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Appendix A
Maximum Permissible Exposure (MPE) for the Eye

Table A1. Point Source MPEs for the Eye for Commonly Used Lasers

Laser Type	Wavelength (nm)	MPE ($W \cdot cm^{-2}$)			
		* t=0.25 s	t=10 s	t=600 s	$t=3 \times 10^4$ s
XeCl [a]	308	—	—	—	1.33×10^{-6}
XeF [a]	351	—	—	—	3.33×10^{-5}
Argon	514	2.6×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
Krypton	530	2.6×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
	568	2.6×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
	647	2.6×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
HeNe	633	2.6×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
InGaAlP (diode)	670	2.6×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
GaAs (diode)	808	—	1.6×10^{-3}	—	1.6×10^{-3}
GaAs (diode)	840	—	1.9×10^{-3}	—	1.9×10^{-3}
InGaAs (diode)	940	—	3.0×10^{-3}	—	3.0×10^{-3}
	980	—	3.6×10^{-3}	—	3.6×10^{-3}
Yb:YAG Q-switched [b]	1030	—	1.0×10^{-5}	—	1.0×10^{-5}
Nd:YAG Q-switched [b]	1064	—	2.2×10^{-5}	—	2.2×10^{-5}
Yb: Fiber Q-switched [b]	1070	—	2.2×10^{-5}	—	2.2×10^{-5}
Yb:YAG (CW)	1030	—	4.6×10^{-3}	—	4.6×10^{-3}
Nd:YAG (CW)	1064	—	5.0×10^{-3}	—	5.0×10^{-3}
Yb: Fiber (CW)	1070	—	5.0×10^{-3}	—	5.0×10^{-3}
CO_2	10,600	—	0.1	—	0.1
NOTE—This table provides summary point source maximum permissible exposure values for a select group of lasers and key exposure durations. Reference ANSI Z136.1 for comprehensive information.					

* t is the exposure duration in seconds (s)

[a] When repeated exposure levels are anticipated over two successive days the MPE must be reduced by a factor of 2.5

[b] Operating in repetitive pulsed mode at 11 Hz, 12-ns pulse, 20 mJ/pulse

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Table A2. MPE for the Eye for Selected Single Pulse Lasers

Laser Type	Wavelength (nm)	Pulse Duration (s)	MPE ($J\ cm^{-2}$)
Excimer (ArF)	193	2×10^{-8}	3.0×10^{-3}
Excimer (XeCl)	308	2×10^{-8}	6.7×10^{-3}
Ruby	694	1×10^{-3}	1.0×10^{-5}
Yb:YAG (pulsed)	1030	1×10^{-3}	4.6×10^{-5}
Nd:YAG (pulsed)	1064	1×10^{-3}	5.1×10^{-5}
Yb:Fiber (pulsed)	1070	1×10^{-3}	5.1×10^{-5}
Yb:YAG (Q-switched)	1030	$5\text{-}100 \times 10^{-9}$	9.1×10^{-7}
Nd:YAG (Q-Switched)	1064	$5\text{-}100 \times 10^{-9}$	2.0×10^{-6}
Yb:Fiber (Q-switched)	1070	$5\text{-}100 \times 10^{-9}$	2.0×10^{-6}
Carbon Dioxide (CO_2)	10,600	1×10^{-3}	0.1

NOTE—Table A2 is provided as a reference of MPEs for a selected set of single pulse lasers for the noted wavelengths and duration levels.

Table A3. Typical Laser Hazard Classification, Continuous Wave (CW) Lasers

Laser Type	Wavelength (nm)	Power Range (W)	Maximum Hazard Class
Helium-Cadmium (HeCd)	325	1.6×10^{-5} to 0.5	Class 3B
Argon (Ar)	351, 363	1.6×10^{-5} to 0.5	Class 3B
Argon (Ar)	488, 514	≤0.001	Class 2
Helium-Neon (HeNe)	633	≤0.001	Class 2
InGaAlP (diode)	670	≤0.001	Class 2
Argon (Ar)	488, 514	0.001 to 0.005	Class 3R
Helium-Neon (HeNe)	633	0.001 to 0.005	Class 3R
InGaAlP (diode)	670	0.001 to 0.005	Class 3R
Argon (Ar)	488, 514	> 0.5	Class 4
InGaAlP (diode)	670	> 0.5	Class 4
Dye	400 to 550	> 0.5	Class 4
InGaAs (diode)	940, 980	> 0.5	Class 4
GaAlAs (diode)	780	0.0028 to 0.5	Class 3B
Yb:YAG	1030	0.0088 to 0.5	Class 3B
Nd:YAG	1064	0.0096 to 0.5	Class 3B
Yb:Fiber	1070	0.0096 to 0.5	Class 3B
InGaAsP (diode)	1310	0.148 to 0.5	Class 3B
Doubled Yb:YAG	515	> 0.5	Class 4
Doubled Nd:YAG	532	> 0.5	Class 4
Doubled Yb:Fiber	535	> 0.5	Class 4
Yb:YAG	1030	> 0.5	Class 4
Nd:YAG	1064	> 0.5	Class 4
Yb:Fiber	1070	> 0.5	Class 4
Carbon dioxide (CO_2)	10,600	> 0.5	Class 4

NOTE—Table A3 provides a quick reference for some of the various lasing mediums, lasers and laser systems that may find use in educational institutions. For a respective lasing medium and wavelength, its corresponding hazard classification is provided for an output emission level, based upon an eight-hour exposure duration (most restrictive). Those wavelengths below 400 nm do not include the reduction factor for two successive exposure eight-hour shifts within a 24-hour period per Z136.1-2014, Section 8.

This table is not to serve for reclassification purposes. It is only for summary guidance as to the applicable hazard class associated with a laser and its output characteristics. The appropriate documentation and assessment for the subject laser or laser system shall prevail. Reference ANSI Z136.1 (latest revision) for comprehensive information pertaining to laser hazard classification

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A4. Bibliography.

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Mathes, R., Feychting, M., Ahlborn, A., Breitbart, E., Croft, R., Green, A., de Grujil, F.R., Hietanen, M., Jokela, K., Lin, J.C., Marino, C., Peralta, AP., Saunders, R., Schulmeister, K., Sienkiewicz, Z., Söderberg, P., Stuck, B.E., Swerdlow, A.J., Taki, M., van Rongen, E.,…Zuchlich, J.A. (2013). ICNIRP guidelines on limits of exposure to laser radiation of wavelengths between 180 nm and 1,000 µm. *Health Physics Society*, 105(3): 271-295. https://doi.org/10.1097/HP.0b013e3182983fd4

Appendix B
Control Measures for Laser Classes

Table B1. Engineering Controls

Engineering Control Measures	Classification						
	1	**1M**	**2**	**2M**	**3R**	**3B**	**4**
Protective Housing (4.5.1, 4.5.1.2)	X	X	X	X	X	X	X
Without Protective Housing (4.5.1.1)	LSO shall establish Alternative Controls						
Interlocks on Removable Protective Housings (4.5.2)	∇	∇	∇	∇	∇	X	X
Service Access Panel (4.5.3)	∇	∇	∇	∇	∇	X	X
Key Control (4.5.4)	—	—	—	—	—	•	X
Viewing Windows and Display Screens (4.5.5.1)	Assure viewing limited < MPE						
Collecting Optics (4.5.5.2)							
Fully Open Beam Path (4.5.6.1)	—	—	—	—	—	X NHZ	X NHZ
Limited Open Beam Path (4.5.6.2)	—	—	—	—	—	X NHZ	X NHZ
Enclosed Beam Path (4.5.6.3)	None is required if 4.3.1 and 4.3.2 fulfilled						
Remote Interlock Connector (4.5.7)	—	—	—	—	—	•	X
Beam Stop or Attenuator (4.5.8)	—	—	—	—	—	•	X

Legend:	X	Shall	∇	Shall, if enclosed Class 3B or 4
	•	Should	MPE	Shall, if MPE is exceeded
	—	No requirement	NHZ	Nominal Hazard Zone analysis required
			*	May apply with use of optical aids

(Table B1 Continued on Next Page)

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Table B1. Engineering Controls (cont.)

Engineering Control Measures	Classification						
	1	1M	2	2M	3R	3B	4
Activation Warning Systems (4.5.9)	—	—	—	—	—	•	X
Indoor Laser-Controlled Area (4.5.10)	—	*	—	*	—	X NHZ	X NHZ
Class 3B Indoor Laser-Controlled Area (4.5.10.1)	—	—	—	—	—	X	—
Class 4 Laser-Controlled Area (4.5.10.1, 4.5.10.2)	—	—	—	—	—	—	X
Outdoor Control Measures (4.5.11)	X	* NHZ	X NHZ	* NHZ	X NHZ	X NHZ	X NHZ
Laser in Navigable Airspace (4.5.11.1)	X	* NHZ	X NHZ	* NHZ	X NHZ	X NHZ	X NHZ
Temporary Laser-Controlled Area (4.5.12)	∇ MPE	∇ MPE	∇ MPE	∇ MPE	∇ MPE	—	—
Remote Firing and Monitoring (4.5.13)	—	—	—	—	—	—	•
Equipment Labels (4.5.14)	X	X	X	X	X	X	X
Laser Area Warning Signs and Activation Warnings (4.5.15)	—	—	—	—	•	X NHZ	X NHZ

Legend:				
	X	Shall	∇	Shall, if enclosed Class 3B or 4
	•	Should	MPE	Shall, if MPE is exceeded
	—	No requirement	NHZ	Nominal Hazard Zone analysis required
			*	May apply with use of optical aids

Table B2. Administrative and Procedural Controls

Administrative and Procedural Control Measures	**Classification**						
	1	**1M**	**2**	**2M**	**3R**	**3B**	**4**
Standard Operating Procedures 4.6.1)	—	—	—	—	—	•	X
Output Emission Limitations (4.6.2)	—	—	—	—	LSO Determination		
Education and Training (4.6.3)	—	•	•	•	•	X	X
Authorized Personnel (4.6.4)	—	*	—	*	—	X	X
Alignment Procedures (4.6.5)	∇	∇	∇	∇	∇	X	X
Protective Equipment (4.6.6)	—	*	—	*	—	•	X
Spectators (4.6.7)	—	*	—	*	—	•	X
Service Personnel (4.6.8)	∇	∇	∇	∇	∇	X	X
Laser Optical Fiber Transmission Systems	MPE	MPE	MPE	MPE	MPE	X	X
Laser Robotic Installations (4.5.16)	—	—	—	—	—	X NHZ	X NHZ
Protective Eyewear (4.6.6.2)	—	—	—	—	—	•	X
Window Protection (4.6.6.3)	—	—	—	—	—	X NHZ	X NHZ
Protective Barriers and Curtains (4.6.6.1)	—	—	—	—	—	•	•
Skin Protection (4.6.6.5)	—	—	—	—	—	X MPE	X MPE
Other Protective Equipment (4.6.9)	Use may be required						
Warning Signs and Labels (Design Requirements) (4.5.14, 4.5.15)	—	—	•	•	•	X NHZ	X NHZ
Service Personnel (4.6.8)	LSO Determination						
Laser System Modifications (4.1.3)							

Legend:				
	X	Shall	∇	Shall, if enclosed Class 3B or 4
	•	Should	MPE	Shall, if MPE is exceeded
	—	No requirement	NHZ	Nominal Hazard Zone analysis required
			*	May apply with use of optical aids

B3. Bibliography.

Laser Institute of America. (2014). *American national standard for safe use of lasers* (ANSI Z136.1-2014).

Appendix C
Laser Beam Hazard Terms and Assessment for Selected Lasers

C1. General

The following is provided as summary information for laser hazard assessment and key terms of use. Reference ANSI Z136.1 (latest revision) for more comprehensive information.

Many examples available will illustrate the eye as the part of the human body exposed, as this is generally the most sensitive organ at risk. Hazard analysis must account for eye and skin exposure conditions, and then apply the most restrictive evaluation for establishing the hazard areas and respective safety control measures.

C2. Laser Beam Profile and Dimensions

Beam profiles are referenced against an idealized Gaussian beam. For laser safety calculations, the beam diameter and beam divergence values are measured at the 1/e points of the beam intensity profile. This is the radial position at which the beam intensity has dropped to 1/e (~37%) of its peak value.

Using this for the beam diameter will then provide the peak intensity values when using beam power or energy in the respective equations:

$$\text{Irradiance} = \text{Power intensity} = \frac{\text{Power}}{\text{Area}} = \frac{\text{Power}}{\pi\left(r_{(1/e)}\right)^2} = \frac{4 \cdot \text{Power}}{\pi\left(d_{(1/e)}\right)^2} \tag{C1}$$

$$\text{Radiant exposure} = \text{Energy intensity} = \frac{\text{Energy}}{\text{Area}} = \frac{\text{Energy}}{\pi\left(r_{(1/e)}\right)^2} = \frac{4 \cdot \text{Energy}}{\pi\left(d_{(1/e)}\right)^2} \tag{C2}$$

Where,

$r_{(1/e)}$ = beam radius at 1/e intensity point,

$d_{(1/e)}$ = beam diameter at 1/e intensity points, and

a = beam diameter (1/e points) at the laser exit port within the Z136 family of standards.

In many cases, the manufacturer may provide the $1/e^2$ beam diameter information. Using this for intensity calculations will provide only the average intensity value for the beam.

For laser safety analysis and calculations, it is the peak intensity that is of interest.

To determine the d(1/e) value from a given d(1/e²) beam diameter, then,

$$d(1/e) = \frac{d(1/e2)}{\sqrt{2}} \tag{C3}$$

Figure C1 illustrates this relationship.

Using Z136 notation, then, at the beam exit port:

$$\text{Irradiance}_{\text{exit port}} = E_0 = \frac{\text{Power}}{\text{Area}} = \frac{\text{Power}}{\pi\left(r_{(1/e)}\right)^2} = \frac{4\cdot\text{Power}}{\pi\left(d_{(1/e)}\right)^2} = \frac{4\cdot\Phi}{\pi a^2} \tag{C4}$$

$$\text{Radiant exposure}_{\text{exit port}} = H_0 = \frac{\text{Energy}}{\text{Area}} = \frac{\text{Energy}}{\pi\left(r_{(1/e)}\right)^2} = \frac{4\cdot\text{Energy}}{\pi\left(d_{(1/e)}\right)^2} = \frac{4\cdot Q}{\pi a^2} \tag{C5}$$

Where,

E_0=irradiance, in terms of Watt per square centimeter, $W/cm^2 = W\cdot cm^{-2}$,

H_0 = radiant exposure, in terms of Joules per square centimeter, $J/cm^2 = W\cdot cm^{-2}$,

a = beam diameter (1/e points) at the laser exit port, in terms of centimeters (cm),

Φ = power, in terms of Watts (W), and

Q = energy, in terms of Joules (J).

C3. Types of Exposure Conditions

There are typically three types of exposure conditions referenced when dealing with laser safety. The illustrations provided are with a collimated beam arrangement, although other exposure conditions with different beam arrangements can also apply. If it is not reasonably foreseeable to be dealing with a given exposure condition for a specific lesson plan or experiment, then the associated hazard distance will not apply.

C3.1 Intrabeam Viewing. This is direct exposure within the beam. With a collimated beam generally, this will produce the greatest hazard distance (see Figure C2).

C3.2 Specular Reflection. This is a mirror like reflection where the redirected beam essentially maintains its original properties. The total hazard distance will be essentially the same as that for an intrabeam condition (see Figure C3).

C3.3 Diffuse Reflection. In comparison to the laser wavelength, a rough surface reflection. A diffuse reflection will redirect the incoming beam, but disrupt, disperse, and diffuse the incoming beam characteristics (see Figures C4 and C8). The hazard distance of a diffuse reflection is the smallest of these three.

C4. Types of Beam Conditions for Hazard Distance Evaluations

The formulas in ANSI Z136.1 (latest revision) provide the calculation of the following laser beam arrangements.

C4.1 Collimated Beam. This will normally generate the greatest hazard distance (see Figure C5). No laser beam can be purely collimated. At some distant point, the beam will be dispersed sufficiently so that its maximum intensity is below the MPE. This distance where maximum intensity equals the MPE is known as the nominal hazard distance or nominal ocular hazard distance (NOHD). The illustration below identifies this relationship.

Formula:

$$r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{4\Phi}{\pi MPE{:}E_{eye}} - a^2}; \qquad or \qquad r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{4Q}{\pi MPE{:}H_{eye}} - a^2} \qquad \text{(C6)}$$

$$r_{NSHD} = \frac{1}{\phi} 4\Phi\pi MPE{:}Eskin - a^2; \qquad or \qquad r_{NSHD} = \frac{1}{\phi}\sqrt{\frac{4Q}{\pi MPE{:}H_{\mathrm{skin}}} - a^2} \qquad \text{(C7)}$$

NOTE—If the beam diameter 'a' is unknown, it can be set to zero, producing a slightly more restrictive value, erring on the side of caution.

Where,

NOHD is the distance along the unobstructed beam from the laser beyond which the irradiance, *E*, or radiant exposure, *H*, is not expected to exceed the ocular MPE. In terms of centimeters, cm.

NSHD is the distance along the unobstructed beam from the laser beyond which the irradiance, *E*, or radiant exposure, *H*, is not expected to exceed the skin MPE. In terms of centimeters, cm.

ϕ is the full angle emergent beam divergence measured at the 1/e peak irradiance points of the beam profile. In terms of radians (rad).

MPE:E is the exposure expressed as irradiance. In terms of $W \cdot cm^{-2}$

MPE:H is the exposure expressed as radiant exposure. In terms of $J \cdot cm^{-2}$