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Laser Selection Based On Maximum Permissible Exposure Limits for Visible and Middle-Near Infrared Repetitively Pulsed Lasers

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Laser Selection Based On Maximum Permissible Exposure Limits for Visible and Middle-Near Infrared Repetitively Pulsed Lasers

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Abstract

The Maximum Permissible Exposure (*MPE*) is central to laser hazard analysis and is in general a function of the radiant wavelength. The selection of a laser for a particular application may allow for flexibility in the selection of the radiant wavelength. This flexibility would allow the selection of a particular laser based on the *MPE* and the hazards associated with that radiant wavelength. The Calculations of the *MPE*s for various laser wavelength ranges are presented. Techniques for determining eye safe viewing distances for both aided and unaided viewing and the determination of flight hazard distances are presented as well.

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Maximum Permissible Exposure

Repetitively Pulsed Lasers

The **maximum permissible exposure** (*MPE*) for repetitively pulsed lasers is always the smallest *MPE* value determined by the application of ANSI Rules-1 through 3 [*ANSI Std. Z136.1-2000 (8.2.3.2)*] applied over the area of the limiting aperture.

$$MPE_{appropriate} = \min\left[MPE_{rule1}, MPE_{rule2}, MPE_{rule3}\right]$$

Repetitively Pulsed Visible Lasers (400 nm ≤ λ ≤ 700 nm):

The appropriate *MPE* for repetitively pulsed visible lasers is the minimum *MPE* determined from the evaluation of ANSI Rules 1 through 3 applied over the area of the limiting aperture.

The **limiting aperture** (d_{lim}) for visible lasers is given as 7 mm in *ANSI Std. Z136.1-2000 Table 8*. The **limiting area** for this aperture is:

$$A_{\lim} = \frac{\pi d_{\lim}^2}{4} = \frac{\pi(0.7cm)^2}{4} = 0.385cm^2$$

Rule-1 (Single Pulse):

No single pulse in a train of pulses shall exceed the *MPE* for a single pulse of that same pulse duration [*ANSI Std. Z136.1-2000 (8.2.3- Rule 1)*]. For laser pulse duration of from 1 nanosecond to 18 microseconds the single pulse *MPE* is given in *Table 5a* of the ANSI Standard.

$$MPE_{rule1} = 5\times10^{-7}\ {}^{J}\!/_{cm^2} \qquad \text{for: } 10^{-9}\sec \le t \le 18\times10^{-6}\sec$$

Rule-2 (Average Power):

The average power per pulse *MPE* is the *MPE* for the exposure time (*T*) given in *Table 5a* of the ANSI Standard distributed over the number of laser pulses in the exposure (*T*) [*ANSI Std. Z136.1-2000 (8.2.3-Rule 2)*].

$$MPE_{rule2} = \frac{MPE_T}{n}$$

The number of pulses (n) in the exposure is the product of the **Pulse Repetition Frequency** (*PRF*) and the exposure time (T).

$$n = PRF \cdot T$$

The ANSI *Rule-2 MPE* (per pulse *MPE*) can be expressed in terms of the *PRF*.

$$MPE = \frac{MPE_T}{PRF \cdot T}$$

The standard time (T), for a Class 2-exposure (visible lasers only), is given as a quarter of a second [*ANSI Std. Z136.1-2000 (Table 4a)*].

$$T = 0.25\,\text{sec}$$

The number of pulses in a Class 2 exposure is then:

$$n = Int[0.25 \cdot PRF]$$

It should be noted that the number of pulses in an exposure is always considered as an integer for laser hazard evaluations. Fractional numbers are rounded up to the next higher integer.

The *MPE* for a quarter second exposure is calculated from the form given in ANSI *Table 5a*.

$$MPE = 1.8t^{0.75} \times 10^{-3}\ {}^{J}\!/_{cm^2} \qquad \text{for: } 18\times10^{-6}\,\text{sec} \le t < 10\,\text{sec}$$

$$MPE_{Class2} = 1.8(0.25)^{0.75} \times 10^{-3}\ {}^{J}\!/_{cm^2}$$

$$MPE_{Class2} = 636\times10^{-6}\ {}^{J}\!/_{cm^2}$$

The *Rule-2 MPE* for visible lasers can be expressed in terms of the *PRF* as follows:

$$MPE_{rule2} = \frac{636\times10^{-6}\ {}^{J}\!/_{cm^2}}{(0.25)PRF}$$

Rule-3 (Multiple Pulse, Thermal Hazard):

ANSI Rule-3 applies to multiple pulse exposures, where the pulses are separated by at least t_{min}. The ANSI standard defines t_{min} as the maximum exposure (time) that produces the same *MPE* as a one nanosecond exposure [*ANSI Std.Z136.1-2000 (Appendix B2)*].

The t_{min} for visible pulsed lasers is given by *Table 5a* as 18 microseconds. The *PRF* associated with t_{min}, is also referred to as the **critical frequency** and is given, in general, as 55 kHz [*ANSI Std. Z136.1-2000 (8.2.3.2-Note)*].

The ANSI *Rule-3 MPE* applies only to the *thermal MPE* and is given as the product of the *single pulse MPE* (MPE_{rule1}) and a **multiple pulse correction factor** (C_p).

$$MPE_{rule3} = C_p \cdot MPE_{thermal} = C_p MPE_{rule1}$$

The multiple-pulse-correction factor is given in *ANSI Std. Z136.1-2000 Table 6* as a function of the number of pulses in the exposure.

$$C_p = n^{-0.25}$$

The number of pulses in the exposure is the product of the *PRF* and the exposure duration (*T*). The standard time, for a Class 2-exposure (visible lasers only), is given as a quarter of a second [*ANSI Std. Z136.1-2000 (Table 4a)*]. The number of laser pulses in a Class 2-exposure can be expressed in terms of the *PRF*.

$$n = Int(0.25 \cdot PRF)$$

As noted previously the number of pulses considered in an exposure is always an integer, where fractional numbers are rounded up to the next higher integer.

The *Rule-3 MPE* for multiple pulse visible lasers operated below the critical frequency can be expressed as follow:

$$MPE_{rule3} = [Int(0.25 \cdot PRF)]^{-0.25} \left[5 \times 10^{-7} \, {}^{J}\!/_{cm^2} \right]$$

Rule-3 to Rule-2 Crossover

In general, ANSI Rule-3 applies to multiple pulse lasers until the *PRF* reaches a value, usually at the critical frequency, where the *MPE* switches to ANSI Rule-2.

For visible lasers this crossover point can be calculated by equating the *MPE* derived from the application of ANSI Rule-2 and Rule-3.

$$MPE_{rule3} = MPE_{rule2}$$

$$n^{-0.25}\left(5\times10^{-7}\ {}^{J}\!\!\diagup_{cm^2}\right) = \frac{636\times10^{-6}\ {}^{J}\!\!\diagup_{cm^2}}{n}$$

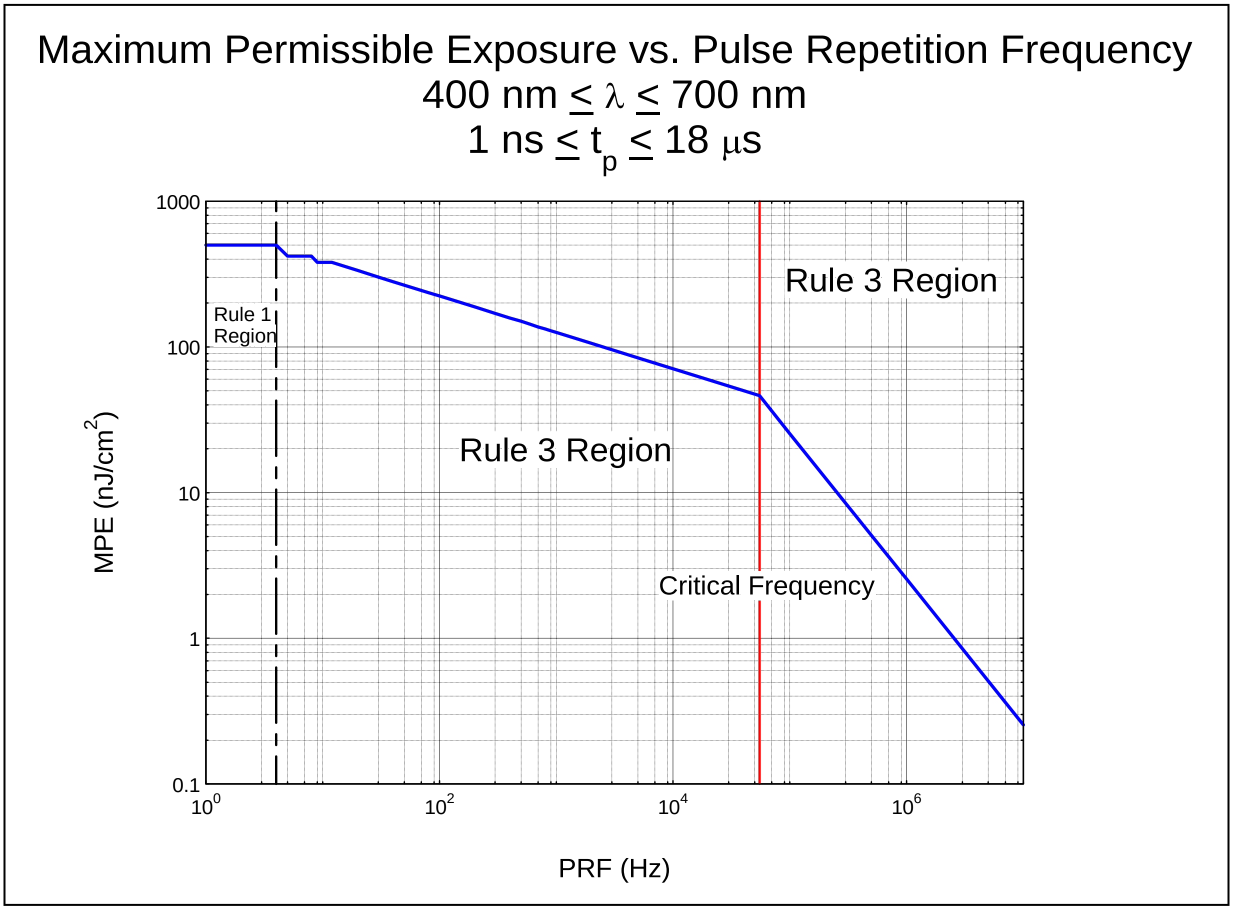
$$n^{0.75} = \frac{636\times10^{-6}}{5\times10^{-7}}$$

$$n = 13.8\times10^{3}\ pulses$$

$$n = 0.25PRF = 13.8\times10^{3}$$

$$PRF_{X_{3\to2}} = 55.1\times10^{3}\ Hz$$

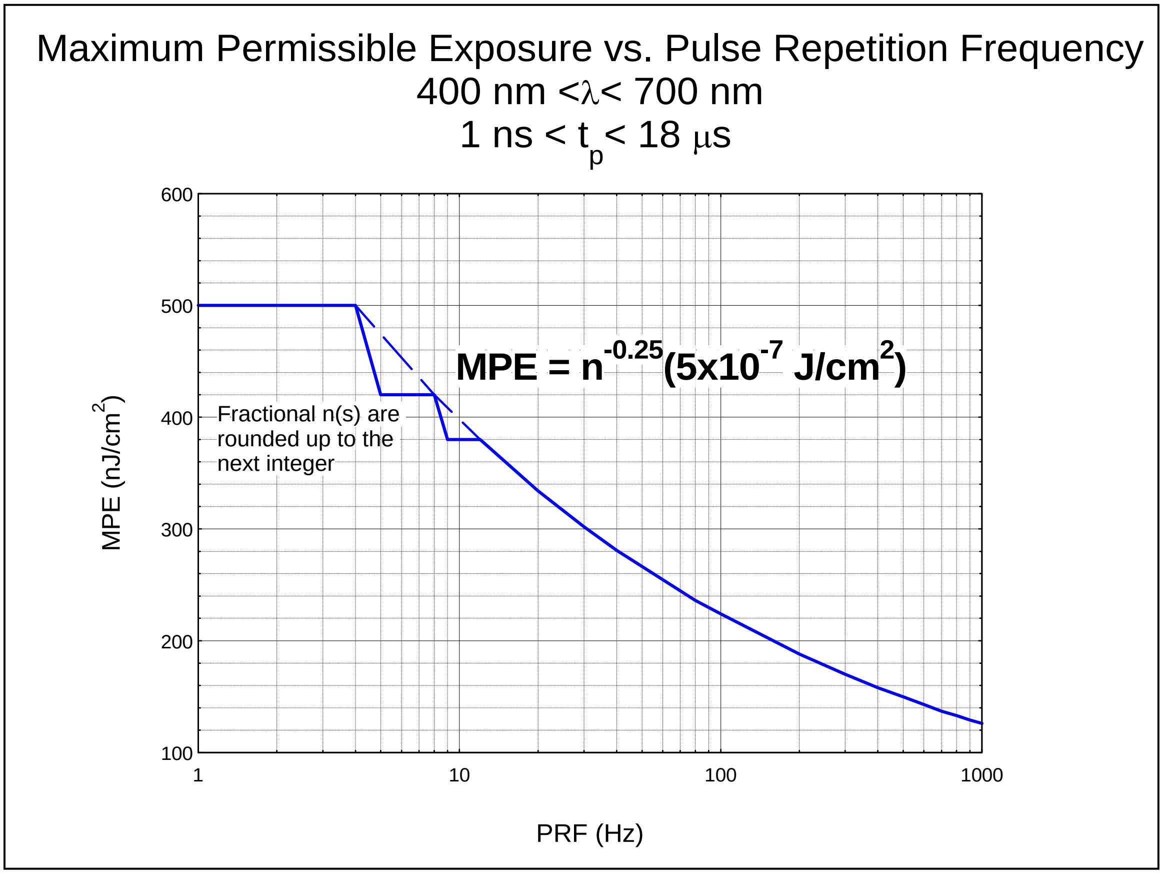
Note the ANSI standard uses as a rule of thumb 55 KHz [*ANSI Std. Z136.1-2000 (8.2.3.2 – Note)*] for the spectral range of 400 nm to 1.4 µm.



Maximum Permissible Exposure versus Pulse Repetition Frequency (1 to 1 MHz) for visible lasers with pulse durations from 1 nanosecond to t_{min}.

Note: That low *PRF* produces fractional pulse counts which are rounded up to the next higher integer pulse count.

In general, the *PRF* for a visible laser is usually less than 1 kilohertz. The following plot more accurately reflects this.



Maximum Permissible Exposure versus Pulse Repetition Frequency for visible lasers with pulse durations from 1 nanosecond to t_{min}.

Sub-Nanosecond Pulses

The *MPE* for sub-nanosecond laser pulses are generally dependent on the duration of the pulse [*ANSI Std. Z136.1-2000 (Table 5a)*].

$$MPE = 2.7t^{0.75}\ {}^{J}\!/_{cm^2} \qquad 10^{-11}\ \text{sec} \le t < 10^{-9}\ \text{sec}$$

For shorter pulses *Table 5a* gives:

$$MPE = 1.5 \times 10^{-8}\ J/cm^2 \qquad 10^{-13}\ \text{sec} \le t < 10^{-11}\ \text{sec}$$

<u>Example</u>: **Sub-Nanosecond Pulse**

The following example is for a 500-picosecond visible laser with a variable *PRF* up to 1 kilohertz.

The appropriate $MPE_{1\text{-}3}$ is always the smallest value of the three rules applied across the area of the limiting aperture.

<u>Rule-1</u> (Single Pulse)

$$MPE = 2.7t^{0.75}\ J/cm^2 \qquad 10^{-11}\ \text{sec} \le t < 10^{-9}\ \text{sec}$$

$$MPE_{500\,ps} = 2.7\left(500 \times 10^{-12}\right)^{0.75}\ J/cm^2$$

$$MPE_{500\,ps} = 285 \times 10^{-9}\ J/cm^2$$

<u>Rule-2</u>

As was shown previously for visible repetitively pulsed lasers operated at a *PRF* less than the critical frequency (~55 kilohertz) the *MPE* derived from Rule-3 will always be smaller than the MPE derived from Rule-2.

<u>Rule 3</u> (Multiple Pulse)

Although the pulse duration in this example is sub-nanosecond the appropriate exposure for Rule-3 is 1 nanosecond [*ANSI Std. Z136.1-2000 (8.2.3.2-Note)*]. The *MPE* derived from the application of Rule-3 for sub-nanosecond visible laser pulses is the same as that derived for laser pulse durations of up to t_{min} and for pulse separations greater than t_{min}.

$$MPE_{rule3} = \left[Int(0.25 \cdot PRF)\right]^{-0.25} \left[5 \times 10^{-7}\ J/cm^2\right]$$

Rule-1 to Rule-3 Crossover

The *MPE* for sub-nanosecond visible laser pulse is dominated by ANSI Rule 1 until a crossover PRF_X is reach. At this crossover *PRF* the *MPE* becomes ANSI Rule 3 dominated until the *PRF* exceeds the critical frequency. At the critical frequency the *MPE* becomes ANSI Rule 2 dominated.

The crossover PRF_X can be determined by equating the *MPE* determined from ANSI Rule 1 to that determined from ANSI Rule 3.

$$MPE_{rule1} = MPE_{rule3}$$

Example Determination of the $\mathrm{PRF}_{\mathrm{X1\text{-}3}}$ for t=500 ps:

$$285\times10^{-9}\ J/cm^2 = \left(Int[0.25\sec\cdot PRF_{X_{1-3}}]\right)^{-025}\left(500\times10^{-9}\ J/cm^2\right)$$

$$(Int[0.25\sec\cdot PRF_{X_{1-3}}])^{-0.25} = \frac{285\times10^{-9}\ J/cm^2}{500\times10^{-9}\ J/cm^2} = 0.571$$

$$(Int[0.25\sec\cdot PRF_{X_{1-3}}])^{0.25} = 1.75$$

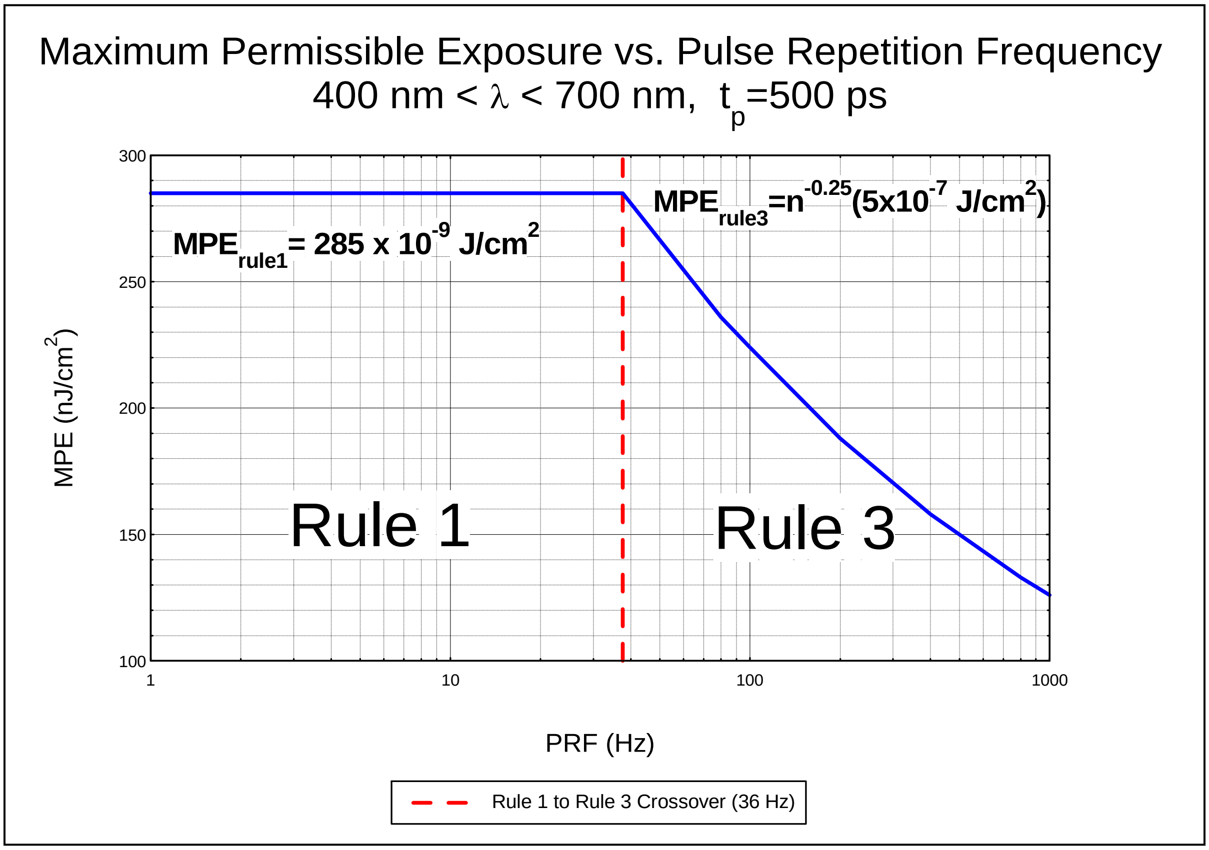
$$Int[0.25\sec\cdot PRF_{X_{1-3}}] = Int(1.75)^4 = Int(9.41) = 9$$

$$0.25\sec\cdot PRF_{X_{1-3}} = 9$$

$$PRF_{X_{1-3}} = 36\sec^{-1}$$

$$PRF_{X_{1-3}} = 36Hz$$

At a *PRF* of 36 Hz the *MPE*, for a 500-ps visible laser, switches from ANSI Rule 1 dominated to ANSI Rule 3 dominated.



Maximum Permissible Exposure versus Pulse Repetition Frequency for a 500-ps visible laser pulse.

IR Repetitively Pulsed Lasers (1.5 µm to 1.8 µm)

The *MPE* applied across the area of the limiting aperture for **Infrared** (*IR*) repetitively pulsed laser is given by *Table 5a* as:

$$MPE_{(1.5\mu m \rightarrow 1.8\mu m)} = 1 \ {}^{J}\!/_{cm^2} \qquad\qquad 10^{-9}\sec \le t \le 10\sec$$

The limiting aperture, both skin and eye, for this wavelength range is given as 3.5 mm [*ANSI Std. Z136.1-2000 (Table 8)*].

For exposure of 10 seconds or less, to repetitively pulsed IR lasers; the appropriate per pulse *MPE* is the value presented above distributed over the number of pulses that occur in the exposure.

$$MPE_{pulse} = \frac{1 \ {}^{J}\!/_{cm^2}}{n} \qquad\qquad T \le 10\sec$$

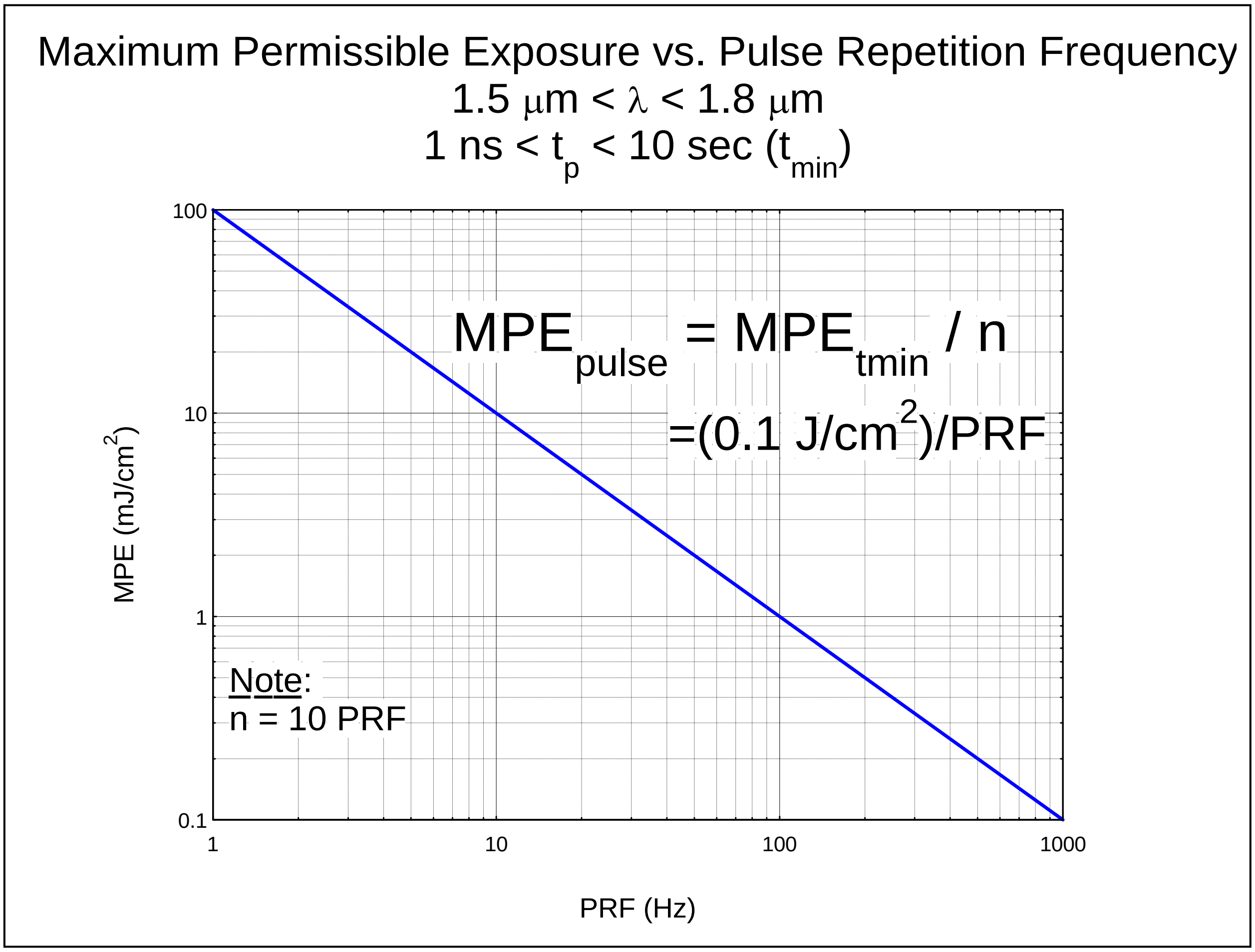
The per-pulse *MPE* can be related to the *PRF* and the duration of the exposure as follows:

$$MPE_{pulse}\langle T\rangle = \frac{1 \ {}^{J}\!/_{cm^2}}{PRF \cdot T} \qquad\qquad T \le 10\sec$$

The suggested exposure for both diffused and intrabeam ocular exposure to laser wavelengths from 1400 nm to 1 mm is 10 seconds [*ANSI Std. Z136.1-2000 (Table 4a)*]. The suggested exposure should be used unless the actual exposure (*T*) is less.

Assuming worst case condition for a Class 1 exposure the suggested exposure of 10 seconds from *Table 4a* is used. The appropriate *MPE* as a function of the PRF can be expressed as follows:

$$MPE_{pulse} = \frac{0.1 \ {}^{J}\!/_{cm^2}}{PRF} \qquad\qquad T = 10\sec$$



Maximum Permissible Exposure for laser emissions from 1.5 µm to 1.8 µm versus the Pulse Repetition Frequency.

Sub-Nanosecond Pulse Duration

The current *ANSI Standard Z136.1-2000* does not list *MPE* forms for sub-nanosecond exposures to laser wavelengths longer than 1.4 microns.

Nominal Ocular Hazard Distance

The **nominal ocular hazard distance** (*NOHD*) is the distance, line of sight, from the emitting source (laser) beyond which a Class 1 laser ("eye safe") hazard exists. The ***NOHD* applies to unaided intrabeam viewing only**. The *NOHD* for a multiple pulsed laser can be calculated by the formula presented in the appendix of the ANSI Standard.

$$NOHD = \frac{1}{\theta}\sqrt{\frac{4Q}{\pi \cdot MPE} - d_o^2} \quad cm$$

Where;
$NOHD$: Nominal Ocular Hazard Distance (in centimeters)
θ: Beam divergence (in radians)
Q: Radiant output (in joules)
MPE: Maximum Permissible Exposure (in joules/square centimeters)
d_o: Exit diameter of the laser (in centimeters)

Similarly for CW lasers the *NOHD* can be expressed as:

$$NOHD = \frac{1}{\theta}\sqrt{\frac{4\Phi}{\pi \cdot MPE} - d_o^2} \quad cm$$

Where;
$NOHD$: Nominal Ocular Hazard Distance (in centimeters)
θ: Beam divergence (in radians)
Φ: Radiant output (in watts)
MPE: Maximum Permissible Exposure (in watts/square centimeters)
d_o: Exit diameter of the laser (in centimeters)

Atmospheric Transmission Factor

For outdoor laser transmissions over distances less than 1 kilometer atmospheric transmission factors, generally, are not considered.

Atmospheric transmission factor is a function of the laser wavelength and the distance from the laser. If the atmospheric transmission factor is known the *NOHD* can be estimated.

$$NOHD_{atm} \sim \sqrt{\tau_{atm}} \cdot NOHD$$

<u>Where;</u>

$NOHD_{atm}$: Nominal Ocular Hazard Distance atmospheric corrected
τ_{atm}: Atmospheric transmission f(wavelength, distance)
NOHD: Nominal Ocular Hazard Distance

Extended Ocular Hazard Distance

The **extended ocular hazard distance** (*EOHD*) is similar to the *NOHD* but applies to intrabeam aided-viewing.

Aided Viewing

The use of optical aides such as a pair of 7x50 binoculars for intrabeam viewing will increase the viewing hazard by as much as the square of the magnifying power (optical gain) of the optical system [*ANSI Std. Z136.1–2000 (B6.4.3)*].

Increased Hazard

The *MPE* is the quantification of the laser **ocular hazard** (*HAZ*) for unaided intrabeam viewing presented by the laser (since it is the threshold into the ocular hazard regime). The increased hazard as a result of aided intrabeam viewing can be expressed as a function of the *MPE* and the **magnifying power** (*P*) of the viewing aid:

$$HAZ_{\uparrow} = \frac{MPE}{P^2}$$

Where;
$HAZ_{\uparrow}$: Increased ocular hazard
MPE: Maximum Permissible Exposure
P: Magnifying Power

Optical Gain

The **optical gain factor** (*G*) represents the maximum increase in the ocular hazard from aided viewing of the laser beam. In general for a 7x50 binocular, for wavelengths in the retinal hazard region (400 nm $\leq \lambda <$ 1.40 μm) with an assumed 100% optical transmission and the exit pupil is approximately equal to the limiting aperture ($D_{f(\text{visible})}$ = 7 mm) the optical gain (*G*) can be expressed as:

$$G = \left[\frac{D_o}{D_e}\right]^2 = P^2 \qquad \text{(\textit{ANSI Std. Z136.1 Eq B55})}$$

Where;
G: Optical Gain
P: Magnifying Power
D_o: Diameter of Objective optic
D_e: Diameter of exit pupil

Maximum Gain

As for example a pair of (**7**x50) binoculars (viewing in the retinal hazard region) the maximum gain is:

$$G_{\max} = (7)^2 = 49$$

Actual Gain

The actual gain of the optical system considers the transmission factor to the optical system.

$$G = \tau_\lambda \left[\frac{D_o}{D_e}\right]^2 = \tau_\lambda P^2$$

Where;
- G: Optical Gain
- P: Magnifying Power
- D_o: Diameter of objective optic
- D_e: Diameter of exit pupil
- τ_λ: Transmission factor of the optical system

Effective Gain

The **effective optical gain** (G_{eff}) is usually used when considering intrabeam aided viewing of laser sources at closer distances, where the collecting aperture is not necessarily the same as the diameter of the objective optic, generally in the retinal hazard region; however, "the effective gain is useful for calculating the hazards for lasers with wavelengths outside the retinal hazard region (302 nm $\leq \lambda_{UV} <$ 400 nm and 1.4 μm $\leq \lambda <$ 2.8 μm)" [*ANSI Std. Z136.1–2000 (B6.4.3.2)*]. The limiting aperture (diameters) in these wavelength regions are 3.5 mm for exposures of ten seconds or greater.

For laser wavelengths in these regions (302 nm $\leq \lambda_{UV} <$ 400 nm and 1.4 μm $\leq \lambda_{IR} <$ 2.8 μm) the hazard is to the cornea of the eye instead of to the retina.

The effective gain (G_{eff}) can be expressed as:

$$G_{eff} = \tau_\lambda \frac{\min\left(D_c^2, D_L^2\right)}{D_f^2} \qquad \text{(\textit{ANSI Std. Z136.1 Eq B57})}$$

Where;
- G_{eff}: Effective Optical Gain.
- D_c: Diameter of collecting aperture.
- D_L: Diameter of laser beam at the viewing range from the laser
- D_f: Diameter of limiting aperture (*ANSI Std. Z136.1–Table 8*)
- τ_λ: Transmission factor of the optical system

Collecting Aperture

The diameter of the **collecting aperture** (D_c) can be determined from:

$$D_c = \min\left(D_o, P \cdot D_f\right) \quad (\textit{ANSI Std. Z136.1 Eq B56})$$

Where;
P: Magnifying power of the optical system
D_c: Diameter of the collecting aperture
D_o: Diameter of the objective optic
D_f: Diameter of the limiting aperture (*ANSI Std. Z136.1-Table 8*)

The following evaluation is an example for the case of intrabeam aided viewing of an Erbium (1.54 microns) laser output with a pair of (7x50) binoculars.

Evaluation for 7x50 Binoculars

Example: for an Erbuim laser (1.54 µm).

The radiant output is in the corneal hazard region (1.4 µm $\leq \lambda_{1.540\ \mu m}$ < 2.8 µm).

Given:
P: 7 (**7** x 50) binoculars
D_o: 50 mm (7 x **50**) binoculars
D_f: 3.5 mm (for T $\geq$ 10 seconds – *ANSI Z136.1 Table 8*)

$$D_c = \min\left(D_o, P \cdot D_f\right)$$

= min (50 mm, 7 x 3.5 mm)

= min (50 mm, 24.5 mm)

$$D_c = 24.5 \ mm$$

The effective optical gain (G_{eff}) for intrabeam aided viewing of the Erbium laser using a pair of 7x50 binoculars can be determined as follows:

$$G_{eff} = \tau_{\lambda} \frac{\min\left(D_c^2, D_L^2\right)}{D_f^2}$$

<u>Where</u>;
G_{eff}: Effective optical gain
D_c: 24.5 mm (calculated above)
D_L: Diameter of laser beam at the collecting optic
D_f: 3.5 mm [*ANSI Std. Z136.1-2000 (Table 8)*]
τ_λ: Transmission coefficient {0.7 [*ANSI Std. Z136.1-2000 (Table 9)*]}

The diameter of the laser beam (D_L) is a function of the distance from the laser.

$$D_L = d_o + \theta R$$

<u>Where</u>;
D_L: Diameter of the laser beam at range, R.
d_o: Exit diameter of the laser beam.
θ: Beam divergence at the 1/e points.
R: Distance from the laser.

The range (R_c) at which the diameter of the laser beam is equaled to the diameter of the collecting aperture can be determined as follows:

$$D_L = D_c = d_{out} + \theta R_c$$

$$R_c = \frac{\left(D_c - d_{out}\right)}{\theta}$$

$$R_c = \frac{\left(24.5mm - d_{out}\right)}{\theta}$$

Evaluation of the Effective Gain

For intrabeam aided viewing of an Erbium laser at distances greater than "R_c" the effective optical gain can be calculated from.

$$G_{eff} = \tau_\lambda \frac{D_c^2}{D_f^2}$$

The effective gain for a 7x50 binocular viewing an Erbium laser intrabeam at a distance where the laser beam is larger than the collecting aperture can be calculated as follows:

<u>Given the following parameters</u>:

D_f: 3.5 mm [*ANSI Std. Z136.1–2000 (Table 8*)]
D_c: 24.5 mm (Calculated previously for 7x50 binoculars)
τ_λ: 0.7 [*ANSI Std. Z136.1–2000 (Table 9*)]

G_{eff}: Effective gain

$$G_{eff} = (0.7)\frac{(24.5\ mm)^2}{(3.5\ mm)^2}$$

$$G_{eff} = 34.3 \qquad \text{For: } R \geq R_c$$

Applicable for the wavelength ranges $302\,nm \leq \lambda < 400\,nm \ \ and \ \ 1.4\,\mu m \leq \lambda \leq 2.8\,\mu m$, for exposures equal to ten seconds or greater.

Evaluation of Increased Hazard

The increase in the ocular hazard for the intrabeam aided viewing of an **Erbium laser** (1.54 µm) using a pair of (7x50) binoculars at viewing distances greater than R_c, exposure at or longer than 10 seconds over similar unaided interviewing is as follows.

$$HAZ_{7\times 50} = \frac{MPE}{34.3}$$

MPE for Erbium laser at 1.54 µm

The *MPE* for a radiant wavelength of 1.54 µm can be determined from *ANSI Std. Z136.1-2000 Table 5a*.

$$MPE_{1.54\mu m} = 1\ {}^{J}\!/_{cm^2} \qquad 1.5\mu m \le \lambda \le 1.8\mu m$$

$$10^{-9}\sec \le T \le 10\sec$$

The increase hazard associated with intrabeam viewing of this laser is:

$$HAZ_{7\times 50} = \frac{MPE_{1.54\mu m}}{34.3}$$

$$HAZ_{7\times 50} = \frac{1\ {}^{J}\!/_{cm^2}}{34.3}$$

$$HAZ_{7\times 50} = 29.2\times 10^{-3}\ {}^{J}\!/_{cm^2}$$

Extended Ocular Hazard Distance

The Extended Ocular Hazard Distance (*EOHD*) can be determined from the increased hazard as a result of the optical gain of the optical system.

The formula for calculating the *EOHD* is derived from the formula for the *NOHD* given in the Appendix of the *ANSI Std. Z136.1–2000* as follows, where *MPE* is replaced by the increased hazard term ($HAZ_{\uparrow}$):

Recall;

$$NOHD = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi \cdot MPE} - d_{out}^2} \quad cm$$

Where;

NOHD:	Nominal Ocular Hazard Distance, in centimeters.
θ:	Beam divergence, in radians at the 1/e points.
Q_o:	Output radiant energy, in joules.
MPE:	Maximum Permissible Exposure, in joules/cm^2.
d_{out}:	Output beam diameter of the laser, in centimeters.

The *EOHD* can be calculated as follows:

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi \cdot HAZ_{\uparrow}} - d_{out}^2} \quad cm$$

Where;

EOHD:	Extended Ocular Hazard Distance, in centimeters.
θ:	Beam divergence, in radians at the 1/e points.
Q_o:	Output radiant energy, in joules.
$HAZ_{\uparrow}$:	Increased hazard, in joules/cm^2.
d_{out}:	Output beam diameter of the laser, in centimeters.

Where;

$$HAZ_{\uparrow} = \frac{MPE}{G_{eff}}$$

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4 \cdot Q_o}{\pi \frac{MPE}{G_{eff}}} - d_{out}^2} \quad cm$$

Simplified as;

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4 \cdot G_{eff} \cdot Q_o}{\pi \cdot MPE} - d_{out}^2} \quad cm$$

As applied to the intrabeam viewing of the Erbium laser with a pair of 7x50 binoculars at a distance greater than R_c for viewing times greater than 10 seconds.

$$EOHD \ = \frac{1}{\theta}\sqrt{\frac{(4) \cdot (34.3) \cdot Q_o}{\pi \cdot MPE} - d_o^2} \quad cm$$

$$EOHD \ = \frac{1}{\theta}\sqrt{\frac{(137.2) \cdot Q_o}{\pi \cdot MPE} - d_o^2} \quad cm$$

Applicable for the wavelength ranges: $302nm \leq \lambda < 400nm \ and \ 1.4\mu m \leq \lambda \leq 2.8\mu m$ for exposures, T $\geq$ 10 seconds.

Visible and Near IR

The actual optical gain (G) is used in the determination of the increased hazard for *EOHD* evaluation for wavelengths in the visible and **near IR** wavelengths (*NIR*).

$$HAZ_{\uparrow} = \frac{MPE}{G} \qquad 400\ nm \le \lambda \le 1.4\mu m$$

$$G = \tau_{\lambda}\left[\frac{D_o}{D_e}\right]^2 = \tau_{\lambda}P^2 \qquad 400\ nm \le \lambda \le 1.4\mu m$$

$$EOHD = \frac{1}{\theta}\sqrt{\frac{4 \cdot G \cdot Q_o}{\pi \cdot MPE} - d_{out}^2} \quad cm$$

The transmission factor at the visible wavelengths $(400nm \le \lambda \le 700nm)$ for 7x50 binocular is given as 0.9 [*ANSI Std. Z136.1-2000 (Table 9)*] and the limiting aperture is given as 0.7 cm [*ANSI Std. Z136.1-2000 (Table 8)*].

$$G_{VIS} = (0.9)\left[\frac{50mm}{7mm}\right]^2 = 45.9$$

The transmission factor at the NIR wavelengths $(700nm < \lambda \le 1.4\mu m)$ for 7x50 binocular is given as 0.7 [*ANSI Std. Z136.1-2000 (Table 9)*] and the limiting aperture is given in *ANSI Std. Z136.1-2000 (Table 8)* as 0.7 cm.

$$G_{NIR} = (0.7)\left[\frac{50mm}{7mm}\right]^2 = 35.7$$

The *EOHD* for the visible wavelengths is:

$$EOHD_{VIS} = \frac{1}{\theta}\sqrt{\frac{184 \cdot Q_o}{\pi \cdot MPE} - d_{out}^2} \quad cm$$

The *EOHD* for the visible wavelengths is:

$$EOHD_{NIR} = \frac{1}{\theta}\sqrt{\frac{143 \cdot Q_o}{\pi \cdot MPE} - d_{out}^2} \quad cm$$

Approximation Method

The *EOHD* can be approximated from the *NOHD* multiplied by a scale factor (square root of the effective optical gain) if:

$$\frac{4 \cdot Q}{\pi \cdot MPE} >> d_o^2$$

Then the *EOHD*, for the **corneal hazard region**, is approximately:

$$EOHD \approx \sqrt{G_{eff}} \times NOHD \qquad \begin{array}{l} 302nm \le \lambda < 400nm \\ 1.4\mu m \le \lambda < 2.8\mu m \end{array}$$

Where;

EOHD: Extended Ocular Hazard Distance
G_{eff}: Effective Gain
NOHD: Nominal Ocular Hazard Distance

Alternatively for the **retinal hazard region**, the *EOHD* is approximately:

$$EOHD \approx \sqrt{\tau_\lambda} \left[\frac{D_c}{D_f} \right] NOHD \qquad 400nm \le \lambda < 1.4\mu m$$

Where;

EOHD: Extended Ocular Hazard Distance
D_c: Collecting aperture (50 mm) for 7x50 binocular
D_f: Limiting aperture [*ANSI Std. Z136.1-2000 (Table 8*)]
τ_λ: Optic transmission factor [*ANSI Std. Z136.1-2000 (Table 9)*]

The approximation method is useful when used with a laser hazard computer program such as RLI® family of LAZAN© laser safety programs, which can readily be used to calculate the *NOHD* but not the *EOHD*.

Estimated *EOHD* Examples for 7x50 binoculars

The following examples demonstrate the application of the estimation method for determining the extended ocular hazard distances for the various wavelength ranges.

UV-1 ($180nm \le \lambda < 302nm$):

$\tau < 0.02$ [*ANSI Std. Z136.1-2000 (Table 9)*]

$$EOHD \approx \sqrt{G_{eff}} \times NOHD$$

$$G_{eff} = (0.02)\frac{(24.5\ \ mm)^2}{(3.5\ \ mm)^2} = 0.980$$

$$EOHD \approx \sqrt{0.98} \times NOHD$$

$$EOHD \approx 0.99 \times NOHD$$

UV-2 ($302nm \le \lambda < 400nm$):

$\tau < 0.7$ [*ANSI Std. Z136.1-2000 (Table 9)*]

$$EOHD \approx \sqrt{G_{eff}} \times NOHD$$

$$G_{eff} = (0.7)\frac{(24.5\ \ mm)^2}{(3.5\ \ mm)^2} = 34.3$$

$$EOHD \approx \sqrt{34.3} \times NOHD$$

$$EOHD \approx 5.86 \times NOHD$$

Visible ($400nm \leq \lambda \leq 700nm$):

$\tau < 0.9$ [*ANSI Std. Z136.1-2000 (Table 9)*]

$$G = \tau_\lambda \left[\frac{D_o}{D_e} \right]^2 = \tau_\lambda P^2$$

$$EOHD \approx \sqrt{0.9} \cdot \left[\frac{50mm}{7mm} \right] \cdot NOHD$$

$$EOHD \approx 6.78 \times NOHD$$

Near IR ($700nm < \lambda < 1.4\mu m$):

$\tau < 0.7$ [*ANSI Std. Z136.1-2000 (Table 9)*]

$$G = \tau_\lambda \left[\frac{D_o}{D_e} \right]^2 = \tau_\lambda P^2$$

$$EOHD \approx \sqrt{0.7} \cdot \left[\frac{50mm}{7mm} \right] \cdot NOHD$$

$$EOHD \approx 5.98 \times NOHD$$

IR ($1.4\mu m \le \lambda < 2.8\mu m$):

τ < 0.7 [*ANSI Std. Z136.1-2000 (Table 9)*]

$$EOHD \approx \sqrt{G_{eff}} \times NOHD$$

$$G_{eff} = (0.7)\frac{(24.5\ \ mm)^2}{(3.5\ \ mm)^2} = 34.3$$

$$EOHD \approx \sqrt{34.3} \times NOHD$$

$$EOHD \approx 5.86 \times NOHD$$

Table 1

Summary of Estimated EOHD Scale Factors for 7x50 Binoculars

[where: $\frac{4 \cdot Q}{\pi \cdot MPE} >> d_o^2$ **]**

Wavelength Range	Optic Transmission	**Estimated Scale Factor (approximation)**
$180nm \le \lambda < 302nm$	<0.02	**0.99**
$302nm \le \lambda < 400nm$	0.7	**5.86**
$400nm \le \lambda \le 700nm$	0.9	**6.78**
$700nm < \lambda < 1.4\mu m$	0.7	**5.98**
$1.4\mu m \le \lambda \le 2.8\mu m$	0.7	**5.86**

Lasers Used In Navigable Air Space

Visible lasers* used in navigable air space pose hazards to aircrews beyond the *NOHD*. Air crew exposure to visible laser light, at levels below the *MPE*, pose special concerns due to startle and glare which can cause pilot distraction and vision impairments, such as flashblindness. The use of visible lasers in navigable air space has the potential to distract the pilot, disrupt critical flight crew activities, disorient the pilot or flight crew and in the extreme incapacitate the pilot.

* $400nm \le \lambda \le 700nm$ [*ANSI Std.Z136.1-2000(1.2)*]
$380nm \le \lambda \le 780nm$ [*ANSI Std.Z136.6-2000(1.1.1)*]

Flight Hazard Distance

The **Flight Hazard Distance** (*FHD*) is the distance from laser where the irradiance defines the boundary of the various hazard zones.

Normal Flight Zone

The **Normal Flight Zone** (*NFZ*) is all the air space about the laser that is not include in any other visual interference zones. In the Normal Flight Zone the boundary of the Ocular Hazard Zone (distance from the laser over which an ocular hazard exists) is defined as the *NOHD*. The irradiance at this boundary is defined to be the *MPE*. Ocular exposure at or greater than this distance would present no more than a Class 1 hazard to invisible laser light and a Class 2* hazard to visible laser light. Although considered eye safe, visible laser light can still present startle and glare concerns to flight crews, which could lead to distraction, disruption or disorientation.

*There are no Class 2 single pulse lasers [*ANSI Std.Z136.1-2000 (Table 2)*]. Class 2 applies to CW or multiple pulse visible lasers only.

Sensitive Zone

The **Sensitive Zone** (*SZ*) is the air space (including the ground) where exposure to visible laser light would interfere with critical tasks but **does not jeopardize** safety [*ANSI Std. Z136.6-2000 (4.7.2.1)*]. The visual interference levels are presented in *ANSI Standard Z136.6-2000 (Table 5).*

The effective radiant exposure (E_{eff}) for the sensitive zone is given as:

ANSI Std. Z136.6-2000 (Table 5)

$$H_{eff-SZ} = 25 \times 10^{-6} \, J/cm^2$$

$380nm \le \lambda \le 780nm$

$T_{\max} \le 0.25 \sec$

The effective irradiance (H_{eff}) for the sensitive zone is given as:

ANSI Std. Z136.6-2000 (Table 5)

$$E_{eff-SZ} = 100 \times 10^{-6}\ {}^{W}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm \qquad T_{\max} \le 0.25\sec$$

Critical Zone

The **Critical Zone** (*CZ*) is the ground and air space where "laser caused" visual interference with critical tasks **would jeopardize** the safe accomplishment of the task [*ANSI Std. Z136.6-2000 (4.7.2.2)*].

The **effective radiant exposure** (H_{eff}) for the critical zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$H_{eff-CZ} = 1.25 \times 10^{-6}\ {}^{J}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm \qquad T_{\max} \le 0.25\sec$$

The **effective irradiance** (E_{eff}) for the critical zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$E_{eff-CZ} = 5.0 \times 10^{-6}\ {}^{W}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm \qquad T_{\max} \le 0.25\sec$$

Laser–Free Zone

The **Laser-Free Zone** (*LFZ*) is the ground and air space where visual interference would be very serious and might prevent the accomplishment of critical tasks, such as aircraft operation about or around airports [*ANSI Std. Z136.6-2000 (4.7.2.3)*].

The effective radiant exposure (H_{eff}) for the laser-free zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$H_{eff-LFZ} = 12.5 \times 10^{-9}\ {}^{J}\!/_{cm^2} \qquad 380nm \le \lambda \le 780nm \qquad T_{\max} \le 0.25\sec$$

The effective irradiance (E_{eff}) for the laser-free zone is given as:

ANSI Std. Z136.6-2000 (*Table 5*)

$$E_{eff-LFZ} = 50 \times 10^{-9}\ {}^{w}\!\!\diagup_{cm^2} \qquad 380nm \le \lambda \le 780nm \qquad T_{\max} \le 0.25\sec$$

Irradiance (CW Lasers)

The irradiance at a particular distance (line-of-sight) from the laser can be calculated from:

$$E = \frac{1.27\Phi}{D^2 + R^2 \cdot \theta^2}$$

Where;
- E: Irradiance (in w/cm^2)
- Φ: Radiant Power (watts)
- D: Exit diameter of the laser (in cm)
- R: Distance from the laser (in cm)
- θ: Beam divergence at the 1/e points

Effective Irradiance

The effective irradiance is defined to be the product of the irradiance of the visible laser and relative visual response [*ANSI Std. Z136.6-2000* (*Table 1*)], which is a function of the laser wavelength.

$$E_{eff} = v_{\lambda} \cdot E$$

Where;
- E_{eff}: Effective Irradiance (in J/cm^2)
- v_{λ}: Photopic Luminous Efficiency (relative visual response of the eye)
- E: Laser Irradiance (in J/cm^2)

Radiance (Pulse Lasers)

The radiant exposure at a particular distance (line-of-sight) from the laser can be calculated from:

$$H = \frac{1.27Q}{D^2 + R^2 \cdot \theta^2}$$

<u>Where</u>;

H: Irradiance (in J/cm^2)
Q: Radiant Power (joules)
D: Exit diameter of the laser (in cm)
R: Distance from the laser (in cm)
θ: Beam divergence at the 1/e points

Effective Radiant Exposure

The effective radiant exposure is defined to be the product of the radiant exposure of the visible laser and relative visual response [*ANSI Std. Z136.6-2000* (*Table 1*)], which is a function of the laser wavelength.

$$H_{eff} = \nu_\lambda \cdot H$$

<u>Where</u>;

H_{eff}: Effective Irradiance (in J/cm^2)
ν_λ: Photopic Luminous Efficiency (relative visual response of the eye)
H: Laser Irradiance (in J/cm^2)

Example 1: The Determination of Flight Hazard Distances For: A CW Visible Laser

Laser Parameters:

Argon Ion (λ = 514 nm)
Radiant Power (Φ = 8 watts)
Exit Beam Diameter (0.8 cm)
Beam Divergence at 1/e, θ = 1.25 mR

Calculation for the Flight Hazard Distances

The calculation for the flight hazard distances are based on the Range Equation presented in the appendix of both *ANSI Std. Z136.1-2000* and *ANSI Std. Z136.6-2000*.

(1) Normal Flight Zone (Hazard Zone) Distance

$$NOHD = \frac{1}{\theta}\sqrt{\frac{4 \cdot \Phi}{\pi \cdot MPE} - d_{out}^2} \quad cm$$

$$NOHD = \frac{1}{1.25 \times 10^{-3}}\sqrt{\frac{4 \cdot (8w)}{\pi \cdot \left(2.5 \times 10^{-3}\ {w}/{cm^2}\right)} - (0.8\ cm)^2}$$

$$NOHD = 511 \quad meters$$

(2) Sensitive Zone Distance

$$R_{SZ} = \frac{1}{\theta}\sqrt{\frac{4 \cdot \Phi}{\pi \cdot E_{eff-SZ}} - d_{out}^2} \quad cm$$

$$E_{eff-SZ} = 100 \times 10^{-6}\ {w}/{cm^2}$$ [*ANSI Std. Z136.6-2000 (Table 5)*]

$$R_{SZ} = \frac{1}{\theta}\sqrt{\frac{4 \cdot (8w)}{\pi \cdot \left(100 \times 10^{-6}\ {w}/{cm^2}\right)} - (0.8\ cm)^2}$$

$$R_{SZ} = 2.55\ km$$

(3) Critical Zone Distance

$$R_{CZ} = \frac{1}{\theta}\sqrt{\frac{4\cdot\Phi}{\pi\cdot E_{eff-CZ}} - d_{out}^2} \quad cm$$

$$E_{eff-CZ} = 5\times10^{-6}\ {}^{w}\!/_{cm^2} \qquad \text{[}\textit{ANSI Std. Z136.6-2000 (Table 5)}\text{]}$$

$$R_{CZ} = \frac{1}{1.25\times10^{-3}}\sqrt{\frac{4\cdot(8w)}{\pi\cdot\left(5.0\times10^{-6}\ {}^{w}\!/_{cm^2}\right)} - (0.8\ cm)^2}$$

$$R_{CZ} = 11.4\ \ km$$

(4) Laser-Free Zone Distance

$$R_{LFZ} = \frac{1}{\theta}\sqrt{\frac{4\cdot\Phi}{\pi\cdot E_{eff-LFZ}} - d_{out}^2} \quad cm$$

$$E_{eff-LFZ} = 50\times10^{-9}\ {}^{w}\!/_{cm^2} \qquad \text{[}\textit{ANSI Std. Z136.6-2000 (Table 5)}\text{]}$$

$$R_{LFZ} = \frac{1}{1.25\times10^{-3}}\sqrt{\frac{4\cdot(8w)}{\pi\cdot\left(50\times10^{-9}\ {}^{w}\!/_{cm^2}\right)} - (0.8\ cm)^2}$$

$$R_{LFZ} = 114\ \ km$$

Table 2

Flight Hazard Distances For:
8 watt-Ar$^+$ Laser with divergence of 1.25 mR @ 1/e

Flight Hazard Zones	Flight Hazard Distances
Normal Flight Zone	0.511 km
Sensitive Zone	2.55 km
Critical Zone	11.4 km
Laser Free Zone	114 km

Example 2: The Determination of Flight Hazard Distances For: A Pulsed-Visible Laser

Laser Parameters:

Frequency Doubled YAG (λ = 532 nm)
Pulse Energy, Q = 25 mJ
Pulse duration, t = 10 ns
Pulse Repetition Frequency = 20 Hz
Exit Diameter, D_o = 0.5 cm
Beam Divergence, φ = 1.5 mR @ $1/e^2$

Calculation for the Flight Hazard Distances

The calculation for the flight hazard distances are based on the Range Equation presented in the appendix of both *ANSI Std. Z136.1-2000* and *ANSI Std. Z136.6-2000*.

The beam divergence associated with laser safety is measured at the 1/e points. When the beam divergence is given in $1/e^2$ point the beam divergence in divided by the square root of two.

$$\theta\left(1/e\right) = \frac{\phi\left(1/e^2\right)}{\sqrt{2}}$$

$$\theta\left(1/e\right) = \frac{1.5\times10^{-3}}{\sqrt{2}} \quad radians$$

$$\theta = 1.06\times10^{-3} \quad radians$$

(1) Normal Flight Zone (Hazard Zone).

$$MPE_{rule3} = C_p \cdot MPE_{rule1}$$

$$n = PRF \cdot T = \left(20\sec^{-1}\right)\cdot\left(0.25\sec\right) = 5 \ pulses$$

$$C_p = n^{-0.25} = \left(5\right)^{-0.25} = 0.669$$

$$MPE_{rule3} = (0.669) \cdot \left(5 \times 10^{-7} \ J/cm^2 \right)$$

$$MPE_{rule3} = 334 \times 10^{-9} \ J/cm^2$$

Nominal Ocular Hazard Distance

$$NOHD = \frac{1}{\theta} \sqrt{\frac{4 \cdot Q}{\pi \cdot MPE} - d_{out}^2} \quad cm$$

$$NOHD = \frac{1}{1.06 \times 10^{-3}} \sqrt{\frac{4 \cdot 25 \times 10^{-3} \ J}{\pi \cdot \left(334 \times 10^{-9} \ J/cm^2 \right)} - (0.5 \ cm)^2}$$

$$NOHD = 2.91 \quad km$$

(2) Sensitive Zone Distance

$$R_{SZ} = \frac{1}{\theta} \sqrt{\frac{4 \cdot Q_{tot}}{\pi \cdot H_{eff-SZ}} - d_{out}^2} \quad cm$$

$$H_{eff-SZ} = 25 \times 10^{-6} \ J/cm^2$$ [*ANSI Std. Z136.6-2000 (Table 5)*]

The total energy delivered in the event window (T = 0.25 seconds) is the product of the average pulse radiant energy and the number of pulses delivered in the event window.

$$Q_{total} = n \cdot Q = (5) \cdot (25 \times 10^{-3} \ J) = 125 \times 10^{-3} \ J$$

$$R_{SZ} = \frac{1}{\left(1.06\times10^{-3}\right)}\sqrt{\frac{4\cdot\left(125\times10^{-3}\,J\right)}{\pi\cdot\left(25\times10^{-6}\,J/cm^2\right)} - \left(0.5\ cm\right)^2}$$

$$R_{SZ} = 0.753 \quad km$$

(3) Critical Zone Distance

$$R_{CZ} = \frac{1}{\theta}\sqrt{\frac{4\cdot Q_{tot}}{\pi\cdot H_{eff-CZ}} - d_{out}^2} \quad cm$$

$H_{eff-CZ} = 1.25\times10^{-6}\,J/cm^2$ [*ANSI Std. Z136.6-2000 (Table 5)*]

$$R_{CZ} = \frac{1}{\left(1.06\times10^{-3}\right)}\sqrt{\frac{4\cdot\left(125\times10^{-3}\,J\right)}{\pi\cdot\left(1.25\times10^{-6}\,J/cm^2\right)} - \left(0.5\ cm\right)^2} \quad cm$$

$$R_{CZ} = 3.37 \quad km$$

(4) Laser-Free Zone Distance

$$R_{LFZ} = \frac{1}{\theta}\sqrt{\frac{4\cdot Q_{total}}{\pi\cdot H_{eff-LFZ}} - d_{out}^2} \quad cm$$

$H_{eff-LFZ} = 12.5\times10^{-9}\,J/cm^2$ [*ANSI Std. Z136.6-2000 (Table 5)*]

$$R_{LFZ} = \frac{1}{\left(1.06\times10^{-3}\right)}\sqrt{\frac{4\cdot\left(125\times10^{-3}\ J/_{cm^2}\right)}{\pi\cdot\left(12.5\times10^{-9}\ J/_{cm^2}\right)} - \left(0.5\ cm\right)^2}\quad cm$$

$$R_{LFZ} = 33.7\quad km$$

Table 3

Flight Hazard Distances For:
25 mJ @ 20 Hz- Doubled YAG Laser with 1.5 mR @ $1/e^2$

Flight Hazard Zones	**Flight Hazard Distances**
Normal Flight Zone	2.91 km
Sensitive Zone	0.753 km*
Critical Zone	3.37 km
Laser Free Zone	33.7 km

*Whenever the visual interference distance is less than the MPE Hazard Distance (*NOHD*) the MPE and the *NOHD* takes precedence [*ANSI Std. Z136.6-2000* (*Table 5 – Visual Interference Levels- note †)]*.

Computer Program

Rockwell Laser Institute provides a computer program (SKYZAN®) which can be used to determine these distances, but the results are in units of feet. This computer program is based on the *FAA Standard 7400.2D: Part 8, Miscellaneous Procedures, Chapter 34, Outdoor Laser Operations* and the *MPE* and *NHZ* outlined in the *ANSI Z136.1 (1993)* National Standard.

Note there were no differences in the *MPE* (for exposures greater than one nanosecond), listed in Table 5a, between the 1993 and 2000 National Standard for the visible-wavelength region; although there were *MPE* listed for sub-nanosecond exposures and there are some differences in the UV and IR regions.

Symbols and Abbreviations

A	Area (in cm^2).
A_{lim}	Area of the limiting aperture.
ANSI	American National Standard Institute.
C_A	Wavelength correction factor.
C_p	Multiple pulse correctionfactor.
CZ	Critical Zone
D, d	Diameter.
D_c	Diameter of the collecting optic.
D_e	Diameter of the exit pupil.
D_f	Diameter of the limiting aperture.
D_L	Diameter of the laser beam.
d_{lim}	Limiting aperture *ANSI Z136.1 Table 8*.
d_o	Exit diameter of the laser.
D_o	Diameter of the objective optic.
E	Irradiance (in watts/cm^2).
E_{eff}	Effective irradiance (in watts/cm^2).
EOHD	Extended optical hazard distance associated with aided viewing.
$EOHD_{NIR}$	Extended optical hazard distance associated with intrabeam aided viewing of near infrared wavelengths.
$EOHD_{VIS}$	Extended optical hazard distance associated with intrabeam aided viewing of visible wavelengths.
FHD	Flight Hazard Distance.
G	Optical gain.
G_{eff}	Effective optical gain.
G_{max}	Maximum optical gain.
H	Radiant Exposure (in J/cm^2).
H_{eff}	Effective Radiant Exposure (in J/cm^2).
HAZ	Ocular hazard (in J/cm^2 or w/cm^2).
$HAZ_{\uparrow}$	Increase in the ocular hazard (in J/cm^2 or w/cm^2).
Int	Integer.
LFZ	Laser Free Zone
min	Minimum value.

MPE	Maximum permissible exposure (J/cm^2 or w/cm^2).
$MPE_{appropriate}$	The appropriate maximum permissible exposure.
MPE_{rule1}	Maximum permissible exposure derived from ANSI Rule 1.
MPE_{rule2}	Maximum permissible exposure derived from ANSI Rule 2.
MPE_{rule3}	Maximum permissible exposure derived from ANSI Rule 3.
MPE_T	The maximum permissible exposure for the exposed duration T.
$MPE_{thermal}$	The MPE derived from the thermal limit.
n	Number of pulses.
NFZ	Normal Flight Zone.
NOHD	Nominal ocular hazard zone.
$NOHD_{atm}$	Nominal ocular hazard zone atmospheric transmission corrected.
P	Magnification power.
PRF	Pulse repetition frequency.
PRF_x	Crossover PRF
Q	Radiant energy (in joules).
Q_o	Output radiant energy.
R	Range, distance from the laser
R_c	Distance from the laser where the beam diameter is equaled to the collecting aperture.
SZ	Sensitive Zone
T	Time (in seconds).
t	Duration (in seconds).
t_{min}	The maximum exposure time for the MPE equaled to that of 1 ns.
t_p	Pulse duration (in seconds).
Φ	Radiant power (in watts).
τ	Transmission.
τ_{atm}	Atmospheric transmission factor.
τ_{λ}	Transmission as a function of wavelength.
ν_{λ}	Photopic Luminous Efficiency.
λ	Wavelength.

References

ANSI Std. Z136.1-2000: for Safe Use of Lasers, Published by the Laser Institute of America.

ANSI Std. Z136.6-2000: for Safe Use of Lasers Outdoors, Published by the Laser Institute of America.

FAA 7400.2D Chapter 34, Outdoor Laser/High Intensity Light Demonstrations

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