Definitions

Accessible Emission Limit (AEL)
- The maximum total power of radiation that can be emitted from a laser of a particular class.

Maximum Permissible Exposure (MPE)
- The minimum irradiance or radiant exposure that may be incident upon the eye (or skin) without causing biological damage.
- The MPE is related to the AEL by the limiting aperture of the eye (function of wavelength and exposure time)

Nominal Hazard Zone (NHZ)
- The distance within which the irradiance of a beam is greater than the MPE.
  - Is specific to the wavelength and exposure time
- NHZ is different for the 3 possible paths to the eye:
  - Direct Viewing
  - Specular Reflectance
  - Diffuse Reflectance

Method for Evaluating Laser Safety

1. Calculate the maximum irradiance that an unprotected eye might experience while the system is operating in a particular manner.
   - Optical alignment
   - Changing optics
2. Check if #1 is less than the MPE.
3. Calculate the NHZ for each of the operating scenarios
4. For each NHZ, calculate the OD for laser safety goggles needed to reduce the irradiance at the eye to be below the MPE.

Approximations for Determining Exposure Time to the Eye

1. Limiting time of inadvertent exposure to visible radiation
   - 250 msec (blink reflex)
2. Limiting time of inadvertent exposure to UV or NIR radiation
   - 10 sec (natural eye motion)
3. Limiting time of exposure for intentional viewing
   - 100 sec (during laser alignment)
4. Limiting time of long-term exposure
   - 28,800 sec or 8 hours

Measurement Values and Units

a :	Beam Diameter	(cm)
f :	Beam Divergence	(radians)
Q :	Radiant Energy	(Joules)
Φ :	Radiant Power	(Watts)
H :	Radiant Exposure	(J/cm^2)
E :	Irradiance	(W/cm^2)

H and E: MPE reported in these units

Beam Diameter

Gaussian

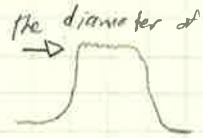
$1/e^2$: Contains ≈ 90% of beam's energy

$1/e$: More common among laser manufacturers

$$a(1/e^2) = \sqrt{2}\, a(1/e)$$

Non-Gaussian (Top Hat)

Radiant exposure is equal for all points in the diameter of beam



$$E_0 = \frac{4\Phi}{\pi a^2} \quad \text{(Irradiance at laser's exit port)}$$

$$H_0 = \frac{E_0}{\text{exposure time (sec)}}$$

Beam Diameter (continued)

Gaussian beams, Central irradiance ≠ average irradiance

Recall, MPE is determined by averaging the incident power of the beam over an area defined by the limiting aperture of the eye.

Visible Light,
Diameter of a fully dialated pupil is 7mm

Non-Visible Radiation,

Wavelength Range	Exposure Time	Aperture Diameter
180nm to 400nm	1nsec to 250 msec	1.0 mm
180 nm to 400 nm	250 msec to 28,800 sec	3.5 mm
400nm to 1400 nm	1 nsec to 28,800 sec	7.0 mm
1400 nm to 100 μm	1 nsec to 250 msec	1.0 mm
1400 nm to 100 μm	250 msec to 28,800 sec	3.5 mm
100 μm to 1000 μm	1 nsec to 28,800 sec	11.0 mm

If the diameter of your Gaussian beam is similar to the limiting aperture for your wavelength, the irradiance can be calculated using a Top-Hat approximation:

$$E_0 = \frac{4\Phi}{\pi[\max(a, D_f)]^2}$$

where,

Φ is the total radiant power of the beam

a is the beam diameter (1/e points)

D_f is the limiting aperture at the appropriate wavelength

Beam diam = 0.8 mm

$\frac{1}{e^2} \simeq 1.2\,mm$ Gaussian

$\lambda = 631\ nm$

Table 5a

MPE for an exposure time between 18 μsec and 10 seconds

$1.8\,t^{3/4} \times 10^{-3}\ J/cm^2$

for an exposure time between 10 seconds and 30,000 seconds

$1 \times 10^{-3}\ W/cm^2$

Aperture diameter for eye = 7mm → Area = $0.385\ cm^2$

Direct exposure, accidental

$\underline{H} = 1.8(0.25s)^{0.75} \times 10^{-3} = \underline{0.636\ mJ/cm^2}$

$\underline{E} = \frac{0.636\ J/cm^2}{0.25\ sec} = \underline{2.55\ mW/cm^2}$

∴ The maximum flux of a visible laser to avoid harm due to accidental, direct exposure is

$2.55\ mW/cm^2 \times 0.385\ cm^2 = 1.0\,mW$

AEL is 2W @ ~~634~~ 639 nm ∴ is a class 4 las

CW $2.55 \ mW/cm^2$

Pulsed $6.7 \ \mu W/cm^2$

CW $\dfrac{5.2 \ W/cm^2}{2.55 \ mW/cm^2} = 2039$

$\log_{10}(2039) = 3.3$

round up to $OD = 4$

$2.55 \ mW/cm^2$

$6.7 \ \mu W/cm^2$

$$\frac{5.2 \ W/cm^2}{2.55 \ mW/cm^2} = 2039$$

$\log_{10}(2039) = 3.3$

round up to $OD = 4$

Diffuse Reflections

$$H = \frac{P_\lambda \cos \Phi_v \, Q}{\pi r^2}$$

Q : Energy of incident beam
r : Distance from reflection

Worst case is $P_\lambda = 1$ and $P\cos\Phi = 1$

Katari's laser, $Q = 2W$

$$r = \sqrt{\frac{P_\lambda \cos \Phi_v \, Q}{\pi H}}$$

Solve for safe distance of $MPE = 0.636 \ mJ/cm^2$

$$r = \sqrt{\frac{1 \times 2 \ J/s \times 0.25 s}{\pi \times 0.636 \ mJ/cm^2}} = \sqrt{\frac{0.5}{2 \times 10^{-3}}} = 15.8 \text{ cm}$$

Must be at least 16 cm, or 6.3 inches away

$$E_0 = \frac{4\Phi}{\pi [0.7 \text{ cm}]^2} = \frac{4(2W)}{\pi \ 0.490 cm^2} = 5.2 \ W/cm^2 = \text{Maximum Irradiance}$$

Maximum MPE $\rightarrow$ $\frac{5.2 \ W/cm^2}{2.55 \ mW/cm^2} = 2039$

$\log_{10}(2039) = 3.3$ round up to $\boxed{OD \ 4 \ @ \ 639 \text{ nm}}$