THE UNIVERSITY OF CHICAGO | Office of Research Safety

Laser Safety Calculations

Formulas for Calculating the MPE, NOHD, and NHZ

The Office of Radiation Safety (ORS), under the guidance of the Laser Safety Officer (LSO), administers the University of Chicago Laser Safety Program to ensure the safe and compliance use of lasers.

This document has been developed to provide an overview of how to perform the MPE, NOHD, and NHZ calculations for lasers and laser systems used at the University of Chicago to assist the user in laser hazard evaluations. Important definitions and a summary of the most common causes of laser accidents are added to provide the laser user more context. Additional information and resources are available through the Laser Safety Officer.

Important Definitions:

Maximum Permissible Exposure (MPE)

One of the most useful values in laser safety calculations is the Maximum Permissible Exposure (MPE). This is the irradiance or radiant exposure that may be incident upon the eye (or the skin) without causing an adverse biological affect. The MPE varies by wavelength and duration of exposure and is documented in tables published in ANSI z136.1 standard. We can think of this as your laser safety speed limit.

Nominal Ocular Hazard Distance (NOHD)

The Nominal Ocular Hazard Distance (NOHD), sometimes referred to as the Nominal Hazard Distance, is the distance along the axis of the emitted beam at which the irradiance is equal to the MPE. The NOHD is dependent on beam characteristics such as the power, diameter, and divergence. The NOHD is usually much greater than the largest dimension of your laboratory space.

The Nominal Hazard Zone (NHZ)

Another important definition for laser safety calculations is the Nominal Hazard Zone (NHZ). This is a distance within which exposure to a direct, reflected, or scattered beam is greater than the MPE. Mirrors, optics, and reflective materials in the beam path may result in diffuse or specular reflections in unintended directions. Specular reflections are hazardous over a greater range than diffuse reflections. If you are in the NHZ, you are at risk of an exposure above the MPE.

Optical Density (OD)

A measure of the attenuation of laser radiation through a material. The OD is a logarithmic relationship with a higher OD providing increased attenuation of the laser radiation. This value is primarily used in laser safety eyewear and viewing window specifications.

Accessible Exposure Limit (AEL)

The Accessible Emission Limit (AEL) is primarily used for the classification of lasers and defines the maximum total power of radiation that can be emitted from a laser of a particular class. The AEL is the product of the MPE and the Aperture of the eye at that wavelength.

Lasers may be found in all shapes and sizes capable of producing a vast range of wavelengths, power levels, and exposure times. By recognizing the situations where accidents involving lasers are most prevalent we are able to be proactive and design a safer work environment.

Most Common Causes of Documented Laser Accidents:

- Not wearing appropriate safety eyewear
- Not reducing power for alignments, or unintended power increases
- Stray beams left uncontained by beam stops of other barriers

Alignment procedures and laser safety eyewear non-compliance are two of the most frequent causes of ocular accidents involving lasers. The fundamental purpose of a laser safety program is to mitigate risks associated with laser systems. By increasing awareness of known hazards we are on the right track to keep everyone safe.

Safety Calculation Parameters:

Calculations allow us to assign quantitative values to laser safety parameters. As mentioned above, the MPE value varies by wavelength and time of exposure and while under some circumstances the MPE may be represented by a single value, in other cases, notably those of visible and near-infrared radiation during ordinary time-periods of exposure, the MPE is found via a calculation with numerous variables. Therefore, it is important to verify the MPE for each laser.

The human body has developed aversion responses to certain wavelengths such as turning or blinking in response to bright light or responding to the heating of tissues. Table 1 below provides us with approximate exposure times to use in MPE calculations.

Table 1. Maximum anticipated exposure durations for CW and Repetitive Pulse MPEs:

Wavelength Range	Diffuse Viewing (seconds)	Intrabeam Viewing (seconds)
UV: 180 nm – 400 nm	30,000 (8 hour work day / 24hr period)	100
Visible: 400 nm – 700 nm	600	0.25
Near IR: 700 nm – 1400 nm	600	10
Far IR: 1400 nm – 1000 µm	10	10

The times listed above are provided for unintentional viewing and are based upon natural reaction times and other limits such as the length of a typical work day. Any intentional exposure to laser radiation must receive prior authorization by the laser safety officer.

In addition to the proper exposure time, proper calculations will depend on the beam diameter. The most common profile of a laser beam is a Gaussian profile. The diameter of a Gaussian beam be specified according the $1/e$ or $1/e^2$ point. Laser manufacturers may often use the $1/e^2$ definition since this area encompasses 90% of the total beam energy. However, safety calculations use the $1/e$ diameter, so check which one you are using for consistency in your calculations.

The formulas used for laser safety calculations include numerous variables. Below is a table including some of the variables that you will see in laser safety calculations. For a more comprehensive list of laser safety variables and example calculations, please see the ANSI z136.1 Safe Use of Lasers Standard.

Table 2. Important Symbols and Conventions:

beam diameter: a (cm)	**beam divergence: f (radians)**
radiant energy: Q (J)	**radiant power: Φ (W)**
radiant exposure: H (J/cm2)	**Irradiance: E (W/cm2)**
Diameter of limiting aperture: D_f (cm)	

Table 3. Limiting Aperture by wavelength and exposure time:

Spectral Region	Period of Exposure (s)	Aperture Diameter (mm)
180 to 400 nm	10^{-9} to 0.3	1.0
	10 to 3×10^{4}	3.5
400 to 1200 mm	10^{-13} to 3×10^{4}	7.0
1400 nm to 100 μm	10^{-13} to 0.3	1.0
	10 to 3×10^{4}	3.5
100 to 1000 μm	10^{-9} to 3×10^{4}	11.0

Table 3 provides some of the more common viewing conditions and is an excerpt from Table 8a in ANSI z136.1.

Laser Safety Evaluations

Laser safety programs utilize a combination of hazard evaluation and risk assessments to create workspaces that are as safe as reasonably achievable. Simple actions such as using a lower class laser for alignments when possible eliminates unnecessary risk. Taking time to identify laser safety hazards, and complete laser safety calculations makes the laboratory safer for everybody.

The University of Chicago Laser Safety Officer evaluates each Class 3b and Class 4 laser system on campus. The laser users are ultimately responsible for the everyday safe use of these devices and by becoming more familiar with safety requirements and the characteristics of the lasers they work with, researchers will be better equipped to keep everybody in the area safe.

The following sections will provide the formulas necessary to complete a basic laser safety evaluation along with some examples of the calculations.

Laser Safety Formulas

Relationship between beam diameters given in 1/e and 1/e2:

$$a\left(\frac{1}{e^2}\right) = \sqrt{2a(\frac{1}{e})}$$

Relationship between beam radiant power and irradiance:

$$E = \frac{\Phi}{\pi\left(\frac{D_f}{2}\right)^2}$$

Maximum Permissible Exposure (MPE)

The MPE of a laser depends on the characteristics of the laser and the time of exposure. Tables 5a – 5f in ANSI z136.1 provide the comprehensive list of formulas for calculating the MPEs for the different possible exposures.

Continuous Wave Laser:

Determination of the MPE for incidental direct viewing of a visible laser:

$$MPE(H): 1.8t^{0.75}\ \frac{mJ}{cm^2}$$

Where: $E = \frac{H}{t}$

And: $MPE\ (E): \frac{MPE(H)}{t}$

For an incidental exposure to a visible laser, we are able to reference Table 1 to determine the exposure time of 0.25 seconds.

$$MPE(H): 1.8(0.25)^{0.75}\ \frac{mJ}{cm^2} = \ 0.636\ \frac{mJ}{cm^2}$$

$$MPE\ (E): \frac{0.636\ \frac{mJ}{cm^2}}{0.25\ s} = 2.55\ \frac{mW}{cm^2}$$

Repetitively Pulsed Lasers:

A repetitively pulsed laser provides unique challenges in designating the appropriate MPE. The MPE shall be calculated to access the hazard from the single pulse (Rule 1), the average power (Rule 2), and the thermal hazards from multiple pulses (Rule 3). As of ANSI Z136.1 – 2014, Rule 3 only applies in specific circumstances such as extended sources and is not widely applicable.

Determination of the MPE for a repetitive pulsed laser:

Determine the MPE for a Dye laser rated at 220μJ per pulse with emissions of 500 nm at 10Hz and a pulse duration of 800 ps.

Rule 1:

Rule 1 determines the MPE based on a single pulse of laser radiation. Using Table 5b of ANSI z136.1 we find the MPE to be a constant value:

$$\mathbf{MPE_{Single\ Pulse}: 2E - 7\ \frac{J}{cm^2}}$$

$$\mathbf{MPE: E = MPE_{Single\ Pulse} * F = 2E - 7\ \frac{J}{cm^2} * 10\ Hz = 2E - 6\ \frac{W}{cm^2}}$$

Rule 2:

Rule 2 determines the MPE based on the average power of the pulsed laser. For the 500nm wavelength, the aversion response limits exposure time to 0.25 seconds. In this time the eye may be exposed to 3 pulsed from this laser.

$$\boldsymbol{MPE_{Avg\ Power}: 1.8 * t^{0.75} * 10E - 3\ \frac{J}{cm^2}}$$

$$\boldsymbol{MPE_{Avg\ Power}: 1.8 * 0.25^{0.75} * 10E - 3\ \frac{J}{cm^2} = \frac{6.36E - 4\ \frac{J}{cm^2}}{3\ pulses} = 2.14\ E - 4\ \frac{J}{cm^2}}$$

Rule 3:

Rule three does not apply in this scenario.

Comparing the MPE values calculated from Rules 1 and 2, Rule 1 is more restrictive therefore the appropriate MPE for this laser is 2E-7 J/cm^2 or 2E-6 W/cm^2.

Nominal Ocular Hazard Distance

The properties of a laser, such as the directionality and coherence, typically contribute to the NOHD being a rather great distance. The NOHD is calculated using different formulas depending on the use of the laser.

NOHD of an unaltered beam:

$$NOHD: \frac{1}{\phi}\left[\left(\frac{4\Phi}{\pi MPE}\right) - a^2\right]^{\frac{1}{2}}$$

NOHD for a lens on laser:

$$NOHD: \frac{f_o}{b_o}\left(\frac{4\Phi}{\pi MPE}\right)^{\frac{1}{2}}$$

NOHD for a fiber laser:

$$NOHD: \frac{1.7}{NA}\left(\frac{\Phi}{\pi MPE}\right)^{\frac{1}{2}}$$ **Multi-mode fibers**

$$NOHD: \frac{\omega_o}{\lambda}\left(\frac{\pi\Phi}{2MPE}\right)^{\frac{1}{2}}$$ **Single-mode fibers**

Where:

ϕ – emergent beam divergence (measured at 1/e peak of irradiance points
NA – numerical aperture of the fiber
b_o – diameter of beam incident on a focusing lens
f_o – focal length of a lens
ω_o – spot size of a single mode fiber

Determination of NOHD for a laser with no lens or fibers:

Given a 250 mW visible CW laser with a divergence of 1 mrad, determine where along the axis of the beam is the irradiance equal to the MPE.

An acceptable shorthand NOHD equation may be used in the absence of optics and fibers:

$$NOHD: \frac{1}{\phi}\left(\frac{1.27\Phi}{MPE}\right)^{\frac{1}{2}}$$

$$NOHD: \frac{1}{0.001\,rad}\left(\frac{1.27 * 250\text{ mW}}{2.55\frac{\text{mW}}{\text{cm}^2}}\right)^{\frac{1}{2}} = 1000 * (124.51\,cm^2)^{\frac{1}{2}}$$

$$= 1000 * 11.158cm = 111.58\,m$$

Nominal Hazard Zone

The NOHD is the dominant value for determining the radial extend of the NHZ if the bean be reasonably expected to be incidentally directed towards people. The NHZ surrounding an optical set-up may be calculated using the following formulas:

$$r_{NHZ}: \left(\frac{\rho_\lambda \Phi \cos\theta}{\pi MPE}\right)^{\frac{1}{2}} \qquad \text{Diffuse reflection}$$

$$r_{NHZ}: \frac{1}{\phi}\left(\frac{1.27\,\rho_\lambda \Phi}{MPE}\right)^{\frac{1}{2}} \qquad \text{Specular reflection}$$

Where:

ρ$_\lambda$ - the spectral reflectance of a diffuse or specular object at wavelength λ

Note how the NHZ for a specular reflection is nearly identical to the NOHD formula with the additional variable p$_\lambda$. For conservative calculation, you may use the NOHD formula for a specular reflection.

Determination of NHZ from the reflection of a laser:

Given a 250 mW visible CW laser with a divergence of 1mrad and an incident surface spectral reflectance of 0.2, determine the range that a reflected beam is equal to the MPE.

$$diffuse - r_{NHZ}: \left(\frac{0.2 * 250\ \mathrm{mW} * 1.0}{\pi * 2.55\,\frac{\mathrm{mW}}{\mathrm{cm^2}}}\right)^{\frac{1}{2}} = 2.5\ cm$$

$$specular - r_{NHZ}: \frac{1}{0.001}\left(\frac{1.27 * 0.2 * 250\ \mathrm{mW}}{2.55\,\frac{\mathrm{mW}}{\mathrm{cm^2}}}\right)^{\frac{1}{2}} = 50\ m$$

When specific reflective properties of incident surfaces is not provided, conservative estimates can be found by using a viewing angle of 0° and a reflectance ρ$_\lambda$ of 100%.

Diffuse reflections from matte surfaces can be hazardous from high powered lasers and the degree of hazard depends on the irradiance (or radiant exposure) at the viewer's location. To calculate the irradiance for a diffuse reflection:

$$E: \frac{\rho_\lambda * \Phi * \cos\Theta_v}{\pi * \mathrm{r}^2}$$

Where:

r - is the distance from the laser target to the viewer (cm)
cos θ$_v$ - is the viewing angle from the normal to a reflecting surface
The equation for irradiance is the same as for radiant exposure.

Optical Density (OD) Calculations

When full containment of a Class 3b or Class 4 beam path is not possible, an ocular hazard may be present and laser safety eyewear may be required. Laser Safety Eyewear utilizes specially formulated lenses to attenuate laser radiation to different degrees for different wavelengths. The properties of the lenses are such that protection from laser radiation is offered to only the specific wavelengths indicated on the eyewear. The Optical Density (OD) and corresponding wavelengths or range of wavelengths, must be permanently etched into the lenses or frames of the eyewear.

To calculate the Optical Density required for your laser system you will need the have calculated the MPE, as well as the irradiance *E* or radiant exposure *H*.

$$OD_\lambda = \log\frac{E}{MPE} \text{ or } OD_\lambda = \log\frac{H}{MPE}$$

The OD is unit-less and rounded up from 0.05 to the next whole integral. Laser safety eyewear with a higher OD than required are acceptable however, it is important to recognize the Visible Light Transmission (VLT) of the eyewear to ensure adequate vision of the workspace while wearing the eyewear. A VLT of at least 20% is recommended. In instances of multiple wavelengths, one pair of eyewear may not be available to provide adequate safety and enclosing the beam path may be required.

The State of Illinois requires that eyewear be inspected at least every six-months. The Laser Safety Officer will approve the laser safety eyewear used for each application and can make recommendations to ensure the appropriate safety glasses are procured for each laser.

Determination of minimum required OD:

Given a 250 mW laser at a wavelength of 500 nm, determine the minimum OD required.

$$OD_\lambda = \log\frac{E}{MPE} = \log\frac{E}{2.55\,\frac{\mathrm{mW}}{\mathrm{cm}^2}}$$

$$E = \frac{250\,mW}{\pi\,(0.35\,cm)^2} = 650\,\frac{mW}{cm^2}$$

$$OD_\lambda = \log\frac{650\,\frac{\mathrm{mW}}{\mathrm{cm}^2}}{2.55\,\frac{\mathrm{mW}}{\mathrm{cm}^2}} = 2.4$$

This laser would require laser safety eyewear marked for an OD of **3** covering the wavelength of 500nm.

If you have additional safety questions, please contact: lasersafety@lists.uchicago.edu