LASER EXPOSURE LIMITS. At present either the FDA criteria for medical lasers or the following ANSI standards can be useful in evaluating laser safety.

1. FDA Long-Term Exposure Limits. The FDA/CDRH Federal Laser Product Performance Standard (FLPPS) assumes a linearly additive biological effect for exposures to visible light between 10 and 104 seconds (2.8 hours). The standard accepts that a cumulative radiant energy exposure of 3.85 millijoules (mJ) will not cause a biological effect. Hence a 10-second total accumulated exposure corresponds to an average power entering a 7-mm aperture of 385 microwatts (mW). For an exposure of 104 seconds, the average power would be 0.385 mW. In the FLPPS, the power level of 0.385 mW is referred to as the Class I Accessible Emission Limit (AEL) for a visible CW laser.
2. ANSI Z 136.1, Long-Term Exposure Limits.
    a. The ANSI Z 136.1 (1993) standard is a "user" standard and therefore provides maximum permissible exposure (MPE) limits. These were derived by normalizing the power (or pulse energy) data derived from biological research studies relative to a defined limiting aperture. For example, in the visible and near-infrared spectra, the limiting aperture is based upon the diameter of a fully dilated pupil of the human eye, 7 mm. The area of a 7-mm pupil is 0.385 cm^2. Hence, the irradiance limit for long-term ocular exposure is computed by dividing the AEL value of 0.385 mW by the area of the limiting aperture of 0.385 cm^2. This yields the worst-case MPE value of 1.0 mW/cm^2 for long-term exposure in the wavelength range of 0.400 to 0.550 mm.
    b. The ANSI Z 136 and FDA/CDRH allowable-exposure limits for CW lasers (Class I limits) are essentially identical for wavelengths between 0.400 and 0.550 mm. The ANSI limits are, however, more relaxed for wavelengths between 0.550 and 1.40 mm. ANSI recognizes a decreased biological hazard in the red and infrared regions that is not recognized by the CDRH.
    c. The ANSI Z 136 MPE level for a very long term exposure by a helium-neon laser is, in fact, seventeen times greater than the CDRH standard. In the 1976 revision, ANSI Z 136 introduced the correction factor CB which has a value of 17.5 at the 0.633-μm HeNe laser wavelength, and, thus, permitted a radiant exposure of 185 mJ/cm^2 accumulated exposure for times from T_1 = 453 seconds to 104 seconds, and about 18 w/cm^2 (7 w in a 7-mm limiting aperture) for continuous operation of exposure durations exceeding 104 seconds.
3. ANSI Z 136.1, Repetitively Pulsed Exposures.
    a. The ANSI Z 136 standard requires a decrease in the maximum permissible exposure (MPE) for scanned or repetitive-pulse radiation as compared to continuous-wave radiation for pulse repetition frequencies (PRF) in the general range of 1000-15000 Hz. Because of pulse additivity, scanned or repetitively pulsed radiation with repetition rates less than 15 KHz have lower retinal damage threshold levels than CW radiation of comparable power.
    b. The ANSI Z 136 Standard includes a reduction factor of the threshold for each of the single pulses based on biological data that are not yet well explained by any theory. The FDA/CDRH standard does not recognize this repetitive-pulse correction factor. However, some experts envision the possibility of a repetitively pulsed laser which is Class I by the FDA/CDRH standard could be rated Class II or even Class IIIB by the ANSI Z 136 standard.
    c. The ANSI standard requires that multiple-pulse (scanning) lasers operating from 1 to 15,000 Hz have a correction to the single pulse MPE. The correction factor is determined by taking the fourth root of the total number of pulses (N) in a pulse train. Then, the correction factor is calculated such that the MPE radiant exposure or integrated radiance of an individual pulse within the train is reduced by a factor $N^{-1/4}$.
4. ANSI Z 136.1, Maximum Permissible Exposure Limits.
    a. A summary of Maximum Permissible Exposure (MPE) limits for direct ocular exposures for some of the more common lasers is presented in Table III:6-6. For further information on MPE values, refer to the ANSI Z 136.1 "Safe Use of Lasers" Standard.

b. The information in Table III:6-6 provides the MPE value for different lasers operating for different overall exposure times. The times chosen were:

1. *0.25 second:* The human aversion time for bright-light stimuli (the blink reflex). Thus, this becomes the "first line of defense" for unexpected exposure to some lasers and is the basis of the Class II concept.
2. *10 seconds:* The time period chosen by the ANSI Z 136.1 committees represents the optimum "worst-case" time period for ocular exposures to infrared (principally near-infrared) laser sources. It was argued that natural eye motions dominate for periods longer than 10 seconds.
3. *600 seconds:* The time period chosen by the ANSI Z 136.1 committees represents a typical worst-case period for viewing visible diffuse reflections during tasks such as alignment.
4. *30,000 seconds:* The time period that represents a full 1-day (8-hour) occupational exposure. This results from computing the number of seconds in 8 hours; e.g.: 8 hours × 60 minutes/hour × 60 seconds/minute = 28,800 seconds. Rounded off, it becomes 30,000 seconds.

c. The "safety" exposure limits (MPE's) in Table III:6-6 are expressed in irradiance terms (W/cm2) that would be measured at the cornea. Note that they vary by wavelength and exposure time.

TABLE III:6-6. SUMMARY: MAXIMUM PERMISSIBLE EXPOSURE LIMITS*

Laser type	***Wavelength (μm)***	***-------------- MPE level (W/cm²) --------------***			
		0.25 sec	***10 sec***	***600 sec***	***30,000 sec***
CO2 (CW)	10.6	---	100.0×10^{-3}	---	100.0×10^{-3}
Nd: YAG (CW)	1.33	---	5.1×10^{-3}	---	1.6×10^{-3}
Nd: YAG (CW)	1.064	---	5.1×10^{-3}	---	1.6×10^{-3}
Nd: YAG (Q-switched)	1.064	---	17.0×10^{-6}	---	2.3×10^{-6}
GaAs (Diode/CW)	0.840	---	1.9×10^{-3}	---	610.0×10^{-6}
HeNe (CW)	0.633	2.5×10^{-3}	---	293.0×10^{-6}	17.6×10^{-6}
Krypton (CW)	0.647 0.568 0.530	2.5×10^{-3} 31.0×10^{-6} 16.7×10^{-6}	--- --- ---	364.0×10^{-6} 2.5×10^{-3} 2.5×10^{-3}	28.5×10^{-6} 18.6×10^{-6} 1.0×10^{-6}
Argon (CW)	0.514	2.5×10^{-3}	---	16.7×10^{-6}	1.0×10^{-6}
XeFl (Excimer/CW)	0.351	---	---	---	33.3×10^{-6}
XeCl (Excimer/CW)	0.308	---	---	---	1.3×10^{-6}

* *Source:* ANSI Z 136.1 (1993)

<u>LASER HAZARD COMPUTATIONS</u>.

1. <u>NHZ Definition, Use, and Values</u>.
   a. The Nominal Hazard Zone (NHZ) describes the space within which the level of direct, reflected, or scattered radiation during normal operation exceeds the MPE. The NHZ

associated with open-beam Class IIIB and Class IV laser installations can be useful in assessing area hazards and implementing controls.

b. It is often necessary in some applications where open beams are required (e.g., industrial processing, laser robotics, surgical uses) to define the area where the possibility exists for potentially hazardous exposure. This is done by determining the NHZ. Consequently, persons outside the NHZ boundary would be exposed below the MPE level and are considered to be in a non-hazardous location.

c. The NHZ boundary may be defined, for example, by direct beams (intrabeam) and diffusely scattered laser beams, as well as beams transmitted from fiber optics and/or through lens arrays. The NHZ perimeter is the envelope of MPE exposure levels from any specific laser installation geometry.

d. The purpose of an NHZ evaluation is to define that space where control measures are required. This is an important factor since, as the scope of laser uses has expanded, controlling lasers by total enclosure in a protective housing or interlocked room is limiting and, in many instances, an expensive overreaction to the real hazards. The following factors are required in NHZ computations:
   - laser power or energy output;
   - beam diameter;
   - beam divergence;
   - pulse repetition frequency (prf) (if applicable);
   - wavelength;
   - beam optics and beam path; and
   - maximum anticipated exposure duration.

e. Note that the ANSI Z 136 MPE value is required in all NHZ calculations. Examples of NHZ calculations can be found in the appendix of ANSI Z 136.1 (1993). In addition, computer software is also available to assist in the computations for NHZ, optical densities of protective eye wear, and other aspects of laser hazard analysis.

2. <u>NHZ Example Summary</u>. The intrabeam (direct) hazard for a Nd:YAG laser extends from 792 meters to 1410 meters, depending upon whether a 10-second or 8-hour criterion is used, as summarized in Table III:6-7. Similarly, with a lens on the laser, the hazard for a Nd:YAG laser exists over a range from 6.3 meters to 11.3 meters. The diffuse reflection zone for this laser type is, however, markedly smaller, 0.8 meter to 1.4 meters. Nonetheless, the analysis suggests that operating personnel and support staff close to the laser still need eye protection even for diffuse reflections.

Other calculations are also presented in Table III:6-7 for a 500-Watt CO_2 and a 5-Watt argon laser. Note that the NHZ's do not vary for the CO_2 laser (because the MPE values are nearly identical for 10-second and 8-hour criteria). Also note that the diffuse reflection NHZ's are very small except for the 8-hour criterion for the argon laser. In most cases, 0.25 second can be used with visible lasers unless intentional staring is required or intended.

TABLE III:6-7. NHZ DISTANCE VALUES FOR VARIOUS LASERS

Laser type	***Exposure criteria***	***----- Hazard range (meters) -----***		
		Diffuse	***Lens-on-laser***	***Direct***
Nd:YAG 100 Watt 1.064 μm	8 hours 10 seconds	1.4 0.8	11.3 6.3	1410 792
CO_2 500 Watt 10.6 μm	8 hours 10 seconds	0.4 0.4	5.3 5.3	309 390
Argon 5.0 Watt 0.488 μm	8 hours 0.25 seconds	12.6 0.25	1.7×10^3 33.3	25.2×10^3 240

Laser criteria used for NHZ distance calculations:			
Laser parameter	***Nd-YAG***	***CO_2***	***Argon***
Wavelength (μm) Beam power (Watts) Beam divergence (mrad) Beam size at aperture (mm) Beam size at lens (mm) Lens focal length (mm) MPE for 8 hours (w/cm^2) MPE for 10 seconds (w/cm^2) 5.1× 10^3 MPE for 0.25 second (w/cm^2)	1.064 100.0 2.0 2.0 6.3 25.4 1.6 × 10^3 1.0 × 10^5 ---	10.6 500.0 2.0 20.0 30.0 200.0 1.0 × 10^5 --- ---	0.488 5.0 1.0 2.0 3.0 200.0 1.0 2.5 × 10^3

Source: ANSI A 136.1 (1993)

D. <u>INTRABEAM OPTICAL DENSITY DETERMINATION</u>.

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

EQUATION III:6-1. OPTICAL DENSITY

$$OD = \log_{10} \frac{H_0}{MPE}$$

Where:

H_0 = Anticipated worst-case exposure (J/cm^2 or W/cm^2)
MPE = Maximum permissible exposure level expressed in the same units as H_0

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

Where:

ϕ = 5 Watts

MPE = 16.7 W/cm^2 (using 600-second criterion)

d = 7 mm (worst-case pupil size)

Computing the worst-case exposure H_0:

H_0 = [Power/Area] = ϕ/A = $4\phi/\pi d^2$

H_0 = $[(4)(5.0)/\pi(0.7)^2]$

H_0 = 12.99 W/cm^2

Substitution gives:

OD = $\log_{10} [(12.99)/(16.7 \times 10^{-6})]$

OD = 5.9

3. The most conservative approach would be to choose an 8-hour (occupational) exposure. In this case, the optical density at 0.514 μm is increased to OD = 7.1 for a 5.0-watt intrabeam exposure because the 8-hour (30,000 sec.) MPE is reduced to 1.0×10^{-6} W/cm^2. The OD values for various lasers, computed for various appropriate exposure times, are presented in Table III:6-8. It should be stressed these values are for intrabeam viewing (worst case) only. Viewing Class IV diffuse reflections (such as during alignment tasks) require, in general, less OD. These should be determined for each situation and would be dependent upon the laser parameters and viewing distance.

TABLE III:6-8. OPTICAL DENSITIES FOR PROTECTIVE EYEWEAR FOR VARIOUS LASER TYPES

Laser type & power	***Wavelength (mm)***	***Optical density for exposure durations***			
		0.25 sec.	***10 sec.***	***600 sec.***	***30,000 sec.***
XeCl 50 Watts	0.308[a]	--	6.2	8.0	9.7
XeFl 50 Watts	0.351[a]	--	4.8	6.6	8.3
Argon 1.0 Watts	0.514	3.0	3.4	5.2	6.4
Krypton 1.0 Watt	0.530	3.0	3.4	5.2	6.4
Krypton 1.0 Watt	0.568	3.0	3.4	4.9	6.1
HeNe 0.005 Watt	0.633	0.7	1.1	1.7	2.9
Krypton 1 Watt	0.647	3.0	3.4	3.9	5.0
GaAs 50 mW	0.840[c]	--	1.8	2.3	3.7
Nd: YAG 100 Watt	1.064[a]	--	4.7	5.2	5.2
Nd: YAG (Q-switch)[b]	1.064[a]	--	4.5	5.0	5.4
Nd: YAG[c] 50 Watts	1.33[a]	--	4.4	4.9	4.9
CO_2 1000 Watts	10.6[a]	--	6.2	8.0	9.7

a. Repetitively pulsed at 11 Hertz, 12-nanosecond pulses, 20 mJ/pulse.
b. OD for UV and FIR beams computed using a 1-mm limiting aperture, which presents a "worst-case" scenario. All visible and NIR computations assume a 7-mm limiting aperture.
c. Nd:YAG operating at a less-common 1.33 μm wavelength.

Note: All OD values determined using MPE criteria of ANSI Z 136.1 (1993).