MAXIMUM PERMISSIBLE EXPOSURE FOR EXTENDED SOURCES

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Laser Safety Specialties

Maximum Permissible Exposure (MPE)

- Laser exposure limits have been established for
  - Wavelengths between 180 nm to 1 mm
  - Exposure duration between 100 fs and 30,000 s
  - CW, pulsed and repetitively pulsed lasers
  - Point sources and extended sources
- Separate exposure limits
  - Retina, Cornea, Skin
- Due to time constraints, discussion is limited to:
  - Visible wavelengths (400 nm to 700 nm) (e.g. 450 nm)
  - Single retinal exposure > 0.25 s duration (e.g. 10 s)
  - Single location of 10 cm from the emitting source

Damage Mechanisms

- MPEs have been established from empirical data
- Two primary damage mechanisms were observed
  - Thermal damage
    - Irreversible damage due to heating of cells
    - Evidence of injury is immediate
    - MPE is provided as radiant exposure
  - Photochemical damage
    - Damage caused by cell interaction with light that is not dependent on temperature rise in the cells
    - Evidence of injury is often visible 24 hours later
    - MPE is provided as integrated radiance

Retinal Thermal Damage Mechanism

- Point source
  - Retinal image of 25 μm (Angular subtense of 1.5 mrad)
  - All power entering the eye contributes to the hazard
- A relaxation of the point source MPE can be applied by the use of a correction factor (C_E) for extended sources
- Intermediate extended source
  - Angular subtense is between 1.5 mrad and 100 mrad
  - C_E is equal to the ratio of source angle, α, and 1.5 mrad
- Large extended source
  - Retinal image is larger than 100 mrad
  - Hazard is related to radiance (retinal irradiance)
  - C_E is proportional to the square of the source angle

Retinal Photochemical Damage

- Small source
  - Retinal image < 187 μm (11 mrad) for *T* < 100 s
  - Definition of "small" increases with exposure duration
  - Eye movements blur image so that the averaging cone (γ) increases from 11 mrad to 110 mrad at 10,000 s
  - All power entering the eye contributes to the hazard regardless of actual size due to normal eye movements
- Large extended source
  - Retinal image is larger than γ (11 mrad for *T*< 100 s), but only the power within γ contributes to the hazard
  - Hazard is related to integrated radiance, which is directly proportional to radiant exposure on the retina

Photochemical MPE

- For all sources, regardless of angular subtense
  - Exposure less than 10,000 s

$$MPE = 100 \times C_B \ \mathrm{J \cdot cm^{-2} \cdot sr^{-1}}$$

  - Exposure greater than 10,000 s

$$MPE = 0.01 \times C_B \ \mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$$

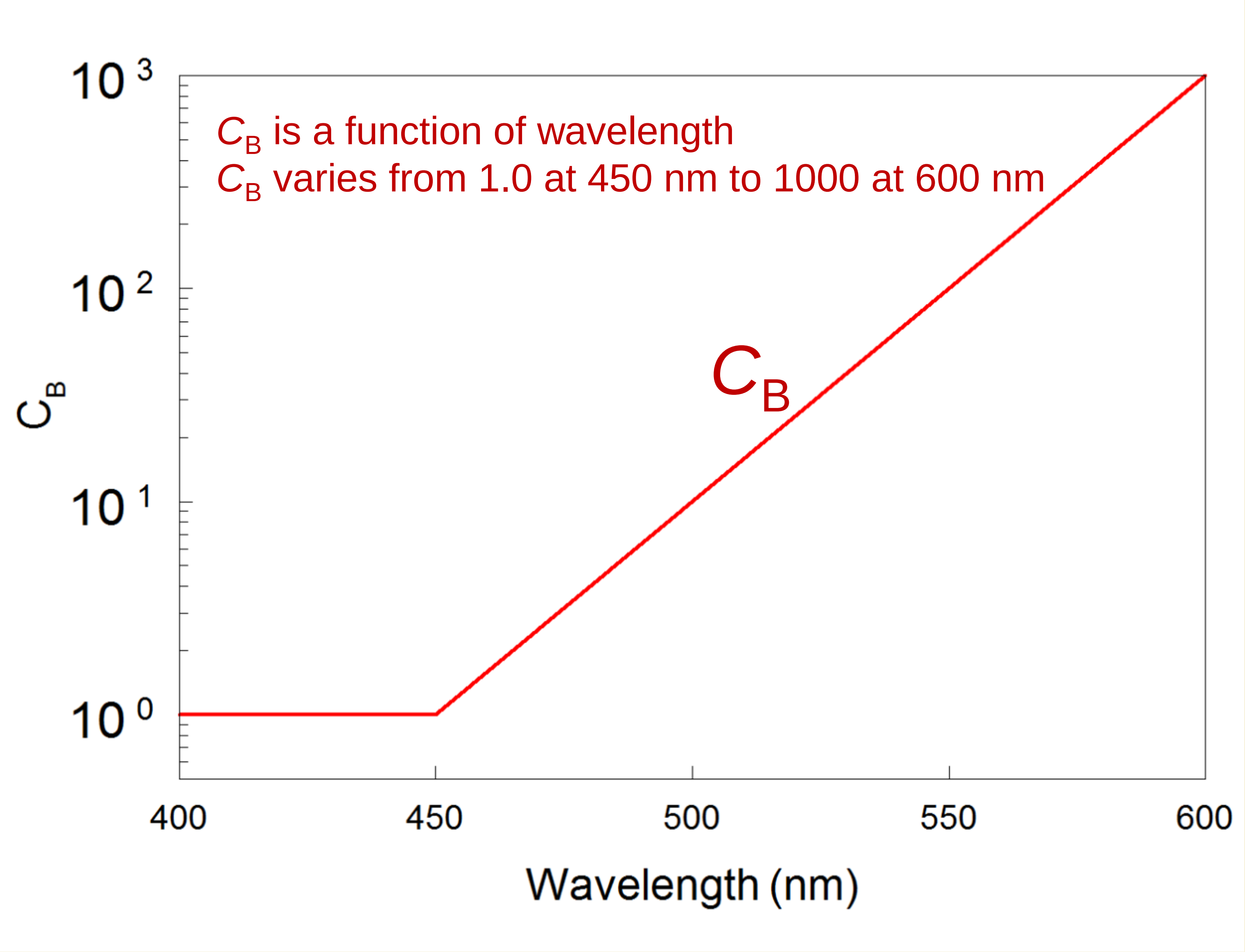
  - Averaged over a cone angle equal to gamma (γ)

$$\gamma = 1.1 \times \sqrt{t} \ \mathrm{mrad} \quad \text{for } 100\,\mathrm{s} < t < 10{,}000\,\mathrm{s}$$

Note that at 10,000 s, the two limits are equal

- Direct comparison between the thermal MPE and the photochemical MPE is hindered because of different units

Photochemical Correction Factor, C_B



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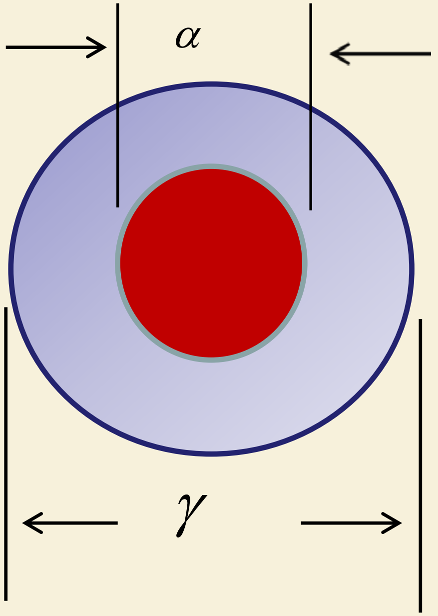
Small Photochemical Sources

- When $\alpha < \gamma$, the source is a small source
- The solid angle for a small source is averaged over the cone angle γ



$$\Omega_{small} = \frac{\pi \gamma^2}{4}$$

- The actual source angle is not used

Photochemical MPE (small source)

- The linear angle of γ is 11 mrad for T < 100 s
- All the power that enters the eye contributes to the hazard for $\alpha < \gamma$
- The solid angle of γ is,

$$\Omega_{small} = \frac{\pi \gamma^2}{4} = \frac{\pi \times (0.011)^2}{4} = 9.5 \times 10^{-5} \text{ sr}$$

- This solid angle is rounded to 1×10^{-4} sr (5% error)

Photochemical MPE as Radiant Exposure

- For small sources ($\alpha \leq \gamma$) and T < 100 s
- The MPE as radiant exposure is computed by multiplying $MPE{:}L_P$ by Ω_{small}

$$MPE : H_{ph} = MPE : L_p \times \Omega_{small}$$

$$MPE : H_{ph} = \left(100 \times C_B \ \mathrm{J \cdot cm^{-2} \cdot sr^{-1}}\right) \times \left(1 \times 10^{-4} \ \mathrm{sr}\right)$$

- The photochemical MPE for small sources is then:

$$MPE : H_{\mathrm{ph\,small}} = 0.01 \times C_B \ \mathrm{J \cdot cm^{-2}}$$

- For small sources, the photochemical MPE can be compared directly with the thermal MPE

Example 1: MPE (small source)

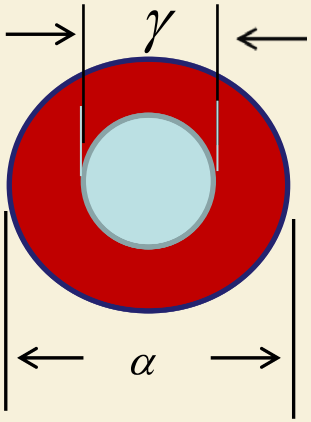
- Diode laser, 5 mW power at 450 nm ($C_B = 1$)
  3 mm beam, 3 mrad source at 10 cm from exit
- Calculate MPE for 10 s exposure
- Photochemical
  - Small source since 3 mrad < 11 mrad

$$MPE:H = 0.01\,\mathrm{J}\cdot\mathrm{cm}^{-2} \qquad MPE:E = \frac{MPE:H}{T}$$

  - MPE = 1.0 mW·cm^{-2} (same MPE as thermal point source)
- Thermal
  - Intermediate source since 3 mrad is twice 1.5 mrad
  - C_E = 2 and MPE = 2.0 mW·cm^{-2}

Large Photochemical Source

- For a large source ($\alpha > \gamma$), the hazard is based on the angular subtense of the source, α



- Averaging over γ is not necessary for larger sources and γ is not used in the evaluation

$$\Omega_{source} = \frac{\pi \alpha^2}{4}$$

Photochemical MPE (large source)

- The same photochemical MPE applies to all sources

$$MPE : L_p = 100 \times C_B \ \mathrm{J \cdot cm^{-2} \cdot sr^{-1}}$$

- However, for large sources, the solid angle of the source is used to compute the MPE

$$MPE : H_{\mathrm{ph\,(large)}} = MPE : L_p \times \Omega_{\mathrm{source}}$$

Example 2: Photochemical MPE (large source)

- Diffuse reflection, 5 mW power at 450 nm, 3 mm beam, 30 mrad source at 10 cm from target
- Calculate MPE for 10 s exposure (C_B = 1)
- Since 30 mrad > 11 mrad

$$\Omega_{source} = \frac{\pi \alpha^2}{4} = \frac{\pi \times (0.03)^2}{4} = 7.07 \times 10^{-4} \ \ \mathrm{sr}$$

$$MPE : H = 100\,\mathrm{J} \cdot \mathrm{cm}^{-2} \cdot \mathrm{sr}^{-1} \times 7.07 \times 10^{-4}\,\mathrm{sr}$$

- MPE = 70.7 mJ·cm^{-2}
- MPE = 7.07 mW·cm^{-2} for 10 s

Correction Factor Method

- Proposal is to use a correction factor (C_{blue}) to adjust the small source MPE for large sources
- The ratio between the small source MPE and the large source MPE may be computed

$$\text{ratio} = \frac{MPE : H_{\text{ph (large)}}}{MPE : H_{\text{ph (small)}}} = \frac{MPE : L_p \times \Omega_{\text{source}}}{MPE : L_p \times \Omega_{\text{small}}}$$

$$\text{ratio} = \frac{MPE : L_p \times \left(\pi \alpha^2 / 4\right)}{MPE : L_p \times \left(\pi \gamma^2 / 4\right)} = \frac{\alpha^2}{\gamma^2}$$

$$C_{blue} = \frac{\alpha^2}{\gamma^2} \quad \text{for } \alpha > \gamma$$

- This factor is in footnote 3 of Table 5e of ANSI Z136.1(2014)

Example 2 Using Correction Factors

- Diffuse reflection, 5 mW power at 450 nm, 3 mm beam, 30 mrad source at 10 cm from target
- MPE = 1.0 mW·cm^{-2} for 10 s for small/point source

$$C_{blue} = \frac{\alpha^2}{\gamma^2} = \frac{(30\,\text{mrad})^2}{(11\,\text{mrad})^2} = 7.44$$

The thermal and photochemical point source MPEs are the same for 10 s

  – MPE = 7.44 mW·cm^{-2} for 10 s
  – This MPE is 5% greater than computed earlier
- Thermal
  – Intermediate source since 30 mrad < 100 mrad
  – C_E = 30/1.5 = 20
  – MPE = 20 mW·cm^{-2} for 10 s

Thoughts on Using C_{blue}

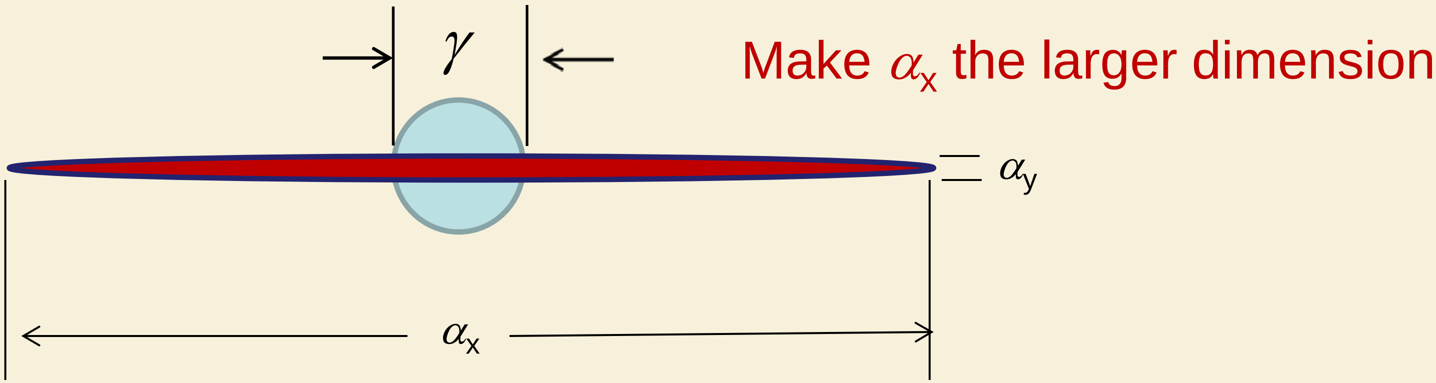
- For large retinal images, the hazard is related to the retinal irradiance
- Only the portion inside γ contributes to the hazard
- The factor α^2/γ^2 effectively eliminates power outside of γ by increasing the MPE
- An alternate approach would be to eliminate the portion outside of γ from the power measurement by restricting the field of view of the instrument
- This alternate method is used in IEC 60825-1

Elongated Extended Sources

- Elongated sources present unique challenge
- Source consists of α_x and α_y
- The larger source angle is defined by α_x
- Includes both rectangular and elliptical sources
  - For thermal evaluation, a correction to the point source MPE may be used
  - For photochemical evaluation, the evaluation has been based on radiance using an averaging cone of γ
- By effectively eliminating the power outside of γ, a correction factor method is still possible

Photochemical MPE (narrow elongated source)

- The portion outside of γ does not contribute to the hazard



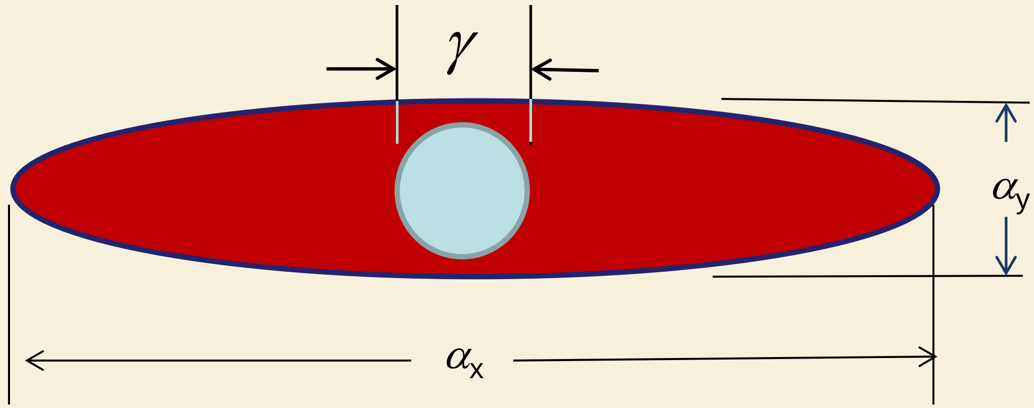
- The fraction of energy inside the cone is γ / α_x
- Increase the MPE by α_x/γ for source larger than γ

$$MPE:E_{\text{large}} = \left(\frac{\alpha_x}{\gamma}\right) \times MPE:E_{\text{small}}$$

$$MPE:E_{\text{large}} = \left(\frac{\alpha_x}{\gamma}\right) \times 1 \times 10^{-4}\, C_B \,\mathrm{W \cdot cm^{-2}}$$

Photochemical MPE (larger rectangular source)

- Both dimensions larger than γ
- Only the portion inside γ contributes to the hazard



- The fraction inside the cone is $(\gamma/\alpha_x)\times(\gamma/\alpha_y)$

$$MPE: E_{\mathrm{large}} = \left(\frac{\alpha_x \times \alpha_y}{\gamma^2}\right) \times 1 \times 10^{-4}\ C_B \mathrm{W}\cdot\mathrm{cm}^{-2}$$

Conclusion

- Having the thermal MPE and Photochemical MPE in the same units allows easier hazard comparison
- Extended source photochemical correction factors may appear next to those for thermal in the next edition of ANSI Z136.1

$$C_{blue} = 1.0 \quad \text{for } \alpha < \gamma \qquad\qquad C_{blue} = \frac{\alpha^2}{\gamma^2} \quad \text{for } \alpha > \gamma$$

- For a rectangular or elliptical source

$$C_{blue} = \frac{\alpha_x}{\gamma} \quad \text{for } \alpha_x > \gamma \text{ and } \alpha_y < \gamma$$

$$C_{blue} = \frac{\alpha_x \times \alpha_y}{\gamma^2} \quad \text{for } \alpha_x > \gamma \text{ and } \alpha_y > \gamma$$