red goggles have optical density values at the following wavelengths: 5 (400 nm), > 4 (400 - 520 nm), > 3 (520 - 570 nm), > 2 (570 - 600 nm), > 1 (600 - 620 nm), and < 1 (620 - 900 nm). The price quoted for the blue goggles was $ 245 and $175 for the red goggles.

UVEX Winter Optical, Inc
10 Thurber Blvd
Smithfield RI, 02917-1896
Com: (401) 232-1200

UVEX manufactures laser safety eyewear for applications involving many different lasers. In response to Armstrong Laboratory's query for information, they provided the following information. The price quotes were made August 1989. No details were given for optical density or luminous intensity. For all of the devices both goggles or spectacles are available except for the helium-neon/gallium-arsenide/Nd:YAG/CO_2.

Lasers that protection is afforded	Cost	Lasers that protection is afforded	Cost
Nd:Yag, Erbium, Holium Ti:Sapphire, CO, CO_2	$ 442	CO_2	$ 300
Broadband (200 - 578 nm)	$ 300	Excimers (UV)	$ 300
Rhodamine 6G, Dye lasers	$ 590	Excimers (UV), Argon, Doubled YAG	$ 340
Argon	$ 330	He-Ne, GaAs, Nd:YAG, CO_2	$ 350
Excimers (UV), Argon, Doubled YAG, Nd:YAG	$ 675	Nd:YAG	$ 385

Newport Corp
18235 Mt Baldry Circle
Fountain Valley, CA 92708

Newport stocks the Laser-Gard 2500 series spectacles and LGS series goggles. Since optical density and luminous intensity values were stated previously in the Glendale Optical Corp summary, they are omitted here.

Model	Laser line (s)	Cost	Model	Laser line (s)	Cost
G-LGS-A	Argon	$ 140	G-2566-A	Argon	$ 140
G-LGS-NN	Neon/Nitrogen	$ 140	G-2566-NN	Neon/Nitrogen	$ 140
G-LGS-HN	He-Ne	$ 140	G-2566-HN	He-Ne	$ 140
G-LGS-R	Ruby	$ 140	G-2566-R	Ruby	$ 140
G-LGS-NDGA	Nd:YAG/GaAs	$ 140	G-2566-NDGA	Nd:YAG/GaAs	$ 140
G-LGS-CO2	Carbon dioxide	$ 140	G-2566-CO2	Carbon dioxide	$ 140
G-LGS-K	Krypton	$ 140	G-2566-K	Krypton	$ 140
G-LGA	Broad spectrum	$ 255	G-LGB	Broad spectrum	$ 255
G-LGS-A-NDGA	Broad spectrum	$ 285	G-2500LOD-A	LoOptDen Argon	$ 140
G-2500LOD-HN	LoOptDen He-Ne	$ 140			

Spindler and Hoyer

Spindler and Hoyer offer both spectacles and goggles with a variety of filtering glasses for the wavelengths of different lasers. The list below gives the laser application, optical density for the wavelength of interest, and luminous intensity. Cost was not included in the brochure submitted to Armstrong Laboratory.

Laser type	λ region	OD	LumTrans	Laser type	λ region	OD	Lum Trans
Excim/Nitro/Argon	200-515 nm	>10	30 %	He-Ne/Gold vapor	627-650 nm	> 5	26 %
GaAs/Nd:YAG	700-1320 nm	> 10	30 %	GaAlAs/Nd:YAG	900-1050 nm	> 4	70 %
GaALAs/Nd:YAG	900-1050 nm	>7	65 %		1050-1400 nm	> 8	
	1050-1400 nm	> 11			1400-2200 nm	> 6	
	1400-2200 nm	> 8		CO_2	10,600 nm	> 4	90 %

U.S. Laser Corp
825 Windham Court North
Wyckoff, N.J. 07481
Com: (201) 848-9200

U.S. Laser Corp stocks safety spectacles and goggles for a variety of laser applications. Discounts are available for orders of 10 or more items with the same part number.

Laser type	λ region	OD	LumTrans	Cost	Laser type	λ region	OD	Lum Trans	Cost
Nd:YAG	1064 nm	> 6	85 %	$ 93	CO_2	10,600 nm	> 10	90 %	$ 57
Nd:YAG	1064 nm	> 12	80 %	$ 169	Ruby/Alex	690-850 nm	> 6	70 %	$ 99
Db YAG/Ar	532 nm	> 6	50 %	$ 96	He-Ne	633 nm	> 7	40 %	$ 91

Fish-Schurman Corp
70 Portman Rd
New Rochelle NY 10802
Com: (914) 636-1300

Fish-Schurman manufactures two styles of protective eyewear: goggles that use two 50 mm lenses and a goggles shield that uses a 2" x 4.25" filter. The model numbers along with optical density, luminous transmission, and cost are given in the following table.

Model No	λ (nm)	OD	LumTrans	Cost	Model No	λ (nm)	OD	Lum Trans	Cost
AL-430-6	≤ 430	6	90%	$ 115	AL-515	≤ 515	7	46 %	$ 115
AL-565	≤ 565	4	15 %	$ 115	AL-633	633-1500	4	30 %	$ 115
AL-694-12	694-1300	12	26%	$ 135	AL-1060-9	1060-1320	9	63 %	$ 115
AL-10600	10600	> 20	92 %	$ 115	AL-578-5	578	5	12 %	$ 115
						511	10		

Omega Optical Inc.
3 Grove Street
Brattleboro VT 05301
Com: (802) 254-2690

Omicron, a division of Omega Optical, laser safety eyewear reflects a small band of wavelengths (rejection) while transmitting other visible wavelengths. The rejection band required must be specified by the purchaser; costs for the goggles is dependent on the optical density required, for OD=3, the cost is $ 300; for OD=4, the cost is $ 350; and for OD=5, the cost is $ 385. Omega manufactures the model S3A for protection from 532 nm, 694 nm, and 1064 nm. The cost of the goggles is dependent on the OD required; for OD=3, the cost is $ 385; for OD=4, the cost is $ 540; and for OD=5, the cost is $ 625. Omega makes a two goggles set that provides effective coverage for specified wavelengths from the UV to mid-IR range. The pair is designed to complement each other, one goggles transmits in a particular wavelength region, while the other attenuates. Goggles 1 have an OD≥4 for the following regions: > 440 nm, 475 - 520 nm, 570 - 625 nm. Goggles 2 have an OD ≥ for the following regions: 440 - 475 nm, 520 - 570 nm, and mid-IR - 625 nm. The price of the set of goggles is $ 890.

APPENDIX C

Common Air Force Laser Systems

LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Intermec 9500/	9420/1600		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Barcode Scanner	He Ne	

MODE OF OPERATION: [X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length)

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.001 J (W)	0.001 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	CW Hz	CW Hz	Hz
PULSE WIDTH	CW sec	CW sec	sec
BEAM DIAMETER (at 1/e point)	0.02 cm	0.02 cm	cm
BEAM DIVERGENCE (at 1/e point)	0.9 mrad	0.9 m rad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR POINT	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR EXT.	CW OR SINGLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
OCULAR EXT.	MULTIPLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
SKIN POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
SKIN POINT	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	OD	OD	OD	OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI 20

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LASER HAZARD EVALUATION

LASER HAZARD EVALUATION	DATE (YYMMDD)	WORKPLACE IDENTIFIER
(Use this space for mechanical imprint)	BASE	ORGANIZATION
	WORKPLACE	
	BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Laser Designator	G/VGLD or TVQ-	2	

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
	Nd : YAG	

MODE OF OPERATION ☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length)

EMISSION CHARACTERISTICS

TIME (sec) & WAVELENGTH (λ)	10 sec 1064 nm	30,000 sec 1064 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.125 J (W)	0.125 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	20 Hz	20 Hz	Hz
PULSE WIDTH	25 nsec	25 n sec	sec
BEAM DIAMETER (at 1/e point)	7.3 cm	7.3 cm	cm
BEAM DIVERGENCE (at 1/e point)	0.07-0.13 mrad	0.07-0.13 m rad	rad

MAX PERMISSABLE EXPOSURE (MPE)

OCULAR POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR EXT.	CW OR SINGLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
	MULTIPLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
SKIN POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2

SAFE EXPOSURE DISTANCES

		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES

		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	OD	OD	OD	OD		OD
	AT ______ m	OD	OD	OD	OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ______ m	OD		OD		OD	
	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	☒ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☒ YES ☐ NO	☐ A ☐ B ☐ C ☐ D ☐ E ANSI4

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LASER HAZARD EVALUATION

DATE *(YYMMDD)*	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Cooper Lasersonics	CO2		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Surgical	CO2	

MODE OF OPERATION

[X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME *(Train Length)*

EMISSION CHARACTERISTICS			
TIME *(sec)* & WAVELENGTH *(λ)*	10 sec 10,600 nm	10 sec 10,600 nm	sec nm
ENERGY/PULSE *(J)* OR CW POWER *(W)*	60 J (W)	60 J (W)	J (W)
PULSE REPETITION FREQUENCY *(PRF)*	CW Hz	CW Hz	Hz
PULSE WIDTH	CW sec	CW sec	sec
BEAM DIAMETER *(at 1/e point)*	0.03 cm	0.03 cm	cm
BEAM DIVERGENCE *(at 1/e point)*	50 mrad	50 mrad	rad

MAX PERMISSABLE EXPOSURE *(MPE)*					
OCULAR	POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
		MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2
	EXT.	CW OR SINGLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
		MULTIPLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
SKIN	POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
		MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2

SAFE EXPOSURE DISTANCES			SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE		m	m	m	m	m	m
	MULTIPLE PULSE		m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE		m	m	m	m	m	m
	MULTIPLE PULSE		m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	OD	OD	OD	OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ______ m	OD		OD		OD	
	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI4

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LASER HAZARD EVALUATION

LASER HAZARD EVALUATION	DATE (YYMMDD)	WORKPLACE IDENTIFIER	
(Use this space for mechanical imprint)		BASE	ORGANIZATION
		WORKPLACE	
		BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Surgilase	40		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Surgery	CO2	

MODE OF OPERATION	MAX EXPOSURE TIME (Train Length)
[X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE	

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	10 sec 10,600 nm	30,000 sec 10,600 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	40 J (W)	40 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	CW Hz	CW Hz	Hz
PULSE WIDTH	CW sec	CW sec	sec
BEAM DIAMETER (at 1/e point)	0.01 cm	0.01 cm	cm
BEAM DIVERGENCE (at 1/e point)	.08 rad	.08 rad	rad

MAX PERMISSABLE EXPOSURE (MPE)					
OCULAR	POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR	POINT	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR	EXT.	CW OR SINGLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
OCULAR	EXT.	MULTIPLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
SKIN	POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
SKIN	POINT	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2

SAFE EXPOSURE DISTANCES			SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE		m	m	m	m	m	m
NO ATM ATTEN.	MULTIPLE PULSE		m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE		m	m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE		m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	OD	OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI4

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LASER HAZARD EVALUATION

LASER HAZARD EVALUATION	DATE (YYMMDD)	WORKPLACE IDENTIFIER	
(Use this space for mechanical imprint)		BASE	ORGANIZATION
		WORKPLACE	
		BLDG NO/LOCATION	ROOM/AREA
RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Symbol Technologies	LS7000		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Bar Code Scanner	He Ne	

MODE OF OPERATION: [X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length):

EMISSION CHARACTERISTICS

TIME (sec) & WAVELENGTH (λ)	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.001 J (W)	0.001 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	CW Hz	CW Hz	Hz
PULSE WIDTH	CW sec	CW sec	sec
BEAM DIAMETER (at 1/e point)	0.67 cm	0.67 cm	cm
BEAM DIVERGENCE (at 1/e point)	2.3 mrad	2.3 mrad	rad

MAX PERMISSABLE EXPOSURE (MPE)

OCULAR	POINT	CW OR SINGLE PULSE	J/cm²	J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
	EXT.	CW OR SINGLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
		MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN	POINT	CW OR SINGLE PULSE	J/cm²	J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES

			SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE		m	m	m	m	m	m
	MULTIPLE PULSE		m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE		m	m	m	m	m	m
	MULTIPLE PULSE		m	m	m	m	m	m

OPTICAL DENSITIES

		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	OD	OD	OD	OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ____ m	OD		OD		OD	
	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI2A

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LASER HAZARD EVALUATION

LASER HAZARD EVALUATION	DATE *(YYMMDD)*	WORKPLACE IDENTIFIER
(Use this space for mechanical imprint)	BASE	ORGANIZATION
	WORKPLACE	
	BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Hughes	3221		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Pave Spike Alignment	He Ne	

MODE OF OPERATION: [X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME *(Train Length)*:

EMISSION CHARACTERISTICS	TIME *(sec)* & WAVELENGTH *(λ)*	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
	ENERGY/PULSE *(J)* OR CW POWER *(W)*	0.005 J (W)	0.005 J (W)	J (W)
	PULSE REPETITION FREQUENCY *(PRF)*	CW Hz	CW Hz	Hz
	PULSE WIDTH	CW sec	CW sec	sec
	BEAM DIAMETER *(at 1/e point)*	0.45 cm	0.45 cm	cm
	BEAM DIVERGENCE *(at 1/e point)*	0.92 m rad	0.92 m rad	rad
MAX PERMISSABLE EXPOSURE *(MPE)* — OCULAR — POINT	CW OR SINGLE PULSE	6.36×10^{-4} J/cm²	5.24×10^{-1} J/cm²	J/cm²
	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
OCULAR — EXT.	CW OR SINGLE PULSE	6.30 J/cm² sr	1.1×10^{3} J/cm² sr	J/cm² sr
	MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN — POINT	CW OR SINGLE PULSE	7.78×10^{-1} J/cm²	6×10^{3} J/cm²	J/cm²
	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	1.23×10^{1} m	Ø m	2.03×10^{2} m	Ø m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	1.09 OD	Ø OD	3.26 OD	Ø OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ______ m	OD		OD		OD	
	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER	APERTURE	TRANSMITTANCE	[X] OEHL HAZARD EVALUATION	[ ] YES [X] NO	[ ] A [ ] B [ ] C
X	cm	%	[ ] AFOSH STD 161-10 CALCULATIONS		[ ] D [ ] E ANSI3A

AF FORM 2760 JAN 82

LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Phillips Products	Pave Penny Align		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Alignment	He Ne	

MODE OF OPERATION: [X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length):

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.005 J (W)	0.005 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	CW Hz	CW Hz	Hz
PULSE WIDTH	CW sec	CW sec	sec
BEAM DIAMETER (at 1/e point)	0.57 cm	0.57 cm	cm
BEAM DIVERGENCE (at 1/e point)	0.7 m rad	0.7 m rad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR POINT	CW OR SINGLE PULSE	6.36×10^{-4} J/cm²	5.24×10^{-1} J/cm²	J/cm²
OCULAR POINT	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
OCULAR EXT.	CW OR SINGLE PULSE	6.30 J/cm² sr	1.1×10^{3} J/cm² sr	J/cm² sr
OCULAR EXT.	MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN POINT	CW OR SINGLE PULSE	7.78×10^{-1} J/cm²	6×10^{3} J/cm²	J/cm²
SKIN POINT	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	Ø m	Ø m	Ø m	Ø m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	Ø OD	Ø OD	Ø OD	Ø OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI3A

AF FORM JAN 82 2760

LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Federal Products	900B		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
A-10 Boresight	He Ne	

MODE OF OPERATION: [X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length):

EMISSION CHARACTERISTICS

TIME (sec) & WAVELENGTH (λ)	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.005 J (W)	0.005 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	CW Hz	CW Hz	Hz
PULSE WIDTH	CW sec	CW sec	sec
BEAM DIAMETER (at 1/e point)	0.14 cm	0.14 cm	cm
BEAM DIVERGENCE (at 1/e point)	5.7 m rad	5.7 m rad	rad

MAX PERMISSABLE EXPOSURE (MPE)

OCULAR	POINT	CW OR SINGLE PULSE	6.36×10^{-4} J/cm²	5.24×10^{-1} J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
	EXT.	CW OR SINGLE PULSE	6.3 J/cm² sr	1.1×10^{3} J/cm² sr	J/cm² sr
		MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN	POINT	CW OR SINGLE PULSE	7.78×10^{-1} J/cm²	6×10^{3} J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES

		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	2.53 m	Ø m	3.33×10^{1} m	6.74×10^{-2} m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES

		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	2.11 OD	Ø OD	4.27 OD	2.11×10^{-1} OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ______ m	OD		OD		OD	
	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER	APERTURE	TRANSMITTANCE	[X] OEHL HAZARD EVALUATION	[ ] YES [X] NO	[ ] A [ ] B [ ] C
X	cm	%	[ ] AFOSH STD 161-10 CALCULATIONS		[ ] D [ ] E ANSI3A

AF FORM 2760 JAN 82

LASER HAZARD EVALUATION	DATE (YYMMDD)	WORKPLACE IDENTIFIER	
(Use this space for mechanical imprint)		BASE	ORGANIZATION
		WORKPLACE	
		BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Astronaurics of America	OSU		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Optical Scan Unit	He Ne	

MODE OF OPERATION	MAX EXPOSURE TIME (Train Length)
[X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE	8hrs

EMISSION CHARACTERISTICS	TIME (sec) & WAVELENGTH (λ)	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
	ENERGY/PULSE (J) OR CW POWER (W)	0.001 J (W)	0.001 J (W)	J (W)
	PULSE REPETITION FREQUENCY (PRF)	CW Hz	CW Hz	Hz
	PULSE WIDTH	CW sec	CW sec	sec
	BEAM DIAMETER (at 1/e point)	0.0064 cm	0.0064 cm	cm
	BEAM DIVERGENCE (at 1/e point)	0.75 m rad	0.75 m rad	rad
MAX PERMISSABLE EXPOSURE (MPE) OCULAR POINT	CW OR SINGLE PULSE	6.36 E − 04 J/cm²	5.24 E − 01 J/cm²	J/cm²
	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
OCULAR EXT.	CW OR SINGLE PULSE	6.30 E + 00 J/cm² sr	1.10 E + 03 J/cm² sr	J/cm² sr
	MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN POINT	CW OR SINGLE PULSE	7.78 E − 01 J/cm²	6.00 E + 03 J/cm²	J/cm²
	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

		SEED	SSED	SEED	SSED	SEED	SSED
SAFE EXPOSURE DISTANCES NO ATM ATTEN.	CW OR SINGLE PULSE	7.01 m	0.138 m	85.3 m	0.734 m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m

		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
OPTICAL DENSITIES UNAIDED	AT EXIT APERTURE	4.09 OD	1 OD	6.25 OD	2.19 OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ____ m	OD		OD		OD	
	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI2

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LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)	BASE	ORGANIZATION
	WORKPLACE	
	BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Harris	850		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Laser Copier	He Ne	

MODE OF OPERATION: [X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length):

EMISSION CHARACTERISTICS

TIME (sec) & WAVELENGTH (λ)	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.004 J (W)	0.004 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	CW Hz	CW Hz	Hz
PULSE WIDTH	CW sec	CW sec	sec
BEAM DIAMETER (at 1/e point)	0.035 cm	0.035 cm	cm
BEAM DIVERGENCE (at 1/e point)	0.0012 rad	0.0012 rad	rad

MAX PERMISSABLE EXPOSURE (MPE)

OCULAR	POINT	CW OR SINGLE PULSE	6.36×10^{-4} J/cm²	5.24×10^{-1} J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
	EXT.	CW OR SINGLE PULSE	6.30 J/cm² sr	1.10×10^{3} J/cm² sr	J/cm² sr
		MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN	POINT	CW OR SINGLE PULSE	7.78×10^{-1} J/cm²	6×10^{3} J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES

			SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE		1.15×10^{1} m	4.55×10^{-2} m	1.42×10^{2} m	1.04 m	m	m
	MULTIPLE PULSE		m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE		m	m	m	m	m	m
	MULTIPLE PULSE		m	m	m	m	m	m

OPTICAL DENSITIES

		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	3.21 OD	1.26×10^{-1} OD	5.38 OD	1.32 OD		OD
	AT ________ m	OD	OD	OD	OD	OD	OD
	AT ________ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ________ m	OD		OD		OD	
	AT ________ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI3A

AF FORM JAN 82 2760

LASER HAZARD EVALUATION	DATE *(YYMMDD)*	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)	BASE	ORGANIZATION
	WORKPLACE	
	BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Cognitronics	446600		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Standard Remote Term.	He Ne	

MODE OF OPERATION: [X] CONTINUOUS WAVE (CW) [ ] SINGLE PULSE [ ] MULTIPLE PULSE

MAX EXPOSURE TIME *(Train Length)*:

EMISSION CHARACTERISTICS		TIME *(sec)* & WAVELENGTH *(λ)*	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
		ENERGY/PULSE *(J)* OR CW POWER *(W)*	0.001 J (W)	0.001 J (W)	J (W)
		PULSE REPETITION FREQUENCY *(PRF)*	CW Hz	CW Hz	Hz
		PULSE WIDTH	CW sec	CW sec	sec
		BEAM DIAMETER *(at 1/e point)*	0.09 cm	0.09 cm	cm
		BEAM DIVERGENCE *(at 1/e point)*	0.001 rad	0.001 rad	rad
MAX PERMISSABLE EXPOSURE *(MPE)*	OCULAR POINT	CW OR SINGLE PULSE	6.36×10^{-4} J/cm²	5.24×10^{-1} J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
	OCULAR EXT.	CW OR SINGLE PULSE	6.3 J/cm² sr	1.1×10^{3} J/cm² sr	J/cm² sr
		MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
	SKIN POINT	CW OR SINGLE PULSE	7.78×10^{-1} J/cm²	6.00×10^{3} J/cm²	J/cm²
		MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

			SEED	SSED	SEED	SSED	SEED	SSED
SAFE EXPOSURE DISTANCES	NO ATM ATTEN.	CW OR SINGLE PULSE	6.17 m	Ø m	8.45×10^{1} m	Ø m	m	m
		MULTIPLE PULSE	m	m	m	m	m	m
	ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
		MULTIPLE PULSE	m	m	m	m	m	m

			OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
OPTICAL DENSITIES	UNAIDED	AT EXIT APERTURE	1.79 OD	Ø OD	3.95 OD	Ø OD	OD	OD
		AT ______ m	OD	OD	OD	OD	OD	OD
		AT ______ m	OD	OD	OD	OD	OD	OD
	OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
		AT ______ m	OD		OD		OD	
		AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	[X] OEHL HAZARD EVALUATION [ ] AFOSH STD 161-10 CALCULATIONS	[ ] YES [X] NO	[ ] A [ ] B [ ] C [ ] D [ ] E ANSI 2

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LASER HAZARD EVALUATION

DATE (YYMMDD)

WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE

ORGANIZATION

WORKPLACE

BLDG NO/LOCATION

ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Pave Spike	AN/ASQ-153		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Laser Designator	Nd : YAG	F-4/F-111

MODE OF OPERATION: ☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length)

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	10 sec 1064 nm	30,000 sec 1064 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.168 J (W)	0.168 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	10 Hz	10 Hz	Hz
PULSE WIDTH	0.015×10^{-6} sec	0.015×10^{-6} sec	sec
BEAM DIAMETER (at 1/e point)	3.6 cm	3.6 cm	cm
BEAM DIVERGENCE (at 1/e point)	0.35 mrad	0.35 mrad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR – POINT	CW OR SINGLE PULSE	5×10^{-6} J/cm²	5×10^{-6} J/cm²	J/cm²
OCULAR – POINT	MULTIPLE PULSE	1.58×10^{-6} J/cm²	2.14×10^{-7} J/cm²	J/cm²
OCULAR – EXT.	CW OR SINGLE PULSE	1.31×10^{-1} J/cm² sr	1.31×10^{-1} J/cm² sr	J/cm² sr
OCULAR – EXT.	MULTIPLE PULSE	1.31×10^{-1} J/cm² sr	3.2×10^{-1} J/cm² sr	J/cm² sr
SKIN – POINT	CW OR SINGLE PULSE	1×10^{-1} J/cm²	1×10^{-1} J/cm²	J/cm²
SKIN – POINT	MULTIPLE PULSE	1×10^{-1} J/cm²	1×10^{-1} J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	6.16×10^{3} m	Ø m	6.16×10^{3} m	Ø m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	1.1×10^{4} m	Ø m	3.02×10^{4} m	Ø m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	4.02 OD	Ø OD	4.89 OD	Ø OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	5.71 OD		6.58 OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER: 7 x	APERTURE: 5 cm	TRANSMITTANCE: 100 %	☒ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☐ YES ☒ NO	☐ A ☐ B ☐ C ☐ D ☐ E ANSI 4

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LASER HAZARD EVALUATION	DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)	BASE	ORGANIZATION
	WORKPLACE	
	BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Pave Tack	AN/AVQ - 25		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Laser Designator	Nd : YAG	F-4/RF-4/F-111F

MODE OF OPERATION	MAX EXPOSURE TIME (Train Length)
☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE	

EMISSION CHARACTERISTICS	TIME (sec) & WAVELENGTH (λ)	10 sec 1064 nm	30,000 sec 1064 nm	sec nm
	ENERGY/PULSE (J) OR CW POWER (W)	0.18 J (W)	0.18 J (W)	J (W)
	PULSE REPETITION FREQUENCY (PRF)	20 Hz	20 Hz	Hz
	PULSE WIDTH	0.025×10^{-6} sec	0.025×10^{-6} sec	sec
	BEAM DIAMETER (at 1/e point)	0.45 cm	0.45 cm	cm
	BEAM DIVERGENCE (at 1/e point)	1.8 mrad	1.8 mrad	rad
MAX PERMISSABLE EXPOSURE (MPE) — OCULAR POINT	CW OR SINGLE PULSE	5×10^{-6} J/cm²	5×10^{-6} J/cm²	J/cm²
	MULTIPLE PULSE	1.33×10^{-6} J/cm²	1.8×10^{-7} J/cm²	J/cm²
OCULAR EXT.	CW OR SINGLE PULSE	1.46×10^{-1} J/cm² sr	1.46×10^{-1} J/cm² sr	J/cm² sr
	MULTIPLE PULSE	1.46×10^{-1} J/cm² sr	1.6×10^{-1} J/cm² sr	J/cm² sr
SKIN POINT	CW OR SINGLE PULSE	1×10^{-1} J/cm²	1×10^{-1} J/cm²	J/cm²
	MULTIPLE PULSE	5×10^{-2} J/cm²	5×10^{-2} J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	1.19×10^{3} m	5.91 m	1.19×10^{3} m	5.91 m	m	m
	MULTIPLE PULSE	2.3×10^{3} m	9.39 m	6.27×10^{3} m	9.39 m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	5.93 OD	1.35 OD	6.8 OD	1.35 OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	7.62 OD		8.49 OD		OD	
	AT ____ m	OD		OD		OD	
	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER 7 X	APERTURE 5 cm	TRANSMITTANCE 100 %	☒ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☐ YES ☒ NO	☐ A ☐ B ☐ C ☐ D ☐ E ANSI4

AF FORM JAN 82 2760

LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Target Designator	AN/PAQ-1		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
	Nd : YAG	

MODE OF OPERATION

☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE

MAX EXPOSURE TIME (*Train Length*)

EMISSION CHARACTERISTICS	TIME (sec) & WAVELENGTH (λ)	10 sec 1064 nm	30,000 sec 1064 nm	sec nm
	ENERGY/PULSE (J) OR CW POWER (W)	0.1 J (W)	0.1 J (W)	J (W)
	PULSE REPETITION FREQUENCY (PRF)	20 Hz	20 Hz	Hz
	PULSE WIDTH	20 nsec	20 n sec	sec
	BEAM DIAMETER (at 1/e point)	1.6 cm	1.6 cm	cm
	BEAM DIVERGENCE (at 1/e point)	0.5 mrad	0.5 m rad	rad
MAX PERMISSABLE EXPOSURE (MPE) — OCULAR — POINT	CW OR SINGLE PULSE	5×10^{-6} J/cm²	5×10^{-6} J/cm²	J/cm²
	MULTIPLE PULSE	1.33×10^{-6} J/cm²	1.8×10^{-7} J/cm²	J/cm²
OCULAR — EXT.	CW OR SINGLE PULSE	1.36×10^{-1} J/cm² sr	1.36×10^{-1} J/cm² sr	J/cm² sr
	MULTIPLE PULSE	1.36×10^{-1} J/cm² sr	1.60×10^{-1} J/cm² sr	J/cm² sr
SKIN — POINT	CW OR SINGLE PULSE	1×10^{-1} J/cm²	1×10^{-1} J/cm²	J/cm²
	MULTIPLE PULSE	5×10^{-2} J/cm²	5×10^{-2} J/cm²	J/cm²

		SEED	SSED	SEED	SSED	SEED	SSED
SAFE EXPOSURE DISTANCES — NO ATM ATTEN.	CW OR SINGLE PULSE	3.16×10^{3} m	Ø m	3.16×10^{3} m	Ø m	m	m
	MULTIPLE PULSE	6.16×10^{3} m	Ø m	1.68×10^{4} m	Ø m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m

		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
OPTICAL DENSITIES — UNAIDED	AT EXIT APERTURE	4.57 OD	Ø OD	5.44 OD	Ø OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	6.26 OD		7.13 OD		OD	
	AT ____ m	OD		OD		OD	
	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER	APERTURE	TRANSMITTANCE	☒ OEHL HAZARD EVALUATION	☐ YES ☒ NO	☐ A ☐ B ☐ C
7 X	5 cm	100 %	☐ AFOSH STD 161-10 CALCULATIONS		☐ D ☐ ANSI4

AF FORM JAN 82 2760

LASER HAZARD EVALUATION	DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)	BASE	ORGANIZATION
	WORKPLACE	
	BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

[illegible]	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
KEI LH-83	AN/GMQ-33		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Ceilometer	Erbium	

MODE OF OPERATION	MAX EXPOSURE TIME (Train Length)
☐ CONTINUOUS WAVE (CW) ☒ SINGLE PULSE ☐ MULTIPLE PULSE	

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	0.03×10^{-6} sec 1540 nm	sec nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.025 J (W)	J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	Hz	Hz	Hz
PULSE WIDTH	0.03×10^{-6} sec	sec	sec
BEAM DIAMETER (at 1/e point)	0.3 cm	cm	cm
BEAM DIVERGENCE (at 1/e point)	2.25 mrad	rad	rad

MAX PERMISSABLE EXPOSURE (MPE)					
OCULAR	POINT	CW OR SINGLE PULSE	1 J/cm²	J/cm²	J/cm²
OCULAR	POINT	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
OCULAR	EXT.	CW OR SINGLE PULSE	1 J/cm² sr	J/cm² sr	J/cm² sr
OCULAR	EXT.	MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN	POINT	CW OR SINGLE PULSE	1 J/cm²	J/cm²	J/cm²
SKIN	POINT	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES			SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.		CW OR SINGLE PULSE	Ø m	Ø m	m	m	m	m
NO ATM ATTEN.		MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.		CW OR SINGLE PULSE	m	m	m	m	m	m
ATM ATTEN.		MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES			OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED		AT EXIT APERTURE	Ø OD	Ø OD	OD	OD	OD	OD
UNAIDED		AT ____ m	OD	OD	OD	OD	OD	OD
UNAIDED		AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED		AT EXIT APERTURE	OD		OD		OD	
OPTICALLY AIDED		AT ____ m	OD		OD		OD	
OPTICALLY AIDED		AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FOA EXEMPTION	LASER CATEGORY
POWER	APERTURE	TRANSMITTANCE	☒ OEHL HAZARD EVALUATION	☐ YES ☒ NO	☐ A ☐ B ☐ C
X	cm	%	☐ AFOSH STD 161-10 CALCULATIONS		☐ D ☐ E ANSI3A

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LASER HAZARD EVALUATION

DATE (YYMMDD)	
WORKPLACE IDENTIFIER	
(Use this space for mechanical imprint)	
BASE	
ORGANIZATION	
WORKPLACE	
BLDG NO/LOCATION	
ROOM/AREA	
RESPONSIBLE INDIVIDUAL – NAME & GRADE	
POSITION	
DUTY PHONE	

DESCRIPTION / CHARACTERISTICS

	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Pave Spectre	AN/AVQ-19		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Laser Designator	Nd : YAG	C-130

MODE OF OPERATION	MAX EXPOSURE TIME (Train Length)
☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE	

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	10 sec 1064 nm	30,000 sec 1064 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	0.11 J (W)	0.11 J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	10 Hz	10 Hz	Hz
PULSE WIDTH	0.018×10^{-6} sec	0.018×10^{-6} sec	sec
BEAM DIAMETER (at 1/e point)	4.2 cm	4.2 cm	cm
BEAM DIVERGENCE (at 1/e point)	0.33 mrad	0.33 mrad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR – POINT	CW OR SINGLE PULSE	5.00 E - 06 J/cm²	5.00 E - 06 J/cm²	J/cm²
OCULAR – POINT	MULTIPLE PULSE	1.58 E - 06 J/cm²	2.14×10^{-7} J/cm²	J/cm²
OCULAR – EXT.	CW OR SINGLE PULSE	1.31×10^{-1} J/cm² sr	1.31×10^{-1} J/cm² sr	J/cm² sr
OCULAR – EXT.	MULTIPLE PULSE	1.31×10^{-1} J/cm² sr	3.20×10^{-1} J/cm² sr	J/cm² sr
SKIN – POINT	CW OR SINGLE PULSE	1.00×10^{-1} J/cm²	1.00×10^{-1} J/cm²	J/cm²
SKIN – POINT	MULTIPLE PULSE	1.00×10^{-1} J/cm²	1.00×10^{-1} J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	1.63×10^{3} m	Ø m	1.63×10^{3} m	Ø m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	2.93×10^{3} m	Ø m	8.05×10^{3} m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	3.7 OD	Ø OD	4.57 OD	Ø OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	5.39 OD		6.26 OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER 7 x	APERTURE 5 cm	TRANSMITTANCE 100 %	☒ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☐ YES ☒ NO	☐ A ☐ B ☐ C ☐ D ☐ E ANSI 4

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LASER HAZARD EVALUATION

LASER HAZARD EVALUATION	DATE (YYMMDD)	WORKPLACE IDENTIFIER
(Use this space for mechanical imprint)	BASE	ORGANIZATION
	WORKPLACE	
	BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
VAISALA CT-12K	AN/GMQ- 13/34		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Ceilometer	Ga As	

MODE OF OPERATION: ☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length):

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	10 sec 904 nm	30,000 sec 904 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	6.6×10^{-6} J (W)	6.6×10^{-6} J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	770 Hz	770 Hz	Hz
PULSE WIDTH	0.15×10^{-6} sec	0.15×10^{-6} sec	sec
BEAM DIAMETER (at 1/e point)	8 - 3 cm	8 - 3 cm	cm
BEAM DIVERGENCE (at 1/e point)	2.5 mrad	2.5 rad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR POINT	CW OR SINGLE PULSE	1.28×10^{-6} J/cm²	1.28×10^{-6} J/cm²	J/cm²
OCULAR POINT	MULTIPLE PULSE	1.37×10^{-7} J/cm²	1.85×10^{-8} J/cm²	J/cm²
OCULAR EXT.	CW OR SINGLE PULSE	6.95×10^{-2} J/cm² sr	6.95×10^{-2} J/cm² sr	J/cm² sr
OCULAR EXT.	MULTIPLE PULSE	7.16×10^{-3} J/cm² sr	2.13×10^{-3} J/cm² sr	J/cm² sr
SKIN POINT	CW OR SINGLE PULSE	5.12×10^{-2} J/cm²	5.12×10^{-2} J/cm²	J/cm²
SKIN POINT	MULTIPLE PULSE	6.65×10^{-4} J/cm²	6.65×10^{-4} J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	Ø m	Ø m	Ø m	Ø m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	Ø m	Ø m	52.2 m	Ø m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	Ø OD	Ø OD	0.82 OD	Ø OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	☒ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☐ YES ☒ NO	☐ A ☐ B ☐ C ☐ D ☐ E ANSI 3B

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LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
	AN/GVS-5		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Laser Range Finder	nd:YAG	

MODE OF OPERATION: ☐ CONTINUOUS WAVE (CW) ☒ SINGLE PULSE ☐ MULTIPLE PULSE

MAX EXPOSURE TIME (*Train Length*)

EMISSION CHARACTERISTICS	TIME (*sec*) & WAVELENGTH (λ)	5 nsec 1064 nm	sec nm	sec nm
	ENERGY/PULSE (*J*) OR CW POWER (*W*)	0.02 J (W)	J (W)	J (W)
	PULSE REPETITION FREQUENCY (*PRF*)	Hz	Hz	Hz
	PULSE WIDTH	5 nsec	sec	sec
	BEAM DIAMETER (*at 1/e point*)	1.2 cm	cm	cm
	BEAM DIVERGENCE (*at 1/e point*)	0.6 m rad	rad	rad
MAX PERMISSABLE EXPOSURE (MPE) — OCULAR — POINT	CW OR SINGLE PULSE	1 J/cm^2	J/cm^2	J/cm^2
	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR — EXT.	CW OR SINGLE PULSE	1 $J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
	MULTIPLE PULSE	$J/cm^2 sr$	$J/cm^2 sr$	$J/cm^2 sr$
SKIN — POINT	CW OR SINGLE PULSE	1 J/cm^2	J/cm^2	J/cm^2
	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2

		SEED	SSED	SEED	SSED	SEED	SSED
SAFE EXPOSURE DISTANCES — NO ATM ATTEN.	CW OR SINGLE PULSE	Ø m	Ø m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
	MULTIPLE PULSE	m	m	m	m	m	m

		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
OPTICAL DENSITIES — UNAIDED	AT EXIT APERTURE	Ø OD	Ø OD	OD	OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
	AT ______ m	OD		OD		OD	
	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	☒ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☒ YES ☐ NO	☐ A ☐ B ☐ C ☐ D ☐ E Ans14

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LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Xerox Electro Optical XM -60	Miles Old Version		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Training	Gallium Arsenide	

MODE OF OPERATION	MAX EXPOSURE TIME (Train Length)
☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE	

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	10 sec 900 nm	30,000 sec 900 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	78 nJ (W)	78 nJ (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	1604 Hz	1604 Hz	Hz
PULSE WIDTH	150 nsec	150 nsec	sec
BEAM DIAMETER (at 1/e point)	0.7 cm	0.7 cm	cm
BEAM DIVERGENCE (at 1/e point)	2.2 mrad	2.2 mrad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR POINT	CW OR SINGLE PULSE	1.8×10^{-6} J/cm²	J/cm²	J/cm²
OCULAR POINT	MULTIPLE PULSE	1.1×10^{-7} J/cm²	J/cm²	J/cm²
OCULAR EXT.	CW OR SINGLE PULSE	1.3×10^{-3} J/cm² sr	J/cm² sr	J/cm² sr
OCULAR EXT.	MULTIPLE PULSE	1.0×10^{-3} J/cm² sr	J/cm² sr	J/cm² sr
SKIN POINT	CW OR SINGLE PULSE	5.3×10^{-2} J/cm²	J/cm²	J/cm²
SKIN POINT	MULTIPLE PULSE	3×10^{-4} J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	0 m	0 m	m	m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	7 m	0 m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	0 m	0 m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	7 m	0 m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	OD	OD	OD	OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ______ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	
OPTICALLY AIDED	AT ______ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	☒ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☒ YES ☐ NO	☐ A ☐ B ☐ C ☐ D ☐ E ANSI 3B

AF FORM JAN 82 2760

LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
Loral Electro Optical	Miles New Version		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
Training	Ga As	

MODE OF OPERATION: ☐ CONTINUOUS WAVE (CW) ☒ SINGLE PULSE ☐ MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length):

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	1×10^{-7} sec 904 nm	sec nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	1×10^{-7} J (W)	J (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	Hz	Hz	Hz
PULSE WIDTH	1×10^{-7} sec	sec	sec
BEAM DIAMETER (at 1/e point)	1.53 cm	cm	cm
BEAM DIVERGENCE (at 1/e point)	0.841 mrad	rad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR POINT	CW OR SINGLE PULSE	1.28×10^{-6} J/cm²	J/cm²	J/cm²
OCULAR POINT	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²
OCULAR EXT.	CW OR SINGLE PULSE	0.119 J/cm² sr	J/cm² sr	J/cm² sr
OCULAR EXT.	MULTIPLE PULSE	J/cm² sr	J/cm² sr	J/cm² sr
SKIN POINT	CW OR SINGLE PULSE	5×10^{-2} J/cm²	J/cm²	J/cm²
SKIN POINT	MULTIPLE PULSE	J/cm²	J/cm²	J/cm²

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	0 m	0 m	m	m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	0 m	0 m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	0.3 OD	0 OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	0 OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER	APERTURE	TRANSMITTANCE	☒ OEHL HAZARD EVALUATION	☒ YES ☐ NO	☐ A ☐ B ☐ C
10 X	5 cm	100 %	☐ AFOSH STD 161-10 CALCULATIONS		☐ D ☐ E ANSI 1

AF FORM JAN 82 2760

LASER HAZARD EVALUATION

DATE (YYMMDD)	WORKPLACE IDENTIFIER

(Use this space for mechanical imprint)

BASE	ORGANIZATION

WORKPLACE

BLDG NO/LOCATION	ROOM/AREA

RESPONSIBLE INDIVIDUAL	NAME & GRADE	POSITION	DUTY PHONE

DESCRIPTION / CHARACTERISTICS

MANUFACTURER	MODEL	NO SAME UNITS	SERIAL NUMBER(S)
NCR	7820		

FUNCTIONAL USE	LASER MEDIUM	OPERATING LOCATION(S)
BAR CODE READER	He Ne	

MODE OF OPERATION ☐ CONTINUOUS WAVE (CW) ☐ SINGLE PULSE ☒ MULTIPLE PULSE

MAX EXPOSURE TIME (Train Length)

EMISSION CHARACTERISTICS			
TIME (sec) & WAVELENGTH (λ)	0.25 sec 632.8 nm	30,000 sec 632.8 nm	sec nm
ENERGY/PULSE (J) OR CW POWER (W)	100 nJ (W)	100 nJ (W)	J (W)
PULSE REPETITION FREQUENCY (PRF)	100 Hz	100 Hz	Hz
PULSE WIDTH	41×10^{-6} sec	41×10^{-6} sec	sec
BEAM DIAMETER (at 1/e point)	0.16 cm	0.16 cm	cm
BEAM DIVERGENCE (at 1/e point)	2.6 mrad	2.6 mrad	rad

MAX PERMISSABLE EXPOSURE (MPE)				
OCULAR POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR POINT	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2
OCULAR EXT.	CW OR SINGLE PULSE	J/cm^2 sr	J/cm^2 sr	J/cm^2 sr
OCULAR EXT.	MULTIPLE PULSE	J/cm^2 sr	J/cm^2 sr	J/cm^2 sr
SKIN POINT	CW OR SINGLE PULSE	J/cm^2	J/cm^2	J/cm^2
SKIN POINT	MULTIPLE PULSE	J/cm^2	J/cm^2	J/cm^2

SAFE EXPOSURE DISTANCES		SEED	SSED	SEED	SSED	SEED	SSED
NO ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
NO ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m
ATM ATTEN.	CW OR SINGLE PULSE	m	m	m	m	m	m
ATM ATTEN.	MULTIPLE PULSE	m	m	m	m	m	m

OPTICAL DENSITIES		OCULAR	SKIN	OCULAR	SKIN	OCULAR	SKIN
UNAIDED	AT EXIT APERTURE	OD	OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
UNAIDED	AT ____ m	OD	OD	OD	OD	OD	OD
OPTICALLY AIDED	AT EXIT APERTURE	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	
OPTICALLY AIDED	AT ____ m	OD		OD		OD	

OPTICAL AID DESCRIPTION			DATA SOURCE	FDA EXEMPTION	LASER CATEGORY
POWER X	APERTURE cm	TRANSMITTANCE %	☐ OEHL HAZARD EVALUATION ☐ AFOSH STD 161-10 CALCULATIONS	☐ YES ☐ NO	☐ A ☐ B ☐ C ☐ D ☐ E ANSI 2A

AF FORM JAN 82 2760

APPENDIX D

Atmospheric Attenuation Coefficients

Source: Optical Properties of the Atmosphere (Third Edition),
Air Force Cambridge Research Laboratories,
L.G. Hanscom Field, Bedford MA
AFCRL-72-0497 (Ref 19)

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

λ=337μm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	2.07E+01	<E-06	2.03E+01	<E-06	5.39E+00	<E-06	1.37E+01	<E-06	1.71E+00	<E-06	<E-06	<E-06	<E-06	<E-06
0-1	2.12E+01		1.80E+01		4.35E+00		1.07E+01		1.60E+00					
1-2	1.33E+01		9.66E+00		2.84E+00		6.39E+00		1.39E+00					
2-3	8.72E+00		5.58E+00		1.82E+00		4.09E+00		9.79E-01					
3-4	4.00E+00		2.87E+00		1.10E+00		2.39E+00		6.33E-01					
4-5	1.75E+00		1.50E+00		5.46E-01		1.36E+00		3.45E-01					
5-6	1.06E+00		7.17E-01		2.83E-01		7.24E-01		1.52E-01					
6-7	5.52E-01		3.87E-01		1.42E-01		3.56E-01		6.68E-02					
7-8	2.78E-01		2.17E-01		5.13E-02		1.73E-01		3.29E-02					
8-9	1.34E-01		1.12E-01		1.87E-02		6.98E-02		5.96E-03					
9-10	5.78E-02		5.72E-02		7.73E-03		2.02E-02		3.91E-03					
10-11	2.16E-02		2.75E-02		3.10E-03		6.39E-03		2.20E-03					
11-12	6.64E-03		8.43E-03		2.49E-03		3.43E-03		1.30E-03					
12-13	2.07E-03		2.05E-03		1.85E-03		1.88E-03		7.57E-04					
13-14	5.59E-04		5.41E-04		4.81E-04		4.88E-04		4.53E-04					
14-15	2.66E-04		2.47E-04		2.21E-04		2.24E-04		2.08E-04					
15-16	1.79E-04		1.61E-04		1.46E-04		1.48E-04		1.36E-04					
16-17	1.35E-04		1.20E-04		1.09E-04		1.11E-04		1.02E-04					
17-18	9.63E-05		8.73E-05		7.91E-05		8.58E-05		7.41E-05					
18-19	6.98E-05		7.00E-05		6.38E-05		6.15E-05		5.98E-05					
19-20	6.14E-05		5.59E-05		5.12E-05		5.28E-05		4.80E-05					
20-21	4.13E-05		4.44E-05		4.08E-05		4.24E-05		3.84E-05					
21-22	4.22E-05		4.33E-05		3.98E-05		4.17E-05		3.52E-05					
22-23	3.54E-05		3.45E-05		3.19E-05		3.59E-05		3.21E-05					
23-24	3.18E-05		3.33E-05		3.09E-05		3.27E-05		2.92E-05					
24-25	2.85E-05		3.17E-05		2.94E-05		2.95E-05		2.64E-05					
25-30	1.64E-05		1.74E-05		1.58E-05		1.74E-05		1.50E-05					
30-35	4.02E-06		4.32E-06		3.83E-06		4.36E-06		3.56E-06					
35-40	<E-06		<E-06		<E-06		<E-06		<E-06					
40-45														
45-50														
50-70														
70-100														

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

λ=27.9μm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	>30	<E-06	>30	<E-06	>30	<E-06	>30	<E-06	>30	<E-06	1.95E-03	7.78E-04	9.49E-03	3.78E-03
0-1	>30		>30		>30		>30		>30		1.29E-03	5.16E-04	5.73E-03	2.29E-03
1-2	>30		>30		>30		>30		>30		5.63E-04	2.25E-04	2.10E-03	8.38E-04
2-3	>30		>30		>30		>30		>30		2.40E-04	9.58E-05	7.67E-04	3.07E-04
3-4	>30		>30		>30		>30		>30		1.13E-04	4.51E-05	2.80E-04	1.12E-04
4-5	>30		>30		>30		>30		>30		7.13E-05	2.85E-05	1.02E-04	4.09E-05
5-6	>30		>30		>30		>30		1.25E+01		5.20E-05	2.08E-05	5.20E-05	2.08E-05
6-7	>30		>30		1.35E+01		>30		4.69E+00		4.21E-05	1.68E-05	4.21E-05	1.68E-05
7-8	>30		2.95E+01		4.29E+00		1.82E+01		1.94E+00		4.12E-05	1.65E-05	4.12E-05	1.65E-05
8-9	1.67E+01		1.32E+01		1.35E+00		6.22E+00		3.08E-01		4.09E-05	1.64E-05	4.09E-05	1.64E-05
9-10	6.18E+00		5.77E+00		4.69E-01		1.49E+00		1.97E-01		3.96E-05	1.58E-05	3.96E-05	1.58E-05
10-11	1.91E+00		2.33E+00		1.73E-01		4.30E-01		1.14E-01		3.78E-05	1.51E-05	3.78E-05	1.51E-05
11-12	4.86E-01		5.87E-01		1.39E-01		2.36E-01		6.90E-02		3.75E-05	1.50E-05	3.75E-05	1.50E-05
12-13	1.23E-01		1.16E-01		1.04E-01		1.33E-01		4.07E-02		3.70E-05	1.48E-05	3.70E-05	1.48E-05
13-14	2.60E-02		2.77E-02		2.68E-02		3.48E-02		2.46E-02		3.51E-05	1.40E-05	3.51E-05	1.40E-05
14-15	9.71E-03		1.28E-02		1.22E-02		1.61E-02		1.14E-02		3.37E-05	1.35E-05	3.37E-05	1.35E-05
15-16	5.05E-03		8.46E-03		7.94E-03		1.07E-02		7.44E-03		3.19E-05	1.27E-05	3.19E-05	1.27E-05
16-17	3.16E-03		6.33E-03		5.85E-03		8.10E-03		5.46E-03		3.09E-05	1.23E-05	3.09E-05	1.23E-05
17-18	2.36E-03		4.63E-03		4.20E-03		6.30E-03		3.90E-03		3.02E-05	1.21E-05	3.02E-05	1.21E-05
18-19	2.04E-03		3.80E-03		3.33E-03		4.53E-03		3.09E-03		2.73E-05	1.09E-05	2.73E-05	1.09E-05
19-20	2.13E-03		3.15E-03		2.65E-03		3.90E-03		2.42E-03		2.14E-05	8.57E-06	2.14E-05	8.57E-06
20-21	1.69E-03		2.61E-03		2.12E-03		3.13E-03		1.90E-03		1.56E-05	6.25E-06	1.56E-05	6.25E-06
21-22	2.02E-03		2.63E-03		2.07E-03		3.09E-03		1.71E-03		1.16E-05	4.62E-06	1.16E-05	4.62E-06
22-23	1.90E-03		2.20E-03		1.66E-03		2.66E-03		1.52E-03		8.77E-06	3.50E-06	8.77E-06	3.50E-06
23-24	1.84E-03		2.26E-03		1.61E-03		2.47E-03		1.35E-03		6.83E-06	2.73E-06	6.83E-06	2.73E-06
24-25	1.77E-03		2.23E-03		1.53E-03		2.35E-03		1.20E-03		5.58E-06	2.23E-06	5.58E-06	2.23E-06
25-30	1.28E-03		1.48E-03		8.61E-04		1.61E-03		7.36E-04		2.81E-06	1.12E-06	2.81E-06	1.12E-06
30-35	4.50E-04		5.15E-04		2.62E-04		5.43E-04		2.14E-04		<E-06	<E-06	<E-06	<E-06
35-40	9.05E-05		1.06E-04		5.53E-05		1.16E-04		4.08E-05					
40-45	2.35E-05		2.84E-05		1.58E-05		3.16E-05		1.09E-05					
45-50	6.50E-06		8.01E-06		4.67E-06		8.73E-06		3.26E-06					
50-70	<E-06		<E-06		<E-06		<E-06		<E-06					
70-100														

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

$\lambda = 10.591 \mu m$														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL			
											CLEAR		HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	5.788E-01	<1.0E-06	3.582E-01	<1.0E-06	7.937E-02	<1.0E-06	2.006E-01	<1.0E-06	4.118E-02	<1.0E-06	5.48E-03	4.65E-03	2.67E-02	2.27E-02
0-1	5.172E-01		3.256E-01		7.312E-02		1.818E-01		4.147E-02		3.64E-03	3.09E-03	1.61E-02	1.37E-02
1-2	2.848E-01		1.877E-01		5.895E-02		1.137E-01		4.002E-02		1.58E-03	1.34E-03	5.90E-03	5.01E-03
2-3	1.807E-01		1.152E-01		4.911E-02		8.152E-02		3.516E-02		6.75E-04	5.73E-04	2.16E-03	1.83E-03
3-4	9.616E-02		7.582E-02		4.043E-02		6.090E-02		3.048E-02		3.18E-04	2.70E-04	7.88E-04	6.68E-04
4-5	6.290E-02		5.544E-02		3.240E-02		4.863E-02		2.453E-02		2.01E-04	1.70E-04	2.88E-04	2.44E-04
5-6	5.010E-02		4.468E-02		2.622E-02		3.737E-02		1.932E-02		1.46E-04	1.24E-04	1.46E-04	1.24E-04
6-7	3.968E-02		3.752E-02		2.147E-02		2.861E-02		1.509E-02		1.18E-04	1.00E-04	1.18E-04	1.00E-04
7-8	3.200E-02		3.018E-02		1.738E-02		2.277E-02		1.171E-02		1.16E-04	9.83E-05	1.16E-04	9.83E-05
8-9	2.634E-02		2.378E-02		1.405E-02		1.788E-02		9.593E-03		1.15E-04	9.77E-05	1.15E-04	9.77E-05
9-10	2.074E-02		1.952E-02		1.083E-02		1.375E-02		8.932E-03		1.11E-04	9.45E-05	1.11E-04	9.45E-05
10-11	1.651E-02		1.374E-02		9.813E-03		1.195E-02		8.921E-03		1.06E-04	9.04E-05	1.06E-04	9.04E-05
11-12	1.287E-02		1.241E-02		9.484E-03		1.229E-02		8.908E-03		1.06E-04	8.96E-05	1.06E-04	8.96E-05
12-13	1.036E-02		9.534E-03		9.358E-03		1.181E-02		8.733E-03		1.04E-04	8.83E-05	1.04E-04	8.83E-05
13-14	7.382E-03		8.337E-03		9.340E-03		1.229E-02		9.109E-03		9.89E-05	8.39E-05	9.89E-05	8.39E-05
14-15	5.850E-03		8.700E-03		9.001E-03		1.222E-02		8.891E-03		9.49E-05	8.05E-05	9.49E-05	8.05E-05
15-16	4.330E-03		8.491E-03		8.749E-03		1.166E-02		8.773E-03		8.97E-05	7.61E-05	8.97E-05	7.61E-05
16-17	3.316E-03		8.364E-03		8.573E-03		1.217E-02		8.559E-03		8.69E-05	7.38E-05	8.69E-05	7.38E-05
17-18	3.586E-03		8.467E-03		8.556E-03		1.203E-02		8.324E-03		8.50E-05	7.21E-05	8.50E-05	7.21E-05
18-19	4.350E-03		8.560E-03		8.249E-03		1.199E-02		8.209E-03		7.68E-05	6.51E-05	7.68E-05	6.51E-05
19-20	5.194E-03		8.929E-03		8.011E-03		1.217E-02		7.864E-03		6.04E-05	5.12E-05	6.04E-05	5.12E-05
20-21	6.273E-03		9.186E-03		8.186E-03		1.186E-02		7.784E-03		4.40E-05	3.74E-05	4.40E-05	3.74E-05
21-22	7.471E-03		9.719E-03		8.194E-03		1.208E-02		7.523E-03		3.25E-05	2.76E-05	3.25E-05	2.76E-05
22-23	8.361E-03		1.010E-02		8.161E-03		1.208E-02		7.209E-03		2.47E-05	2.09E-05	2.47E-05	2.09E-05
23-24	9.041E-03		1.114E-02		8.107E-03		1.199E-02		7.329E-03		1.92E-05	1.63E-05	1.92E-05	1.63E-05
24-25	9.909E-03		1.112E-02		8.378E-03		1.275E-02		6.837E-03		1.57E-05	1.33E-05	1.57E-05	1.33E-05
25-30	1.203E-02		1.327E-02		8.087E-03		1.453E-02		7.238E-03		7.90E-06	6.71E-06	7.90E-06	6.71E-06
30-35	1.190E-02		1.319E-02		6.848E-03		2.007E-02		5.785E-03		2.23E-06	1.89E-06	2.23E-06	1.89E-06
35-40	1.101E-02		1.269E-02		6.714E-03		1.395E-02		5.099E-03		<1.0E-06	<1.0E-06	<1.0E-6	<1.0E-06
40-45	8.865E-03		1.063E-02		6.023E-03		1.189E-02		4.100E-03					
45-50	6.038E-03		7.522E-03		4.405E-03		8.186E-03		3.082E-03					
50-70	9.007E-04		1.077E-03		2.744E-04		1.097E-03		7.761E-04					
70-100	1.838E-05		1.743E-05		1.580E-04		1.762E-05		1.785E-05					

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

3.39225 µm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	1.77E+00	7.79E-06	1.83E+00	7.95E-06	1.98E+00	8.63E-06	1.88E+00	8.12E-06	2.03E+00	9.09E-06	1.58E-02	1.65E-02	7.71E-02	8.05E-02
0-1	1.75E+00	7.44E-06	1.79E+00	7.56E-06	1.92E+00	8.17E-06	1.84E+00	7.72E-06	1.97E+00	8.50E-06	1.05E-02	1.09E-02	4.66E-02	4.86E-02
1-2	1.68E+00	6.77E-06	1.70E+00	6.83E-06	1.79E+00	7.29E-06	1.75E+00	6.98E-06	1.84E+00	7.46E-06	4.57E-03	4.77E-03	1.70E-02	1.78E-02
2-3	1.63E+00	6.13E-06	1.65E+00	6.18E-06	1.75E+00	6.49E-06	1.65E+00	6.29E-06	1.75E+00	6.69E-06	1.95E-03	2.03E-03	6.24E-03	6.58E-03
3-4	1.59E+00	5.54E-06	1.60E+00	5.59E-06	1.65E+00	5.80E-06	1.66E+00	5.65E-06	1.67E+00	5.86E-06	9.18E-04	9.57E-04	2.27E-03	2.37E-03
4-5	1.54E+00	5.02E-06	1.54E+00	5.05E-06	1.60E+00	5.20E-06	1.54E+00	5.07E-06	1.62E+00	5.23E-06	5.79E-04	6.04E-04	8.31E-04	8.67E-04
5-6	1.52E+00	4.54E-06	1.54E+00	4.55E-06	1.54E+00	4.64E-06	1.61E+00	4.56E-06	1.57E+00	4.67E-06	4.22E-04	4.40E-04	4.22E-04	4.40E-04
6-7	1.47E+00	4.09E-06	1.46E+00	4.08E-06	1.54E+00	4.14E-06	1.47E+00	4.09E-06	1.54E+00	4.16E-06	3.42E-04	3.57E-04	3.42E-04	3.57E-04
7-8	1.45E+00	3.69E-06	1.52E+00	3.66E-06	1.46E+00	3.68E-06	1.45E+00	3.67E-06	1.50E+00	3.68E-06	3.35E-04	3.49E-04	3.35E-04	3.49E-04
8-9	1.46E+00	3.30E-06	1.41E+00	3.27E-06	1.44E+00	3.26E-06	1.51E+00	3.28E-06	1.47E+00	3.23E-06	3.33E-04	3.47E-04	3.33E-04	3.47E-04
9-10	1.41E+00	2.95E-06	1.43E+00	2.92E-06	1.49E+00	2.88E-06	1.40E+00	2.92E-06	1.44E+00	2.79E-06	3.22E-04	3.35E-04	3.22E-04	3.35E-04
10-11	1.42E+00	2.63E-06	1.40E+00	2.60E-06	1.41E+00	2.51E-06	1.42E+00	2.55E-06	1.41E+00	2.38E-06	3.07E-04	3.21E-04	3.07E-04	3.21E-04
11-12	1.37E+00	2.34E-06	1.39E+00	2.31E-06	1.39E+00	2.15E-06	1.38E+00	2.19E-06	1.38E+00	2.04E-06	3.05E-04	3.18E-04	3.05E-04	3.18E-04
12-13	1.40E+00	2.06E-06	1.37E+00	2.04E-06	1.36E+00	1.81E-06	1.35E+00	1.89E-06	1.34E+00	1.74E-06	3.00E-04	3.13E-04	3.00E-04	3.13E-04
13-14	1.31E+00	1.82E-06	1.34E+00	1.77E-06	1.30E+00	1.58E-06	1.34E+00	1.62E-06	1.31E+00	1.49E-06	2.86E-04	2.98E-04	2.86E-04	2.98E-04
14-15	1.35E+00	1.60E-06	1.36E+00	1.51E-06	1.29E+00	1.36E-06	1.32E+00	1.39E-06	1.27E+00	1.27E-06	2.74E-04	2.86E-04	2.74E-04	2.86E-04
15-16	1.32E+00	1.40E-06	1.28E+00	1.29E-06	1.24E+00	1.16E-06	1.21E+00	1.19E-06	1.21E+00	1.09E-06	2.59E-04	2.70E-04	2.59E-04	2.70E-04
16-17	1.21E+00	1.20E-06	1.20E+00	1.10E-06	1.19E+00	<E-06	1.19E+00	1.03E-06	1.16E+00	<E-06	2.51E-04	2.62E-04	2.51E-04	2.62E-04
17-18	1.17E+00	1.01E-06	1.14E+00	<E-06	1.13E+00		1.13E+00	<E-06	1.09E+00		2.45E-04	2.56E-04	2.45E-04	2.56E-04
18-19	1.10E+00	<E-06	1.09E+00		1.03E+00		1.07E+00		1.01E+00		2.22E-04	2.31E-04	2.22E-04	2.31E-04
19-20	9.95E-01		1.00E+00		9.47E-01		9.97E-01		9.10E-01		1.74E-04	1.82E-04	1.74E-04	1.82E-04
20-21	8.96E-01		9.09E-01		8.64E-01		8.92E-01		8.07E-01		1.27E-04	1.33E-04	1.27E-04	1.33E-04
21-22	7.82E-01		8.14E-01		7.19E-01		7.99E-01		6.99E-01		9.39E-05	9.79E-05	9.39E-05	9.79E-05
22-23	6.55E-01		6.62E-01		6.52E-01		6.99E-01		5.86E-01		7.12E-05	7.43E-05	7.12E-05	7.43E-05
23-24	5.48E-01		6.23E-01		5.08E-01		5.92E-01		4.84E-01		5.55E-05	5.79E-05	5.55E-05	5.79E-05
24-25	4.51E-01		4.76E-01		4.41E-01		4.68E-01		3.69E-01		4.53E-05	4.73E-05	4.53E-05	4.73E-05
25-30	2.33E-01		2.63E-01		2.18E-01		2.61E-01		1.93E-01		2.28E-05	2.38E-05	2.28E-05	2.38E-05
30-35	1.93E-01		2.07E-01		1.84E-01		7.02E-02		1.71E-01		6.43E-06	6.70E-06	6.43E-06	6.70E-06
35-40	9.62E-02		1.03E-01		8.70E-02		1.04E-01		8.04E-02		1.69E-06	1.76E-06	1.69E-06	1.76E-06
40-45	4.86E-02		5.30E-02		4.14E-02		5.22E-02		3.79E-02		<E-06	<E-06	<E-06	<E-06
45-50	2.46E-02		2.67E-02		2.05E-02		2.73E-02		1.83E-02					
50-70	6.75E-03		7.50E-03		4.83E-03		7.77E-03		4.51E-03					
70-100	3.21E-04		3.72E-04		2.61E-04		3.91E-04		2.25E-04					

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

λ=1.536μm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	1.47E-04	1.77E-04	1.52E-04	1.81E-04	1.81E-04	1.96E-04	1.74E-04	1.85E-04	2.22E-04	2.07E-04	2.35E-02	4.09E-02	1.15E-01	1.99E-01
0-1	1.31E-04	1.69E-04	1.36E-04	1.72E-04	1.62E-04	1.86E-04	1.55E-04	1.76E-04	1.98E-04	1.93E-04	1.56E-02	2.71E-02	6.93E-02	1.20E-01
1-2	1.09E-04	1.54E-04	1.11E-04	1.56E-04	1.30E-04	1.66E-04	1.27E-04	1.59E-04	1.53E-04	1.70E-04	6.80E-03	1.18E-02	2.53E-02	4.40E-02
2-3	8.99E-05	1.40E-04	9.24E-05	1.41E-04	1.04E-04	1.48E-04	1.04E-04	1.43E-04	1.20E-04	1.50E-04	2.90E-03	5.03E-03	9.27E-03	1.61E-02
3-4	7.48E-05	1.26E-04	7.62E-05	1.27E-04	8.39E-05	1.32E-04	8.54E-05	1.29E-04	9.64E-05	1.34E-04	1.36E-03	2.37E-03	3.38E-03	5.88E-03
4-5	6.14E-05	1 14E-04	6.09E-05	1.15E-04	6.82E-05	1.18E-04	6.80E-05	1.15E-04	7.68E-05	1.19E-04	8.62E-04	1.50E-03	1.24E-03	2.15E-03
5-6	5.06E-05	1.03E-04	5.09E-05	1.04E-04	5.45E-05	1.06E-04	5.69E-05	1.04E-04	6.20E-05	1.06E-04	6.28E-04	1.09E-03	6.28E-04	1.09E-03
6-7	4.12E-05	9.31E-05	4.20E-05	9.29E-05	4.38E-05	9.42E-05	4.51E-05	9.32E-05	4.95E-05	9.46E-05	5.09E-04	8.83E-04	5.09E-04	8.83E-04
7-8	3.36E-05	8.38E-05	3.35E-05	8.33E-05	3.47E-05	8.37E-05	3.69E-05	8.35E-05	3.92E-05	8.39E-05	4.98E-04	8.65E-04	4.98E-04	8.65E-04
8-9	2.75E-05	7.51E-05	2.63E-05	7.46E-05	2.77E-05	7.42E-05	2.97E-05	7.46E-05	3.04E-05	7.36E-05	4.95E-04	8.59E-04	4.95E-04	8.59E-04
9-10	2.17E-05	6.71E-05	2.15E-05	6.66E-05	2.10E-05	6.55E-05	2.35E-05	6.64E-05	2.26E-05	6.34E-05	4.78E-04	8.31E-04	4.78E-04	8.31E-04
10-11	1.77E-05	5.99E-05	1.73E-05	5.93E-05	1.65E-05	5.70E-05	1.79E-05	5.81E-05	1.65E-05	5.42E-05	4.57E-04	7.94E-04	4.57E-04	7.94E-04
11-12	1.38E-05	5.32E-05	1.38E-05	5.36E-05	1.20E-05	4.89E-05	1.36E-05	4.99E-05	1.20E-05	4.63E-05	4.54E-04	7.88E-04	4.54E-04	7.88E-04
12-13	1.12E-05	4.70E-05	1.07E-05	4.65E-05	8.87E-06	4.20E-05	9.68E-06	4.29E-05	8.64E-06	3.96E-05	4.47E-04	7.76E-04	4.47E-04	7.76E-04
13-14	8.40E-06	4.15E-05	8.01E-06	4.04E-05	6.65E-06	3.60E-05	7.45E-06	3.69E-05	6.59E-06	3.39E-05	4.25E-04	7.38E-04	4.25E-04	7.38E-04
14-15	6.87E-06	3.65E-05	6.08E-06	3.44E-05	4.81E-06	3.09E-05	5.45E-06	3.16E-05	4.69E-06	2.89E-05	4.07E-04	7.08E-04	4.07E-04	7.08E-04
15-16	5.28E-06	3.18E-05	4.30E-06	2.93E-05	3.51E-06	2.64E-05	3.85E-06	2.72E-05	3.44E-06	2.48E-05	3.85E-04	6.69E-04	3.85E-04	6.69E-04
16-17	3.76E-06	2.74E-05	3.10E-06	2.50E-05	2.59E-06	2.27E-05	2.98E-06	2.34E-05	2.33E-06	2.12E-05	3.73E-04	6.48E-04	3.73E-04	6.48E-04
17-18	2.70E-06	2.30E-05	2.29E-06	2.14E-05	1.93E-06	1.94E-05	2.18E-06	2.01E-05	1.86E-06	1.82E-05	3.65E-04	6.34E-04	3.65E-04	6.34E-04
18-19	1.85E-06	1.90E-05	1.66E-06	1.83E-05	1.40E-06	1.66E-05	1.61E-06	1.73E-05	1.38E-06	1.56E-05	3.30E-04	5.73E-04	3.30E-04	5.73E-04
19-20	1.26E-06	1.58E-05	1.21E-06	1.56E-05	1.01E-06	1.42E-05	1.21E-06	1.49E-05	<E-06	1.33E-05	2.59E-04	4.50E-04	2.59E-04	4.50E-04
20-21	<E-06	1.31E-05	<E-06	1.33E-05	<E-06	1.21E-05	<E-06	1.28E-05		1.14E-05	1.89E-04	3.28E-04	1.89E-04	3.28E-04
21-22		1.10E-05		1.13E-05		1.04E-05		1.10E-05		9.75E-06	1.40E-04	2.43E-04	1.40E-04	2.43E-04
22-23		9.23E-06		9.66E-06		8.85E-06		9.47E-06		8.34E-06	1.06E-04	1.84E-04	1.06E-04	1.84E-04
23-24		7.83E-06		8.24E-06		7.57E-06		8.13E-06		7.13E-06	8.25E-05	1.43E-04	8.25E-05	1.43E-04
24-25		6.65E-06		7.04E-06		6.46E-06		6.95E-06		6.09E-06	6.74E-05	1.17E-04	6.74E-05	1.17E-04
25-30		4.43E-06		4.73E-06		4.31E-06		4.70E-06		4.05E-06	3.39E-05	5.90E-05	3.39E-05	5.90E-05
30-35		2.03E-06		2.18E-06		1.94E-06		2.20E-06		1.80E-06	9.56E-06	1.66E-05	9.56E-06	1.66E-05
35-40		<E-06		1.04E-06		<E-06		1.04E-06		<E-06	2.52E-06	4.37E-06	2.52E-06	4.37E-06
40-45				<E-06				<E-06			<E-06	1.15E-06	<E-06	1.15E-06
45-50												<E-06		<E-06
50-70														
70-100														

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

λ=1.06μm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAN		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	<E-06	8.04E-04	<E-06	8.20E-04	<E-06	8.91E-04	<E-06	8.30E-04	<E-06	9.39E-04	1.98E-02	6.79E-02	9.63E-02	3.31E-01
0-1		7.6[illegible]E-04		7.81E-04		8.43E-04		7.98E-04		8.77E-04	1.31E-02	4.50E-02	5.82E-02	2.00E-01
1-2		6.90E-04		7.06E-04		7.52E-04		7.21E-04		7.70E-04	5.71E-03	1.96E-02	2.13E-02	7.31E-02
2-3		6.33E-04		6.38E-04		6.70E-04		6.50E-04		6.82E-04	2.43E-03	8.36E-03	7.78E-03	2.67E-02
3-4		5.72E-04		5.77E-04		5.90E-04		5.84E-04		6.06E-04	1.15E-03	3.94E-03	2.84E-03	9.76E-03
4-5		5.19E-04		5.21E-04		5.37E-04		5.24E-04		5.40E-04	7.23E-04	2.49E-03	1.04E-03	3.56E-03
5-6		4.69E-04		4.69E-04		4.80E-04		4.71E-04		4.82E-04	5.27E-04	1.81E-03	5.27E-04	1.81E-03
6-7		4.22E-04		4.21E-04		4.27E-04		4.23E-04		4.29E-04	4.27E-04	1.47E-03	4.27E-04	1.47E-03
7-8		3.80E-04		3.78E-04		3.80E-04		3.79E-04		3.81E-04	4.18E-04	1.44E-03	4.18E-04	1.44E-03
8-9		3.41E-04		3.38E-04		3.36E-04		3.38E-04		3.34E-04	4.15E-04	1.43E-03	4.15E-04	1.43E-03
9-10		3.04E-04		3.02E-04		2.97E-04		3.01E-04		2.88E-04	4.01E-04	1.38E-03	4.01E-04	1.38E-03
10-11		2.72E-04		2.69E-04		2.59E-04		2.64E-04		2.46E-04	3.84E-04	1.32E-03	3.84E-04	1.32E-03
11-12		2.41E-04		2.39E-04		2.22E-04		2.26E-04		2.10E-04	3.81E-04	1.31E-03	3.81E-04	1.31E-03
12-13		2.13E-04		2.11E-04		1.90E-04		1.95E-04		1.80E-04	3.75E-04	1.29E-03	3.75E-04	1.29E-03
13-14		1.88E-04		1.83E-04		1.63E-04		1.67E-04		1.54E-04	3.56E-04	1.22E-03	3.56E-04	1.22E-03
14-15		1.66E-04		1.56E-04		1.40E-04		1.44E-04		1.31E-05	3.42E-04	1.18E-03	3.42E-04	1.18E-03
15-16		1.44E-04		1.33E-04		1.20E-04		1.23E-04		1.12E-05	3.23E-04	1.11E-03	3.23E-04	1.11E-03
16-17		1.24E-04		1.14E-04		1.03E-04		1.06E-04		9.63E-05	3.13E-04	1.08E-03	3.13E-04	1.08E-03
17-18		1.05E-04		9.72E-05		8.80E-05		9.14E-05		8.25E-05	3.06E-04	1.05E-03	3.06E-04	1.05E-03
18-19		8.63E-05		8.29E-05		7.53E-05		7.86E-05		7.06E-05	2.77E-04	9.51E-04	2.77E-04	9.51E-04
19-20		7.18E-05		7.07E-05		6.45E-05		6.75E-05		6.05E-05	2.18E-04	7.48E-04	2.18E-04	7.48E-04
20-21		5.96E-05		6.02E-05		5.51E-05		5.80E-05		5.17E-05	1.59E-04	5.45E-04	1.59E-04	5.45E-04
21-22		4.98E-05		5.14E-05		4.70E-05		4.99E-05		4.42E-05	1.17E-04	4.03E-04	1.17E-04	4.03E-04
22-23		4.19E-05		4.38E-05		4.01E-05		4.29E-05		3.78E-05	8.89E-04	3.06E-04	8.89E-04	3.06E-04
23-24		3.55E-05		3.74E-05		3.43E-05		3.69E-05		3.23E-05	6.93E-05	2.38E-04	6.93E-05	2.38E-04
24-25		3.02E-05		3.19E-05		2.93E-05		3.15E-05		2.76E-05	5.66E-05	1.94E-04	5.66E-05	1.94E-04
25-30		2.01E-05		2.15E-05		1.95E-05		2.13E-05		1.84E-05	2.85E-05	9.79E-05	2.85E-05	9.79E-05
30-35		9.20E-06		9.89E-06		8.79E-06		9.98E-06		8.14E-06	8.02E-06	2.76E-05	8.02E-06	2.76E-05
35-40		4.37E-06		4.71E-06		3.95E-06		4.73E-06		3.66E-06	2.11E-06	7.26E-06	2.11E-06	7.26E-06
40-45		2.15E-06		2.31E-06		1.83E-06		2.33E-06		1.68E-06	<E-06	1.91E-06	<E-06	1.91E-06
45-50		1.09E-06		1.19E-06		<E-06		1.21E-06		<E-06		<E-06		<E-06
50-70		<E-06		<E-06				<E-06						
70-100														

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

$\lambda = 0.86\,\mu m$														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL			
											CLEAR		HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	<E-06	1.89E-03	<E-06	1.93E-03	<E-06	2.09E-03	<E-06	1.97E-03	<E-06	2.21E-03	1.52E-02	9.03E-02	7.43E-02	4.40E-01
0-1		1.81E-03		1.84E-03		1.98E-03		1.87E-03		2.06E-03	1.01E-02	5.99E-02	4.49E-02	2.66E-01
1-2		1.64E-03		1.66E-03		1.77E-03		1.69E-03		1.81E-04	4.41E-03	2.61E-02	1.64E-03	9.72E-02
2-3		1.49E-03		1.50E-03		1.58E-03		1.53E-03		1.60E-04	1.88E-03	1.11E-02	6.00E-03	3.56E-02
3-4		1.34E-03		1.36E-03		1.41E-03		1.37E-03		1.42E-04	8.84E-04	5.24E-03	2.19E-03	1.30E-02
4-5		1.22E-03		1.22E-03		1.26E-03		1.23E-03		1.27E-04	5.58E-04	3.30E-03	8.00E-04	4.74E-03
5-6		1.10E-03		1.10E-03		1.13E-03		1.11E-03		1.13E-04	4.07E-04	2.41E-03	4.07E-04	2.41E-03
6-7		9.92E-04		9.90E-04		1.00E-03		9.93E-04		1.01E-04	3.29E-04	1.95E-03	3.29E-04	1.95E-03
7-8		8.94E-04		8.87E-04		8.92E-04		8.90E-04		8.94E-04	3.22E-04	1.91E-03	3.22E-04	1.91E-03
8-9		8.00E-04		7.96E-04		7.90E-04		7.95E-04		7.84E-04	3.20E-04	1.90E-03	3.20E-04	1.90E-03
9-10		7.15E-04		7.11E-04		6.98E-04		7.08E-04		6.76E-04	3.10E-04	1.83E-03	3.10E-04	1.83E-03
10-11		6.38E-04		6.32E-04		6.08E-04		6.19E-04		5.78E-04	2.96E-04	1.75E-03	2.96E-04	1.75E-03
11-12		5.67E-04		5.60E-04		5.22E-04		5.32E-04		4.94E-04	2.94E-04	1.74E-03	2.94E-04	1.74E-03
12-13		5.01E-04		4.95E-04		4.47E-04		4.57E-04		4.22E-04	2.89E-04	1.71E-03	2.89E-04	1.71E-03
13-14		4.43E-04		4.30E-04		3.84E-04		3.93E-04		3.61E-04	2.75E-04	1.63E-03	2.75E-04	1.63E-03
14-15		3.89E-04		3.67E-04		3.29E-04		3.37E-04		3.08E-04	2.64E-04	1.56E-03	2.64E-04	1.56E-03
15-16		3.39E-04		3.12E-04		2.82E-04		2.90E-04		2.64E-04	2.49E-04	1.48E-03	2.49E-04	1.48E-03
16-17		2.92E-04		2.67E-04		2.42E-04		2.50E-04		2.26E-04	2.42E-04	1.43E-03	2.42E-04	1.43E-03
17-18		2.45E-04		2.28E-04		2.07E-04		2.15E-04		1.94E-04	2.36E-04	1.40E-03	2.36E-04	1.40E-03
18-19		2.03E-04		1.95E-04		1.77E-04		1.85E-04		1.66E-04	2.13E-04	1.26E-03	2.13E-04	1.26E-03
19-20		1.68E-04		1.66E-04		1.52E-04		1.59E-04		1.42E-04	1.68E-04	9.94E-04	1.68E-04	9.94E-04
20-21		1.40E-04		1.42E-04		1.29E-04		1.36E-04		1.22E-04	1.22E-04	7.25E-04	1.22E-04	7.25E-04
21-22		1.17E-04		1.21E-04		1.10E-04		1.17E-04		1.04E-04	9.04E-05	5.36E-04	9.04E-05	5.36E-04
22-23		9.84E-05		1.03E-04		9.43E-05		1.01E-04		8.89E-05	6.86E-05	4.06E-04	6.86E-05	4.06E-04
23-24		8.35E-05		8.78E-05		8.06E-05		8.66E-05		7.60E-05	5.34E-05	3.16E-04	5.34E-05	3.16E-04
24-25		7.09E-05		7.50E-05		6.88E-05		7.41E-05		6.49E-05	4.36E-05	2.59E-04	4.36E-05	2.59E-04
25-30		4.73E-05		5.64E-05		4.59E-05		5.01E-05		4.31E-05	2.20E-05	1.30E-04	2.20E-05	1.30E-04
30-35		2.16E-05		2.32E-05		2.07E-05		2.35E-05		1.91E-05	6.19E-06	3.67E-05	6.19E-06	3.67E-05
35-40		1.03E-05		1.11E-05		9.27E-06		1.11E-05		8.60E-06	1.63E-06	9.65E-06	1.63E-06	9.65E-06
40-45		5.04E-06		5.44E-06		4.31E-06		5.48E-06		3.94E-06	<E-06	2.54E-06	<E-06	2.54E-06
45-50		2.56E-06		2.79E-06		2.12E-06		2.85E-06		1.88E-06		<E-06		<E-06
50-70		<E-06		1.05E-06		<E-06		1.09E-06		<E-06				
70-100				<E-06		<E-06		<E-06						

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

λ=0.6943μm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	8.62E-02	4.29E-03	6.44E-02	4.37E-03	1.55E-02	4.75E-03	4.07E-02	4.47E-03	4.48E-03	5.00E-03	7.60E-03	1.20E-01	3.70E-02	5.85E-01
0-1	6.84E-02	4.10E-03	5.07E-02	4.16E-03	1.25E-02	4.50E-03	3.18E-02	4.25E-03	4.19E-03	4.68E-03	5.04E-03	7.97E-02	2.24E-02	3.54E-01
1-2	4.22E-02	3.73E-03	3.03E-02	3.76E-03	8.13E-03	4.01E-03	1.88E-02	3.84E-03	3.66E-03	4.11E-03	2.20E-03	3.47E-02	8.18E-03	1.29E-01
2-3	2.73E-02	3.38E-03	1.72E-02	3.40E-03	5.15E-03	3.57E-03	1.18E-02	3.47E-03	2.56E-03	3.64E-03	9.35E-04	1.48E-02	2.99E-03	4.73E-02
3-4	1.23E-02	3.05E-03	8.67E-03	3.08E-03	3.06E-03	3.19E-03	6.78E-03	3.11E-03	1.65E-03	3.23E-03	4.41E-04	6.96E-03	1.09E-03	1.73E-02
4-5	5.24E-03	2.77E-03	4.43E-03	2.78E-03	1.48E-03	2.86E-03	3.76E-03	2.79E-03	8.60E-04	2.88E-03	2.78E-04	4.40E-03	3.99E-04	6.30E-03
5-6	3.09E-03	2.50E-03	2.06E-03	2.50E-03	7.41E-04	2.56E-03	1.95E-03	2.51E-03	3.66E-04	2.57E-03	2.03E-04	3.20E-03	2.03E-04	3.20E-03
6-7	1.56E-03	2.25E-03	1.11E-03	2.25E-03	3.60E-04	2.28E-03	9.26E-04	2.25E-03	1.54E-04	2.29E-03	1.64E-04	2.59E-03	1.64E-04	2.59E-03
7-8	7.61E-04	2.03E-03	5.87E-04	2.01E-03	1.26E-04	2.02E-03	4.32E-04	2.05E-03	7.26E-05	2.03E-03	1.61E-04	2.54E-03	1.61E-04	2.54E-03
8-9	3.54E-04	1.82E-03	2.92E-04	1.80E-03	4.42E-05	1.79E-03	1.68E-04	1.83E-03	1.27E-05	1.78E-03	1.60E-04	2.52E-03	1.60E-04	2.52E-03
9-10	1.47E-04	1.62E-03	1.44E-04	1.61E-03	1.75E-05	1.58E-03	4.64E-05	1.61E-03	8.23E-06	1.53E-03	1.54E-04	2.44E-03	1.54E-04	2.44E-03
10-11	5.28E-05	1.45E-03	6.66E-05	1.44E-03	6.87E-06	1.38E-03	1.43E-05	1.41E-03	4.63E-06	1.31E-03	1.48E-04	2.33E-03	1.48E-04	2.33E-03
11-12	1.55E-05	1.29E-03	1.95E-05	1.27E-03	5.51E-06	1.18E-03	7.70E-06	1.21E-03	2.76E-06	1.12E-03	1.46E-04	2.31E-03	1.46E-04	2.31E-03
12-13	4.63E-06	1.14E-03	4.54E-06	1.12E-03	4.07E-06	1.01E-03	4.23E-06	1.04E-03	1.59E-06	9.56E-04	1.44E-04	2.28E-03	1.44E-04	2.28E-03
13-14	1.19E-06	1.00E-03	1.18E-06	9.75E-04	1.06E-06	8.70E-04	1.10E-06	8.92E-04	<E-06	8.18E-04	1.37E-04	2.17E-03	1.37E-04	2.17E-03
14-15	<E-06	8.82E-04	<E-06	8.32E-04	<E-06	7.46E-04	<E-06	7.65E-04		7.00E-04	1.31E-04	2.08E-03	1.31E-04	2.08E-03
15-16		7.68E-04		7.05E-04		6.39E-04		6.57E-04		6.00E-04	1.24E-04	1.96E-03	1.24E-04	1.96E-03
16-17		6.63E-04		6.02E-04		5.48E-04		5.66E-04		5.13E-04	1.20E-04	1.90E-03	1.20E-04	1.90E-03
17-18		5.57E-04		5.18E-04		4.69E-04		4.87E-04		4.39E-04	1.18E-04	1.86E-03	1.18E-04	1.86E-03
18-19		4.60E-04		4.42E-04		4.01E-04		4.19E-04		3.76E-04	1.06E-04	1.68E-03	1.06E-04	1.68E-03
19-20		3.81E-04		3.76E-04		3.44E-04		3.60E-04		3.22E-04	8.36E-05	1.32E-03	8.36E-05	1.32E-03
20-21		3.18E-04		3.21E-04		2.94E-04		3.09E-04		2.76E-04	6.10E-05	9.64E-04	6.10E-05	9.64E-04
21-22		2.65E-04		2.74E-04		2.51E-04		2.66E-04		2.36E-04	4.51E-05	7.12E-04	4.51E-05	7.12E-04
22-23		2.23E-04		2.34E-04		2.14E-04		2.29E-04		2.02E-04	3.42E-05	5.41E-04	3.42E-05	5.41E-04
23-24		1.90E-04		1.99E-04		1.83E-04		1.97E-04		1.73E-04	2.66E-05	4.21E-04	2.66E-05	4.21E-04
24-25		1.61E-04		1.70E-04		1.56E-04		1.68E-04		1.48E-04	2.18E-05	3.44E-04	2.18E-05	3.44E-04
25-30		1.07E-04		1.14E-04		1.04E-04		1.14E-04		9.80E-05	1.10E-05	1.73E-04	1.10E-05	1.73E-04
30-35		4.90E-05		5.27E-05		4.69E-05		5.32E-05		4.34E-05	3.08E-06	4.87E-05	3.08E-06	4.87E-05
35-40		2.33E-05		2.51E-05		2.11E-05		2.53E-05		1.95E-05	<E-06	1.28E-05	<E-06	1.28E-05
40-45		1.14E-05		1.23E-05		9.77E-06		1.24E-05		8.91E-06		3.38E-06		3.38E-06
45-50		5.81E-06		6.32E-06		4.80E-06		6.45E-06		4.26E-06		<E-06		<E-06
50-70		2.17E-06		2.38E-06		1.76E-06		2.47E-06		1.50E-06				
70-100		<E-06		<E-06		<E-06		<E-06		<E-06				

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering k_a = aerosol absorption, σ_a = aerosol scattering)

λ=0.6328μm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL			
											CLEAR		HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	<E-06	6.31E-03	<E-06	6.44E-03	<E-06	6.79E-03	<E-06	6.58E-03	<E-06	7.37E-03	3.14E-03	1.36E-01	1.53E-02	6.63E-01
0-1		6.03E-03		6.13E-03		6.62E-03		6.26E-03		6.88E-03	2.08E-03	9.03E-02	9.26E-03	4.01E-01
1-2		5.40E-03		5.54E-03		5.91E-03		5.66E-03		6.04E-03	9.09E-04	3.93E-02	3.39E-03	1.47E-01
2-3		4.97E-03		5.01E-03		5.26E-03		5.10E-03		5.36E-03	3.87E-04	1.67E-02	1.24E-03	5.36E-02
3-4		4.49E-03		4.53E-03		4.70E-03		4.58E-03		4.75E-03	1.82E-04	7.89E-03	4.52E-04	1.96E-02
4-5		4.07E-03		4.09E-03		4.21E-03		4.11E-03		4.24E-03	1.15E-04	4.98E-03	1.65E-04	7.14E-03
5-6		3.68E-03		3.68E-03		3.76E-03		3.69E-03		3.79E-03	8.39E-05	3.63E-03	8.39E-05	3.63E-03
6-7		3.31E-03		3.31E-03		3.35E-03		3.32E-03		3.37E-03	6.78E-05	2.94E-03	6.79E-05	2.94E-03
7-8		2.99E-03		2.98E-03		2.98E-03		2.97E-03		2.99E-03	6.65E-05	2.88E-03	6.65E-05	2.88E-03
8-9		2.67E-03		2.66E-03		2.64E-03		2.66E-03		2.62E-03	6.61E-05	2.86E-03	6.61E-05	2.86E-03
9-10		2.39E-03		2.37E-03		2.33E-03		2.36E-03		2.26E-03	6.39E-05	2.77E-03	6.39E-05	2.77E-03
10-11		2.13E-03		2.11E-03		2.03E-03		2.07E-03		1.93E-03	6.11E-05	2.64E-03	6.11E-05	2.64E-03
11-12		1.89E-03		1.87E-03		1.74E-03		1.78E-03		1.65E-03	6.06E-05	2.62E-03	6.06E-05	2.62E-03
12-13		1.67E-03		1.66E-03		1.49E-03		1.53E-03		1.41E-03	5.97E-05	2.58E-03	5.97E-05	2.58E-03
13-14		1.48E-03		1.44E-03		1.28E-03		1.31E-03		1.21E-03	5.67E-05	2.45E-03	5.67E-05	2.45E-03
14-15		1.30E-03		1.23E-03		1.10E-03		1.13E-03		1.03E-03	5.44E-05	2.35E-03	5.44E-05	2.35E-03
15-16		1.13E-03		1.04E-03		9.41E-04		9.68E-04		8.82E-04	5.14E-05	2.23E-03	5.14E-05	2.23E-03
16-17		9.76E-04		8.92E-04		8.07E-04		8.34E-04		7.56E-04	4.99E-05	2.16E-03	4.99E-05	2.16E-03
17-18		8.20E-04		7.63E-04		6.91E-04		7.17E-04		6.47E-04	4.88E-05	2.11E-03	4.88E-05	2.11E-03
18-19		6.77E-04		6.51E-04		5.91E-04		6.17E-04		5.54E-04	4.40E-05	1.91E-03	4.40E-05	1.91E-03
19-20		5.62E-04		5.55E-04		5.06E-04		5.30E-04		4.75E-04	3.46E-05	1.50E-03	3.46E-05	1.50E-03
20-21		4.68E-04		4.73E-04		4.32E-04		4.55E-04		4.06E-04	2.52E-05	1.09E-03	2.52E-05	1.09E-03
21-22		3.91E-04		4.03E-04		3.69E-04		3.92E-04		3.47E-04	1.87E-05	8.07E-04	1.87E-05	8.07E-04
22-23		3.29E-04		3.44E-04		3.15E-04		3.37E-04		2.97E-04	1.42E-05	6.13E-04	1.42E-05	6.13E-04
23-24		2.79E-04		2.93E-04		2.69E-04		2.89E-04		2.54E-04	1.10E-05	4.77E-04	1.10E-05	4.77E-04
24-25		2.37E-04		2.51E-04		2.30E-04		2.48E-04		2.17E-04	9.00E-06	3.90E-04	9.00E-06	3.90E-04
25-30		1.58E-04		1.68E-04		1.53E-04		1.67E-04		1.44E-04	4.53E-06	1.96E-04	4.53E-06	1.96E-04
30-35		7.22E-05		7.76E-05		6.90E-05		7.83E-05		6.39E-05	1.28E-06	5.52E-05	1.28E-06	5.52E-05
35-40		3.43E-05		3.69E-05		3.10E-05		3.72E-05		2.87E-05	<E-06	1.45E-05	<E-06	1.45E-05
40-45		1.68E-05		1.82E-05		1.44E-05		1.83E-05		1.32E-05		3.83E-06		3.83E-06
45-50		3.57E-06		8.31E-06		7.06E-06		8.51E-06		6.27E-06		1.01E-06		1.01E-06
50-70		3.20E-06		3.51E-06		2.59E-06		3.64E-06		2.22E-06		<E-06		<E-06
70-100		<E-06		<E-06		<E-06		<E-06		<E-06				

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

$\lambda = 0.5145 \mu m$														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	<E-06	1.47E-02	<E-06	1.50E-02	<E-06	1.63E-02	<E-06	1.53E-02	<E-06	1.71E-02	<E-06	1.68E-01	<E-06	8.20E-01
0-1		1.40E-02		1.43E-02		1.54E-02		1.46E-02		1.60E-02		1.12E-01		4.96E-01
1-2		1.28E-02		1.29E-02		1.37E-02		1.32E-02		1.41E-02		4.86E-02		1.81E-01
2-3		1.15E-02		1.16E-02		1.22E-02		1.19E-02		1.25E-02		2.07E-02		6.63E-02
3-4		1.04E-02		1.05E-02		1.09E-02		1.06E-02		1.10E-02		9.76E-03		7.42E-02
4-5		9.46E-03		9.51E-02		9.79E-03		9.55E-03		9.86E-03		6.16E-03		8.84E-03
5-6		8.55E-03		8.56E-02		8.75E-03		8.58E-03		8.80E-03		4.49E-03		4.49E-03
6-7		7.70E-03		7.68E-02		7.80E-03		7.71E-03		7.83E-03		3.64E-03		3.64E-03
7-8		6.94E-03		6.89E-02		6.93E-03		6.91E-03		6.94E-03		3.56E-03		3.56E-03
8-9		6.22E-03		6.16E-03		6.14E-03		6.17E-03		6.09E-03		3.54E-03		3.54E-03
9-10		5.55E-03		5.50E-03		5.42E-03		5.50E-03		5.25E-03		3.42E-03		3.42E-03
10-11		4.96E-03		4.90E-03		4.72E-03		4.81E-03		4.49E-03		3.27E-03		3.27E-03
11-12		4.40E-03		4.35E-03		4.05E-03		4.13E-03		3.84E-03		3.24E-03		3.24E-03
12-13		3.89E-03		3.85E-03		3.47E-03		3.55E-03		3.28E-03		3.19E-03		3.19E-03
13-14		3.44E-03		3.34E-03		2.98E-03		3.05E-03		2.80E-03		3.04E-03		3.04E-03
14-15		3.02E-03		2.85E-03		2.55E-03		2.62E-03		2.40E-03		2.91E-03		2.91E-03
15-16		2.63E-03		2.42E-03		2.19E-03		2.25E-03		2.05E-03		2.75E-03		2.75E-03
16-17		2.27E-03		2.07E-03		1.88E-03		1.94E-03		1.76E-03		2.67E-03		2.67E-03
17-18		1.91E-03		1.77E-03		1.61E-03		1.67E-03		1.51E-03		2.61E-03		2.61E-03
18-19		1.57E-03		1.51E-03		1.38E-03		1.43E-03		1.29E-03		2.36E-03		2.36E-03
19-20		1.31E-03		1.29E-03		1.18E-03		1.23E-03		1.10E-03		1.85E-03		1.85E-03
20-21		1.09E-03		1.10E-03		1.01E-03		1.06E-03		9.44E-04		1.35E-03		1.35E-03
21-22		9.08E-04		9.38E-04		8.57E-04		9.11E-04		8.07E-04		9.98E-04		9.98E-04
22-23		7.64E-04		8.00E-04		7.32E-04		7.83E-04		6.90E-04		7.58E-04		7.58E-04
23-24		6.48E-04		6.82E-04		6.26E-04		6.72E-04		5.90E-04		5.90E-04		5.90E-04
24-25		5.50E-04		5.83E-04		5.34E-04		5.75E-04		5.04E-04		4.82E-04		4.82E-04
25-30		3.67E-04		3.91E-04		3.56E-04		3.89E-04		3.35E-04		2.43E-04		2.43E-04
30-35		1.68E-04		1.80E-04		1.60E-04		1.82E-04		1.49E-04		6.83E-05		6.83E-05
35-40		7.97E-05		8.59E-05		7.20E-05		8.64E-05		6.67E-05		1.80E-05		1.80E-05
40-45		3.91E-05		4.22E-05		3.35E-05		4.26E-05		3.06E-05		4.73E-06		4.73E-06
45-50		1.99E-05		2.17E-05		1.64E-05		2.21E-05		1.46E-05		1.25E-06		1.25E-06
50-70		[illegible].45E-06		8.16E-06		6.01E-06		8.45E-06		5.15E-06		<E-06		<E-06
70-100		<E-06		<E-06		<E-06		<E-06		<E-06				

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

λ=0.4880μm														
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	<E-06	1.82E-02	<E-06	1.86E-02	<E-06	2.02E-02	<E-06	1.90E-02	<E-06	2.13E-02	<E-06	1.76E-01	<E-06	8.58E-01
0-1		1.74E-02		1.77E-02		1.91E-02		1.80E-02		1.99E-02		1.17E-01		5.19E-01
1-2		1.58E-02		1.60E-02		1.70E-02		1.63E-02		1.74E-02		5.09E-02		1.90E-01
2-3		1.43E-02		1.45E-02		1.52E-02		1.47E-02		1.55E-02		2.17E-02		6.94E-02
3-4		1.30E-02		1.31E-02		1.36E-02		1.32E-02		1.37E-02		1.02E-02		2.53E-02
4-5		1.18E-02		1.18E-02		1.22E-02		1.19E-02		1.22E-02		6.45E-03		9.25E-03
5-6		1.06E-02		1.06E-02		1.09E-02		1.07E-02		1.09E-02		4.70E-03		4.70E-03
6-7		9.56E-03		9.54E-03		9.66E-03		9.57E-03		9.72E-03		3.80E-03		3.80E-03
7-8		8.61E-03		8.55E-03		8.60E-03		8.58E-03		8.62E-03		3.72E-03		3.72E-03
8-9		7.72E-03		7.65E-03		7.62E-03		7.66E-03		7.56E-03		3.70E-03		3.70E-03
9-10		6.89E-03		6.83E-03		6.73E-03		6.82E-03		6.52E-03		3.58E-03		3.58E-03
10-11		6.16E-03		6.09E-03		5.86E-03		5.97E-03		5.57E-03		3.42E-03		3.42E-03
11-12		5.46E-03		5.40E-03		5.03E-03		5.13E-03		4.76E-03		3.39E-03		3.39E-03
12-13		4.83E-03		4.77E-03		4.31E-03		4.41E-03		4.07E-03		3.34E-03		3.34E-03
13-14		4.27E-03		4.15E-03		3.70E-03		3.79E-03		3.48E-03		3.18E-03		3.18E-03
14-15		3.75E-03		3.53E-03		3.17E-03		3.25E-03		2.97E-03		3.05E-03		3.05E-03
15-16		3.27E-03		3.01E-03		2.72E-03		2.79E-03		2.54E-03		2.88E-03		2.88E-03
16-17		2.82E-03		2.57E-03		2.33E-03		2.41E-03		2.18E-03		2.79E-03		2.79E-03
17-18		2.37E-03		2.20E-03		1.99E-03		2.07E-03		1.87E-03		2.73E-03		2.73E-03
18-19		1.95E-03		1.88E-03		1.71E-03		1.78E-03		1.60E-03		2.47E-03		2.47E-03
19-20		1.62E-03		1.60E-03		1.46E-03		1.53E-03		1.37E-03		1.94E-03		1.94E-03
20-21		1.35E-03		1.36E-03		1.25E-03		1.31E-03		1.17E-03		1.41E-03		1.41E-03
21-22		1.13E-03		1.16E-03		1.06E-03		1.13E-03		1.00E-03		1.04E-03		1.04E-03
22-23		9.48E-04		9.93E-04		9.09E-04		9.72E-04		8.57E-04		7.93E-04		7.93E-04
23-24		8.04E-04		8.46E-04		7.77E-04		8.35E-04		7.32E-04		6.17E-04		6.17E-04
24-25		6.83E-04		7.23E-04		6.63E-04		7.14E-04		6.26E-04		5.04E-04		5.04E-04
25-30		4.56E-04		4.86E-04		4.42E-04		4.83E-04		4.16E-04		2.54E-04		2.54E-04
30-35		2.08E-04		2.24E-04		1.99E-04		2.26E-04		1.64E-04		7.15E-05		7.15E-05
35-40		9.90E-05		1.07E-04		8.94E-05		1.07E-04		8.28E-05		1.88E-05		1.88E-05
40-45		4.86E-05		5.24E-05		4.15E-05		5.28E-05		3.79E-05		4.95E-06		4.95E-06
45-50		2.47E-05		2.69E-05		2.04E-05		2.74E-05		1.81E-05		1.31E-06		1.31E-06
50-70		9.24E-06		1.01E-05		7.47E-06		1.05E-05		6.39E-06		<E-06		<E-06
70-100		<E-06		<E-06		<E-06		<E-06		<E-06				

Values of Attenuation Coefficient/km as a Function of Altitude for Each Laser Wavelength and Each Atmospheric Model in Section 2 (k_m = molecular absorption, σ_m = molecular scattering, k_a = aerosol absorption, σ_a = aerosol scattering)

$\lambda = 0.337\ \mu m$												
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	2.34E-04	8.46E-02	2.52E-04	8.64E-02	2.52E-04	9.38E-02	2.07E-04	8.83E-02	1.71E-04	9.89E-02	<E-06	2.35E-01	<E-06	1.14E-00
0-1	2.32E-04	8.07E-02	2.52E-04	8.25E-02	2.38E-04	8.73E-02	2.16E-04	8.40E-02	1.71E-04	4.94E-02		1.56E-01		6.92E-01
1-2	2.27E-04	7.34E-02	2.52E-04	7.47E-02	2.16E-04	7.94E-02	2.30E-04	7.59E-02	1.71E-04	9.24E-02		6.39E-02		2.53E-01
2-3	2.18E-04	6.68E-02	2.57E-04	6.76E-02	2.07E-04	7.23E-02	2.39E-04	6.85E-02	1.76E-04	8.11E-02		2.89E-02		9.25E-02
3-4	1.93E-04	6.05E-02	2.65E-04	6.12E-02	2.07E-04	6.32E-02	2.48E-04	6.15E-02	1.85E-04	7.19E-02		1.36E-02		3.37E-02
4-5	1.84E-04	5.49E-02	2.74E-04	5.53E-02	2.25E-04	5.66E-02	2.61E-04	5.52E-02	1.94E-04	6.38E-02		8.60E-03		1.23E-02
5-6	1.75E-04	4.96E-02	2.83E-04	4.98E-02	2.56E-04	5.06E-02	2.84E-04	4.96E-02	2.03E-04	5.08E-02		6.27E-03		6.27E-03
6-7	1.66E-04	4.47E-02	2.99E-04	4.47E-02	2.97E-04	4.51E-02	3.06E-04	4.45E-02	2.52E-04	4.52E-02		5.07E-03		5.07E-03
7-8	1.62E-04	4.02E-02	3.22E-04	4.01E-02	3.51E-04	4.01E-02	3.24E-04	3.99E-02	3.38E-04	4.01E-02		4.97E-03		4.97E-03
8-9	1.62E-04	3.61E-02	3.44E-04	3.59E-02	4.50E-04	3.55E-02	3.87E-04	3.57E-02	5.27E-04	3.52E-02		4.94E-03		4.94E-03
9-10	1.62E-04	3.23E-02	3.67E-04	3.21E-02	5.99E-04	3.14E-02	4.95E-04	3.17E-02	8.19E-04	3.03E-02		4.77E-03		4.77E-03
10-11	1.66E-04	2.88E-02	4.14E-04	2.85E-2	7.83E-04	2.7[illegible]E-02	6.44E-04	2.78E-02	1.17E-03	2.59E-02		4.56E-03		4.56E-03
11-12	1.75E-04	2.56E-02	4.86E-04	2.53E-02	9.96E-04	2.34E-02	8.33E-04	2.39E-02	1.57E-03	2.21E-02		4.53E-03		4.53E-03
12-13	1.82E-04	2.26E-02	5.76E-04	2.24E-02	1.16E-03	2.01E-02	9.89E-04	2.05E-02	1.85E-03	1.89E-02		4.46E-03		4.46E-03
13-14	1.87E-04	2.00E-02	6.84E-04	1.94E-02	1.27E-03	1.72E-02	1.12E-03	1.76E-02	2.03E-03	1.62E-02		4.24E-03		4.24E-03
14-15	1.91E-04	1.76E-02	7.74E-04	1.66E-02	1.37E-03	1.48E-02	1.25E-03	1.51E-02	2.22E-03	1.38E-02		4.06E-03		4.06E-03
15-16	1.96E-04	1.54E-02	8.46E-04	1.42E-02	1.55E-03	1.26E-02	1.37E-03	1.20E-02	2.45E-03	1.18E-02		3.84E-03		3.84E-03
16-17	2.43E-04	1.33E-02	9.56E-04	1.22E-02	1.64E-03	1.08E-02	1.51E-03	1.12E-02	2.58E-03	1.01E-02		3.72E-03		3.72E-03
17-18	3.33E-04	1.11E-02	1.10E-03	1.04E-02	1.73E-03	9.29E-03	1.66E-03	9.62E-03	2.60E-03	8.69E-03		3.64E-03		3.64E-03
18-19	4.86E-04	9.12E-03	1.25E-03	8.79E-03	1.84E-03	7.97E-03	1.71E-03	8.27E-03	2.55E-03	7.44E-03		3.29E-03		3.29E-03
19-20	6.98E-04	7.57E-03	1.40E-03	7.46E-03	1.84E-03	6.82E-03	1.66E-03	7.11E-03	2.42E-03	6.37E-03		2.59E-03		2.59E-03
20-21	8.89E-04	6.32E-03	1.48E-03	6.36E-03	1.86E-03	5.81E-03	1.58E-03	6.11E-03	2.27E-03	5.45E-03		1.89E-03		1.89E-03
21-22	1.06E-03	5.28E-03	1.50E-03	5.42E-03	1.80E-03	4.96E-03	1.45E-03	5.26E-03	2.08E-03	4.66E-03		1.39E-03		1.39E-03
22-23	1.23E-03	4.44E-03	1.47E-03	4.63E-03	1.71E-03	4.24E-03	1.34E-03	4.52E-03	1.87E-03	3.98E-03		1.06E-03		1.06E-03
23-24	1.40E-03	3.76E-03	1.40E-03	3.95E-03	1.61E-03	3.62E-03	1.23E-03	3.88E-03	1.66E-03	3.41E-03		8.23E-04		8.23E-04
24-25	1.48E-03	3.19E-03	1.33E-03	3.38E-03	1.48E-03	3.09E-03	1.12E-03	3.32E-03	1.44E-03	2.91E-03		6.73E-04		6.73E-04
25-30	1.24E-03	2.12E-03	1.06E-03	2.28E-03	1.10E-03	2.18E-03	8.24E-04	2.25E-03	9.75E-04	1.93E-03		3.39E-04		3.39E-04
30-35	6.98E-04	9.72E-04	6.12E-04	1.05E-03	5.94E-04	1.04E-03	4.86E-04	1.65E-03	5.09E-04	8.58E-04		9.53E-05		9.53E-05
35-40	2.79E-04	4.63E-04	2.79E-04	5.00E-04	2.79E-04	4.16E-04	2.79E-04	4.99E-04	2.79E-04	3.85E-04		2.51E-05		2.51E-05
40-45	1.13E-04	2.28E-04	1.13E-04	2.46E-04	1.13E-04	1.94E-04	1.13E-04	2.46E-04	1.13E-04	1.76E-04		6.61E-06		6.61E-06
45-50	3.60E-05	1.16E-04	3.60E-05	1.26E-04	3.60E-05	9.53E-05	3.60E-05	1.28E-04	3.60E-05	3.42E-05		1.74E-06		1.74E-06
50-70	9.00E-06	4.31E-05	9.00E-06	4.75E-05	9.00E-06	3.48E-05	9.00E-06	4.88E-05	9.00E-06	2.97E-05		<E-06		<E-06
70-100	<E-06	3.35E-06	<E-06	3.90E-06	<E-06	2.56E-06	<E-06	4.12E-06	1.80E-06	2.07E-06		<E-06		<E-06

APPENDIX E

Summary of Lasers by Emission Wavelength and Laser Type

Summary of Lasers by Emission Wavelength and Laser Type

Wavelength (nanometers)	Active Medium	Laser Type
172	Xenon	Gas (Ion)
173.6	Ruby (quadrupled)	Doped Insulator
193	Argon Fluoride	Molecular (Excimer)
231.4	Ruby (tripled)	Doped Insulator
235.8	Neon	Gas (Ion)
248	Krypton Fluoride	Molecular-Excimer
266	Neodymium (quadrupled)	Doped Insulator
330	Zinc Sulfide	Semiconductor Diode
325	Helium Cadmium	Gas (Metal Vapor)
332.4	Neon	Gas (Ion)
337.1	Nitrogen (Argon Excimer Pumped)	Molecular (Excimer)
337.1	Nitrogen	Molecular (Excimer)
350	Xenon Fluoride	Molecular (Excimer)
354.7	Neodymium (tripled)	Doped Insulator
357.7	Nitrogen (Argon Excimer Pumped)	Molecular (Excimer)
380.4	Nitrogen (Argon Excimer Pumped)	Molecular (Excimer)
441.6	Helium Cadmium	Gas (Metal Vapor)
457.7	Krypton	Gas (Ion)
457.9	Argon	Gas (Ion)
460.4	Helium Selenium	Gas (Metal Vapor)
461.9	Krypton	Gas (Ion)
463.4	Krypton	Gas (Ion)
464.8	Helium Selenium	Gas (Metal Vapor)
465.8	Argon	Gas (Ion)
468	Krypton	Gas (Ion)
472.7	Argon	Gas (Ion)
476.2	Krypton	Gas (Ion)
476.5	Argon	Gas (Ion)
482.5	Krypton	Gas (Ion)
484.5	Helium Selenium	Gas (Metal Vapor)
484.6	Krypton	Gas (Ion)
488.0	Argon	Gas (Ion)
495.6	Xenon	Gas (Ion)
496.5	Argon	Gas (Ion)
497.5	Helium Selenium	Gas (Metal Vapor)
499.5	Helium Selenium	Gas (Metal Vapor)
500	Cadmium Sulfide	Semiconductor Diode
501.5	Argon	Gas (Ion)
501.7	Argon	Gas (Ion)
506.8	Helium Selenium	Gas (Metal Vapor)
510.8	Copper	Gas (Metal Vapor)
514.5	Argon	Gas (Ion)
517.5	Helium Selenium	Gas (Metal Vapor)
520.8	Krypton	Gas (Ion)
522.7	Helium Selenium	Gas (Metal Vapor)
525.3	Helium Selenium	Gas (Metal Vapor)
530	Neodymium-KDP	Doped Insulator
530.5	Helium Selenium	Gas (Metal Vapor)
530.9	Krypton	Gas (Ion)
539.5	Xenon	Gas (Ion)
532.1	Neodymium (doubled)	Doped Insulator

Wavelength (nanometers)	Active Medium	Laser Type
540.1	Neon	Gas (Ion)
543.5	Helium Neon	Gas (Atomic)
552.3	Helium Selenium	Gas (Metal Vapor)
568.2	Krypton	Gas (Ion)
578.1	Copper	Gas (Metal Vapor)
595.6	Xenon	Gas (Ion)
605.6	Helium Selenium	Gas (Metal Vapor)
610	Europium	Doped Insulator
628	Gold	Gas (Metal Vapor)
632.8	Helium Neon	Gas (Atomic)
644.4	Helium-Selenium	Gas (Metal Vapor)
647.1	Krypton	Gas (Ion)
649	Helium Selenium	Gas (Metal Vapor)
676.4	Krypton	Gas (Ion)
680-1070	Titanium Sapphire	Doped Insulator
687.1	Krypton	Gas (Ion)
690	Cadmium Selenide	Semiconductor Diode
692.9	Chromium	Doped Insulator
693.4	Chromium (cooled)	Doped Insulator
694.3	Ruby	Doped Insulator
696.9	Samarium	Doped Insulator
708.2	Samarium	Doped Insulator
720-800	Alexandrite	Doped Insulator
800	Cadmium Telluride	Semiconductor Diode
844.5	Argon Oxygen	Molecular (Excimer)
850	*Europium/Lithium*-Fluoride	Doped Insulator
850	Gallium Arsenide	Semiconductor Diode
850	Gallium Arsenide (Cooled)	Semiconductor Diode
850	Gallium-Aluminum-Arsenide	Semiconductor Diode
900	Indium Phosphide	Semiconductor Diode
905	Gallium Arsenide	Semiconductor Diode
1037	Neodymium-SrF_2	Doped Insulator
1046.1	Neodymium-CaF_2	Doped Insulator
1046.8	Praseodymium-$CaWO_4$	Doped Insulator
1047	Praseodymium-$SrMoO_4$	Doped Insulator
1054	Neodymium:YLF	Doped Insulator
1060	Neodymium-BaF_2	Doped Insulator
1060	Neodymium-Glass	Doped Insulator
1064.5	Neodymium:YAG	Doped Insulator
1064.6	Neodymium-$CaWO_4$	Doped Insulator
1123	Neodymium	Doped Insulator
1152.3	Helium Neon	Gas (Atomic)
1315	Alkyl Iodide	Gas (Molecular)
1318	Neodymium	Doped Insulator
1370	Neodymium	Doped Insulator
1454	Helium Carbon Dioxide	Gas (Molecular)
1540	Erbium-Glass	Doped Insulator
1600	Gallium Antimonide	Semiconductor Laser
1612	Erbium-$CaWO_4$	Doped Insulator
1617	Erbium-CaF_2	Doped Insulator
1910	Thulium-SrF_2	Doped Insulator
1911	Thulium-SrF_2	Doped Insulator

Wavelength (nanometers)	Active Medium	Laser Type
2000-5000	Xenon	Gas (Ion)
2046	Holmium-$CaWO_4$	Doped Insulator
2061	Xenon	Gas (Atomic)
2100	Holmium:YAG	Doped Insulator
2100	Holmium:YSGG	Doped Insulator
2360	Dysprosium	Doped Insulator
2407	Uranium-SrF_2	Doped Insulator
2510	Uranium-CaF_2	Doped Insulator
2556	Uranium-BaF_2	Doped Insulator
2600-3300 (Many Lines)	Hydrogen Fluoride	Chemical
2613	Uranium-CaF_2	Doped Insulator
2940	Er:YAG	Doped Insulator
3200	Indium Arsenide	Doped Insulator
3390	Helium Neon	Gas (Atomic)
3392	Helium Neon	Gas (Atomic)
3500	Helium Xenon	Gas (Ion)
3773	Hydrogen Chloride	Chemical
3800-4200	Deuterium Fluoride	Chemical
4300	Lead Sulfide	Semiconductor Diode
4800-8000 (Many Lines)	Carbon Monoxide	Gas (Molecular)
5300	Indium Arsenide	Semiconductor Diode
6500	Lead Telluride	Semiconductor Diode
7182.1	Cesium	Gas (Metal Vapor)
8500	Lead Selenide	Semiconductor Diode
9000-12000	N_2O	Chemical
10000-20000	Hydrogen Fluoride	Chemical
10600	Carbon Dioxide	Gas (Atomic)
27900	Water	Gas (Molecular)
27970	Water	Gas (Molecular)
33700	HCN	Chemical
47700	Water	Gas (Molecular)
78460	Water	Gas (molecular)
95800	Helium	Gas (Atomic)
118000	Water	Gas (molecular)
118400	Water	Gas (molecular)
216300	Helium	Gas (Atomic)
311000	HCN	Chemical
337000	HCN	Chemical

APPENDIX F

Selected Tables from AFOSH Standard 161-10

TABLE 2
MPE for Direct Ocular Exposure, Intrabeam Viewing, to a Laser Beam

Wavelength, λ (nm)	Exposure Duration, t (s)	Maximum Permissible Exposure (MPE)	
Ultraviolet			
200 to 302	10^{-9} to $3 \cdot 10$	$3 \cdot 10^{-3}$ J/cm^2	
303	10^{-9} to $3 \cdot 10^4$	$4 \cdot 10^{-3}$ J/cm^2	
304	10^{-9} to $3 \cdot 10^4$	$6 \cdot 10^{-3}$ J/cm^2	
305	10^{-9} to $3 \cdot 10^4$	$1.0 \cdot 10^{-2}$ J/cm^2	
306	10^{-9} to $3 \cdot 10^4$	$1.6 \cdot 10^{-2}$ J/cm^2	
307	10^{-9} to $3 \cdot 10^4$	$2.5 \cdot 10^{-2}$ J/cm^2	
308	10^{-9} to $3 \cdot 10^4$	$4.0 \cdot 10^{-2}$ J/cm^2	
309	10^{-9} to $3 \cdot 10^4$	$6.3 \cdot 10^{-2}$ J/cm^2	*
310	10^{-9} to $3 \cdot 10^4$	$1.0 \cdot 10^{-1}$ J/cm^2	
311	10^{-9} to $3 \cdot 10^4$	$1.6 \cdot 10^{-1}$ J/cm^2	
312	10^{-9} to $3 \cdot 10^4$	$2.5 \cdot 10^{-1}$ J/cm^2	
313	10^{-9} to $3 \cdot 10^4$	$4.0 \cdot 10^{-1}$ J/cm^2	
314	10^{-9} to $3 \cdot 10^4$	$6.3 \cdot 10^{-1}$ J/cm^2	
315 to 400	10^{-9} to 10	$0.56t^{1/4}$ J/cm^2	
315 to 400	10 to $3 \cdot 10^4$	1 J/cm^2	
Visible and Near-Infrared			
400 to 700	10^{-9} to $1.8 \cdot 10^{-5}$	$5 \cdot 10^{-7}$ J/cm^2	
400 to 700	$1.8 \cdot 10^{-5}$ to 10	$1.8t^{3/4} \cdot 10^{-3}$ J/cm^2	
400 to 550	10 to 10^4	$10 \cdot 10^{-3}$ J/cm^2	
550 to 700	10 to T_1	$1.8t^{3/4} \cdot 10^{-3}$ J/cm^2	
550 to 700	T_1 to 10^4	$10C_B \cdot 10^{-3}$ J/cm^2	
400 to 700	10^4 to $3 \cdot 10^4$	$C_B \cdot 10^{-6}$ W/cm^2	**
700 to 1050	10^{-9} to $1.8 \cdot 10^{-5}$	$5C_A \cdot 10^{-7}$ J/cm^2	
700 to 1050	$1.8 \cdot 10^{-5}$ to 10^3	$1.8C_At^{3/4} \cdot 10^{-3}$ J/cm^2	
1051 to 1400	10^{-9} to $5 \cdot 10^{-5}$	$5 \cdot 10^{-6}$ J/cm^2	
1051 to 1400	$5 \cdot 10^{-5}$ to 10^3	$9t^{3/4} \cdot 10^{-3}$ J/cm^2	
700 to 1400	10^3 to $3 \cdot 10^4$	$320C_A \cdot 10^{-6}$ W/cm^2	
Far-Infrared			
1400 to 10^6	10^{-9} to 10^{-7}	10^{-2} J/cm^2	
1400 to 10^6	10^{-7} to 10	$0.56t^{1/4}$ J/cm^2	
1400 to 10^6	10 to $3 \cdot 10^4$	$0.1t$ J/cm^2	***
1540 only	10^{-9} to 10^{-6}	1.0 J/cm^2	

NOTES:
- * or $0.56t^{1/4}$ J/cm^2, whichever is lower; and use 1-mm limiting aperture; for 302 - 315 nm one can use $10^{(0.2\lambda - 63)}$ J/cm^2
- ** 7-mm limiting aperture
- *** See Table 5 for apertures

$C_A = 1$ for $\lambda = 400$ to 700 nm
$C_A = 10^{0.002(\lambda-700)}$ for $\lambda = 700$ to 1050 nm
$C_A = 5$ for $\lambda = 1050$ to 1400 nm

$C_B = 1$ for $\lambda = 400$ to 550 nm
$C_B = 10^{0.015(\lambda-550)}$ for $\lambda = 550$ to 700 nm
$T_1 = 10 \cdot 10^{0.02(\lambda-550)}$ for $\lambda = 550$ to 700 nm

TABLE 3
MPE for Viewing a Diffuse Reflector
of a Laser Beam or an Extended-Source Laser

Wavelength, λ (nm)	Exposure Duration, t (s)	Maximum Permissible Exposure (MPE)	
Ultraviolet			
200 to 302	10^{-9} to $3 \cdot 10^{4}$	$3 \cdot 10^{-3}$ J/cm^2	
303	10^{-9} to $3 \cdot 10^{4}$	$4 \cdot 10^{-3}$ J/cm^2	
304	10^{-9} to $3 \cdot 10^{4}$	$6 \cdot 10^{-3}$ J/cm^2	
305	10^{-9} to $3 \cdot 10^{4}$	$1.0 \cdot 10^{-2}$ J/cm^2	
306	10^{-9} to $3 \cdot 10^{4}$	$1.6 \cdot 10^{-2}$ J/cm^2	
307	10^{-9} to $3 \cdot 10^{4}$	$2.5 \cdot 10^{-2}$ J/cm^2	
308	10^{-9} to $3 \cdot 10^{4}$	$4.0 \cdot 10^{-2}$ J/cm^2	
309	10^{-9} to $3 \cdot 10^{4}$	$6.3 \cdot 10^{-2}$ J/cm^2	*
310	10^{-9} to $3 \cdot 10^{4}$	$1.0 \cdot 10^{-1}$ J/cm^2	
311	10^{-9} to $3 \cdot 10^{4}$	$1.6 \cdot 10^{-1}$ J/cm^2	
312	10^{-9} to $3 \cdot 10^{4}$	$2.5 \cdot 10^{-1}$ J/cm^2	
313	10^{-9} to $3 \cdot 10^{4}$	$4.0 \cdot 10^{-1}$ J/cm^2	
314	10^{-9} to $3 \cdot 10^{4}$	$6.3 \cdot 10^{-1}$ J/cm^2	
315 to 400	10^{-9} to 10	$0.56t^{1/4}$ J/cm^2	
315 to 400	10 to $3 \cdot 10^{4}$	1 J/cm^2	
Visible			
400 to 700	10^{-9} to 10	$10t^{1/3}$ J/sr·cm^2	
400 to 550	10 to 10^{4}	21 J/sr·cm^2	
550 to 700	10 to T_1	$3.8t^{3/4}$ J/sr·cm^2	
550 to 700	T_1 to 10^{4}	$21C_B$ J/sr·cm^2	
400 to 700	10^{4} to $3 \cdot 10^{4}$	$2.1C_B \cdot 10^{-3}$ W/sr·cm^2	
			**
Near-Infrared			
700 to 1400	10^{-9} to 10	$10C_At^{1/3}$ J/sr·cm^2	
700 to 1400	10 to 10^{3}	$3.83C_At^{3/4}$ J/sr·cm^2	
700 to 1400	10^{3} to $3 \cdot 10^{4}$	$0.64C_A$ W/sr·cm^2	
Far-Infrared			
1400 to 10^{6}	10^{-9} to 10^{-7}	10^{-2} J/cm^2	
1400 to 10^{6}	10^{-7} to 10	$0.56t^{1/4}$ J/cm^2	
1400 to 10^{6}	10 to $3 \cdot 10^{4}$	$0.1t$ J/cm^2	***
1540 only	10^{-9} to 10^{-6}	1.0 J/cm^2	

NOTES:
* or $0.56t^{1/4}$ J/cm^2, whichever is lower; and use 1-mm limiting aperture
** 1-mm limiting aperture or α_{min} whichever is greater
*** See Table 5 for apertures

$C_A = 1$ for $\lambda = 400$ to 700 nm
$C_A = 10^{0.002(\lambda-700)}$ for $\lambda = 700$ to 1050 nm
$C_A = 5$ for $\lambda = 1050$ to 1400 nm
$C_B = 1$ for $\lambda = 400$ to 550 nm
$C_B = 10^{0.015(\lambda-550)}$ for $\lambda = 550$ to 700 nm
$T_1 = 10 \cdot 10^{0.02(\lambda-550)}$ for $\lambda = 550$ to 700 nm

TABLE 4
MPE for Skin Exposure to a Laser Beam

Wavelength, λ (nm)	Exposure Duration, t (s)	Maximum Permissible Exposure (MPE)	
Ultraviolet			
200 to 302	10^{-9} to $3 \cdot 10^{4}$	$3 \cdot 10^{-3}$ J/cm^2	
303	10^{-9} to $3 \cdot 10^{4}$	$4 \cdot 10^{-3}$ J/cm^2	
304	10^{-9} to $3 \cdot 10^{4}$	$6 \cdot 10^{-3}$ J/cm^2	
305	10^{-9} to $3 \cdot 10^{4}$	$1.0 \cdot 10^{-2}$ J/cm^2	
306	10^{-9} to $3 \cdot 10^{4}$	$1.6 \cdot 10^{-2}$ J/cm^2	
307	10^{-9} to $3 \cdot 10^{4}$	$2.5 \cdot 10^{-2}$ J/cm^2	
308	10^{-9} to $3 \cdot 10^{4}$	$4.0 \cdot 10^{-2}$ J/cm^2	
309	10^{-9} to $3 \cdot 10^{4}$	$6.3 \cdot 10^{-2}$ J/cm^2	*
310	10^{-9} to $3 \cdot 10^{4}$	$1.0 \cdot 10^{-1}$ J/cm^2	
311	10^{-9} to $3 \cdot 10^{4}$	$1.6 \cdot 10^{-1}$ J/cm^2	
312	10^{-9} to $3 \cdot 10^{4}$	$2.5 \cdot 10^{-1}$ J/cm^2	
313	10^{-9} to $3 \cdot 10^{4}$	$4.0 \cdot 10^{-1}$ J/cm^2	
314	10^{-9} to $3 \cdot 10^{4}$	$6.3 \cdot 10^{-1}$ J/cm^2	
315 to 400	10^{-9} to 10	$0.56t^{1/4}$ J/cm^2	
315 to 400	10 to 10^{3}	1 J/cm^2	
315 to 400	10^{3} to $3 \cdot 10^{4}$	$10^{-3}t$ J/cm^2	
Visible and Near-Infrared			
400 to 1400	10^{-9} to 10^{-7}	$2C_A \cdot 10^{-2}$ J/cm^2	
400 to 1400	10^{-7} to 10	$1.1C_At^{1/4}$ J/cm^2	**
400 to 1400	10 to $3 \cdot 10^{4}$	$.2C_A$ W/cm^2	
Far-Infrared			
1400 to 10^{6}	10^{-9} to 10^{-7}	10^{-2} J/cm^2	
1400 to 10^{6}	10^{-7} to 10	$0.56t^{1/4}$ J/cm^2	
1400 to 10^{6}	> 10	$0.1t$ J/cm^2	***
1540 only	10^{-9} to 10^{-6}	1.0 J/cm^2	

NOTES:
* or $0.56t^{1/4}$ J/cm^2, whichever is lower; and use 1-mm limiting aperture; for 302 - 315 nm one can use $10^{(0.2\lambda - 63)}$ J/cm^2
** 1-mm limiting aperture
*** See Table 5 for apertures
$C_A = 1$ for $\lambda = 400$ to 700 nm
$C_A = 10^{0.002(\lambda - 700)}$ for $\lambda = 700$ to 1050 nm
$C_A = 5$ for $\lambda = 1050$ to 1400 nm

TABLE 5

Maximum Aperture Diameter (Limiting Aperture) for Measurement Averaging

Medium and Measurement	Duration, t (s)	Ultraviolet (200 - 400 nm)	Visible and Near-IR (400 - 1400 nm)	Far-Infrared (1400 - 10^5 nm)	Submillimeter (0.1 - 1 mm)
Eye MPE	10^{-9} to $3 \cdot 10^4$	1 mm	7 mm	1 mm	11 mm
Skin MPE	10^{-9} to $3 \cdot 10^4$	1 mm	1 mm	1 mm	11 mm
Laser Class.*	10^{-9} to $3 \cdot 10^4$	50 mm	50 mm	50 mm	50 mm

NOTE: * The apertures are used for the measurement of total output power or output energy for laser classification purposes, that is, to distinguish between Class 1 and Class 3 pulsed lasers. The use of the 50-mm apertures as shown in the horizontal line labelled "Laser Class," applies only to those cases where the laser output is intended to be viewed with optical instruments (excluding ordinary eyeglass lenses) or where the Laser Safety Officer determines that there is some probability that the output will be accidentally viewed with optical instruments and that such radiation will be viewed for a sufficient time duration so as to constitute a hazard. Otherwise for apertures listed for Eye MPE and Skin MPE are to be used. For the specific case of optical viewing (beam collecting) instruments, the apertures listed for eye MPE and skin MPE apply to the exit beam of such devices.

Table 8

Maximum Radiant Exposure Incident On a Surface That Will Not Produce Hazardous Reflections

	Maximum Radiant Exposure (J/cm^2)		
Exposure Duration, t (s)	Visible (400 to 700 nm)	Near-Infrared** (700 to 1050 nm)	Near-Infrared (1051 to 1400 nm)
10^{-9}	3.1×10^{-2}	$C_A(3.1 \times 10^{-2})$	1.5×10^{-1}
10^{-8}	6.8×10^{-2}	$C_A(6.8 \times 10^{-2})$	3.1×10^{-1}
10^{-7}	1.5×10^{-1}	$C_A(1.5 \times 10^{-1})$	8.0×10^{-1}
10^{-6}	3.1×10^{-1}	$C_A(3.1 \times 10^{-1})$	1.5
10^{-5}	6.8×10^{-1}	$C_A(6.8 \times 10^{-1})$	3.1
10^{-4}	1.5	$C_A(1.5)$	8.0
10^{-3}	3.1	$C_A(3.1)$*	15*
10^{-2}	6.8	$C_A(6.8)$*	31*
10^{-1}	15*	$C_A(15)$*	80*
0.25	20*	$C_A(20)$*	100*
General expression for Duration t	$10\, t^{1/3}$	$10 C_A\, t^{1/3}$	$50\, t^{1/3}$

* Values for classification are limited to 10 J/cm^2.

** Values for C_A: $C_A = 1$ for $\lambda = 400$ to 700 nm

$C_A = 10^{0.002(\lambda - 700)}$ for $\lambda = 700$ to 1050 nm

$C_A = 5$ for $\lambda = 1050$ to 1400 nm

APPENDIX G

Medical Debriefing for Suspected Laser Incidents

Medical Debriefing for Suspected Laser Incidents

Circumstances

1. Did you see a bright light? How bright was it, like the sun, a full moon, or automobile headlights at night? Were there other light sources on the platform (such as running lights or navigation lights) and were they brighter or dimmer?

2. What was the color(s) of the light? Was it uniform in color? Did the color(s) change during the exposure?

3. Did the light come on suddenly, and did it become brighter as you approached it?

4. Was the light continuous or did it seem to flicker? If it flickered, how rapidly and regularly?

5. For how long was the light on?

6. From what did the light emanate? Was it from an air plane, helicopter, tank, etc. ?

7. How would you describe the brightness of the light? Was it equally bright in all areas or was it brighter in one area?

8. How far away was the light source? Was it moving?

9. At what time of the day did the incident occur?

10. What was the visibility? What were the atmospheric conditions - clear, overcast, rainy, foggy, hazy, sunny?

11. What was between the light source and your eyes - windscreen, glasses, head-up display, lenses, binoculars, filters, visors, or goggles? Describe them in great detail (for example, 2X binoculars, standard issue sun visor, prescription glasses, hazy windscreen). Were any of these things damaged or caused to malfunction by the light?

12. Did you try to move out of the beam? What evasive maneuvers did you attempt? Did the beam follow you as you tried to move away? How successful were you in avoiding it?

13. Was the light coming directly from its source or did it appear to be reflected off other surfaces? Did you notice multiple sources of light?

14. Did the light fill your cockpit or compartment? How wide was the beam at its source? How wide was the beam once it reached you?

Possible Effects

15. How long did you look into the light beam? Did you look straight into the light beam or off to the side?

16. What tasks were you doing when the exposure occurred? Did the light prevent or hamper you from doing those tasks, or was the light more of an annoyance?

17. Were both eyes exposed? If not, describe the difference between the exposures (for example, one eye was shielded or closed, or on the side away from the light beam). Describe any difference in the effects on either eye.

18. Were you startled or disorientated when the light appeared?

19. Was the light so bright that you had to blink or squint, close your eyes, or look away? Was the light painful? Describe the pain. How long did the pain persist after the light exposure?

20. Was your vision affected while the light was on? How much of your visual field was affected? What types of things could you see or not see? Did you notice the color of the instruments or targets change? Did the changes to your vision remain constant or vary during the exposure? If the light source was mounted on a platform (aircraft, ground vehicle, or building), how much of the platform was obscured? [Note: Recommend that the word "dazzle" not be used because its definition varies greatly; "glare" is the preferred.]

21. Did your vision remain affected after the light was extinguished? If so, for how long and how did you estimate the time? How much of your visual field was affected? What types of things could you see or not see (watch, hand, altimeter, map, etc.)? Did you notice afterimages ("spots before your eyes")? If so, how long did they last, what did they look like, and what were their size, shape, and position in your visual field? Describe how your vision was affected 10 seconds after the light exposure ended, 30 seconds afterwards, 1 minute, 2 minutes, etc?

22. Were there any lingering (hours or days) visual effects? If so, were the effects continuous or intermittent? Did you have any problems reading or seeing in low-light conditions? How long until you were able to see normally again?

23. Did you notice any reddening, warming, or burns to your skin?

24. Describe the conditions of your vision before the incident? Do you wear glasses? Are you taking any medications?

25. Did you seek medical attention following the incident? Where and when were you examined? Who performed the examination? Was the examiner an ophthalmologist or optometrist? What were the clinical findings?