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Laser Safety And Hazard Analysis For The Trailer (B70) Based AURA Laser System

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Abstract

A laser safety and hazard analysis was performed for the AURA laser system based on the 2000 version of the American National Standards Institute's (ANSI) Standard Z136.1, *for Safe Use of Lasers* and the 2000 version of the ANSI Standard Z136.6, *for Safe Use of Lasers Outdoors*. The trailer based AURA laser system is a mobile platform, which is used to perform *laser interaction* experiments and tests at various national test sites. The trailer (B70) based AURA laser system is generally operated on the United State Air Force Starfire Optical Range (SOR) at Kirtland Air Force Base (KAFB), New Mexico. The laser is used to perform *laser interaction* testing inside the laser trailer as well as outside the trailer at target sites located at various distances from the exit telescope. In order to protect personnel, who work inside the Nominal Hazard Zone (NHZ), from hazardous laser emission exposures it was necessary to determine the Maximum Permissible Exposure (MPE) for each laser wavelength (wavelength bands) and calculate the appropriate minimum Optical Density (OD_{min}) of the laser safety eyewear used by authorized personnel and the Nominal Ocular Hazard Distance (NOHD) to protect unauthorized personnel who may have violated the boundaries of the control area and enter into the laser's NHZ.

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Summary

A summary of the values for: the minimum Optical Density of the laser safety eyewear which, are required to be worn by the personnel who work in the Nominal Hazard Zone (inside and outside the laser trailer) and the appropriate Safe Eye Exposure Distances also known as the Nominal Ocular Hazard Distance (outside the laser trailer) is presented in Table 1. Laser safety eyewear that is suitable for the NHZ inside the laser trailer will also be suitable for personnel in the NHZ outside the laser trailer. Having one set of laser safety eyewear, which protects against the greater ocular hazards inside the trailer will preclude the inadvertent use, by personnel inside the trailer, of inappropriate eyewear (OD too low to provide adequate protection) intended for use outside the trailer (down range).

Table 1

Laser Output Specifications / Characteristics / NOHD & OD

Wavelength (nm)	Output (mJ)	MPE (J/cm^2)	NOHD/ NHZ (Km)	Time (sec)	OD_{min}	OD Eyewear
		INSIDE		**TRAILER**		
1064	500	1.2×10^{-6}	Room	10	**6.03**	10
633	15 mw	10^{-3} w/cm^2	Room	600 *1	**1.59**	1-2 *4
532	250	297×10^{-9}	Room	0.25	**6.34**	7
355	35	444×10^{-9} *3	Room	30,000	**5.91**	20
266	20	3.33×10^{-9}	Room	30,000	**7.79**	~20
180-280	10	3.33×10^{-9}	Room	30,000	**7.49**	~20
280-302	10	1.33×10^{-9} *3	Room	30,000	**7.89**	7 *4
315-400	20	444×10^{-9} *3	Room	30,000	**5.67**	7 *4
		OUTSIDE		**TRAILER**		
633	15 mw	2.55×10^{-3} w/cm^2	**0.027**	0.25 *2	1.18	1-2 *4
355	35	556×10^{-6}	**0** *5	60	N/A	7 *4
266	20	1.67×10^{-6}	**2.46**	60	5.10	7 *4
180-302	10	1.67×10^{-6}	**1.74**	60	4.79	7 *4
315-400	20	556×10^{-6}	**0** *5	60	N/A	7 *4

Notes:
*1: Alignment exposure (600 seconds) – Class 1 Laser Hazard Protection
*2: Aversion response exposure (0.25 seconds) – Class 2 Laser Hazard Protection
*3: 2nd Day Exposure factor applied
*4: Uvex ® eyewear otherwise Glendale ®
*5: Irradiance at telescope output is less than the MPE

I. Introduction

The trailer (B-70) based AURA laser system contains a Class 4 YAG laser, which serves as pump source to an Optical Parametric Oscillator (OPO) and Optical Parametric Amplifier (OPA) system. The system can produce an output at any of several ultraviolet (UV) wavelengths. It is mounted inside a mobile platform (trailer B-70). The output of the laser system can exit the trailer through a gimbaled telescope, which directs the beam to a distant location or test site to perform remote *interaction* tests. It is assumed that the exiting laser beam **shall not** enter into navigable air space. The AURA laser can also be used to perform *laser interaction* tests and experiments inside the trailer as well as at remote test sites.

A. Laser Parameters

The Coherent ® YAG laser can produce outputs at the fundamental, the second, third and fourth harmonics as indicated in Table 2 below. The Acculite ® OPO can produce outputs in the ultraviolet region as indicated in Table 2 below. The diameter of the laser beam inside the trailer is 5 mm. The diameter of the beam exiting the telescope is ~101 mm. The divergence of the laser beam outside the trailer is on the order of 500 micro-radians.

Table 2

Table Of Laser Parameters

Type	Manufacturer	Model	Output	Wavelength
YAG	Coherent	Infinity	500 mJ @ 30 Hz	1064 nm
Doubled YAG	"	"	250 mJ @ 30 Hz	532 nm
Tripled YAG	"	"	35 mJ @ 30 Hz	355 nm
Quadruple YAG	"	"	20 mJ @ 30 Hz	266 nm
OPO	Acculite	Ultra source	10-20 mJ @ 30 Hz	250-400 nm
HeNe	Hughes*	3227H-C	15 mw	633 nm

* Other HeNe lasers with outputs of 15 mw or less may be used instead or in addition to the one listed.

B. Laser Safety

All laser operations outdoors, involving lasers exceeding the Class 3a Allowable Emission Limit (AEL) must have a laser hazard analysis performed [ANSI Std. Z136.6-2000 (3.3.1)]. Central to a laser hazard analysis is the determination of the appropriate Maximum Permissible Exposure, the Allowable Emission Limit and the "limiting aperture". All of which, to varying degrees, are wavelength dependent.

1. Maximum Permissible Exposure

The appropriate Maximum Permissible Exposure (MPE) for repetitively pulsed lasers is always the **smallest** of the MPE values derived from the application of ANSI Rule 1 through Rule 3 presented in the standard [ANSI Std. Z136.1-2000 (8.2.3)].

a. Ocular vs. Skin Exposure

Throughout the ultraviolet region of the spectrum the ocular MPE is always less than or equal to the MPE for skin (*Table 5a* vs. *Table 5b* of the ANSI Std. Z136.1). The consequence of an ocular exposure, with a resulting possible blindness, is far more severe than the consequence for a skin exposure (burn), which is more readily recoverable. Consequently, the following analysis will pertain to the MPE for ocular exposure. Keeping in mind personnel within the NHZ should always protect their skin through the use of adequate clothing and "sunscreen" products on their exposed skin.

2. Allowable Emission Limit / Allowable Exposure Limit

The Allowable Emission Limit (AEL) is the largest output a laser may have and still be considered in a particular Laser Hazard Class. The Class 1 AEL is the product of the appropriate MPE and the area of the limiting aperture [ANSI Std. Z136.1-2000 (3.2.3.4.1)(2)]. The Class 2 AEL (visible lasers only) uses the MPE calculated for the aversion response time of 0.25 seconds. The values for the limiting aperture, as a function of laser wavelengths and exposure times, are presented in *Table 8* of the ANSI standard. Relative to the exposed person this can be considered an Allowable Exposure Limit and will hence be referred to also as the AEL. Additionally hereafter the term AEL will refer to the Class 1 AEL for "invisible lasers" ($\lambda < 400$ nm or $\lambda > 700$ nm) and to the Class 2 AEL for visible wavelength lasers (400 nm $< \lambda <$ 700 nm). Correction for the non-homogeneity of the laser cross-section is not necessary since the laser output is averaged over the limiting aperture [ANSI Std. Z136.1-2000 (9.2.2.1)].

$$AEL = MPE \times A_{lim}$$

3. Minimum Optical Density For Laser Safety Eyewear

The minimum Optical Density (OD_{min}) necessary for determining the appropriate laser safety eyewear for a particular wavelength or band of wavelengths can be derived at by the logarithm of the ratio of the output Irradiance (E_o) to the MPE or by the logarithm of the ratio of the Radiant Output to the AEL (for small beams) for the particular wavelength or wavelength band involved.

The OD for laser safety eyewear must be great enough to present, to the person wearing the eyewear, an ocular hazard no greater than Class 1 for exposure to an "invisible" laser or no greater than Class 2 for an exposure to "visible" lasers.

In general for small beam lasers, in terms of Irradiance at the eye [ANSI Std. Z136.1-2000 (4.6.2.5.1)] the minimum Optical Density can be expressed as:

$$\mathbf{OD_{min} = log_{10} (H_p/MPE)}$$

Where;

OD_{min}	The minimum Optical Density for laser safety eyewear.
H_p	The irradiance, beam energy average over the limiting aperture, in joules per square centimeters.
MPE	Appropriate MPE, in joules per square centimeters for laser and exposure conditions.

Or in terms of the output Radiance:

$$\mathbf{OD_{min} = log_{10} (Q_o/AEL)}$$

Where;

OD_{min}	The minimum Optical Density for laser safety eyewear.
Q_o	Radiant Output Pulse Energy, in joules.
AEL	Allowable Emission/Exposure Limit (Class 1 for invisible lasers and Class 2 for visible lasers), in joules.

For large beam lasers ($d_o > d_{lim}$), in terms of Irradiance:

$$\mathbf{OD_{min} = log_{10} (E_p/MPE)}$$

Where;

OD_{min}	The minimum Optical Density for laser safety eyewear.
E_p	The irradiance of a beam larger than the limiting aperture, in joules per square centimeters.
MPE	Appropriate MPE, in joules per square centimeters for laser and exposure conditions.

4. Nominal Ocular Hazard Distance

The Nominal Ocular Hazard Distance (NOHD) is the unaided eye-safe viewing distance. The NOHD can be the boundary of the Nominal Hazard Zone (NHZ) unless other engineering controls are installed to reduce the NHZ by terminating the laser beam in a shorter distance.

a. Authorized vs. Unauthorized Exposures

Authorized personnel working inside the NHZ are required to wear appropriate laser safety eyewear selected to provide full protection to the laser threat (laser hazard) present. In general the NHZ is inclusive to the laser control area. Access to the control area should be restricted to only personnel authorized to be in the NHZ [ANSI Std. Z136.6-2000 (4.5.4.1)].

The NOHD pertains to the unprotected and unintended exposure of an unauthorized person to the incident laser beam or to specular reflections of the laser beam. Unauthorized personnel are unexpected in the laser control area and could lead to an unintended, unprotected ocular exposure. Generally, the unauthorized person has violated the boundaries of the laser control area and entered into the NHZ.

The formula for calculating the NOHD is given in the Appendix of the ANSI Std. Z136.1-2000 as follows:

$$\mathrm{NOHD} = \theta^{-1}\left[(4Q_p / \pi\, \mathrm{MPE}) - (d_{out})^2\right]^{0.5}\ \mathrm{cm}$$

Where:

NOHD is the Nominal Ocular Hazard Distance, in centimeters.
θ is the beam divergence, in radians.
Q_p is the laser output radiant energy, in joules.
MPE is the appropriate per pulse Maximum Permissible Exposure, in Joules/cm^2.
d_{out} is the output beam diameter of the laser, in centimeters.

b. Atmospheric Transmission Considerations

Atmospheric transmission conditions are not normally considered for transmissions of less than a kilometer. For laser transmissions of a kilometer or greater atmospheric transmission losses may be considered when calculating the “eye safe” distances.

When atmospheric transmission conditions are considered the NOHD can be approximated as follows:

$$\mathbf{NOHD_{-atm} \sim (\tau_{atm})^{0.5}\ NOHD}$$

Where;

$NOHD_{-atm}$ is the Nominal Ocular Hazard distance for atmospheric transmission conditions considered.

NOHD is the Nominal Ocular Hazard distance (determined to provide a range estimate).

τ_{atm} is the atmospheric *transmission factor* estimate for the range estimated by NOHD.

There are several sources for values of atmospheric *transmission factors* as a function of the laser wavelength and the range or distance. One such source is Appendix C of ANSI Std. Z136.6-2000, which provides a table for atmospherically corrected values of NOHD based on the NOHD in vacuum for select atmospheric conditions. Another source is in Safety with Lasers and Other Optical Sources, Sliney and Wolbarsht.

5. Extended Ocular Hazard Distance

The eye safe distance for aided viewing is referred to as the Extended Ocular Hazard Distance (EOHD). Although the use of optical aides is not anticipated, the possible use of optical aides is usually considered in the hazard evaluation of outdoor laser operations [ANSI Std. Z136.6-2000 (3.2.5.2)].

The determination of the EOHD has been address in SAND2002-1315, Approximation Methods for Estimating the Eye Safe Viewing Distances, with or without Atmospheric Transmission Factors Considered, for Aided and Unaided Viewing Conditions, and can be approximated using the following:

$$\mathbf{EOHD \sim (\tau_{aid})^{0.5}\ [d_{aid} / d_{lim}]\ \ NOHD}$$

Where:

EOHD	Is the Extended Ocular Hazard Distance for aided viewing.
NOHD	Is the Nominal Ocular Hazard Distance for unaided viewing.
$\mathbf{d_{aid}}$	Is the input diameter (entrance or collecting optic) of the optical viewing aid, in centimeters.
$\mathbf{d_{lim}}$	Is the diameter of the *limiting aperture*, in centimeters [ANSI Std.Z136,1-2000 (*Table 8*)].
$\mathbf{\tau_{aid}}$	Is the *transmission factor* through the optical viewing aid, [ANSI Std.Z136.1-2000 (*Table 9*)].

The EOHD with atmospheric transmission conditions considered can be approximated as follows:

$$\mathbf{EOHD_{-atm} \sim (\tau_{atm})^{0.5}\ \ EOHD}$$

Where:

$\mathbf{EOHD_{-atm}}$	is the Extended Ocular Hazard distance for atmospheric transmission conditions considered.
EOHD	is the Extended Ocular Hazard distance (determined to provide a range estimate).
$\mathbf{\tau_{atm}}$	is the atmospheric *transmission factor* estimate for the range estimated by EOHD.

C. Modes Of Operations

The AURA laser system can present several modes of operations. The indoor mode involves system alignment and adjustments or performing interaction tests or experiments inside the trailer. The outdoor mode involves laser interaction tests and experiments outside the trailer (including alignment to the target).

1. Indoor Mode: System Alignment

The process to align the pump laser source (YAG laser) to the various system elements, in the OPO/A, generally involves significantly greater exposure durations than are anticipated for the routine or typical laser interaction tests or experiments.

2. Indoor Testing Mode

   Laser interaction tests can be conducted inside the AURA laser trailer (B-70). These laser interaction tests are expected to be on the order of 60 seconds in duration. The appropriate exposure for workers in the immediate area of the laser operations, suggested by ANSI Std. Z136.1-2000 *Table 4a*, is 30,000 seconds. Consequently indoor laser interaction testing can be considerably longer in duration than outside laser interaction testing.

3. Outdoor Alignment Mode

   The alignment of the test target to the AURA laser output beam is accomplished using a Class 3b visible laser (HeNe). The duration of the alignment process could be as long as 600 seconds (10 minutes). The appropriate exposure to use for this analysis is 600 seconds.

4. Outdoor Testing Mode

   The typical expected duration for outdoor laser interaction testing is on the order of 60 seconds per test with an accumulative exposure of 600 seconds.

D. Appropriate Exposures

The appropriate exposures, which are used in performing a laser safety and hazard evaluation; generally involve the "time of intended use" [ANSI Std. Z136.1-2000 (4.6.2.5.2)] or the exposure times suggested in *Table 4a* of the ANSI Z136.1-2000 standard.

Table 3

Appropriate Exposures

Wavelength (nm)	NHZ Location	Time (Seconds)	Comments
1064	Inside	10	ANSI Std. z136.1 *Table 4a*
532	Inside	0.25	ANSI Std. z136.1 *Table 4a*
355	Inside	30,000	ANSI Std. z136.1 *Table 4a*
266	Inside	30,000	ANSI Std. z136.1 *Table 4a*
250-400	Inside	30,000	ANSI Std. z136.1 *Table 4a*
633	Inside	0.25	ANSI Std. z136.1 *Table 4a*
250-400	Outside	60	Intended Single Test Exposure
250-400	Outside	600	Intended Accumulative Exposure
633	Outside	600	Expected Event Duration

II. Laser Hazard Analysis (Small Beam) **Inside** Trailer

Personnel who work in the NHZ of the AURA laser inside the trailer can be exposed to several laser wavelengths at possibly hazardous levels. The wavelengths presented inside the AURA laser trailer ranges from the UV, through the visible and into the infrared (IR). Laser safety eyewear must protect personnel from the visible as well as the invisible wavelengths present.

A. UV Region (180 nm < λ < 400 nm)

The UV wavelength region from 180 nm to 400 nm is a "dual limit" region. The dual limits are comprised of the "**photochemical limit**" (the *left-hand* formula in *Table 5a* of the ANSI standard) and the "**thermal limit**" (the *right-hand* formula (notes) of *Table 5a* of the ANSI standard). The appropriate MPE is determined from the smallest of these dual limits [ANSI Std. Z136.1 (*Table 5a*)(notes)].

The UV outputs of the AURA laser fall into the **two** major **bands** in the UV region as presented in *Table 5a* of the ANSI Std. Z136.1-2000. These bands are from 180 nm to 302 nm, which is referred to hereafter as UV-1 and the band from 315 nm to 400 nm is referred to as UV-2.

1. UV-1 Region (180 nm < λ < 302 nm)

The appropriate MPE formula present in *Table 5a* of the ANSI Std. Z136.1 is the same for laser emission wavelengths from 180 nm to 302 nm for the first day or "initial exposure". The MPE for UV laser emission wavelengths longer than 280 nm is de-rated by a factor of 2.5 if laser exposures are expected on successive days [ANSI Std. Z136.1-2000 (8.2.3.1)].

a. Appropriate MPE Determination

The appropriate MPE for repetitively pulsed lasers is always the **smallest** of the MPE values derived from Rules 1 through 3 [ANSI Std. Z136.1-2000 (8.2.3)]. Rule 1 pertains to a single pulse exposure. Rule 2 pertains to the average power for thermal and photochemical hazards per pulse and Rule-3 pertains to the multiple-pulse, thermal hazard [ANSI Std. Z136.1-2000 (8.2.3)].

The MPE (for each of the three rules) is dependent on the expected exposure duration. For personnel working inside the NHZ of the AURA trailer the suggested exposure is 30,000 seconds [ANSI Std. Z136.1-2000 (*Table 4a*)].

(1) Rule 1 (Single Pulse):

The exposure to any pulse in a train of pulses shall not exceed the single pulse MPE [ANSI Std. Z136.1-2000 (8.2.3)(Rule 1)].

The appropriate single pulse MPE is the minimum of the MPE values for the photochemical and the thermal limits.

$MPE_{s.p.}$ = min [photochemical limit, thermal limit] {Dual limit region}

$= \min [\ (3 \times 10^{-3}\ J/cm^2),\ \{0.56 t^{0.25}\ J/cm^2\}]$ {*Table 5a* ANSI Std.}

$= \min [\ (3 \times 10^{-3}\ J/cm^2),\ \{0.56\ (2 \times 10^{-9})^{0.25}\ J/cm^2\}]$

$= \min [\ (3 \times 10^{-3}\ J/cm^2),\ \{3.74 \times 10^{-3}\ J/cm^2\}]$

$$\mathbf{MPE_{s.p.} = 3 \times 10^{-3}\ J/cm^2}$$

(2) Rule 2 (CW/pulse):

The MPE for a group of pulses delivered in time "T" shall not exceed the MPE for time "T". The MPE per pulse is the MPE for time "T" divided by the number of pulses delivered in time "T" [ANSI Std. Z136.1-2000 (8.2.3)(Rule 2)].

The appropriate MPE for time "T" is the smallest of the MPE values derived from the photochemical and the thermal limits.

$MPE_{/pulse}$ = min [$MPE_{photochemical}$, $MPE_{thermal}$] / n {Dual limit region}

$$n = PRF \times T$$

$$= (30\ sec^{-1})\ (30{,}000\ sec)$$

$$\mathbf{n = 900 \times 10^{3}\ pulses}$$

$$MPE_{/pulse} = \min\ [3 \times 10^{-3}\ J/cm^{2},\ 0.56(30 \times 10^{3})^{0.25}]\ /\ 900 \times 10^{3}$$

$$= \min\ [3 \times 10^{-3}\ J/cm^{2},\ 7.37\ J/cm^{2}]\ /\ 900 \times 10^{3}$$

$$\mathbf{MPE_{/pulse} = 3.33 \times 10^{-9}\ J/cm^{2}}$$

(3) Rule 3 (Multiple-Pulse):

Rule 3 protects against the sub-threshold pulse-cumulative thermal injury and pertains **only to the thermal limit** [ANSI Std. Z136.1-2000 (8.2.3)(Rule 3)].

The multiple-pulse MPE is the product of the single pulse (thermal limit) MPE and a multiple pulse correction factor (C_p). The multiple pulse correction C_p factor is a function of the number of pulses in the exposure and is presented as a formula in *Table 6* of the ANSI Z136.1 standard.

$$MPE_{m.p.} = C_p\ MPE_{s.p.\text{-}thermal}$$

$$= n^{-0.25}\ MPE_{s.p\text{-}thermal.}$$

$$= (900 \times 10^{3})^{-0.25}\ (3.74 \times 10^{-3}\ J/cm^{2})$$

$$\mathbf{MPE_{m.p.} = 121 \times 10^{-6}\ J/cm^{2}}$$

(4) Appropriate MPE:

The appropriate MPE for the initial (first day) exposure is the smallest of the MPE values derived from ANSI Rules 1 through Rule 3 for laser emissions from 180 nm to 302 nm as presented in Table 4 below.

Table 4

Appropriate MPE (UV-1: Initial Exposure)

(180 nm < λ < 302 nm) - 30,000 Seconds

ANSI Rule	**MPE (J/cm^2)**	**Comment**
1	3×10^{-3}	
2	$\mathbf{3.33 \times 10^{-9}}$	**Appropriate MPE**
3	121×10^{-6}	

MPE For Successive Day Exposure

The MPE for successive day (second day) exposure to UV emissions longer than 280 nm requires that the MPE to be de-rated by a factor of 2.5 [ANSI Std. Z136.1-2000 (8.2.3.1)].

$$\mathbf{MPE_{2nd\ day} = MPE_{(180\text{-}280)} / 2.5}$$

$$= 3.33 \times 10^{-9}\ J/cm^2 / 2.5$$

$$\mathbf{MPE_{2nd\ day} = 1.33 \times 10^{-9}\ J/cm^2}$$

Table 5

Appropriate MPE (UV-1: Successive Day Exposure)

(280 nm < λ < 302 nm) - 30,000 Seconds

ANSI Rule	1st Day MPE (J/cm^2)	2nd Day MPE (J/cm^2)	Comment
1	3×10^{-3}	1.2×10^{-3}	
2	$\mathbf{3.33 \times 10^{-9}}$	$\mathbf{1.33 \times 10^{-9}}$	**Appropriate MPE 2nd Day**
3	121×10^{-6}	48.4×10^{-6}	

b. Appropriate AEL Determination

The appropriate AEL is the product of the appropriate MPE and the area associated with the limiting aperture in ANSI Std. Z136.1-2000 (*Table 8*).

(1) AEL For: 180 nm < λ < 302 nm;

$$AEL = (MPE)\ (A_{lim})$$

$$d_{lim} = 0.35\ cm$$

$$= (3.33 \times 10^{-9}\ J/cm^2)\ \pi\ (0.35\ cm)^2 / 4$$

$$\mathbf{AEL = 320 \times 10^{-12}\ J}$$

(2) AEL For: 280 nm < λ < 302 nm (**2nd Day**);

$$AEL_{2nd\ day} = (MPE_{2nd\ day})\ (A_{lim})$$

$$= (1.33 \times 10^{-9}\ J/cm^2)\ \pi\ (0.35\ cm)^2 / 4$$

$$\mathbf{AEL_{2nd\ day} = 128 \times 10^{-12}\ J}$$

c. ODmin Calculation

(1) **For the Range: 180 nm < λ < 280 nm, use the AEL for initial exposure.**

$OD_{min} = \log_{10} [Q_o / AEL]$

$OD_{min} = \log_{10} [10 \times 10^{-3} J / 320 \times 10^{-12} J]$

$\mathbf{OD_{min} = 7.49}$

(2) **For the Range: 280 nm < λ < 302 nm, Use AEL for successive day exposure.**

$OD_{min} = \log_{10} [Q_o / AEL]$

$OD_{min} = \log_{10} [10 \times 10^{-3} J / 128 \times 10^{-12} J]$

$\mathbf{OD_{min} = 7.89}$

d. Summary

Laser workers and other personnel who work inside the AURA trailer (B-70) NHZ (laser room) are expected to be exposed to the ocular hazards tabulated below and are required to wear laser safety eyewear with minimum OD(s) in the wavelength ranges indicated in the table below whenever the laser system is activated for the duration of their stay in the NHZ. It is assumed that authorized workers shall be a subjected to successive day exposures.

Table 6

AURA Laser Room (UV-1 Exposures)

(180 nm < λ < 302 nm)

Wavelength (nm)	Output	Time (seconds)	MPE (J/cm^2)	AEL (J)	OD_{min}
180 < λ < 280	10 mJ @ 30 Hz	30,000	3.33×10^{-9}	320×10^{-12}	7.49
280 < λ < 302	10 mJ @ 30 Hz	30,000	1.33×10^{-9}	128×10^{-12}	7.89

2. UV-2 Region (315 nm < λ < 400 nm)

The appropriate MPE formula present in *Table 5a* of the ANSI Std. Z136.1 for laser emission wavelengths from 315 nm to 400 nm is identical for both the photochemical and thermal limits. The MPE for UV laser emission wavelengths longer than 280 nm is de-rated by a factor of 2.5 if laser exposures are expected on successive days [ANSI Std. Z136.1-2000 (8.2.3.1)]. The photochemical limit is equal to the thermal limit in this wavelength region for exposure times of 1 nanosecond to 10 seconds, but for exposures of 10 to 30,000 seconds the photochemical limit MPE is 1 J/cm^2 [ANSI Std. Z136.1-2000 (*Table 5a*)].

a. Appropriate MPE Determination

As stated in the previous hazard analysis data set the appropriate MPE is always the smallest value derived from the application of ANSI Rules 1-3 to *Table 5a*.

(1) Rule 1 (Single Pulse):

Again, the appropriate MPE is derived from the smallest of the photochemical and thermal limits. For an exposure between 1 nanosecond and 10 seconds the photochemical limit is equal to the thermal limit. The laser pulse width is 2 nanoseconds.

$$MPE_{s.p.} = \min \text{[photochemical limit, thermal limit]} \qquad \text{\{Dual limit region\}}$$

$$= \min [\ (0.56t^{0.25}\ J/cm^2),\ \{0.56t^{0.25}\ J/cm^2\}] \qquad \{\textit{Table 5a}\ \text{ANSI Std.}\}$$

$$= 0.56\ (2 \times 10^{-9})^{0.25}\ J/cm^2$$

$$\mathbf{MPE_{s.p.} = 3.74 \times 10^{-3}\ J/cm^2}$$

(2) Rule 2 (CW/pulse):

For the wavelength region 315 nm to 400 nm with exposures on the order of 10 to 30,000 seconds the photochemical limit MPE is defined as, "1 J/cm^2". The **thermal limit does not apply** for exposures greater than 10 seconds [ANSI Std. Z136.1-2000 (*Table 5a*)(right-hand note)].

T = 30,000 seconds

$n = PRF \times T$

$= (30\ sec^{-1})\ (30 \times 10^3\ sec)$

$\mathbf{n = 900 \times 10^3\ \ pulses}$

$MPE_{/pulse} = MPE_{cw} / n$

$MPE = 1\ J/cm^2$ 10 sec < T < 3×10^4 sec {*Table 5a*}

$MPE_{/pulse} = [1\ J/cm^2] / 900 \times 10^3$

$\mathbf{MPE_{/pulse} = 1.11 \times 10^{-6}\ J/cm^2}$

(3) Rule 3 (Multiple-pulse):

Rule 3 applies **only** to the **thermal limit** [ANSI Std. Z136.1-2000 (8.2.3.1)]

$T = 3 \times 10^4$ seconds

$MPE_{m.p.} = C_p\ MPE_{s.p.-thermal}$

$C_p = n^{-0.25}$ {*Table 6* ANSI Std.}

$= (PRF \times T)^{-0.25}$

$= [(30\ sec^{-1})\ (30{,}000\ sec)]^{-0.25}$

$= [900 \times 10^3]^{-0.25}$

$\mathbf{C_p = 0.0325}$

$MPE_{m.p.} = (0.0325)\ (3.74 \times 10^{-3}\ J/cm^2)$

$\mathbf{MPE_{m.p.} = 121 \times 10^{-6}\ J/cm^2}$

(4) Summary MPE Table:

Table 7

Appropriate MPE (UV-2: Initial Exposure)

(315 nm < λ < 400 nm) - 30,000 Seconds

ANSI Rule	MPE (J/cm^2)	Comment
1	3.74×10^{-3}	
2	$\mathbf{1.11 \times 10^{-6}}$	**Appropriate MPE**
3	121×10^{-6}	

MPE For Successive Day Exposure

The MPE for successive day or second day exposure to UV emissions longer than 280 nm requires that the MPE to be de-rated by a factor of 2.5 [ANSI Std. Z136.1-2000 (8.2.3.1)].

$$\mathbf{MPE_{2nd\ day} = MPE_{(315\text{-}400)} / 2.5}$$

$$= 1.11 \times 10^{-6}\ J/cm^2\ /\ 2.5$$

$$\mathbf{MPE_{2nd\ day} = 444 \times 10^{-9}\ J/cm^2}$$

b. Appropriate AEL Determination

The appropriate AEL for the wavelength-range: 315 nm to 400 nm is the product of the de-rated MPE, for successive day exposures, and the limiting Area.

$$AEL = (MPE_{2nd\text{-}day}) (A_{lim})$$

$$= (444 \times 10^{-9} \text{ J/cm}^2) \pi (0.35 \text{ cm})^2 / 4$$

$$\mathbf{AEL = 42.7 \times 10^{-9} J}$$

c. ODmin Calculation

(1) For the radiant OPO/A output of 20 mJ @ 30 Hz in the wavelength range: 315 nm $< \lambda <$ 400 nm the minimum OD required is as follows.

$$OD_{min} = \log_{10} (Q_o / AEL)$$

$$= \log_{10} (20 \times 10^{-3} \text{ J} / 42.7 \times 10^{-9} \text{ J})$$

$$\mathbf{OD_{min} = 5.67}$$

(2) For a radiant output of 35 mJ @ 30 Hz from the Tripled YAG (355 nm) the minimum OD required is:

$$OD_{min} = \log_{10} (Q_o / AEL)$$

$$= \log_{10} (35 \times 10^{-3} \text{ J} / 42.7 \times 10^{-9} \text{ J})$$

$$\mathbf{OD_{min} = 5.91}$$

d. Summary

Laser workers and other personnel who work inside the AURA trailer NHZ (laser room) are expected to be exposed to the ocular hazard tabulated below and are required to don and wear laser safety eyewear with minimum OD(s) in the wavelength ranges indicated in the table below whenever the laser system is activated for the duration of their stay in the NHZ. It is assumed that authorized laser workers shall be subjected to successive day exposures.

Table 8

AURA Laser (UV-2 Exposures)

($315 \text{ nm} < \lambda < 400 \text{ nm}$)

Wavelength (nm)	Output	Time (Seconds)	MPE (J/cm^2)	AEL (J)	OD_{min}
$315 < \lambda < 400$	20 mJ @ 30 Hz	30,000	444×10^{-9}	42.7×10^{-9}	5.67
355	35 mJ @ 30 Hz	30,000	444×10^{-9}	42.7×10^{-9}	5.91

B. Visible Region ($400 \text{ nm} < \lambda < 700 \text{ nm}$)

There are two sources of visible wavelengths in the laser room of the AURA trailer (B-70): the doubled YAG (532 nm) output of the pump laser and the CW HeNe (633 nm) alignment laser.

1. **Doubled YAG (532 nm)**

Aversion Response MPE (T = 0.25 seconds)

The aversion response protects up to a Class 2 laser hazard.

a. Rule 1 (Single Pulse):

The single pulse MPE is a constant value throughout the visible region of the spectrum, for exposures of 1 nanosecond to 18 microseconds.

{ANSI Std. Z136.1-2000 (*Table 5a*)}
{$400 \text{ nm} < \lambda < 700 \text{ nm}$}
{$10^{-9} \text{ sec} < t < 18 \times 10^{-6} \text{ sec}$}

$$\mathbf{MPE_{s.p.} = 5 \times 10^{-7}\ J/\ cm^2}$$

b. Rule 2 (CW/pulse):

$$MPE_{/pulse} = MPE_T / n$$

For, T = 0.25 seconds;

$$n = PRF \times T$$

$$= (30\ sec^{-1})\ (0.25\ sec)$$

$$= 7.5\ pulses$$

The value of "n" is always an integer. Whenever the number of pulses is fractional round this number up to the next whole number. Therefore the number of pulses in this exposure will be considered to be 8.

In the time range for the aversion response exposure (0.25 seconds) the MPE is given in ANSI Std. Z136.1-2000 (*Table 5a*) to be of the form:

$$MPE = 1.8\ t^{0.75} \times 10^{-3}\ J/cm^2 \qquad \{400\ nm < \lambda < 700\ nm\}\ \{18 \times 10^{-6}\ sec < t < 10\ sec\}$$

$$MPE_{/pulse} = 1.8\ (0.25)^{0.75} \times 10^{-3}\ J/cm^2 / 8$$

$$= 636 \times 10^{-6}\ J/cm^2 / 8$$

$$\mathbf{MPE_{/pulse} = 79.5 \times 10^{-6}\ J/cm^2}$$

c. Rule 3 (Multiple-Pulse):

The number of pulses in the aversion response exposure (0.25 seconds) has been determined to be 8 (from Rule 2 above).

$$MPE_{m.p.} = C_p\ MPE_{s.p.}$$

$$= n^{-0.25}\ MPE_{s.p.}$$

$$= (8)^{-0.25}\ (5 \times 10^{-7}\ J/\ cm^2)$$

$$= (0.595)\ (5 \times 10^{-7}\ J/\ cm^2)$$

$$\mathbf{MPE_{m.p.} = 297 \times 10^{-9}\ J/cm^2}$$

d. Summary of MPE Table:

Table 9

Appropriate MPE (Doubled YAG)

532 nm, T = 0.25 Seconds

ANSI Rule	**MPE (J/cm^2)**	**Comment**
1	500×10^{-9}	
2	79.5×10^{-6}	
3	$\mathbf{297 \times 10^{-9}}$	**Appropriate MPE**

e. AEL Determination

The appropriate AEL is the product of the appropriate MPE and the area associated with the limiting aperture in ANSI Std. Z136.1-2000 (*Table 8*). The diameter of the limiting aperture is given as: **7 mm**.

$$AEL = MPE\ A_{lim}$$

$$= (297 \times 10^{-9}\ J/cm^2)\ \pi\ (0.7\ cm)^2 / 4$$

$$\mathbf{AEL = 114 \times 10^{-9}\ J}$$

f. ODmin Calculation

The minimum OD necessary to protect against Doubled YAG to the Class 2 aversion response limit is as follows:

$$OD_{min} = \log_{10} (Q_o / AEL)$$

$$OD_{min} = \log_{10} (0.25\ J / 114 \times 10^{-9}\ J)$$

$$\mathbf{OD_{min} = 6.34}$$

2. **HeNe Alignment Laser**

The HeNe alignment laser has a continuous wave (CW) output of 15 milliwatts at 633 nm. The appropriate exposure for a laser alignment is 600 seconds (10 minutes).

a. MPE Determination

The appropriate MPE for a 600 second (T > 10 seconds) exposure at 633 nm is given by ANSI Std. z136.1-2000 (*Table 5a*) as 1 milliwatt per square centimeter.

$$\mathbf{MPE_{600sec} = 1 \times 10^{-3}\ watts/cm^2}$$

b. AEL Calculation

The appropriate (Class 1) AEL for 633 nm is the product of the MPE and the area of the 7 mm limiting aperture.

$$AEL = MPE\ A_{lim}$$

$$= (1 \times 10^{-3}\ \text{watts/cm}^2)\ \pi\ (0.7\ \text{cm})^2 / 4$$

$$\mathbf{AEL = 385 \times 10^{-6}\ watts}$$

c. ODmin Calculation

The minimum OD necessary to provide full protection for a 600-second alignment exposure at 633 nm is:

$$OD_{min} = \log_{10} (\Phi_o / AEL)$$

$$= \log_{10} (15 \times 10^{-3}\ \text{watts} / 385 \times 10^{-6}\ \text{watts})$$

$$\mathbf{OD_{min} = 1.59}$$

3. Summary Of The Visible Region Of The Spectrum

Laser workers and other personnel who work inside the AURA trailer NHZ (laser room) are expected to be exposed to the ocular hazard tabulated below and are required to wear laser safety eyewear with minimum OD(s) in the wavelength ranges indicated in the table below whenever the laser system or the alignment laser is activated for the duration of their stay in the NHZ.

Table 10

AURA Laser Room (Visible Region)

Output Range: 400 nm < λ < 700 nm

Wavelength (nm)	Output (Qo,Φo)	Time (Seconds)	MPE (J/cm^2)	AEL (J)	OD_{min}
532	250 mJ @ 30 Hz	0.25	297×10^{-9}	114×10^{-9}	**6.34**
633	15 mw	600	1×10^{-3} watts/cm^2	385×10^{-6} watts	**1.59**

C. Infrared Region (1050 nm < λ < 1400 nm)

The fundament wavelength of the YAG pump laser is 1.064 µm (1064 nm). Although most of the IR pulse energy is dissipated in the conversion to the second (532 nm), the third (355 nm) and the forth (266 nm) harmonics there is always some fundamental bleed through. For the purpose of this analysis the full amount of the fundament pulse energy will be considered to be available to the laser hazard, especially during system alignment when the alignment of the primary element could subject the laser worker to a possible exposure to the fundamental output of the YAG.

1. Full Protection (T = 10 seconds)

The standard IR laser (1064 nm) exposure is given by the ANSI Std. Z136.1-2000 (*Table 4*) and (8.2.2) as 10 seconds. As with the previous analysis data sets the appropriate MPE for a repetitively pulsed laser is always the smallest value derived by the application of ANSI Rules 1 through 3 to ANSI Std. Z136.1-2000 (*Table 5a*).

a. <u>Rule 1 (Single Pulse)</u>:

The single pulse MPE form for a 2-nanosecond, 1064 nm laser pulse is given by ANSI Std. Z136.1-2000 (*Table 5a*) as:

$MPE_{s.p.} = 5.0\ C_c \times 10^{-6}\ J/cm^2$ {1050 nm < λ < 1400 nm}
{10^{-9} sec < t < 50 x 10^{-6} sec}

{ANSI Std. Z136.1-2000 (*Table 6*)}
Cc = 1.0 {1050 nm < λ < 1150 nm}

$$\mathbf{MPE_{s.p.} = 5.0 \times 10^{-6}\ J/cm^2}$$

b. <u>Rule 2 (CW/pulse)</u>:

For a standard 10-second IR (1050 nm to 1400 nm) exposure the appropriate form of the MPE is given by ANSI Std. Z136.1-2000 *(Table 5*a) as:

$MPE_{10sec} = 9.0\ C_c\ t^{0.75} \times 10^{-3}\ J/cm^2$ {50 x 10^{-6} sec < t ≤ 10 sec}

The ANSI Std. Z136.1-2000 (*Table 6*) gives, C_c as equal to "1" for wavelengths greater than 1050 nm but less than 1150 nm.

$$MPE_{10sec} = 9.0\ (10)^{0.75} \times 10^{-3}\ J/cm^2$$

$$= 9.0\ (5.62) \times 10^{-3}\ J/cm^2$$

$$\mathbf{MPE_{10sec} = 50.6 \times 10^{-3}\ J/cm^2}$$

The "per pulse" MPE for Rule 2 is this 10-second MPE form divided by the number of pulses delivered in 10 seconds.

$$MPE_{/pulse} = MPE_{10sec} / n$$

$$n = PRF \times T$$

$$= (30\ sec^{-1})\ (10\ sec)$$

n = 300 pulses

$MPE_{/pulse} = 50.6 \times 10^{-3}\ J/cm^2 / 300$

$\mathbf{MPE_{/pulse} = 169 \times 10^{-6}\ J/cm^2}$

c. Rule 3 (Multiple-Pulse):

T = 10 seconds
n = 300 pulses

$MPE_{m.p.} = n^{-0.25}\ MPE_{s.p.}$

$= (300)^{-0.25}\ (5.0 \times 10^{-6}\ J/cm^2)$

$= (0.24)\ (5.0 \times 10^{-6}\ J/cm^2)$

$\mathbf{MPE_{m.p.} = 1.2 \times 10^{-6}\ J/cm^2}$

d. Summary MPE Table For The 1064 nm Output:

Table 11

Appropriate MPE (YAG: Fundamental)

1064 nm, T = 10 Seconds

ANSI Rule	MPE (J/cm^2)	Comment
1	5.0×10^{-6}	
2	169×10^{-6}	
3	$\mathbf{1.2 \times 10^{-6}}$	**Appropriate MPE**

e. AEL Determination:

The AEL for a 1064 nm pulsed laser source is the product of the appropriate MPE and the area of the 7-mm limiting aperture indicated in *Table 8* of the ANSI Std. Z136.1.

$$AEL = (MPE)\ (A_{lim})$$

$$= (1.2 \times 10^{-6}\ J/cm^2)\ \pi\ (0.7\ cm)^2 / 4$$

$$\mathbf{AEL = 462 \times 10^{-9}\ J}$$

f. ODmin Calculation:

$$OD = \log_{10} (Q_o / AEL)$$

$$= \log_{10} (0.5\ J / 462 \times 10^{-9}\ J)$$

$$= \log_{10} (541 \times 10^{3})$$

$$\mathbf{OD = 6.03}$$

2. Summary for Indoor Operation

The following table summarizes the ocular hazard mitigation for laser operations inside the laser room of the AURA trailer (B-70).

Table 12

Operations Inside The Laser Room (NHZ) Of The AURA Trailer

Wavelength (nm)	Output (mJ) @ 30 Hz	Time (sec)	MPE (J/cm^2)	AEL (J)	OD_{min}	OD Eyewear (GPT)
1064	500	10	1.2×10^{-6}	462×10^{-9}	**6.03**	10
633	15 mw	600 *2	10^{-3} w/cm^2	385×10^{-6} w	**1.59**	1-2 *3
532	250	0.25	297×10^{-9}	114×10^{-9}	**6.34**	7
355	35	30,000	444×10^{-9}*	42.7×10^{-9}	**5.91**	20
266	20	30,000	3.33×10^{-9}	320×10^{-12}	**7.79**	~20
180-280	10	30,000	3.33×10^{-9}	320×10^{-12}	**7.49**	~20
280-302	10	30,000	1.33×10^{-9}*	128×10^{-12}	**7.89**	~20
315-400	20	30,000	444×10^{-9}*	42.7×10^{-9}	**5.67**	7 *3

Notes:
*: Successive day exposure value.
*2: Alignment (Protection at Class 1), Aversion Response (0.25 seconds) OD = 1.18.
*3: Uvex ® Eyewear

III. Outdoor Operation Of The Trailer Based AURA Laser System

The outdoor operation of the AURA laser consists primarily of select wavelengths in the ultraviolet region of the spectrum, which are used to perform laser interaction tests and experiments on various “targets”. The duration of these individual tests varies but is generally on the order of 60 seconds. Accumulative exposure is expected to be on the order of 600 seconds per day, but may be greater. A visible alignment laser, HeNe-red, at 633 nm is used to align the particular test “target” to the AURA UV source. The alignment process is expected to last for up to 600 seconds in duration.

Laser Hazard Analysis (Large Beam) **Outside** Trailer

The laser beam exits the AURA trailer by means of a gimbaled beam expanding telescope, which directs the laser beam to a remote "target". The beam diameter, exiting the telescope, is approximately 101 mm with a beam divergence on the order of 500 micro-radians.

A. UV Region (180 nm < λ < 400 nm):

1. UV-1 Region: 180 nm < λ < 302 nm

As previously stated during the "indoor" hazard analysis, specific wavelengths in this UV band may be required in the performance of certain laser interaction tests or experiments. The region 180 nm to 302 nm of the optical spectrum is a dual limit region where the smallest value for the MPE form that is derived from the photochemical limit and the thermal limit is used. The MPE form is the same for the wavelengths in this region depending on the particular laser parameters (ie.: Pulse width, Pulse Repetition Frequency and the Exposure).

a. Appropriate MPE Determination For A Typical 60-Second Test

Recall that the appropriate MPE for a multiple pulse laser is always the smallest of the values derived from ANSI Std. Z136.1-2000, *Rules* 1 through 3.

(1) Rule 1 (Single Pulse):

For a typical laser test lasting 60 seconds no single laser pulse in the pulse train may exceed the single pulse MPE. The single pulse MPE is the smallest of the MPE form values for the photochemical limit and the thermal limit.

For exposures in the range of: 10^{-9} sec < T < 3×10^{4} sec:

$MPE_{s.p.}$ = min [photochemical limit, thermal limit] {dual limit region}

$= \min [(3 \times 10^{-3}\ J/cm^2), \{0.56t^{0.25}\ J/cm^2\}]$ {*Table 5a* ANSI Std.}

$= \min [(3 \times 10^{-3}\ J/cm^2), \{0.56\ (2 \times 10^{-9})^{0.25}\ J/cm^2\}]$

$= \min [(3 \times 10^{-3}\ J/cm^2), \{3.74 \times 10^{-3}\ J/cm^2\}]$

$$\mathbf{MPE_{s.p.} = 3 \times 10^{-3}\ J/cm^2}$$

(2) Rule 2 (CW/pulse) For A 60-Second Exposure:

The MPE for a group of pulses delivered in 60 seconds, T, shall not exceed the MPE for a 60-second exposure time. The MPE per pulse is the MPE for 60-second exposure divided by the number of pulses delivered in the time of 60 seconds [ANSI Std. Z136.1-2000 (8.2.3)(rule 2)].

T = 60 seconds

$$n = PRF \times T$$

$$= (30\ sec^{-1})\ (60\ sec)$$

n = 1,800 pulses

The appropriate MPE for a 60-second exposure is always the smallest of the MPE values derived from the photochemical limit and the thermal limit in the dual limit region.

$$MPE_{/pulse} = \min\ [\text{photochemical limit, thermal limit}]\ /\ n$$

$$MPE_{/pulse} = \min\ [MPE_{\ photochemical}, MPE_{\ thermal}]\ /\ n$$

{ANSI Table 5a}

$$MPE_{/pulse} = \min\ [3 \times 10^{-3}\ J/cm^2,\ 0.56\ (60)^{0.25}\ J/cm^2]\ /\ 1.8 \times 10^3$$

$$= \min\ [3 \times 10^{-3}\ J/cm^2,\ 1.56\ J/cm^2]\ /\ 1.8 \times 10^3$$

$$= 3 \times 10^{-3}\ J/cm^2\ /\ 1.8 \times 10^3$$

$$\mathbf{MPE_{/pulse} = 1.67 \times 10^{-6}\ J/cm^2}$$

(3) Rule 3 (Multiple-pulse) For A 60-Second Exposure:

Rule 3 applies to the **thermal limit only** [ANSI Std. Z136.1-2000 (8.2.3.1)].

$$MPE_{m.p.} = C_p\ MPE_{s.p.\text{-}thermal}$$

$C_p = n^{-0.25}$ {ANSI Std. *Table 6*}

$= (PRF \times T)^{-0.25}$

$= [(30 \text{ sec}^{-1}) (60 \text{ sec})]^{-0.25}$

$= [1.8 \times 10^3]^{-0.25}$

$\mathbf{C_p = 0.154}$

$MPE_{m.p.} = (0.154) (3.74 \times 10^{-3} \text{ J/cm}^2)$.

$\mathbf{MPE_{m.p.} = 574 \times 10^{-6} \text{ J/cm}^2}$

(4) Summary MPE Table:

The MPE derived from Rule 2 provides the smallest value for a 60-second exposure to a wavelength in the range from 180 nm to 302 nm.

Table 13

Appropriate MPE (UV-1: Single Outdoor Test)

(180 nm < λ < 302 nm) 60-Second Exposure

ANSI Rule	MPE (J/cm^2)	Comment
1	3×10^{-3}	
2	$\mathbf{1.67 \times 10^{-6}}$	**Appropriate MPE**
3	574×10^{-6}	

b. Irradiance vs. MPE

The average irradiance (E_o) of the laser beam exiting the telescope is approximately the radiant pulse energy distributed over the beam cross-sectional area at the telescope.

$$E_o = Q_o / A_{exit}$$

$$= Q_o / \pi (d_{exit})^2 / 4$$

$$E_o = 4Q_o / \pi (d_{exit})^2$$

The irradiance for a 10 mJ radiant output and the large exit beam (10.1 cm diameter) can be calculated as follows:

$$E_o = 4 (10 \times 10^{-3} \text{ J}) / \pi (10.1 \text{ cm})^2$$

$$\mathbf{E_o = 125 \times 10^{-6} \text{ J/ cm}^2}$$

The irradiance at the exit of the telescope is greater than the MPE for a 60-second exposure and must be considered hazardous.

Extended Source Criteria

Extended source criteria **cannot** be applied to the large diameter UV beams produced by the trailer based AURA laser system. The large beam at the exit could be considered an extended source if the viewing angle (α) is greater than some minimum angle (α_{min}); however, the extended source criteria can only be applied to wavelengths greater than 400 nm but less than 1.4 µm [ANSI Std. Z136.1-2000 (*Table 6*)(note 1).

c. ODmin Calculation

The minimum OD appropriate for laser eyewear for the outdoors operation in this wavelength band is calculated from the logarithm of the ratio of the laser beam irradiance averaged over the limiting aperture to the appropriate MPE.

1. For: 180 nm to 302 nm, 10 mJ @ 30 Hz, T = 60 seconds;

$OD_{min} = \log_{10} (H_p/MPE)$

$= \log_{10} (E_p/MPE)$

$= \log_{10} [(Q_p/A_{lim}) / MPE]$

$= \log_{10} [(10 \times 10^{-3}\ J/ 0.0962\ cm^2) / 1.67 \times 10^{-6}\ J/cm^2]$

$= \log_{10} [62.2 \times 10^3]$

$\mathbf{OD_{min} = 4.79}$

2. For Quadrupled YAG: 266 nm, 20 mJ @ 30 Hz, T = 60 seconds;

$OD_{min} = \log_{10} (H_p/MPE)$

$= \log_{10} [(Q_p/A_{lim}) / MPE]$

$= \log_{10} [(20 \times 10^{-3}\ J/ 0.0962\ cm^2) / 1.67 \times 10^{-6}\ J/cm^2]$

$= \log_{10} [124 \times 10^3]$

$\mathbf{OD_{min} = 5.10}$

d. <u>NOHD Calculation</u>

1. For: 180 nm to 302 nm, 10 mJ @ 30 Hz, T = 60 seconds;

$NOHD = \theta^{-1} [(4Q_p / \pi\ MPE) - (d_{out})^2]^{0.5}\ cm$

$= (500 \times 10^{-6})^{-1} [(4 \times 10^{-2}\ J / \pi\ 1.67 \times 10^{-6}\ J/cm^2) - (10.1\ cm)^2]^{0.5}$

$= (500 \times 10^{-6})^{-1} [7.52 \times 10^3\ cm^2]^{0.5}$

$= (500 \times 10^{-6})^{-1} [86.7\ cm]$

$= 173 \times 10^3\ cm$

NOHD = 1.73 Km

2. For Quadrupled YAG: 266 nm, 20 mJ @ 30 Hz, T = 60 seconds;

$$NOHD = \theta^{-1} [(4Q_p / \pi\ MPE) - (d_{out})^2]^{0.5} \text{ cm}$$

$$= (500 \times 10^{-6})^{-1} [(8 \times 10^{-2} \text{ J} / \pi\ 1.67 \times 10^{-6} \text{ J/cm}^2) - (10.1 \text{ cm})^2]^{0.5}$$

$$= (500 \times 10^{-6})^{-1} [15.1 \times 10^3 \text{ cm}^2]^{0.5}$$

$$= (500 \times 10^{-6})^{-1} [123 \text{ cm}]$$

$$= 246 \times 10^3 \text{ cm}$$

NOHD = 2.46 Km

a. EOHD Approximation

It is assumed that any optical viewing aid that might be used would be a standard, **7 x 50** binoculars with a 50 mm entrance aperture. ANSI Standard Z136.1-2000 (*Table 9*) gives the transmission factor through the optical aid as **less than 2%** for the **UV** region of the spectrum.

1. For: 180 nm to 302 nm, 10 mJ @ 30 Hz, T = 60 seconds;

$$EOHD \sim (\tau_{aid})^{0.5} [d_{aid} / d_{lim}] \text{ NOHD}$$

$$\sim (0.02)^{0.5} [50 \text{ mm} / 3.5 \text{ mm}] \ 1.73 \text{ Km}$$

$$\sim (141 \times 10^{-3}) [14.3] (1.73 \text{ Km})$$

EOHD ~ 3.5 Km

2. For Quadrupled YAG: 266 nm, 20 mJ @ 30 Hz, T = 60 seconds;

$$EOHD \sim (\tau_{aid})^{0.5} [d_{aid} / d_{lim}] \ NOHD$$

$$\sim (0.02)^{0.5} [50 \text{ mm} / 3.5 \text{ mm}] \ 2.46 \text{ Km}$$

$$\sim (141 \times 10^{-3}) [14.3] (2.46 \text{ Km})$$

EOHD ~ 4.96 Km

b. Summary Table

Table 14

Outdoor Operation (UV-1: Single Test)

(180 nm < λ < 302 nm) 60-Second Exposure

Wavelength (nm)	Output (mJ)	MPE (J/cm^2)	OD_{min}	NOHD (Km)	EOHD (Km)
180-302	10 @ 30 Hz	1.67×10^{-6}	**4.79**	**1.73**	**3.5**
266	20 @ 30 Hz	1.67×10^{-6}	**5.10**	**2.46**	**4.96**

B. UV Region (180 nm < λ < 400 nm) - Continued

1. UV-2 Region (315 nm < λ < 400 nm), Outdoor Operation

a. Appropriate MPE Determination for T = 60 Seconds

(1) Rule 1 (Single Pulse):

For exposures: 10^{-9} sec < t < 10 sec

$MPE_{s.p.}$ = min [photochemical limit, thermal limit] {Dual limit region}

= min [($0.56t^{0.25}$ J/cm^2), {$0.56t^{0.25}$ J/cm^2}] {*Table 5a* ANSI Std.}

Photochemical limit = Thermal limit

$= 0.56\ (2 \times 10^{-9})^{0.25}$ J/cm^2

$MPE_{s.p.} = 3.74 \times 10^{-3}$ J/cm^2

(2) Rule 2 (CW/pulse):

T = 60 seconds

n = PRF x T

= (30 sec^{-1}) (60 sec)

n = 1,800 pulses

$MPE_{/pulse} = MPE_{cw} / n$

MPE = 1 J/cm^2 for: 10 sec < T < 3×10^4 sec {*Table 5a* ANSI Std}

$MPE_{/pulse}$ = [1 J/cm^2] / 1.8×10^3

$MPE_{/pulse} = 556 \times 10^{-6}$ J/cm^2

(3) Rule 3 (Multiple-pulse):

Recall that Rule 3 applies to the **thermal limit only** [ANSI Std. Z136.1-2000 (8.2.3.1)].

$MPE_{m.p.} = C_p\ MPE_{s.p.}$ {Thermal limit form for MPE}

$C_p = n^{-0.25}$ {*Table 6* ANSI Standard.}

$= (PRF \times T)^{-0.25}$

$= [(30\ sec^{-1})\ (60\ sec)]^{-0.25}$

$= [1.8 \times 10^3]^{-0.25}$

$\mathbf{C_p = 0.154}$

$MPE_{m.p.} = (0.154)\ (3.74 \times 10^{-3}\ J/cm^2)$

$\mathbf{MPE_{m.p.} = 574 \times 10^{-6}\ J/cm^2}$

(4) Summary Table:

Table 15

Appropriate MPE (UV-2: Single Test Exposure)

($315\ nm < \lambda < 400\ nm$) 60-Second Exposure

ANSI Rule	MPE (J/cm^2)	Comment
1	3.74×10^{-3}	
2	$\mathbf{556 \times 10^{-6}}$	**Appropriate MPE**
3	574×10^{-6}	

b. Irradiance vs. MPE, Outdoor Operation

$E_o = Q_o / A_o$

1. For: 315 nm to 400 nm, 20 mJ @ 30 Hz, T = 60 Seconds, Outdoor Operation;

$E_o = 20 \times 10^{-3}\ J / [\pi\ (10.1\ cm)^2 / 4]$

$\mathbf{E_o = 250 \times 10^{-6}\ J/cm^2}$

2. For Tripled YAG: 355 nm, 35 mJ @ 30 Hz, T = 60 Seconds, Outdoor Operation;

$E_o = 35 \times 10^{-3}$ J / [π (10.1 cm)^2 / 4]

$$\mathbf{E_o = 437 \times 10^{-6}\ J/cm^2}$$

Table 16

Outdoor Operation: At Telescope Exit

(Single Test Exposure - 60 Seconds)

Wavelength (nm)	**Output (mJ)**	**MPE (J/cm^2)**	**E_o (J/cm^2)**	**Comments**
315-400	20	556×10^{-6}	250×10^{-6}	Eye-safe at telescope
355	35	556×10^{-6}	437×10^{-6}	Eye-safe at telescope

c. ODmin Calculation

Recall for **large beam** lasers, in terms of the Irradiance:

$$\mathbf{OD_{min} = \log_{10} (E_p/MPE)}$$

Where;

OD_{min} The minimum Optical Density for laser safety eyewear.

E_p The irradiance, of a beam larger than the limiting aperture, in joules per square centimeters.

MPE Appropriate MPE, in joules per square centimeters for laser and exposure conditions.

For the 101 mm diameter (10.1 cm) beam at the exit of the telescope:

1. For: 315 nm to 400 nm, 20 mJ @ 30 Hz, T = 60 seconds:

$OD_{min} = \log_{10} (250 \times 10^{-6}\ J/cm^2 / 556 \times 10^{-6}\ J/cm^2)$

$= \log_{10} (0.45^*)$

$OD_{min} = -0.347$

$$\mathbf{OD_{min} = 0.00}$$

* For logarithm arguments **less than 1**, the OD_{min} is then considered zero (Eye-Safe).

2. For Tripled YAG: 355 nm, 35 mJ @ 30 Hz, T = 60 seconds;

$OD_{min} = \log_{10} (437 \times 10^{-6}\ J/cm^2 / 556 \times 10^{-6}\ J/cm^2)$

$= \log_{10} (0.786^*)$

$OD_{min} = -0.105$

$$\mathbf{OD_{min} = 0.00}$$

* For logarithm arguments **less than 1**, the OD_{min} is then considered zero. (Eye-Safe)

The laser beam exiting the telescope remains eye-safe as long as the irradiance at the observer is less than the MPE. Assuming no focusing by outside elements the beam should remain "eye-safe" along the propagation path.

d. NOHD Calculation

1. For: 315 nm to 400 nm, 20 mJ @ 30 Hz, T = 60 seconds;

$NOHD = \theta^{-1} [(4Q_p / \pi\ MPE) - (d_{out})^2]^{0.5}$ cm

$= (500 \times 10^{-6})^{-1} [(8 \times 10^{-2}\ J / \pi\ 556 \times 10^{-6}\ J/cm^2) - (10.1\ cm)^2]^{0.5}$

$= (500 \times 10^{-6})^{-1} [45.8\ cm^2 - 102\ cm^2]^{0.5}$

$= (500 \times 10^{-6})^{-1} [\text{negative argument*}]^{0.5}$

$= 0.00$ cm

NOHD = 0.00 Km

* This negative value is caused by the exit irradiance being less than the MPE. For this calculation the value of the square root (negative number) is considered to be zero.

Recall that "authorized personnel" are required to wear the appropriate laser safety eyewear while in the NHZ (target area). The NOHD then would apply only to "unauthorized personnel" entering the NHZ or the target area with an accompanying possibility of exposure to the UV beam. It is assumed that any unauthorized entry (unauthorized exposure) would last for the entire duration of the specific laser test, would not reoccur on the same day and would not occur on successive days. Therefore the successive day de-rating factor (2.5) is not applied to the MPE in the NOHD calculation. The exposure, for a 60-second test, received by an unauthorized person would not pose a threat of ocular injury so long as the irradiance at the target area is below the MPE for the laser parameters (no re-focusing of the beam).

2. For Tripled YAG: 355 nm, 35 mJ @ 30 Hz, T = 60 seconds;

$$\text{NOHD} = \theta^{-1}\ [(4Q_p / \pi\ \text{MPE}) - (d_{out})^2\ ]^{0.5}\ \text{cm}$$

$$= (500 \times 10^{-6})^{-1}\ [(14 \times 10^{-2}\ \text{J} / \pi\ 556 \times 10^{-6}\ \text{J/cm}^2) - (10.1\ \text{cm})^2\ ]^{0.5}$$

$$= (500 \times 10^{-6})^{-1}\ [80.1\ \text{cm}^2 - 102\ \text{cm}^2\ ]^{0.5}$$

$$= (500 \times 10^{-6})^{-1}\ [\text{negative argument*}]^{0.5}$$

$$= 0.00\ \text{cm}$$

NOHD = 0.00 Km

* The negative argument is caused by the exit irradiance being less than the MPE.

Exposure of an unauthorized person to this laser output does not pose a threat of ocular injury, so long as the irradiance in the target area is less than the MPE for the laser conditions. Beam refocusing is not expected

a. <u>EOHD Approximation</u>

Recall that the EOHD is a function of the NOHD.

$$\text{EOHD} \sim f(\text{NOHD})$$

The EOHD is approximately equal to zero, for all conditions where the NOHD is equaled to zero.

b. Summary Table

Table 17

Outdoor Operation (UV-2: Single Test)

60-Second Exposure (315 nm < λ < 400 nm)

Wavelength (nm)	**Output (mJ) @ 30 Hz**	**MPE (J/cm2)**	**OD_{min}**	**NOHD (Km)**	**EOHD (Km)**
315-400	20	556×10^{-6}	0.00	0.00	0.00
355	35	556×10^{-6}	0.00	0.00	0.00

C. Visible Region (400 nm < λ < 700 nm)

HeNe Alignment Laser (λ = 633 nm)

1. Aversion Response (T = 0.25 seconds) MPE

a. MPE:

$MPE_{0.25sec} = 1.8\ t^{0.75} \times 10^{-3}\ J/cm^2$ {ANSI Std. *Table 5a*}
{18×10^{-6} sec < t < 10 sec}

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

$MPE = 636 \times 10^{-6}\ J/cm^2$

The CW MPE for the aversion response can be expressed as follows;

$MPE_{class\ 2cw} = MPE / T$

$= 636 \times 10^{-6}\ J/cm^2 / 0.25\ sec$

$MPE_{class\ 2\ cw} = 2.55 \times 10^{-3}\ w/cm^2$

2. Full Protection (T = 600 seconds) MPE

The MPE for this exposure is simply given as follows:

$MPE_{cw} = 1 \times 10^{-3}$ w/cm^2 {ANSI Std. *Table 5a*}
{10 sec < t < 3×10^4 sec}

Note: Full protection MPE applies to all exposures above 10 seconds.

3. MPE Summary Table

Table 18

Summary of MPE(s) For HeNe Exposure

Wavelength (nm)	**Output (mw)**	**Time (Seconds)**	**MPE (w/cm^2)**	**Comments**
633	15	0.25	2.55×10^{-3}	Aversion
633	15	600	1×10^{-3}	Alignment

4. AEL Determination for HeNe-red (633 nm)

Class 1 AEL = $MPE_{600sec}\ A_{lim}$

$= (MPE_{600sec})\ \pi\ (d_{lim})^2 / 4$

$= (1 \times 10^{-3}\ w/cm^2)\ \pi\ (\mathbf{0.7\ cm})^2 / 4$ {ANSI Std. *Table 8*}

$= (1 \times 10^{-3}\ w/cm^2)\ (0.385\ cm^2)$

Class 1 AEL = 385 x 10^{-6} w

Class 2 AEL = $MPE_{0.25}\ A_{lim}$

$= (MPE_{0.25})\ \pi\ (d_{lim})^2 / 4$

$= (2.55 \times 10^{-3}\ w/cm^2)\ \pi\ (\mathbf{0.7\ cm})^2 / 4$ {ANSI Std. *Table 8*}

$= (2.55 \times 10^{-3}\ w/cm^2)\ (0.385\ cm^2)$

Class 2 AEL = 982 x 10^{-6} w

5. <u>ODmin Calculation (Φ = 15 mw @ 633 nm)</u>

Protection for a 0.25-second exposure (Class 2 Laser Hazard):

$OD_{min} = \log_{10}$ (Φ / Class 2 AEL)

$OD_{min} = \log_{10} (15 \times 10^{-3}\ w / 982 \times 10^{-6}\ w)$

$OD_{min} = \log_{10} (15.3)$

$\mathbf{OD_{min} = 1.18}$

Protection for a 600-second exposure (Class 1 Laser Hazard):

$OD_{min} = \log_{10}$ (Φ / Class 1 AEL)

$OD_{min} = \log_{10} (15 \times 10^{-3}\ w / 385 \times 10^{-6}\ w)$

$OD_{min} = \log_{10} (39)$

$\mathbf{OD_{min} = 1.59}$

The Uvex ® Laser Safety Eyewear currently in use has an OD rating of 1-2 at 633 nm and offers adequate protection.

6. <u>NOHD Calculation for (Φ = 15 mw @ 633 nm)</u>

The appropriate MPE to use for this eye safe viewing distance determination is that used for the "aversion response" where, T = 0.25 seconds

$$NOHD = \theta^{-1} \left[(4\Phi_o / \pi\ MPE_{0.25}) - (d_{out})^2\right]^{0.5}\ cm$$

$$= (10^{-3})^{-1} \left[4\ (15 \times 10^{-3}\ w) / \pi\ (2.55 \times 10^{-3}\ w/cm^2) - (0.01\ cm)^2\right]^{0.5}$$

$$= (10^{-3})^{-1} \left[7.49\ cm^2 - 10^{-4}\ cm^2\right]^{0.5}$$

$$= (10^3)\ [2.74\ cm]$$

NOHD = 27.4 meters

7. <u>EOHD Approximation</u>

Recall that the viewing aid is assumed to be a standard 7 x 50 binocular and the ANSI Std. z136.1-2000 (*Table 8*) lists the diameter of the limiting aperture as 7 mm and *Table 9* lists the transmission factor for the visible region of the spectrum as **90%**.

$$EOHD \sim (\tau_{aid})^{0.5}\ [d_{aid} / d_{lim}]\ NOHD$$

$$\sim (0.9)^{0.5}\ [50\ mm / 7\ mm]\ 27.4\ meters$$

$$\sim (0.949)\ [7.14]\ 27.4\ meters$$

EOHD ~ 186 meters

8. Summary Table

Table 19

Outdoor Operations - Alignment (HeNe) Laser

(15 mw @ 633 nm)

Time (Seconds)	MPE (w/cm^2)	AEL (w)	OD_{min}	NOHD (meters)	EOHD (meters)
0.25	2.55×10^{-3}	982×10^{-6}	1.18	27.4	186
600	1×10^{-3}	385×10^{-6}	1.59	N/A	N/A

D. Infrared Region (1050 nm < λ < 1400 nm)

There is a remote possibility that a small portion of the fundamental output of the YAG (1 to 10 mJ @ 1064 nm) can be used as a range finder.

The standard exposure for this wavelength is 10 seconds.

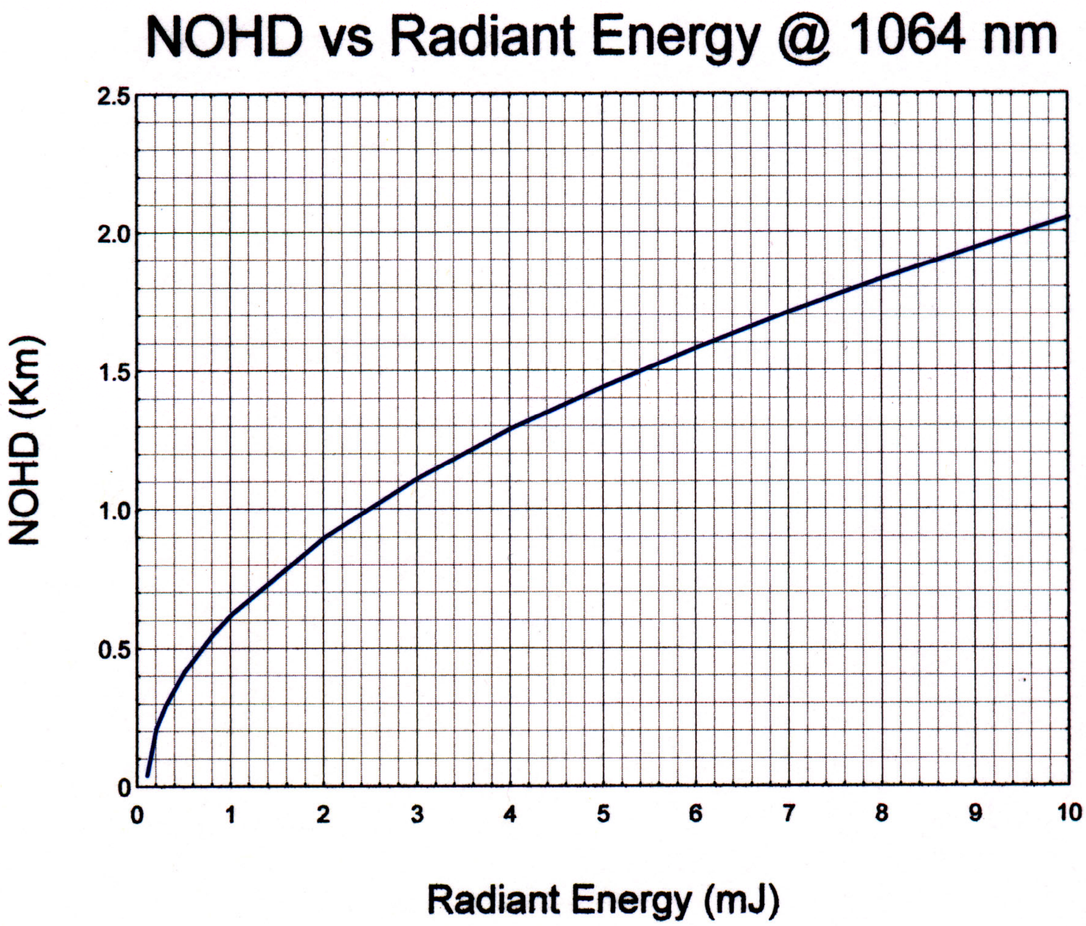
1. Appropriate MPE Determination

The MPE determined for the Indoor Operation is applicable for the Outdoor Operation because the standard exposure (10 second) is the same.

$$\mathbf{MPE = 1.2 \times 10^{-6}\ J/cm^2}$$

2. NOHD vs. Radiant Energy

The NOHD (in Kilometers) for a particular radiant energy (from ~1 to 10 mJ @ 30 Hz) can be read from the plot below.



3. <u>EOHD Approximation</u>

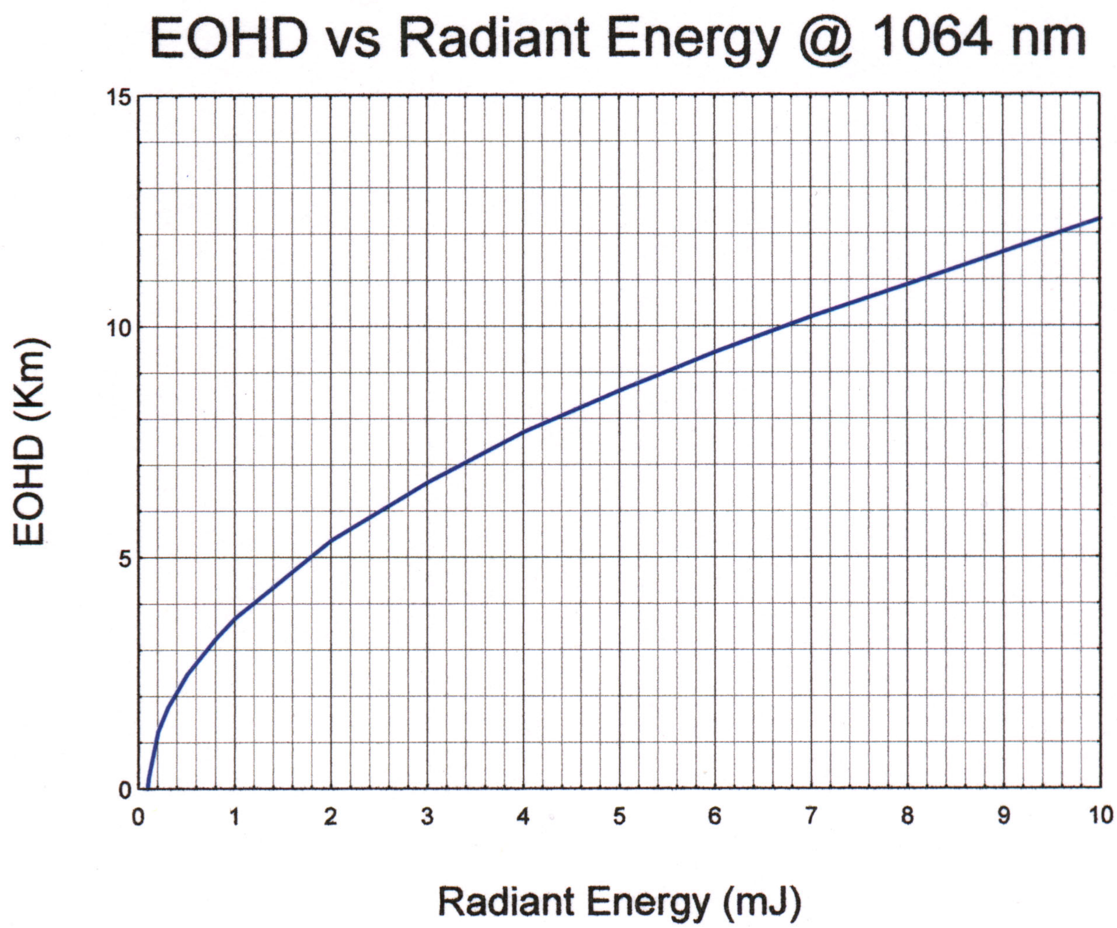
The EOHD can be approximated as a function of the NOHD.

$$EOHD \sim (\tau_{aid})^{0.5}\ [d_{aid} / d_{lim}]\ \ NOHD$$

Recall that the viewing aide is assumed to be a standard 7 x 50 binocular and the ANSI Std. Z136.1-2000 (*Table 8*) lists the diameter of the limiting aperture as 7 mm and *Table 9* lists the transmission factor for the near infrared region of the spectrum as **70%**.

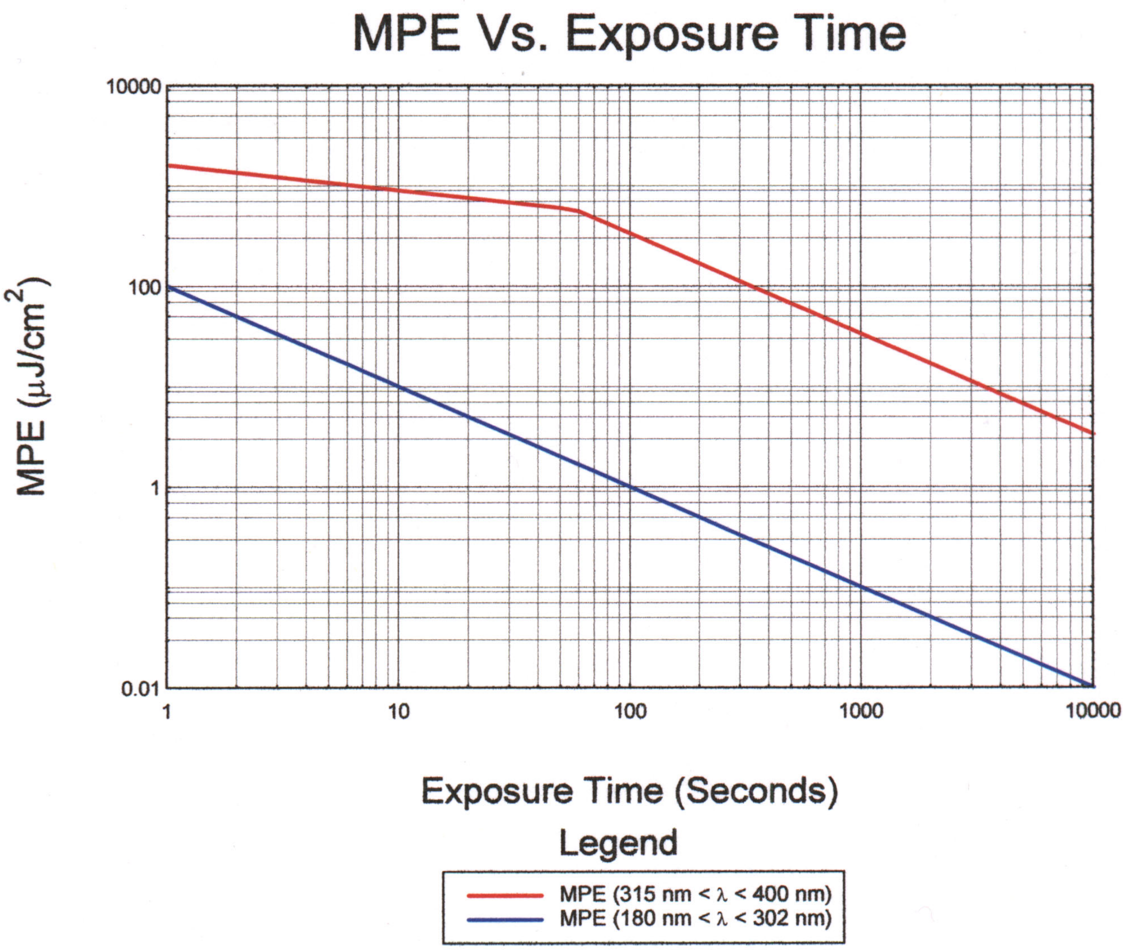
$$EOHD \sim (0.7)^{0.5}\ [50\ mm / 7\ mm]\ \ NOHD$$

$$EOHD \sim 5.98\ NOHD$$



E. UV Output Accumulative Effects

Unlike the visible or IR regions of the spectrum (which have standardized exposure times, 0.25 seconds and 10 seconds respectively) the UV exposure is an accumulative dose over 24 hours. As a result the MPE(s) and the NOHD(s) for the UV region will vary with the exposure time (laser event or the accumulative exposure time). The following plots present MPE(s) and NOHD(s) as a function of exposure time.

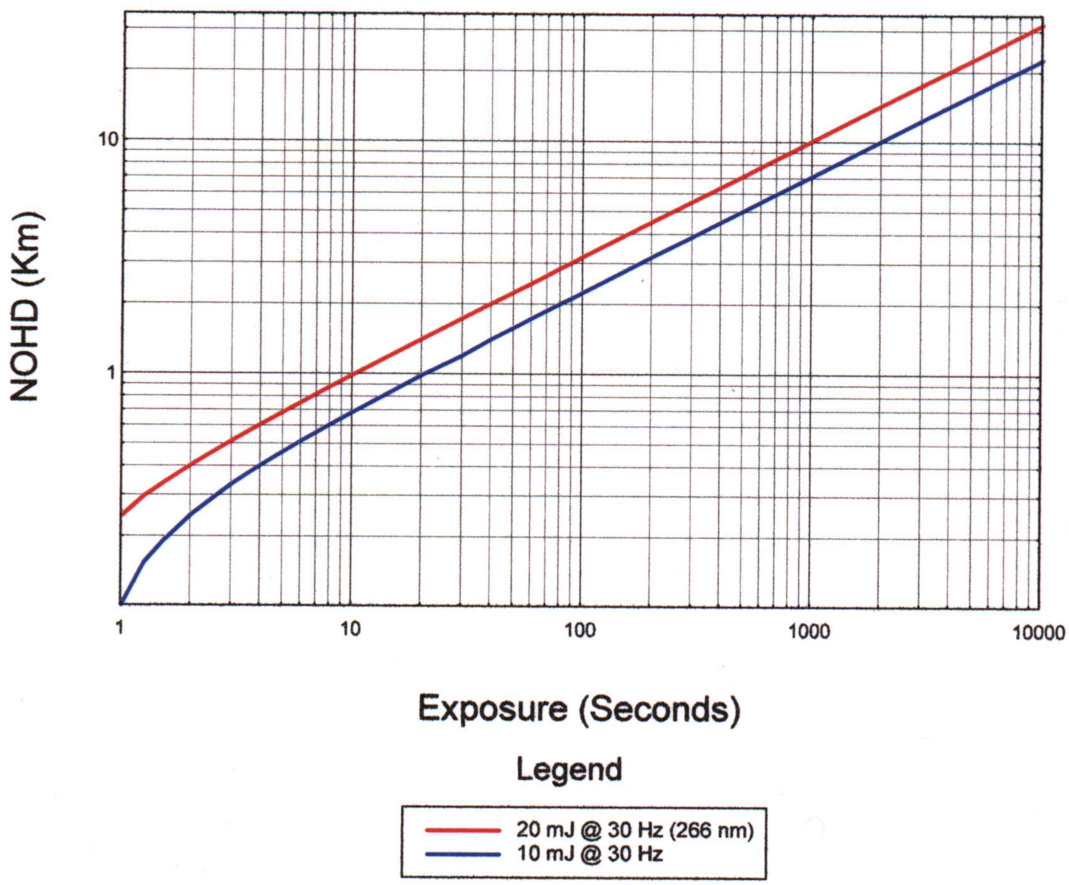


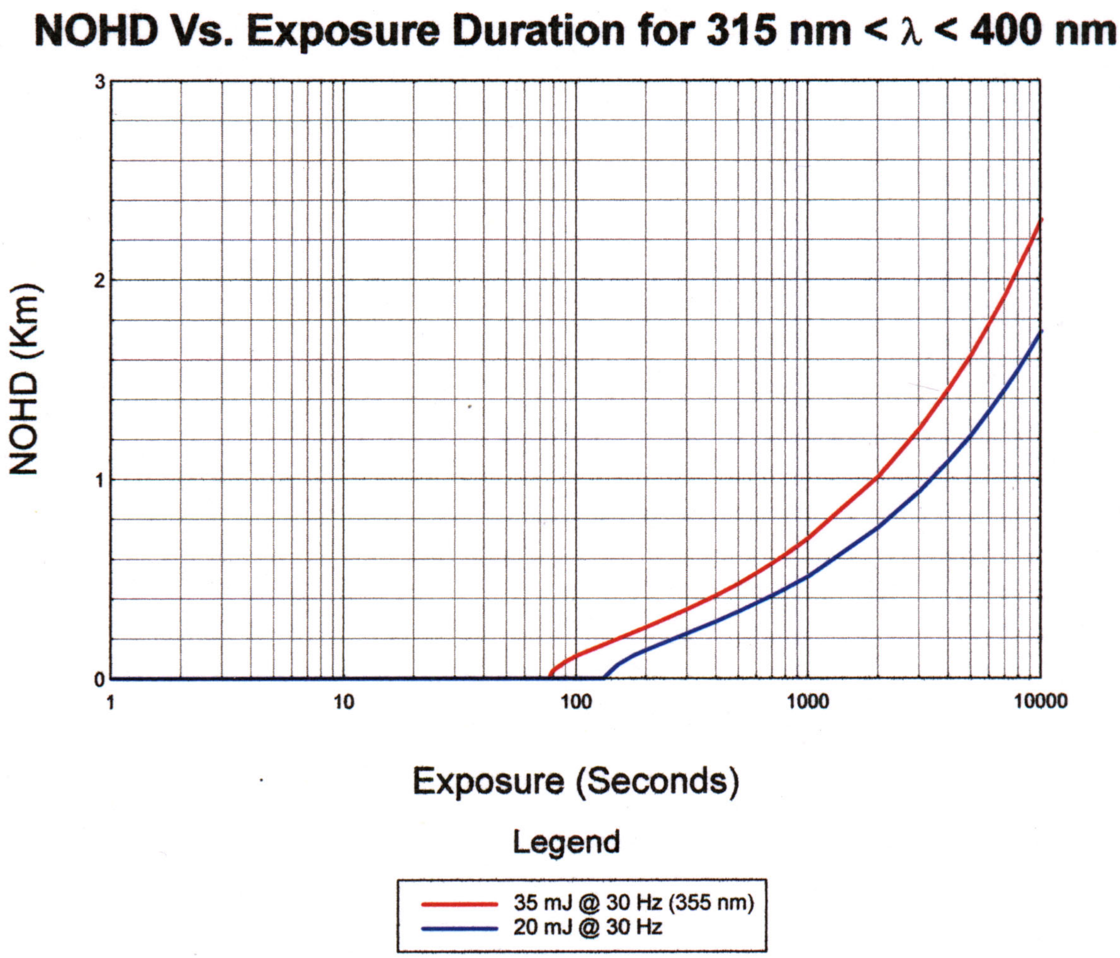
Note that the MPE for the region (315 nm < λ < 400 nm), at an exposure of ~58 seconds, changes from “Rule 3” determined to “Rule 2” determined as depicted by a change in the slope.

The NOHD(s) for exposures outside the expected 60-second test or for accumulative exposures can be read directly from the NOHD vs. Exposure plots below.

The NOHD(s) for exposures outside the expected 60-second test or for accumulative exposures can be read directly from the NOHD vs. Exposure plots below.

NOHD Vs. Exposure Duration for 180 nm < λ < 302 nm





NOHD Vs. Exposure Duration for 315 nm < λ < 400 nm
NOHD (Km)
3
2
1
0
1
10
100
1000
10000
Exposure (Seconds)
Legend
35 mJ @ 30 Hz (355 nm)
20 mJ @ 30 Hz

IV. References

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

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

Safety with Lasers and Other Optical Sources – A Comprehensive Handbook, Sliney, David and Wolbarsht, Myron, Plenum Press, New York and London, 5th Printing, August 1985.

SAND 2002-1315, May 2002, Approximation Methods for Estimating the Eye-Safe Viewing Distances, with or without Atmospheric Transmission Factors Considered, For Aided and Unaided Viewing Conditions, A. L. Augustoni.

V. Abbreviations & Symbols

AEL	Allowable Emission (Exposure) Limit
AF	Air Force
AFRL	Air Force Research Laboratory
A_{lim}	Area of limiting aperture
ANSI	American National Standards Institute.
C_p	Multiple pulse correction factor.
CW	Continuous wave.
d_{aid}	Entrance diameter of optical aid.
d_{exit}	Exit diameter of the telescope.
d_{lim}	Diameter of limiting aperture.
d_o	Output beam diameter.
E	Irradiance, in J/cm$^{2.}$
E_o	Output Irradiance, in J/cm$^{2.}$
EOHD	Extended Ocular Hazard Distance.
Hp	Irradiance of the beam over the limiting aperture.
Hz	Hertz, cycle per second, sec^{-1}.
J	Joules, unit of energy.
Min[a,b]	Minimum of value of a and b.
mJ	Millijoule, 10^{-3} Joules.
MPE	Maximum Permissible Exposure.
MPE	
MPE_{cw}	Continuous Wave Maximum Permissible Exposure.
$MPE_{/pulse}$	Per Pulse Maximum Permissible Exposure.
$MPE_{m.p.}$	Multiple Pulse Maximum Permissible Exposure.
$MPE_{s.p}$	Single Pulse Maximum Permissible Exposure.
mw	Milliwatts, 10^{-3} watts
nm	Nanometer, 10^{-9} meters.
NOHD	Nominal Ocular Hazard Distance.
ns	Nanosecond, 10^{-9} seconds.
NHZ	Nominal Hazard Zone.
OD	Optical Density of the laser safety eye ware.
OD_{min}	Minimum Optical Density required of laser safety eye ware.

PRF	Pulse Repetition Frequency.
Q	Radiant Energy, in Joules.
Q_o	Output Radiant Energy, in Joules.
t	Exposure duration, pulse duration
T	Exposure duration, in seconds.
w	Watts (unit of power)
α	Viewing angle.
θ	Beam divergence.
Φ	Radiant Power.
λ	Wavelength
μm	Micrometer, 10-6 meters.
τ	Transmission factor.
τ_{aid}	Transmission factor of optical aid
τ_{atm}	Atmospheric transmission factor.

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