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Approximation Methods for Estimating the Eye-Safe Viewing Distances, with or without Atmospheric Transmission Factors Considered, for Aided and Unaided Viewing Conditions

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Approximation Methods for Estimating the Eye-Safe Viewing Distances, with or without Atmospheric Transmission Factors Considered, for Aided and Unaided Viewing Conditions

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Abstract

Several first order approximation methods are presented with derivation. These formulae are convenient approximations, which can be used in the determination of *eye-safe* viewing distances for optical viewing aides (of various input diameters). First order approximations and methods are also presented for the determination of these *eye-safe* viewing distances while considering atmospheric transmission factors and conditions. These methods are applicable for both aided as well as unaided viewing conditions. These approximation methods can be used for both pulsed and CW lasers.

Introduction:

The determination of the *eye-safe* viewing distance, also known as the **Nominal Ocular Hazard Distance** (**NOHD**) is critical in a laser safety analysis for outdoor laser operations involving Class 3 or Class 4 lasers. The calculation of the NOHD is necessary for the determination of the **Nominal Hazard Zone** (**NHZ**) associated with the outdoor laser operation. Personnel who are inside the NHZ are at risk of injurious ocular exposure and are required, by the ANSI Std. z136.6, the use of eye protection. Whereas, personnel outside the NHZ are not at risk and therefore do not require the use of eye protection.

The determination of the NOHD for unaided viewing is presented in the ANSI z136 series standards. The calculation of NOHDs for unaided viewing is fairly straightforward. The appendix of ANSI Std. z136.1-2000 provides a formula to calculate this distance. There are, additionally, several laser safety computer programs (LAZAN and LHaz) available to accomplish this calculation, but these computer programs are limited to the unaided viewing condition only.

Generally, the unaided viewing condition for calculating the NOHD is adaquate in the determination of the laser's NHZ. However, there are situations were optical viewing aides, such as binoculars, telescopes and theodolites, are employed by personnel in the area of laser operations. These personnel can be directly involved with or incidental to these laser operations. This situation requires the calculation of the NOHD for aided viewing in the determination of the appropriate NHZ. The NOHD for aided viewing is also known as the **Extended Ocular Hazard Distance** and will hereafter be referred to as the **EOHD**.

Several field tests involving Sandia National Laboratories personnel required the use of optical viewing aids, such as binoculars, "Big Eye" telescopes and theodolites, by various personnel during laser operations. The NHZs for these particular tests required the calculation of EOHDs for aided viewing conditions. These calculations were complicated by the various input diameters (of the entrance or light collecting optic) for the particular optical viewing aid employed. Examples of these input diameters range from 50 mm, for binoculars, to 114 mm, for the "Big Eye". In situations where optical viewing aides of differing input diameters are employed, the viewing aid with the largest input diameter is used to determine the EOHD and therefore the NHZ for the laser operation.

Below are approximate formulae and the derivations for estimating the EOHD, for aided viewing conditions with a viewing aid of any diameter, d_{aid}. Note that many of the parameters necessary for these calculations are a function of the emitted wavelength of the laser. The parameters, which are dependent on or are a function of the wavelength, are: the **Maximum Permissible Exposure** (**MPE**), the diameter of the *limiting aperture*, the *transmission factor* of the optical aid system, and the **Class 1 Allowable Exposure Limit** (**AEL**). The "Class 1 AEL" will hereafter be referred to as the AEL. Additionally, the *atmospheric transmission factor* is also dependent on the emitted wavelength of the laser.

The MPE is, generally, calculated from the formulae presented in table 5a and table 6 of the ANSI Std. z136.1-2000. The governing rules for MPE determination are presented in section 8 of the ANSI z136.1-2000 standard and will not be covered in detail here. Values for the *"limiting aperture"* (in mm) are also presented in table 8 of this same ANSI standard. *Transmission factor* values, for various wavelength ranges, for optical viewing aid systems are presented in table 9 of the ANSI z136.1 standard as well.

The approximations presented below were initially developed for pulse lasers but are applicable to CW lasers as well. Formulae and definitions explicit to **continuous wave** (**CW**) lasers will be presented here *italicized* immediately after that formula specific to pulse lasers.

Summary of Formulae:

1. NOHD Determination for Unaided Viewing – No Atmospheric Transmission Condition Considered. (Also known as the *Range Equation* – ANSI Std. 136.1-2000 Appendix)

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

Where:
R_{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.

For CW lasers the following formula is applicable:

$$\boxed{R_{NOHD} = \theta^{1}\, [(4\Phi_p / \pi\, MPE_{cw}) - (d_{out})^2\,]^{0.5}}$$

Where:
R_{NOHD} *is the Nominal Ocular Hazard Distance, in centimeters.*
θ *is the beam divergence, in radians.*
Φ_p *is the laser output radiant power, in watts.*
MPE_{cw} *is the appropriate CW Maximum Permissible Exposure, in watts/cm^2.*
d_{out} *is the output beam diameter of the laser, in centimeters.*

2. NOHD Estimation for Unaided Viewing – No Atmospheric Transmission Condition Considered.

$$\boxed{R_{NOHD} \sim \theta^{-1}\ [4Q_p / \pi\ MPE\ ]^{0.5}\ \text{cm}}$$

Where:
R_{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.

For CW lasers the following formula is applicable:

$$\boxed{R_{NOHD} = \theta^{1}\ [4\Phi_p / \pi\, MPE_{cw}{}^{2}\ ]^{0.5}\ cm}$$

Where:
R_{NOHD} *is the Nominal Ocular Hazard Distance, in centimeters.*
θ *is the beam divergence, in radians.*
Φ_p *is the laser output radiant power, in watts.*
MPE_{cw} *is the appropriate CW Maximum Permissible Exposure, in watts/cm^2.*

Assumptions:

The above approximations are applicable to lasers with small output beam diameters, such that the following is true:

$$d_{out} < 1\ (\text{cm})$$

And for Class 3 or 4 lasers:

$$1 << 4Q_p / \pi\ MPE$$

And so:

$$(4Q_p / \pi\ MPE) >> 1 > (d_{out})^2$$

And for CW lasers:

$$(4\Phi_p / \pi\, MPE_{cw}) >> 1 > (d_{out})^2$$

Note:
These estimated distances are slightly greater than those calculated using the formulae presented in (1) above and therefore are more conservative in regard to laser safety.

3. EOHD Estimation (for Aided Viewing)- No Atmospheric Transmission Conditions Considered.

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

Where:

$\mathbf{R_{EOHD}}$ is the Extended Ocular Hazard Distance for aided viewing.

$\mathbf{R_{NOHD}}$ 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)*].

$\boldsymbol{\tau_{aid}}$ is the *transmission factor* through the optical viewing aid, [ANSI Std.z136.1-2000 (table 9)].

Note: Generally, $\tau_{aid} < 1$. For "worst case" estimate, use $\tau_{aid} = 1$.

* Table 8 lists diameters of the *limiting apertures*, in millimeters, and these must be converted to centimeters.

4. Atmospheric Transmission Factor Considered.

(a)

$$\boxed{\mathbf{R_{NOHD\text{-}atm} \sim (\tau_{atm})^{0.5}\ \ R_{NOHD}}}$$

(b)

$$\boxed{\mathbf{R_{EOHD\text{-}atm} \sim (\tau_{atm})^{0.5}\ \ R_{EOHD}}}$$

Where:

$\mathbf{R_{NOHD\text{-}atm}}$ is the Nominal Ocular Hazard distance for atmospheric transmission conditions considered.

$\mathbf{R_{EOHD\text{-}atm}}$ is the Extended Ocular Hazard distance for atmospheric transmission conditions considered.

$\mathbf{R_{NOHD}}$ is the Nominal Ocular Hazard distance (determined to provide a range estimate).

$\mathbf{R_{EOHD}}$ is the Extended Ocular Hazard distance (determined to provide a range estimate).

$\boldsymbol{\tau_{atm}}$ is the atmospheric *transmission factor* estimate for the range estimated by R_{EOHD}.

Note: Generally, $\tau_{atm} < 1$. For "worst case" estimate, use $\tau_{atm} = 1$.

Notes to the above expression:

This procedure can be used to estimate the *eye-safe* viewing distance, either for NOHD (unaided viewing) or EOHD (aided viewing) with atmospheric transmission factors considered:

a. Use either equation (1) or (2) above to arrive at a *range estimate* (no atmospheric transmission factor considered). This distance can be arrived at by computer program as well.
b. Use this *range estimate* in turn to estimate an atmospheric transmission factor (from atmospheric transmission curves, tables or charts).
c. The *transmission factor* is then applied in equation (3a or 3b) to arrive at an estimate for the *eye-safe* viewing distance for that particular viewing condition with atmospheric transmission factors considered.

Derivation of the Safe Viewing Distance for Optical Viewing Aids:

The appendix of the ANSI z136.1-2000 standard presents the following formula for determining the range of the NOHD for unaided viewing conditions (specific for pulsed lasers):

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

—

Where:
R_{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 at the laser, in centimeters.

Derivation:

The **radiant exposure**, **H**, (energy density) of the propagating beam at **range**, **R**, can be expressed as the ratio of the **radiant energy**, **Q**, (laser pulse energy) to the cross-sectional **area**, **A**, of the laser beam at that range.

$$H_R = Q_R / A_R \quad \text{joules/cm}^2$$

Where:

H_R is the radiant exposure, in joules/cm^2, at range, R.
Q_R is the radiant energy, in joules, at range, R.
A_R is the cross-section area of the laser beam, in cm^2, at range, R.

Notes and Assumptions:

1. The symbols used here are generally the same as those presented in Appendix B2 of ANSI Std. z136.1-2000.
2. The radiant exposure is assumed to be uniform across the laser beam cross-sectional area.
3. The radiant energy is assumed to be constant pulse to pulse.

Assume no atmospheric transmission losses, such that:

$$Q_R = Q_p$$

Where:

Q_R is the radiant energy, in joules, at range, R.
Q_p is the laser output radiant energy, in joules.

So, the radiant exposure, H_R, at range, R, can be expressed as:

$$H_R = Q_p / A_R \quad \text{joules/cm}^2$$

Where:

H_R is the radiant exposure, in joules/cm^2, at range, R.
Q_p is the laser output radiant energy, in joules.
A_R is the cross-section area of the laser beam, in cm^2, at range, R.

*Likewise for CW lasers the **irradiance, E,** (power density), at range, R, can be expressed as follows:*

$$E_R = \Phi_p / A_R \quad \text{watts/cm}^2$$

Where:

E_R *is the irradiance, in watts/cm^2, at range, R,.*
Φ_p *is the radiant power, in watts, at the exit of the laser.*
A_R *is the cross-section area of the laser beam, in cm^2, at range, R.*

The cross-sectional area of a circular laser beam at range, R, can be expressed as:

$$A_R = \pi \, (d_R)^2 / 4 \quad cm^2$$

Where:
A_R is the cross-section area of the laser beam, in cm^2, at range, R.
d_R is the cross-sectional diameter, in centimeters, at range, R.

Due to the divergence of the laser beam, the laser beam diameter generally expands as a function of the distance from the laser (also known as the range). The diameter of the beam at range, R, can be determined by:

$$d_R = \theta R + d_{out} \quad cm$$

Where:
θ is the beam divergence, in radians.
R is the range, in centimeters.
d_{out} is the output beam diameter at the laser, in centimeters.
d_R is the diameter, in centimeters, of the laser beam at range, R.

The cross-sectional area of the laser beam at range, R, can, then be expressed as:

$$A_R = \pi \, (\theta R + d_{out})^2 / 4 \quad cm^2$$

The radiant exposure, H_R, of the laser beam at range, R, then can be expressed as:

$$H_R = Q_p / [\pi \, (\theta R + d_{out})^2 / 4] \quad joules/cm^2$$

Simplified, the radiant exposure at range, R, can be expressed as:

$$H_R = 4Q_p / \pi \, (\theta R + d_{out})^2 \quad joules/cm^2$$

Where:
H_R is the radiant exposure, in joules/cm^2, at range, R.
Q_p is the laser output radiant energy, in joules.
θ is the beam divergence, in radians.
R is the range, in centimeters.
d_{out} is the output beam diameter at the laser, in centimeters.

For CW lasers the expression for the irradiance at range, R, is:

$$E_R = 4\Phi_p / \pi\,(\theta R + d_{out})^2 \qquad watts/cm^2$$

Where:

$\boldsymbol{E_R}$	*is the irradiance, in watts/cm², at range, R.*
$\boldsymbol{\Phi_p}$	*is the radiant power, in watts, at the exit of the laser.*
$\boldsymbol{\theta}$	*is the beam divergence, in radians.*
$\boldsymbol{R}$	*is the range, in centimeters.*
$\boldsymbol{d_{out}}$	*is the output beam diameter at the laser, in centimeters.*

Let the radiant exposure, H_R, at a range, R_{NOHD}, be equal to the Maximum Permissible Exposure (MPE), calculated from the values in table 5a and table 6 of the ANSI z136.1 standard. Then at the *eye-safe* viewing distance (Nominal Ocular Hazard Distance), NOHD or R_{NOHD}, the radiant exposure, H_{NOHD}, is defined to be:

$$H_{NOHD} = MPE \qquad joules/cm^2$$

Likewise for CW lasers, the irradiance at range, R_{NOHD}, is defined to be the CW MPE:

$$E_{NOHD} = MPE_{cw} \qquad watts/cm^2$$

The radiant exposure at the NOHD, is related to the radiant energy and the beam area as follows:

$$H_{NOHD} = MPE = 4Q_p / \pi\,(\theta R_{NOHD} + d_{out})^2 \qquad joules/cm^2$$

Such that the MPE is equated to the energy density at range, R_{NOHD}:

$$MPE = 4Q_p / \pi\,(\theta R_{NOHD} + d_{out})^2 \qquad joules/cm^2$$

Rearrange terms:

$$\pi\,(\theta R_{NOHD} + d_{out})^2 = 4Q_p / MPE$$

And divide both sides of the equality by π:

$$(\theta R_{NOHD} + d_{out})^2 = 4Q_p / \pi\, MPE$$

Take the square root of both sides of the equality:

$$\theta R_{NOHD} + d_{out} = [4Q_p / \pi \text{ MPE}]^{0.5}$$

Rearrange terms:

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

Combine terms under the same square root:

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

Divide both sides of the equality by θ, finally yields:

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

For CW lasers this can be expressed as follows:

$$R_{NOHD} = \theta^{1} [(4\Phi_p / \pi MPE_{cw}) - (d_{out})^2]^{0.5} \; cm$$

These are known as the *Range Equations* and are presented in the appendix of the ANSI z136.1 & .6-2000 standards.

The **Class 1 Allowable Exposure Limit** (**AEL**) is related to the MPE and the area of the *limiting aperture* as follows [ANSI Std. z136.1-2000 (3.2.3.4)(2)]:

$$\text{AEL} = (\text{MPE}) (A_{lim}) \quad \text{joules}$$

Where:
AEL is the Allowable Exposure Limit, in joules.
MPE is the appropriate per pulse Maximum Permissible Exposure, in joules/cm^2.
$\mathbf{A_{lim}}$ is the area of the *limiting aperture*, in cm^2.

For CW lasers:

$$AEL = (MPE_{cw}) (A_{lim}) \quad watts$$

Where:
AEL *is the Allowable Exposure Limit, in watts.*
$\boldsymbol{MPE_{cw}}$ *is the appropriate CW Maximum Permissible Exposure, in watts/cm^2.*
$\boldsymbol{A_{lim}}$ *is the area of the limiting aperture, in cm^2.*

In terms of the diameter of the *limiting aperture,* d_{lim} :

$$AEL = MPE\ [\pi (d_{lim})^2 / 4] \quad \text{joules}$$

Where:

AEL is the Allowable Exposure Limit, in joules.

MPE is the appropriate per pulse Maximum Permissible Exposure, in joules/cm^2.

$\mathbf{d_{lim}}$ is the diameter, in centimeters, of the *limiting aperture* (given in table 8 of the ANSI z136.1 standard).

The radiant exposure, H_{EOHD}, at range, R_{EOHD}, for *eye-safe* aided viewing (transmission factors not considered) is defined to be:

$$H_{EOHD} = AEL / A_{aid} \quad \text{joules/cm}^2$$

And in terms of the **input diameter** (the diameter of the entrance or light collecting optic), $\mathbf{d_{aid}}$, of the optical viewing aid:

$$H_{EOHD} = AEL / [\pi (d_{aid})^2 / 4] \quad \text{joules/cm}^2$$

Where:

$\mathbf{H_{EOHD}}$ is the radiant exposure at range, R_{EOHD}, in joules/cm^2.

AEL is the Allowable Exposure Limit, in joules.

$\mathbf{d_{aid}}$ is the input diameter of the optical viewing aid, in centimeters.

Recall that the AEL is the product of the MPE and the Area of the *limiting aperture*:

$$AEL = MPE\ [\pi (d_{lim})^2 / 4] \quad \text{joules}$$

And substitute for the expression for the AEL term in the H_{EOHD} expression above:

$$H_{EOHD} = MPE\ [\pi (d_{lim})^2 / 4] / [\pi (d_{aid})^2 / 4] \quad \text{joules/cm}^2$$

And simplify terms:

$$H_{EOHD} = MPE\ (d_{lim})^2 / (d_{aid})^2 \quad \text{joules/cm}^2$$

Recall that the *Range Equation*, for unaided the *eye-safe* viewing distance is:

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

And recall that the radiant exposure at the *eye-safe* viewing distance:

$$H_{NOHD} = MPE$$

The *eye-safe* unaided viewing distance can be expressed as:

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

So the *eye-safe* viewing distance for aided viewing can be related to the radiant exposure at that distance expressed in the form of the *Range Equation*.

$$\mathbf{R_{EOHD} = \theta^{-1}\ [(4Q_p / \pi\ H_{EOHD}) - (d_{out})^2\ ]^{0.5}\quad cm^*}$$

<u>Where</u>:

R_{EOHD} is the Extended Ocular Hazard Distance, in centimeters, for <u>aided</u> viewing.
Q_p is the laser output radiant energy, in joules.
θ is the beam divergence, in radians.
H_{EOHD} is the radiant exposure, in joules/cm^2, at the *eye-safe* <u>aided</u> viewing distance, R_{EOHD}.
d_{out} is the output beam diameter at the laser, in centimeters.

Likewise for CW lasers:

$$R_{EOHD} = \theta^{1}\ [(4\Phi_p / \pi\ E_{EOHD}) - (d_{out})^2\ ]^{0.5}\quad cm^*$$

<u>Where</u>:

R_{EOHD} *is the Extended Ocular Hazard Distance for <u>aided</u> viewing.*
Φ_p *is the output Radiance, in watts.*
θ *is the beam divergence.*
E_{EOHD} *is the irradiance, in watts/cm^2, at the eye-safe <u>aided</u> viewing distance, R_{EOHD}.*
d_{out} *is the output beam diameter at the laser, in centimeters.*

*Note: Since this is of the form of the *Range Equation* it will be referred to as the *Range Equation for <u>aided</u> viewing*.

Recall from earlier:

$$H_{EOHD} = MPE\,[(d_{lim})^2 / (d_{aid})^2\,] \qquad \text{joules/cm}^2$$

And applied to the *Range Equation for* <u>*aided*</u> *viewing* above yields:

$$R_{EOHD} = \theta^{-1}\,[\{4Q_p / \pi\,MPE\,[(d_{lim})^2 / (d_{aid})^2\,]\} - (d_{out})^2\,]^{0.5} \quad \text{cm}$$

Simplify the expression:

$$R_{EOHD} = \theta^{-1}\,[\{4Q_p\,(d_{aid})^2 / \pi\,MPE\,(d_{lim})^2\} - (d_{out})^2\,]^{0.5} \quad \text{cm}$$

Separating the "d_{aid} / d_{lim}" term from the square root:

$$R_{EOHD} = \theta^{-1}\,[d_{aid} / d_{lim}]\;\; [(4Q_p / \pi\,MPE) - \{(d_{lim})^2\,(d_{out})^2 / (d_{aid})^2\}]^{0.5}\,\text{cm}$$

For small exit beam diameters, such as $d_{out} < 1$ cm, generally the following conditions hold true:

$$d_{lim} < 1 \;\;\&\;\; (d_{lim})^2 < 1$$

$$d_{aid} > 1 \;\&\;\; (d_{aid})^2 < < 1$$

Recall that for Class 3 and Class 4 lasers the following is true:

$$1 << \;4Q_p / \pi\,MPE$$

$$(d_{lim})^2\,(d_{out})^2 / (d_{aid})^2 < < 1 << \;4Q_p / \pi\,MPE$$

$$(d_{out})^2 \;<\;\; 1 << \;4Q_p / \pi\,MPE$$

Hence the following two approximations can be made:

$$\mathbf{[\;4Q_p / \pi\,MPE\;]} \sim [(4Q_p / \pi\,MPE) - \{(d_{lim})^2\,(d_{out})^2 / (d_{aid})^2\}]$$

And:

$$\mathbf{[\;4Q_p / \pi\,MPE\;]} \sim [(4Q_p / \pi\,MPE) - (d_{out})^2\,]$$

Apply these approximations to the *Range Equations* above. So, the expression for the *eye-safe* viewing distance (R_{NOHD}), *Range Equation* for unaided viewing can be approximated by:

$$R_{NOHD} \sim \theta^{-1} [\, 4Q_p / \pi \text{ MPE} \,]^{0.5} \quad \text{cm}$$

And for CW lasers this distance can be expressed as:

$$R_{NOHD} \sim \theta^{-1} [\, 4\Phi_p / \pi\, MPE_{cw} \,]^{0.5} \quad cm$$

Likewise, the *eye-safe* viewing distance (R_{EOHD}) for the aided viewing condition can then be approximated by the following expression:

$$\mathbf{R_{EOHD} \sim [d_{aid} / d_{lim}] \; \{\theta^{-1} [\, 4Q_p / \pi \text{ MPE} \,]^{0.5}\} \quad cm}$$

Applied to CW lasers:

$$R_{EOHD} \sim [d_{aid} / d_{lim}] \; \{\theta^{-1} [4\Phi_p / \pi\, MPE_{cw}]^{0.5}\} \quad cm$$

The *eye-safe* viewing (Extended Ocular Hazard) Distance for aided viewing conditions can be related to the *eye-safe* viewing distance for unaided viewing, by the ratio of the input diameter of the optical viewing aid to the diameter of the *limiting aperture* and can be approximated by the following expression:

$$\mathbf{R_{EOHD} \sim [d_{aid} / d_{lim}] \; R_{NOHD}}$$

Where:
R_{EOHD} is the Extended Ocular Hazard Distance for aided viewing, in centimeters.
R_{NOHD} is the Nominal Ocular Hazard Distance for unaided viewing, in centimeters.
d_{aid} is the input diameter of the optical viewing aid, in centimeters.
d_{lim} is the diameter of the *limiting aperture*, in centimeters, [ANSI Std.z136,1-2000 (table 8)].

Note.
1. Transmission losses through the optical viewing aid or atmospheric transmission loss factors are not considered.
2. The ratio, $[d_{aid} / d_{lim}]$, can be considered a scale factor to the unaided *eye-safe* distance.

Derivation of the Safe Viewing Distance for Optical Viewing Aids with Optic Transmission Loss Considered:

The ANSI standard allows for the consideration of optical transmission losses through optical viewing systems. These transmission losses are approximated, for various wavelength bands, and are presented as *transmission factors* in table 9 of the current ANSI z136.1 standard.

Recall that the radiant exposure, H, (energy density) of the laser beam at range, R, can be expressed as:

$$H_R = Q_R / A_R \quad \text{joules/cm}^2$$

Where:

H_R is the radiant exposure, in joules/cm^2, at range, R.
Q_R is the radiant energy, in joules, at range, R.
A_R is the cross-section area, in cm^2, of the beam at range, R.

For aided viewing at range, R, the radiant exposure at the entrance of the optical viewing aid is:

$$H_{aid} = Q_{aid} / A_{aid}$$

Where:

H_{aid} is the radiant exposure, in joules/cm^2, at the entrance to the optical viewing aid.
Q_{aid} is the radiant energy, in joules, at the entrance to the optical viewing aid.
A_{aid} is the cross-section area, in cm^2, of the input optic of the viewing aid.

Assume the radiant exposure is uniform across the laser beam then, the radiant exposure at range, R, is equal to the radiant exposure at the entrance to the optical viewing aid at that same range.

$$H_{aid} = H_R$$

And so:

$$Q_{aid} / A_{aid} = Q_R / A_R$$

Assume no atmospheric transmission losses, then the radiant energy at range, R, is equal to the radiant energy exiting the laser.

This can be expressed as follows:

$$Q_R = Q_p$$

Where:

Q_p is the laser output radiant energy, in joules.
Q_R is the radiant energy, in joules, at range, R.

And so, the radiant energy entering the optical viewing aid can be expressed as:

$$Q_{aid} = Q_R \, [A_{aid} / A_R]$$

The radiant energy, Q_τ, transmitted through the optical viewing aid can be expressed as:

$$Q_\tau = \tau_{aid} \, Q_{aid} \quad \text{joules}$$

Where:

Q_τ is the transmitted energy, in joules, at the exit of the optical viewing aid.
Q_{aid} is the radiant energy, in joules entering the optical viewing aid.
τ_{aid} is the *transmission factor* for the optical aid given in table 9 of the ANSI z136.1 standard.

For CW lasers the following is applicable:

$$\Phi_\tau = \tau_{aid} \, \Phi_{aid} \quad \textit{watts}$$

Where:

Φ_τ *is the transmitted power, in watts, at the exit of the optical viewing aid.*
Φ_{aid} *is the power, in watts entering the optical viewing aid.*
τ_{aid} *is the transmission factor for the optical aid given in table 9 of the ANSI z136.1 standard.*

Note:
It is assumed that all the transmitted or exiting radiant energy (or power) enters the viewer's eye. "No correction for homogeneity", of the beam, "is necessary in cases where the entire beam enters the effective limiting aperture" [ANSI Std. z136.1-2000 (9.2.2.1)].

For *eye-safe* exposure, define the transmitted radiant energy at the exit of the optical aid to be no higher than the AEL. Therefore the largest *eye-safe* transmitted radiant energy is:

$$Q_\tau = AEL = \tau_{aid} \, Q_{aid} \quad \text{joules}$$

Then, the radiant energy at the entrance of the optical aid, for *eye-safe* condition, can be allowed to be as high as:

$$Q_{aid} = AEL / \tau_{aid} \qquad \text{joules}$$

Assume all the radiant energy transmitted through the optical viewing aid is available for an ocular exposure and that <u>all</u> the transmitted radiant energy enter the viewer's eye. Recall from earlier that the radiant exposure at the *eye-safe* range, R_{EOHD}, for aided viewing is equal to the radiant exposure at the entrance to the optical aid at that range:

$$H_{aid} = H_{EOHD}$$

$$H_{aid} = Q_{aid} / A_{aid} = H_{EOHD}$$

Recall that the radiant energy entering the optical viewing aid can be allowed to be as high as:

$$Q_{aid} = AEL / \tau_{aid} \qquad \text{joules}$$

For CW lasers, the radiant power can be allowed to be as high as:

$$\Phi_{aid} = AEL / \tau_{aid} \qquad \textit{watts}$$

Combine this term for the radiant energy entering the optical viewing aid with the radiant exposure expression, at the entrance of the optical viewing aid (expressed above) then, the radiant exposure can be expressed as:

$$H_{EOHD} = [AEL / \tau_{aid}] / A_{aid}$$

Hence, the radiant exposure, H_{EOHD}, at the entrance of the optical viewing aid, at the *eye-safe* range, R_{EOHD}, can be simplified as follows:

$$H_{EOHD} = AEL / \tau_{aid} A_{aid} \qquad \text{joules/cm}^2$$

And recall that the AEL is defined as [ANSI Std. z136.1-2000 (3.2.3.4.1)(2)]:

$$AEL = MPE (A_{lim}) \qquad \text{joules}$$

Then the radiant exposure, H_{EOHD}, at the *eye-safe* aided viewing distance, R_{EOHD}, can be expressed as:

$$H_{EOHD} = MPE\ (A_{lim}) / \tau_{aid}\ A_{aid} \quad \text{joules/cm}^2$$

In terms of the relative diameters, the radiant exposure at the *eye-safe* aided viewing distance can be expressed as:

$$H_{EOHD} = MPE\ (d_{lim})^2 / \tau_{aid}\ (d_{aid})^2 \qquad \text{joules/cm}^2$$

Recall that the *Range Equation for aided viewing* is:

$$R_{EOHD} = \theta^{-1}\ [\ (4Q_p / \pi\ H_{EOHD}) - (d_{out})^2\ ]^{0.5} \quad \text{cm}$$

And the radiant exposure at the EOHD:

$$H_{EOHD} = MPE\ (d_{lim})^2 / \tau_{aid}\ (d_{aid})^2 \quad \text{joules/cm}^2$$

Substitute for H_{EOHD} term in the *Range Equation for aided viewing* yields:

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

Rearranged the terms as follows:

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

$$R_{EOHD} = (\tau_{aid}\ )^{0.5}\ [d_{aid} / d_{lim}]\ (\theta^{-1})\ [\ (4Q_p / \pi\ MPE) - \{(d_{lim})^2 (d_{out})^2 / (\tau_{aid}\ )(d_{aid})^2\}]^{0.5}$$

From the previous approximations:

$$[(d_{lim})^2\ (d_{out})^2 / (\tau_{aid}\ )\ (d_{aid})^2\ ] << [4Q_p / \pi\ MPE]$$

And:

$$[4Q_p / \pi \text{ MPE}] \sim [4Q_p / \pi \text{ MPE} - \{(d_{lim})^2 (d_{out})^2 / (\tau_{aid}) (d_{aid})^2\}]$$

Applied in the *Range Equation for* *aided* *viewing*:

$$R_{EOHD} = (\tau_{aid})^{0.5} [d_{aid} / d_{lim}] (\theta^{-1}) [(4Q_p / \pi \text{ MPE}) - \{(d_{lim})^2 (d_{out})^2 / (\tau_{aid}) (d_{aid})^2\}]^{0.5}$$

Yields:

$$R_{EOHD} \sim (\tau_{aid})^{0.5} [d_{aid} / d_{lim}] \ \boldsymbol{(\theta^{-1}) [4Q_p / \pi \text{ MPE}]^{0.5}}$$

Applied to CW lasers:

$$R_{EOHD} \sim (\tau_{aid})^{0.5} [d_{aid} / d_{lim}] \ \boldsymbol{(\theta^{1}) [4\Phi_p / \pi MPE_{cw}]^{0.5}}$$

Recall that the unaided *eye-safe* viewing distance, R_{NOHD}, has been approximated as:

$$R_{NOHD} \sim \boldsymbol{\theta^{-1} [4Q_p / \pi \text{ MPE}]^{0.5}} \text{ cm}$$

Likewise, for CW lasers:

$$R_{NOHD} \sim \boldsymbol{\theta^{1} [4\Phi_p / \pi MPE_{cw}]^{0.5}} \ cm$$

Then the *eye-safe* aided viewing distance, $\mathbf{R_{EOHD}}$, (in the same units as the unaided distance), applicable to CW as well as pulsed lasers, can be expressed as follows:

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

Where:
R_{EOHD} is the Extended Ocular Hazard Distance for aided viewing.
R_{NOHD} is the Nominal Ocular Hazard Distance for unaided viewing.
d_{aid} is the input diameter of the optical viewing aid, in centimeters.
d_{lim} is the diameter of the *limiting aperture**, in centimeters.
τ_{aid} is the *transmission factor* through the optical viewing aid.

*[ANSI Std. z136.1-2000 (table 8)]

Derivation of the *Eye-Safe* Viewing Distance, With Atmospheric Transmission Factors Considered.

A laser beam transmission through the atmosphere can undergo losses in intensity. These losses are primarily due to atmospheric absorption and scatter effects. This attenuation consists of Mie and Rayleigh scatter and molecular absorption. The degree to which these factors effect the transmission of the laser beam vary depending upon atmospheric conditions, location, the direction of propagation (up or down), as well as the altitude of the propagation, the degree to which particulates and water vapor are present. These can change throughout the day, and from day to day, depending on local weather conditions. Generally, atmospheric transmission losses are only considered for laser beam propagation over several kilometers. However, even for clear weather and clean air these atmospheric transmission factors will have an effect on the laser beam's intensity for laser beam propagations over several kilometers.

Other atmosphere-laser beam interaction effects experienced by "extreme" Class 4 lasers (very high intensity lasers) are: thermal blooming (associated with high power CW lasers) and kinetic cooling (associated with high energy pulsed lasers). Additionally, *air breakdowns*, plasma and filament formation, along the beam path have a major effect on the intensity of the transmitted laser beam. All of these are **non-linear effects** and will not be addressed here. The subsequent analysis is limited only to those lasers (Class 3 and Class 4) that do not produce sufficient intensity to initiate these non-linear atmospheric effects.

Generally, the intensity of the transmitted laser beam, as a function of the distance traveled or range, R, can be express as:

$$I_R = I_o\, e^{-(\alpha + s)R}$$

Where:

I_R is the intensity at range, R.
I_{out} is the intensity at the exit of the laser.
α is coefficient of molecular absorption.
s is the coefficient of scatter.
R is the range or distance of laser beam travel.

And in terms of radiant energy:

$$Q_R = Q_p\, e^{-(\alpha + s)R}$$

Where:

Q_R is the radiant energy, in joules, at range, R.
Q_p is the laser output radiant energy, in joules.
α is coefficient of molecular absorption.
s is the coefficient of scatter.
R is the range or distance of laser beam travel.

Or in terms of radiant power applicable to CW lasers:

$$\Phi_R = \Phi_p\, e^{-(\alpha + s)R}$$

Where:

Φ_R *is the radiant power, in watts, at range, R.*
Φ_p *is the radiant power, in watts, at the exit of the laser.*
α *is coefficient of molecular absorption.*
s *is the coefficient of scatter.*
R *is the range or distance of laser beam travel.*

The **atmospheric *transmission factor***, τ_{atm}, can be expressed as the ratio of the beam intensity at the range, r to the intensity at the exit of the laser.

$$\tau_{atm} = I_R / I_{out} = e^{-(\alpha + s)R}$$

Likewise, the atmospheric *transmission factor,* τ_{atm}, can be expressed as the ratio of the radiant energy at the range, R to the radiant energy at the exit of the laser.

$$\tau_{atm} = Q_R / Q_p = e^{-(\alpha + s)R}$$

Where:
Q_R is the radiant energy, in joules, at range, R.
Q_p is the laser output radiant energy, in joules.
α is coefficient of molecular absorption.
s is the coefficient of scatter.
R is the range or distance of laser beam travel.
τ_{atm} is the atmospheric *transmission factor.*

And of cause for CW lasers it can be expressed in terms of radiant powers.

$$\tau_{atm} = \Phi_R / \Phi_p = e^{-(\alpha + s)R}$$

Where:
Φ_R *is the radiant power, in watts, at range, R.*
Φ_p *is the radiant power, in watts, at the exit of the laser.*
α *is coefficient of molecular absorption.*
s *is the coefficient of scatter.*
R *is the range or distance of laser beam travel.*
τ_{atm} *is the atmospheric transmission factor.*

An **atmospheric absorption coefficient**, μ, can be expressed as sum of the exponential coefficients:

$$\mu = \alpha + s$$

Hence the atmospheric *transmission factor* can also be expressed as follows:

$$\tau_{atm} = Q_R / Q_p = e^{-\mu R}$$

Values for the absorption coefficient, μ, for various atmospheric conditions (transmission curves and tables) can be found in publications, such as, Safety with Lasers and Other Optical Sources, Chapter 13, by David Sliney and Myron Wolbarsht.

Recall from above that the radiant energy at range, R, can be expressed as:

$$Q_R = Q_p\, e^{-\mu R}$$

The radiant energy at R_{NOHD} is:

$$Q_{NOHD} = Q_p\, e^{-\mu R_{NOHD}}$$

Recall that the *Range Equation* for the range, R_{NOHD}:

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

The exponential expression for Q_{NOHD} applied to the *Range Equation* at the range, R_{NOHD}:

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

<u>Note</u>:
This is a *transcendental equation* because the solution of the term R_{NOHD} requires a value of that same term in the exponent on the other side of the equality. That is, the term "R_{NOHD}" cannot be isolated in the above expression. It is then apparent that the *eye-safe* viewing range <u>cannot be solved directly</u> whenever atmospheric transmission factors and conditions are considered. The *eye-safe* viewing range, R_{NOHD}, must then be arrived at, through an <u>estimation method</u> instead. This estimation method is derived as follows:

Again, recall that the radiant exposure at a range, R, is:

$$H_R = Q_R / A_R$$

The radiant energy at range, R, with atmospheric transmission losses considered can be expressed as:

$$Q_R = \tau_{atm}\, Q_p$$

<u>Where</u>:

$\mathbf{Q_R}$	is the radiant energy, in joules, at range, R.
$\mathbf{Q_p}$	is the laser output radiant energy, in joules.
$\boldsymbol{\tau_{atm}}$	is the atmospheric transmission factor.

For CW lasers the following is also applicable:

$$\Phi_R = \tau_{atm}\ \Phi_p$$

<u>Where</u>:

$\boldsymbol{\Phi_R}$	*is the radiant power at range, R, in watts.*
$\boldsymbol{\Phi_p}$	*is the radiant power at the exit of the laser, in watts.*
$\boldsymbol{\tau_{atm}}$	*is the atmospheric transmission factor.*

The radiant exposure at range, R, with atmospheric transmission considered can be expressed as:

$$H_R = \tau_{atm}\ Q_p\ /\ A_R$$

For *eye-safe* unaided viewing at range, NOHD, with atmospheric transmission conditions considered, the radiant exposure, H_{NOHD}, can be allowed to be as great as the MPE. This can be expressed as:

$$H_{NOHD} = \tau_{atm}\ Q_p\ /\ A_R = MPE$$

At the *eye-safe* unaided viewing range, the following is true about the radiant exposure:

$$H_R = H_{NOHD} = MPE$$

And same for the area:

$$A_R = A_{NOHD}$$

Recall that the cross-sectional area of the laser beam at a specific range, R, is:

$$A_R = \pi\ (\theta R + d_{out})^2\ /\ 4$$

And the area at the unaided viewing *eye-safe* range, R_{NOHD}, with atmospheric transmission conditions considered is expressed as:

$$A_{NOHD\text{-}atm} = \pi\ (\theta R_{NOHD\text{-}atm} + d_{out})^2\ /4$$

The radiant exposure at the *eye-safe* range for unaided viewing with atmospheric transmission factors considered can be expressed as:

$$H_{NOHD} = MPE = \tau_{atm}\ Q_p / A_{NOHD\text{-}atm}$$

Substitute for the area term:

$$H_{NOHD} = MPE = \tau_{atm}\ Q_p / [\pi\ (\theta R_{NOHD\text{-}atm} + d_{out})^2 /4]$$

Simplify the expression:

$$MPE = \tau_{atm}\ 4Q_p / [\pi\ (\theta R_{NOHD\text{-}atm} + d_{out})^2]$$

Rearrange terms as follows:

$$(\theta R_{NOHD\text{-}atm} + d_{out})^2 = \tau_{atm}\ 4Q_p / \pi\ MPE$$

Take the square root of both sides of the equality:

$$\theta R_{NOHD\text{-}atm} + d_{out} = [\tau_{atm}\ 4Q_p / \pi\ MPE\ ]^{0.5}$$

Rearrange terms as follows:

$$\theta R_{NOHD\text{-}atm} = [\tau_{atm}\ 4Q_p / \pi\ MPE\ ]^{0.5} - [d_{out}^{\ 2}]^{0.5}$$

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

Divide both side of the equality by θ:

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

Separate the atmospheric *transmission factor* out of the square root:

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

Rearrange terms to yield:

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

For CW lasers:

$$R_{NOHD\text{-}atm} = (\tau_{atm})^{0.5}\ \boldsymbol{\theta^{-1}\,[\,(4\Phi_p / \pi\, MPE_{cw}) - (d_{out}^2 / \tau_{atm})\,]^{0.5}}$$

For small beam lasers, the atmospheric transmission factor is on the same order of magnitude as the exit beam diameter:

$$d_{out} \sim \tau_{atm}$$

And

$$d_{out}^2 / \tau_{atm} \sim 1$$

And recall for Class 3 or 4 lasers:

$$1 << 4Q_p / \pi\, MPE$$

The term (d_{out}^2 / τ_{atm}) is assumed to be such that:

$$d_{out}^2 / \tau_{atm} << 4Q_p / \pi\, MPE$$

Hence the following approximations can be made:

$$\boldsymbol{4Q_p / \pi\, MPE} \sim (4Q_p / \pi\, MPE) - (d_{out}^2 / \tau_{atm})$$

And:

$$R_{NOHD\text{-}atm} \sim (\tau_{atm})^{0.5}\ \boldsymbol{\theta^{-1}\,[\,4Q_p / \pi\, MPE\,]^{0.5}}$$

And for CW lasers this distance can be approximated by:

$$R_{NOHD\text{-}atm} \sim (\tau_{atm})^{0.5}\ \boldsymbol{\theta^{-1}\,[\,4\Phi_p / \pi\, MPE_{cw}\,]^{0.5}}$$

Recall that the *eye-safe* unaided viewing range had previously been approximated as:

$$\boldsymbol{R_{NOHD} \sim \theta^{-1}\,[\,4Q_p / \pi\, MPE\,]^{0.5}}$$

And for CW lasers, this approximated distance is:

$$\boldsymbol{R_{NOHD} \sim \theta^{-1}\,[\,4\Phi_p / \pi\, MPE_{cw}\,]^{0.5}}$$

These approximations are then applied to the expressions for, $R_{NOHD\text{-}atm}$ above. Therefore, the *eye-safe* unaided viewing distance with atmospheric transmission considered, for CW as well as pulsed lasers, can be expressed as:

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

<u>Where</u>:

$R_{NOHD\text{-}atm}$ is the Nominal Ocular Hazard Distance (unaided) with atmospheric transmission considered.

R_{NOHD} is the Nominal Ocular Hazard Distance (unaided) determined to provide a range estimate.

τ_{atm} is the *transmission factor* through the atmosphere at range R_{NOHD}.

This atmospheric *transmission factor*, $\boldsymbol{\tau_{atm}}$, for a known range, would also apply to the range equation for <u>aided</u> viewing, similar to that of the unaided viewing factor present above. This as a coefficient to the *eye-safe* <u>aided</u> viewing distance expression.

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

<u>Where</u>:

$R_{EOHD\text{-}atm}$ is the Extended Ocular Hazard Distance (<u>aided</u> viewing) with atmospheric transmission considered.

R_{EOHD} is the Extended Ocular Hazard Distance (<u>aided</u> viewing) determined to provide a range estimate.

τ_{atm} is the *transmission factor* through the atmosphere at range R_{EOHD}.

The *transmission factor* is a function of the range and is specific to that particular range. Recall that we <u>cannot solve directly</u> for the *eye-safe* viewing range, while considering atmospheric transmission conditions. However, the eye-safe viewing range <u>can be estimated</u> using the above expressions and the following procedure:

1. Calculate the *eye-safe* viewing distance NOHD (unaided), or EOHD (for aided), viewing to arrive at a range estimate.
2. Use this range estimate to estimate an atmospheric *transmission factor*, from curves or tables of atmospheric transmissions.
3. Then use the *transmission factor* and the range estimate to in turn estimate the *eye-safe* viewing distance for particular atmospheric transmission conditions.

This estimation method can be applied to both <u>aided</u> as well as unaided viewing and can be used for both CW and pulsed lasers, with atmospheric conditions considered.

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.

Terms and Abbreviations

AEL	Allowable Exposure Limits
ANSI	American National Standards Institute
A_R	Laser beam cross-sectional area at any range, R
atm	Atmosphere
CW	Continuous Wave
d	Diameter
d_{aid}	Input or entrance diameter of the optical aid
d_{lim}	Diameter of *limiting aperture*
d_{out}	Laser exit beam diameter
d_R	Diameter at any range, R
E	Irradiance or power density, in watts/cm^2
EOHD	Extended Ocular Hazard Distance
E_{EOHD}	Irradiance at the *eye-safe,* aided viewing distance, in watts/cm^2
E_{NOHD}	Irradiance at the *eye-safe,* unaided viewing distance, in watts/cm^2
E_R	Irradiance at a range, R, in watts/cm^2
H	Radiant Exposure, in joules/cm^2
H_{EOHD}	Radiant exposure at the *eye-safe*, aided viewing distance, in joules/cm^2
H_{NOHD}	Radiant exposure at the *eye-safe*, unaided viewing distance, in joules/cm^2
H_R	Radiant exposure at a range, R, in joules/cm^2
I	Intensity
I_{out}	Laser output intensity
I_R	Intensity at a range, R
MPE	Maximum Permissible Exposure, in joules/cm^2 (radiant exposure).
MPE_{cw}	Maximum Permissible Exposure for CW, in watts/cm^2 (irradiance).
NHZ	Nominal Hazard Zone
NOHD	Nominal Ocular Hazard Distance
Q_p	The laser output radiant energy, in joules.
Q_R	Radiant Energy at a range, R, in joules
Q_τ	Transmitted Radiant Energy at the exit of the optical viewing aid, in joules
R	Specific range
R_{NOHD}	Eye-safe viewing distance, range of the Nominal Ocular Hazard Distance
R_{EOHD}	Eye-safe viewing distance, range of the Extended Ocular Hazard Distance
s	Scatter coefficient
α	Molecular absorption coefficient
θ	Beam divergence, in radians
Φ	Radiant power, in watts
Φ_R	Radiant power at a range, R, in watts
Φ_τ	Transmitted radiant power, in watts
τ	Transmission factor
τ_{aid}	Optical aid transmission factor
τ_{atm}	Atmospheric transmission factor
μ	Absorption coefficient

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