ENVIRONMENTAL HEALTH AND SAFETY
University of Nebraska-Lincoln

Safe Operating Procedure

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LASER SAFETY CALCULATION GUIDE

This document has been developed to provide an overview of how to perform the MPE, NOHD, and NHZ calculations that are used in laser hazard evaluations of lasers and laser systems used at the University of Nebraska-Lincoln. This document is a supplement to the EHS web-based Laser Safety Training and the Class 3B and Class 4 Research Lasers and Laser Safety Control Measures Safe Operating Procedures (SOPs).

Definitions and Roles

Understanding what these terms are and how these calculations fit into the broader risk assessment process enables Authorized Users and laser operators to effectively manage laser hazards, protect personnel, and maintain compliance with safety standards and regulations.

Maximum Permissible Exposure (MPE)

The MPE is the level of laser radiation to which an unprotected person may be exposed without adverse biological changes in the eye or skin. The MPE varies by wavelength and duration of exposure and is calculated using the different tables published in ANSI Z136.1-2022 standard.

Context and Use:

- Eye Exposure: The calculations are often focused on eye exposure because the eye is usually the most sensitive to laser radiation. The MPE for the eye is typically more conservative than for the skin.
- Skin Exposure: Although the skin is less sensitive than the eye, it is still essential to consider the MPE for skin exposure to prevent burns or other damage. The MPE for skin exposure is used to ensure that safety measures account for potential risks to skin tissue.

Defining Laser Controlled Area (LCA), Nominal Ocular Hazard Distance (NOHD), and the Nominal Hazard Zone (NHZ)

The MPE helps define the safety zones of a Laser Controlled Area (LCA), Nominal Ocular Hazard Distance (NOHD), and the Nominal Hazard Zone (NHZ).

- The LCA is a laser use area where the occupancy and activity of those within is controlled and supervised. That area may be defined by walls, barriers, or other means. Potentially hazardous beam exposure is possible within the LCA.
- The NOHD is the distance along the axis of the unobstructed beam from a laser, fiber end, or connector to the human eye beyond which the irradiance or radiant exposure does not exceed the applicable MPE.
- The NHZ is the space within which the level of the direct, reflected, or scattered radiation during normal operation exceeds the MPE. Exposure levels beyond the boundary of the NHZ are below the applicable MPE.

Context and Use:

- NHZ Definition: NOHD helps determine the boundary of the NHZ, where laser radiation levels could pose a hazard to the eyes.
- Safety Zones: NOHD calculation helps in establishing safety zones of the LCA and NHZ where control measures are needed to prevent accidental exposure.
- Protection Planning: NOHD calculations ensure that protective measures, such as barriers, eyewear, and signage are implemented effectively to mitigate risks within the NHZ.

Selection of Appropriate Eyewear

Laser safety eyewear is selected based on the wavelength and the optical density (OD) required to reduce the laser exposure to below the MPE. The OD is the logarithm of the base ten of the reciprocal of the transmittance of light at a particular wavelength through a material.

Context and Use:

- Logarithmic Relationship: OD values increase logarithmically, meaning that a higher OD corresponds to greater attenuation of laser radiation.
- Attenuation of Laser Radiation: Higher OD values indicate that eyewear is more effective at blocking or reducing the intensity of laser light at specific wavelengths.
- Selection Criteria: Eyewear is selected based on the laser's wavelength to ensure that the OD of the lenses matches or exceeds the required level to reduce exposure below the MPE.
- Protective Measures: By ensuring the eyewear can reduce the laser exposure to safe levels, workers can be protected from accidental eye exposure.
- Compliance with Standards**:** The selection process ensures compliance with safety standards and regulations found in ANSI Z136 and NFPA 115.

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's 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 workday / 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

Table 1 provides the maximum expected exposure durations ($\mathbf{T_{max}}$) for unintentional viewing as documented on Table 3 in ANSI Z136.1-2022. 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 workday.

In addition to the exposure times provided in Table 1, 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 must be specified according to the 1/e or $1/e^2$ point. Laser manufacturers 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.

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/cm^2)	Irradiance	*E* (W/cm^2)
Diameter of Limiting Aperture	D_f *(cm)*	Pi (π)	*3.14*

Table 3. Limiting Aperture by wavelength and exposure time:

Spectral Region	Period of Exposure (seconds)	Aperture Diameter (mm)		
		Retina	Cornea	Skin
180 to 400 nm	10^{-13} to 0.3		1.0	3.5
	10 to 30,000		3.5	3.5
400 to 1200 nm	10^{-13} to 30,000	7.0	-	3.5
1200 to 1400 nm	10^{-13} to 0.3	7.0	1.0	3.5
	10 to 30,000	7.0	3.5	3.5
1400 nm to 100 µm	10^{-13} to 0.3		1.0	3.5
	10 to 30,000		3.5	3.5
100 to 1000 µm	10^{-13} to 30,000		11.0	11.0

Table 3 provides some of the more common viewing conditions and is an excerpt from Table 10a in ANSI Z136.1-2022.

Laser Safety Evaluations

A combination of hazard evaluations and risk assessments are used 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 Nebraska-Lincoln Laser Safety Officer evaluates each Class 3B and Class 4 laser system on campus, however, laser users are ultimately responsible for everyday safe use of these devices. 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 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:

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

Relationship between beam radiant power and irradiance:

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

Maximum Permissible Exposure (MPE) Calculations

The MPE of a laser depends on the characteristics of the laser and the duration of exposure. Tables 7a – 7f in ANSI Z136.1-2022 provide a comprehensive list of formulas for calculating the MPEs for 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 ruby laser (693 nm), we can reference Table 1 to determine the MPE of an anticipated exposure duration 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:

Step 1: Determine the MPE for a single pulse first. We can use dye laser rated at 220µJ per pulse with emissions of 500 nm at 10Hz and a pulse duration of 800 psec.

Using Table 7b of ANSI Z136.1-2022, we find the MPE to be a constant value for 500 nm at $8E^{-10}$ seconds:

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

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

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

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

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

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

These values of MPE can be used for calculating the NOHD, NHZ, and OD. We will use the MPE for a 250 mW visible continuous wave ruby laser in the calculations below.

Nominal Ocular Hazard Distance (NOHD) Calculations

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:

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

$$NOHD: \frac{\omega_0}{\lambda}\left(\frac{\pi\Phi}{2MPE}\right)^{\frac{1}{2}} \quad \text{Single-mode fibers}$$

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:

For a 250mW visible CW laser with a divergence of 1 mrad, we 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 extent of the NHZ if the bean can be reasonably expected to be incidentally directed towards people. The NHZ surrounding an optical set-up may be calculated using the following formulas:

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

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

Where:

ρ_λ - 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_λ. For conservative calculation, you may use the NOHD formula for a specular reflection.

Determination of NHZ from the reflection of a laser:

For a 250 mW visible CW ruby laser with a divergence of 1 mrad and an incident surface spectral reflectance of 0.2, we need to 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 are not provided, conservative estimates can be found by using a viewing angle of 0° and a reflectance ρ_λ 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:

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

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

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.

To calculate the Optical Density required for a laser system, you will need to calculate the MPE and the irradiance E or radiant exposure H as outlined above.

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

The OD is unit-less and rounded up from 0.05 to the next whole integral. 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 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:

For a 250 mW CW visible ruby laser operating at a wavelength of 693 nm, we determine the minimum OD required as follows:

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

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

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

This laser would require laser safety eyewear marked for an OD of 3 covering the wavelength of 693 nm.