Appendix D
Laser Hazard Evaluation and Classification

D1. General.

Measurements intended to be used to evaluate laser hazards require that the measurements be performed in a specific manner to simulate actual exposure to a laser beam. Hazard classification makes no assumptions on actual exposure, but establishes the hazard potential of a laser under a variety of viewing conditions based on specific test methods. A complete hazard evaluation or hazard classification requires that the following beam parameters be determined.

D2. Wavelength or Wavelengths.

Single wavelengths can be measured using a spectrometer or spectrograph. Common wavelengths are specified and may not need to be measured. If the laser emits multiple wavelengths, the hazard evaluation process becomes more complex. The average power or the energy per pulse at each wavelength is used to determine the additive effects. For a given biological exposure site (corneal, retinal or skin), the effects from each exposure condition are additive. For more information, see Terry L. Lyon, "Hazard Analysis Technique for Multiple Wavelength Lasers", *Health Physics*, Vol. 49, No. 2 (August), pp.221-226, 1985.

D3. Pulse Properties (Temporal Profile).

The inherent design of the laser determines if the laser is pulsed or CW. If the laser is pulsed, the determination of pulse width, pulse repetition frequency and/or structure of pulse groups is necessary. Pulse duration is measured at FWHM or other specification which provides average power during the pulse. Some lasers thought to be CW may in fact have a pulse structure more rapid than is visually perceptible.

D4. Exposure Duration (*T*).

The exposure duration may change for various exposure scenarios and applications. Each of these scenarios may need to be evaluated independently. T_{max} is the maximum exposure duration which is specifically limited by the design or intended use(s) of the laser or laser system. For classification, T_{max} can be assumed to be up to 30,000 s for 180-700 cm and 100 s for 700 nm - 1.0 mm, if the application is unknown. For example, a person in an airplane that flies through a laser beam may be exposed for only a few milliseconds, but would usually be exposed to at least one entire Q-switched pulse. For a Q-switched, repetitively pulsed laser, it is important to determine the maximum number of laser pulses during the exposure interval. For repetitive-pulsed lasers in the retinal hazard region, see ANSI Z136.1-2007 Section 8.2.3.2.

D5. Beam Diameter (D_L) and Divergence (ϕ).

Beam diameter and divergence are critical values for determining the irradiance or radiant exposure at a distance from the laser. The beam divergence and the beam diameter are usually determined at 1/e peak irradiance points for purposes of hazard evaluation. For a circular laser beam operating in the Gaussian TEM_{00} mode, the diameter of the portion of the beam which contains 63.2% of the total power or energy per pulse is considered the beam diameter for safety calculations. Note that the beam diameter and beam divergence for TEM_{00} mode Gaussian beams are 0.707 times their respective values at the $1/e^2$ irradiance points. See Sections 5.6 and 5.8 for methods of determining beam diameter and beam divergence. For elliptical, rectangular or non-Gaussian beams, methods for computing the irradiance or radiant exposure averaged over the limiting aperture as a function of distance from the laser must be devised.

D6. Angular Subtense (Angular Source Size or Apparent Visual Angle).

Also see Sec. 5.5. When a laser could illuminate a discernable area of the retina (e.g., larger than a point source), it is said to be an extended source. The MPE can be relaxed when this occurs. To determine the degree to which the MPE can be relaxed, it is necessary to determine the angular subtense from the laser. This value is a function of range and therefore can significantly increase the difficulty of hazard evaluation and classification.

If the beam is axis-symmetric there is one value for the angular subtense at a given distance; however, for non-axis-symmetric beams there may be more than one value for the angular subtense. The angular subtense for extended source lasers will be larger than α_{min} (1.5 mrad) in either dimension near the laser exit port, but is generally inversely proportional to the beam diameter at farther viewing distances. Beyond the distance where the exit aperture, D_{exit}, of the laser appears filled with laser energy (from an intrabeam point of view), the angular source size is limited by that aperture (source size would be equal to the exit aperture divided by the viewing distance). If the NOHD is farther than a few meters, the laser will generally be considered a point source at the NOHD.

For sources with divergences less than 1.5 mrad, angular subtense does not need to be determined for unaided viewing conditions, since there is no correction for source size in this AEL calculation.

D7. Total Power or Energy.

The total power or energy must be determined for hazard evaluation. The formulas used to compute irradiance or radiant exposure at a distance require the total laser power or pulse energy, the beam diameter and beam divergence. The hazards at each distance are computed from the portion of the power or energy transmitted through the measurement aperture.

D8. MPE.

The MPE for the eye can be determined from Tables 5a and 5b of ANSI Z136.1-2007. Table 5a is used for point-source lasers. For wavelengths less than 600 nm, the MPE is determined based on both photochemical and thermal effects. The thermal MPE for the eye for a source size larger than 1.5 mrad is corrected by a factor, C_E (see Section 3.2.3.4.2 and Table 5b of ANSI Z136.1-2007.) The MPE for skin exposure is provided in Table 7 of ANSI Z136.1-2007. Additional information is available in Sections 8 and 9 of ANSI Z136.1-2007.

Evaluation of pulsed exposure can be summed up in three rules: (1) The exposure from any single pulse in a train of pulses shall not exceed the MPE for a single pulse of that duration, $\boldsymbol{t}$; (2) the summed exposure from any group of pulses within a duration, $\boldsymbol{T}$, shall not exceed the MPE for a single pulse of that duration $\boldsymbol{T}$; (3) the exposure from a number of pulses, $\boldsymbol{n}$, shall not exceed the MPE for a single pulse multiplied by a factor, $\boldsymbol{C_P}$, based on $\boldsymbol{n^{-0.25}}$. The last rule applies only to ocular exposure. Also, for this rule, when the PRF is high enough that the interpulse spacing is less than t_{min} (termed the critical frequency), groups or trains of pulses are treated as a single pulse and quantified with the energy of the entire group or train. Above the critical frequency, the average power generally determines the hazards of a laser rather than exposure to individual pulses. Determination of critical frequency must be modified for extended exposure times, for extended source lasers and for sub-nanosecond pulses. Additionally, critical frequency for wavelengths outside the retinal hazard region may vary as a function of beam size.

For extended sources, the MPE for optically aided viewing is different from that for unaided viewing. In the retinal hazard region, the angular source size at the measurement distance is multiplied by the magnifying power of the optical instrument. It is important to realize that source size decreases with distance from the laser and may be reduced at the minimum distance of 2 m from what it was at 10 cm. For the binoculars recommended in hazard classification, the magnifying power is 7. However, other optical instruments may have a magnifying power of 10, 20, or more. For example, a small-beam laser source subtending an angle of 0.5 mrad at a viewing distance of 10 meters would appear to subtend an angle of 3.5 mrad for 7×50 binocular viewing at that same range, resulting in a relaxed (larger) MPE than for unaided viewing. Measurement of source size may not be necessary as assuming the laser to be a point source will provide a worst-case analysis.

D9. Limiting Aperture ($\boldsymbol{D_f}$).

Table 1 (Tables 8a and 8b of ANSI Z136.1-2007) list the appropriate limiting apertures for the eye and skin, which depend on wavelength and exposure duration. Useful highlights from ANSI Z136.1-2007, are repeated and given in more detail in Table 1. The limiting aperture for the eye from Table 1 of this document is the same for unaided and optically aided viewing conditions. The corneal irradiance or corneal radiant exposure is averaged over the limiting aperture when compared with the MPE for hazard evaluation. When repeated exposures are evaluated using rule 1, the limiting aperture is determined by the pulse width. When the MPE is evaluated using rule 3, the exposure duration, $\boldsymbol{t}$, and associated limiting aperture is minimally limited to T_{max}. When the laser is evaluated using rules 2 and 3, the exposure duration of each pulse grouping and also T_{max} may require measurements through several aperture diameters.

D10. Measurement Aperture.

Table 2 (Table 9 from ANSI Z136.1-2007) can be used to determine the measurement aperture(s). For ocular hazards, different apertures are needed for optically aided viewing and unaided viewing (Conditions 1 and 2). When the laser operates in a wavelength region not transmitted by common optics, the measurement aperture is the same as the limiting aperture for the eye. The measurement aperture for skin hazards is the same as the skin limiting aperture. Note that, when performing evaluations on repetitive pulsed lasers, the measurement aperture for each rule may be different because of the time base used for each model.

D11. Laser Hazard Class.

Commercial lasers are classified and labeled by the manufacturer, and the user may be able to use this information to determine the class for the purposes of hazard evaluation. It is important to note that the FLPPS product classification may be different from ANSI classification. ANSI classification does not change the FLPPS product classification, so the original laser product is still subject to the same built-in control measures. Classification provides a quick assessment of the hazard potential of a particular laser.

To determine the appropriate ANSI laser hazard class, the following steps may be used:

D.11.1 Assume Laser Class. Perform a quick check of laser parameters and compare the output to the known AEL values. For example, a small beam laser with an average output power of 500 W would certainly be a Class 4 laser.

D.11.2 Measurement Distance. Measurement distances are given in Table 2. The measurement distance should not be less than 10 cm from the apparent source for unaided viewing and not less than 2 m from the laser exit port for optically aided viewing (condition 1), due to the inability of the eye or binocular to focus at shorter distances.

D.11.3 AELs. Classification is based on eye hazards, not skin hazards. The Class 1 AEL is the product of the MPE for the eye and the area of the limiting aperture for the eye. For repetitive pulses or pulse groups, several sets of measurements through various aperture diameters may be required to determine the most restrictive exposure condition. Refer to Section 4.2.1 for discussion of AELs for other classes.

D.11.4 Effective Power or Pulse Energy. Classification is based on the effective power or energy rather than the total power or energy. Effective power or pulse energy measurements are required at the appropriate distance through the appropriate aperture. Typically for a CW laser, the highest power observed over T_{max} is used for hazard classification. For repetitively pulsed lasers with fairly uniform pulse energies and pulse widths, the average energy per pulse may be measured. See Figure D-1 for additional information. Note that the measurement apertures used to determine effective power or energy may depend on the applicable viewing condition.

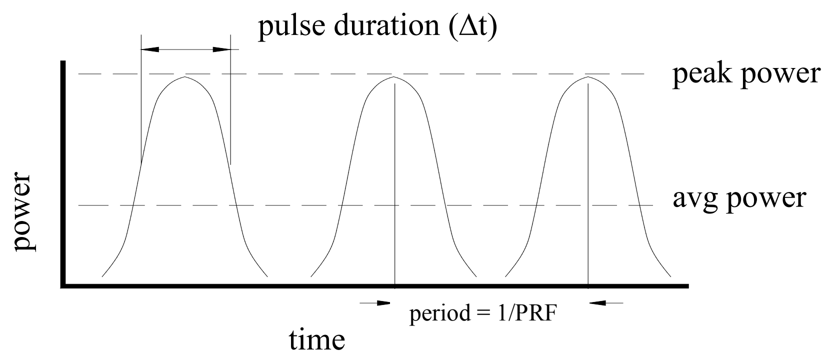

Figure D-1. Pulsed Laser Properties

D.11.5 Assigning a Laser Hazard Class. Determine the laser hazard class by comparing the effective power or energy per pulse (power or energy measured through a specific aperture) to the appropriate AEL for each class for each set of measurement conditions. The overall laser hazard class is the most restrictive of all applicable measurement conditions for all applicable time durations up to T_{max}.

D12. Hazard Evaluation.

Laser hazards are determined at locations where someone could be exposed to the laser radiation. Often, the exposure distance is not known for a particular laser. Therefore, it is usual practice to calculate a nominal ocular hazard distance (NOHD). For direct small-source viewing of the laser source, the MPE is exceeded at points within the beam at distances less than the NOHD, but not at greater distances. Note that it may be possible to not exceed the MPE at close ranges to the output of a focused beam. An NOHD may be computed both for unaided viewing and optically aided viewing. A nominal skin hazard distance (NSHD) is calculated for skin exposure. Exposure conditions for hazard evaluation may vary with distance, and must be updated for each evaluation distance considered.

D.12.1 Diffuse Reflection Hazards. Some high-power lasers can produce a hazard from diffuse reflections. The reflectivity of the target material is generally assumed to be 100% and the viewing angle is generally taken to be normal to the surface to simplify calculations. For close-in viewing of diffuse reflections (when the angular subtense of the diffuse image is greater than 1.5 mrad), the MPE can be calculated based on an extended source. When this applies, it is important to consider that the extended-source MPE decreases with distance since the angular subtense decreases.

D.12.2 Specular Reflection Hazards. The reflected beam properties from a material depend on the laser parameters and the characteristics of the material. Flat, specular reflectors in the laser beam path can greatly increase the NHZ of the laser (the locations where hazardous exposure could occur). Curved reflectors will alter the angular distribution of the beam and may increase the hazard near the reflector (for concave reflectors) but do not typically further increase the NHZ. Radiometric measurement may be required at the location of exposure to determine the actual level of hazard.

D.12.3 Skin Exposure. The MPE for the skin is provided in Table 7 of ANSI Z136.1-2007; however, for lengthy exposures exceeding 100 cm^2 of skin, the MPE may be reduced by as much as a factor of 10 (consult Section 8.4.2 of ANSI Z136.1-2007). In the retinal hazard region, the skin MPE is usually considerably higher (less restrictive) than the MPE for the eye. The limiting aperture diameter is 3.5 mm for skin, except for wavelengths longer than 100 µm (See Table 1 in this document). The value of t_{min} is often much less for skin hazards than ocular hazards; and therefore, determination of pulse width is more critical. Under some circumstances (e.g.,. for lasers operating between 1.5 and 1.8 µm), it is possible to exceed the skin MPE without exceeding the ocular MPE.

D.12.4 Irradiance and/or Radiant Exposure. The irradiance or radiant exposure averaged over the limiting apertures at all potential viewing distances is necessary for a complete hazard evaluation. When the viewing distance is far from the laser, where the laser beam diameter is much larger than the limiting aperture, the center beam irradiance or radiant exposure is adequate for assessing hazards.

D.12.5 Protective Eyewear. When the laser irradiance or radiant exposure exceeds the MPE, the required protection may be computed from the ratio of irradiance or radiant exposure and the MPE. The optical density, D_λ, (also called OD) may be computed from the $\log_{10}$ of the ratio of the irradiance or radiant exposure (averaged over the limiting aperture) and the MPE. Another method for computing the required OD is to compare the power or energy measured through the measurement aperture to the exposure limit in terms of power or energy based on the exposure duration used in the hazard evaluation Class 1 AEL (or 0.25-second exposure limit for visible laser beams), for either viewing condition and based on the intended viewing duration. When more than one wavelength is involved, protection at each wavelength must be assured and the additive effects of multiple wavelength exposure must also be taken into account.

Appendix E
Examples

E1. Detector Selection Example 1.

A pulsed Nd:YAG laser system has the manufacturer specified output parameters shown in Table E1-1. A measurement of laser pulse energy is required, but only three detectors are available for use. The detector specifications are listed in Table E1-2. Determine if any of the detectors can be used for a direct measurement of the laser pulse energy in two instances: (1) The laser beam expander is attached, (2) it is unattached.

Table E1-1. Laser Beam Parameters for Example 1

Parameter	Value (Case 1 with beam expander)	Value (Case 2 without beam expander)
Average Output Power	22 W	25 W
Exit Beam Profile	Gaussian	Gaussian
PRF	20 Hz	20 Hz
Pulse Duration	20 ns	20 ns
Exit Beam Dia. ($1/e^2$) irradiance pts.	3.0 cm	1.0 cm
Beam Divergence ($1/e^2$) irradiance pts.	0.5 mrad	1.5 mrad
Wavelength	1064 nm	1064 nm

Table E1-2. Detector Specifications for Example 1

Parameter	Detector 1	Detector 2	Detector 3
Max. Power (continuous)	30 W	150 W	30 W
Max. Intermittent Power	60 W	300 W	60 W
Min. Power Resolution	10 mW	10 mW	10 mW
Max. Average Irradiance	26 kW·cm^{-2}	26 kW·cm^{-2}	26 kW·cm^{-2}
Max. Pulse Radiant Exposure (20ns pulse)	0.6 J·cm^{-2}	0.6 J·cm^{-2}	10 J·cm^{-2}
Accuracy	+/- 3%	+/- 5%	+/- 3%
Clear Aperture	19 mm	50 mm	19 mm

To determine the appropriate detector, the parameters for comparison with the values listed in the detector specifications must first be determined. Then the comparison can be made to determine the appropriate detector for each case.

Case 1 with beam expander: Detector 2 is our most likely candidate because it is the only detector available with an input aperture of sufficient size. The maximum power handled by detector 2 is sufficient (150 W). To determine the power density (irradiance, *E*) and energy density (radiant exposure, *H*) values present, we divide the average power and pulse energies by the area of the beam. To obtain the peak value, we use the 1/e irradiance point beam diameter (*a*) in the Gaussian beam profile. To convert from the 1/e^2 irradiance point commonly provided by manufacturers, we divide by √2.

$$a = \frac{3.0\ \text{cm}}{\sqrt{2}}$$

$$a = 2.1\ \text{cm}$$

and the peak average irradiance is

$$E_{\text{peak}} = \frac{4\ \Phi}{\pi\ a^2}$$

$$E_{\text{peak}} = \frac{4(22\,\text{W})}{\pi\ (2.1\ \text{cm})^2}$$

$$E_{\text{peak}} = 6.35\ \ \text{W/cm}^2$$

This is significantly lower than the 26 kW·cm^{-2} specification for all of the detectors. However, the value for the per-pulse energy must also be considered. The energy per pulse is simply the average output power divided by the number of pulses per second.

$$Q = \frac{\Phi}{\text{PRF}}$$

$$Q = \frac{22\ \text{W}}{20\ \text{Hz}}$$

$$Q = 1.1\ \text{J}$$

This divided by the beam area at the 1/e radiant exposure point gives us the peak radiant exposure (H_{peak}) on the detector face.

$$H_{\text{peak}} = \frac{4\ Q}{\pi\ a^2}$$

$$H_{\text{peak}} = \frac{4(1.1\ \text{J})}{\pi\ (2.1\ \text{cm})^2}$$

$$H_{\text{peak}} = 0.32\ \ \text{J/cm}^2$$

This is also less than the maximum pulse radiant exposure for the detectors which are rated at $0.6\ \text{J}\cdot\text{cm}^{-2}$ and $10\ \text{J}\cdot\text{cm}^{-2}$. The final consideration is the amount of clipping that occurs. If we assume that the beam profile is a perfect Gaussian, the fraction (δ) that is collected by the clear aperture of the detector can be determined from the following equation.

$$\delta = 1 - \exp\left(-\left(\frac{D_f}{D_L}\right)^2\right)$$

$$\delta = 1 - \exp\left(-\left(\frac{5.0\ \text{cm}}{2.1\ \text{cm}}\right)^2\right)$$

$$\delta = 0.997$$

So that 99.7% of the energy will be collected within the clear aperture of the detector. Therefore detector 2 is appropriate for the application. Note that applying the same equation to the two detectors with 19 mm apertures produces a value of 56% of the energy collected, making detectors 1 and 3 inappropriate for this measurement.

Case 2 without beam expander: Here it appears that all of the detectors available have an input aperture of sufficient size. The maximum power handled by all three detectors is sufficient (>25 W). Again, to determine the power density (irradiance, *E*) and energy density (radiant exposure *H*) values present, we divide the average power and pulse energies by the area of the beam. To obtain the peak value present, we again use the 1/e irradiance point beam diameter (a) in the Gaussian beam profile.

$$E_{\text{peak}} = \frac{4\ \Phi}{\pi\ a^2}$$

$$E_{\text{peak}} = \frac{4(25\ \text{W})}{\pi\ (0.71\ \text{cm})^2}$$

$$E_{\text{peak}} = 63\ \ \text{W/cm}^2$$

This is significantly lower than the 26 kW·cm^{-2} specification. However, the value for the per pulse energy must also be considered. The energy per pulse is simply the average output power divided by the number of pulses per second.

$$Q = \frac{\Phi}{\text{PRF}}$$

$$Q = \frac{25\ \text{W}}{20\ \text{Hz}}$$

$$Q = 1.25\ \text{J}$$

This divided by the beam area at the 1/e radiant exposure point gives us the peak radiant exposure (H_{peak}) on the detector face.

$$H_{\text{peak}} = \frac{4\ Q}{\pi\ a^2}$$

$$H_{\text{peak}} = \frac{4(1.25\ \text{J})}{\pi\ (0.71\ \text{cm})^2}$$

$$H_{\text{peak}} = 3.2\ \ \text{J/cm}^2$$

This peak radiant exposure value eliminates all detectors except detector 3. Detector 3 has a maximum pulse radiant exposure of 10 J·cm^{-2}, sufficient for this application.

The final consideration is the amount of clipping that occurs for detector 3, which has a clear aperture of 19 mm. If we assume that the beam profile is a perfect Gaussian, the fraction (δ) of energy from the beam that is collected by the clear aperture of the detector is calculated from the following equation.

$$\delta = 1 - \exp\left(-\left(\frac{D_f}{D_L}\right)^2\right)$$

$$\delta = 1 - \exp\left(-\left(\frac{1.9\ \text{cm}}{0.71\ \text{cm}}\right)^2\right)$$

$$\delta = 0.999$$

Since 99.9% of the energy will be collected within the clear aperture of the detector, detector 3 is appropriate for the application.