Solution. For direct exposure to the beam, the MPE would normally be based on a maximum exposure duration of 100 s. However, for diffuse reflections, the considered exposure duration could extend to the entire day. Since the technician is only in the lab for part of the day, his total exposure time is 10 minutes (600 s) per hour multiplied by 8 hours in a day, plus a final check at the end of the day, which equals 5400 s. The MPE for 325 nm radiation is 1.0 J·cm^{-2} for exposures lasting from 10 s to 30,000 s. Therefore, the MPE is 1.0 J·cm^{-2} accumulated exposure, whether the exposure is for 5400 s or 30,000 s. The MPE can also be calculated based on average power. The MPE in terms of irradiance is the MPE in terms of radiant exposure divided by the exposure duration. In this case, the MPE is:

$$MPE{:}E = \frac{MPE{:}H}{T}$$

$$= \frac{1\,\mathrm{J \cdot cm^{-2}}}{5400\,\mathrm{s}} = 1.85 \times 10^{-4}\ \mathrm{W \cdot cm^{-2}}$$

$$= 0.185\ \mathrm{mW \cdot cm^{-2}}$$

For direct beam exposure, the MPE for this laser is 10 mW·cm^{-2} using this same method for 100 s exposure duration.

***Example 3.* A 3 mW laser operates at a wavelength of 1550 nm with a beam diameter of 1.1 cm. What is the MPE for a 10 s exposure?**

Solution. From Table 5d, the MPE for a 10 s exposure at 1550 nm is 1 J·cm^{-2}. The MPE in terms of irradiance is then 1 J·cm^{-2}/10 s = 0.1 W·cm^{-2}. Obviously, this laser does not present a hazard.

B3.2 Single-Pulse Laser MPEs. MPEs for a single-pulse laser may be calculated from the information provided in Table 5, Table 6, and Table 7 or one may obtain a good approximate value from Figure 4, Figure 5, Figure 6, and Figure 7.

***Example 4.* Single-Pulse Visible Laser. Determine the MPE for a 694.3 nm ruby laser pulse having a pulse duration of 8×10^{-4} s (0.8 ms).**

Solution. The appropriate MPE is given in Table 5b. Substituting the values for *t* in Equation (B.1) yields:

$$\begin{aligned} MPE{:}H &= 1.8 \times 10^{-3}\, t^{0.75}\ \mathrm{J \cdot cm^{-2}} \\ &= 1.8 \times 10^{-3}\, (8 \times 10^{-4})^{0.75} \\ &= 8.6 \times 10^{-6}\ \mathrm{J \cdot cm^{-2}} \end{aligned}$$

Since $E \times t = H$, the MPE may also be expressed as peak irradiance,

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$$E = \frac{H}{t_p} = \frac{8.6 \times 10^{-6}\ \mathrm{J \cdot cm^{-2}}}{8 \times 10^{-4}\ \mathrm{s}}$$
$$= 1.1 \times 10^{-2}\ \mathrm{W \cdot cm^{-2}}$$

***Example 5.* Extremely-Short-Pulsed Laser. Find the MPE for a single 100 fs pulse at 580 nm.**

Solution. The MPE for a single 100 fs (100×10^{-15} s) pulse at 580 nm can be found using Table 5b.

$$MPE{:}H = 1.0 \times 10^{-7}\ \mathrm{J{\cdot}cm^{-2}}$$

***Example 6.* Near-Infrared Laser. A GaAs laser operating at room temperature has a peak wavelength of 904 nm. What is the MPE for a single pulse of 200 ns duration?**

Solution. The MPE can be calculated from the information in Figure 4 and Figure 8. From Figure 4, the MPE for exposure durations between 10 ps and 5 μs is 2×10^{-7} J·cm^{-2} for wavelengths between 400 nm and 700 nm. This MPE may be corrected for 904 nm by the use of C_A, which is about 2.5 as read from Figure 8a. The product of these two numbers is 3.25×10^{-7} J·cm^{-2}.

Table 5 and Table 6 can also be used to determine the MPE. From Table 5c, under "near infrared," 700–1050 nm, 10^{-11} to 5×10^{-6} s, the MPE is:

$$MPE{:}H = 2.0 \times C_A \times 10^{-7}\ \mathrm{J{\cdot}cm^{-2}} \quad \text{(B.3)}$$

From Table 6a, the value of C_A for the wavelength band of 700 nm to 1050 nm can be calculated from the formula:

$$C_A = 10^{0.002(\lambda\text{-}700\ \mathrm{nm})} = 2.56 \quad \text{(B.4)}$$

The MPE is

$$MPE : H = (2.56)(2 \times 10^{-7}) = 5.12 \times 10^{-7}\ \mathrm{J \cdot cm^{-2}}$$

***Example 7.* Single-Pulse Near-Infrared Laser. Determine the MPE for a 1064 nm (Nd:YAG) laser having a pulse duration of 8×10^{-4} s.**

Solution. The MPE as given for 1050 nm to 1200 nm and 13×10^{-6} to 10 s in Table 5c is:

$$\begin{aligned} MPE{:}H &= 9 \times C_C \times t^{0.75} \times 10^{-3}\ \mathrm{J{\cdot}cm^{-2}} \quad \text{(B.5)} \\ &= 9 \times (1.0) \times (8 \times 10^{-4})^{0.75} \times 10^{-3}\ \mathrm{J{\cdot}cm^{-2}} \\ &= 4.3 \times 10^{-5}\ \mathrm{J{\cdot}cm^{-2}} \end{aligned}$$

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Another way to approach this problem is to note that in Figure 8a, the MPE for this laser is five times that for a visible laser having the same exposure duration (as calculated in Example 4). Therefore, the MPE for this exposure is:

$$MPE{:}H = 5\times(8.6\times10^{-6}\ \mathrm{J\cdot cm^{-2}})$$

$$= 4.3\times10^{-5}\ \mathrm{J\cdot cm^{-2}}$$

In terms of peak irradiance,

$$MPE : E = \frac{MPE : H}{t_{\mathrm{p}}}$$

$$= \frac{4.3\times10^{-5}\ \mathrm{J\cdot cm^{-2}}}{8\times10^{-4}\ \mathrm{s}}$$

$$= 5.4\times10^{-2}\ \mathrm{W\cdot cm^{-2}}$$

***Example 8.* Extremely-Short-Pulsed, Near-Infrared Laser. Find the MPE for a single 20 ps (2×10^{-11} s) laser pulse at 1060 nm.**

Solution. The MPE is found using Table 5c. For exposure durations between 10 ps and 13 µs is:

$$MPE{:}H = 2.0\ C_{\mathrm{C}} \times10^{-6}\ \mathrm{J{\cdot}cm^{-2}} \qquad \text{(B.6)}$$

where t is measured in seconds. For 1060 nm, C_{C} is 1.0. Therefore,

$$MPE{:}H = 2.0\ (1.0)\ (1 \times 10^{-6})\ \mathrm{J{\cdot}cm^{-2}}$$
$$= 2.0 \times 10^{-6}\ \mathrm{J{\cdot}cm^{-2}}$$

***Example 9.* Middle-Infrared Laser. What is the MPE for a single–pulse laser rangefinder operating at a wavelength of 1540 nm? The pulse width is 20 ns.**

Solution. From Table 5d, the MPE for 1540 nm is 1 J·cm^{-2} for all exposure durations from 1 ns to 10 s. Therefore the MPE for this laser is 1 J·cm^{-2}.

B3.3 Repetitive-Pulse Laser MPE. For exposure to n pulses in a pulse train or a group of pulses, the MPE ($MPE{:}H_{\mathrm{group}}$) is expressed in radiant exposure for the sum of all the pulses. $MPE{:}E_{\mathrm{group}}$ represents the MPE expressed in average irradiance. The average irradiance is computed from the sum of the radiant exposures, for all the pulses in the group (H_{group}), divided by the length of the pulse train, T. Therefore:

$$MPE : E_{\mathrm{group}} = \frac{MPE : H_{\mathrm{group}}}{T} \qquad \text{(B.7)}$$

The MPE for a group of pulses may be expressed in a variety of ways. Generally, several computations are necessary to determine the MPE/Pulse expressed in J·cm^{-2}. Usually, the

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first computation involves computing the MPE if a person were exposed to only one pulse, or the pulse with maximum energy, in a pulse train (MPE_{SP}). Another computation involves the MPE for the combined energy in a group of pulses or an entire pulse train ($MPE{:}H_{group}$).

To determine the applicable MPE for an exposure to a repetitive-pulse laser, the wavelength, pulse repetition frequency F, duration of a single pulse t, duration of any pulse groups T, and the duration of a complete exposure T_{max} must be known. The appropriate *MPE/*pulse is the one that indicates the greatest hazard from testing the three rules:

Rule 1. Single-pulse limit. The MPE is limited by the MPE_{SP} for *any* single pulse during the exposure (*assuming exposure to only one pulse*).

Rule 2. Average-power limit. The MPE is limited to the MPE for the duration of all pulse trains T, divided by the number of pulses n, during T, for all exposure durations up to T_{max}.

Rule 3. Repetitive-pulse limit.[5] This rule is now only applied for extended sources when the pulse duration exceeds t_{min}. The MPE is limited to MPE_{SP} multiplied by a correction factor C_P (i.e., $n^{-0.25}$) when necessary, where n is the number of pulses that occur during the exposure duration T_{max}. If there are no spaces between pulses of a width at least as large as t_{min}, this rule need not be applied. Although this factor has generally been applied in past versions of this standard, it is no longer necessary for most exposure conditions due to lowering of the single pulse exposure durations. In most cases, C_P is generally equal to 1.0.

***Example 10.* Repetitive-Pulse Visible Laser with Very High PRF. Determine the MPE for a 514.5 nm argon laser operating at a PRF of 10 MHz and a pulse width t of 10 ns (10^{-8} s). Assume an exposure duration T_{max} of 0.25 s.**

Solution. Since the PRF is high, the average irradiance limitation from Rule 2 would be expected to apply. In this case, t in Equation (B.8) is actually T_{max}. From Table 5b:

$$\begin{aligned} MPE{:}H_{group} &= 1.8\times t^{0.75}\times 10^{-3}\ \mathrm{J{\cdot}cm^{-2}} \qquad \text{(B.8)} \\ &= 1.8\times (0.25\ \mathrm{s})^{0.75}\times 10^{-3}\ \mathrm{J{\cdot}cm^{-2}} \\ &= 6.36\times 10^{-4}\ \mathrm{J{\cdot}cm^{-2}} \end{aligned}$$

This MPE corresponds to 2.5×10^{-10} J·cm^{-2} per pulse, which is much smaller than the single pulse MPE of 2×10^{-7} J·cm^{-2}. The MPE based on the group exposure is the same as for a CW laser and may be expressed in terms of average irradiance:

$$\begin{aligned} MPE:E &= \frac{MPE:H_{group}}{T} = \frac{6.36\times10^{-4}\,\mathrm{J\cdot cm^{-2}}}{0.25\,\mathrm{s}} \\ &= 2.55\times 10^{-3}\ \mathrm{W{\cdot}cm^{-2}}\ \ \text{(often rounded to 2.6 mW·cm}^{2}\text{)} \end{aligned}$$

***Example 11.* Repetitive-Pulse, Near-Infrared Laser with Moderate PRF. Determine the MPE for a 905 nm (GaAs) laser that has a pulse width t of 100 ns (1×10^{-7} s) and a PRF of 1 kHz.**

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[5] For Rule 3, pulses that occur within t_{min} are considered a single pulse. Rule 3 does not apply for wavelengths less than 400 nm.

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Solution. Since the 905 nm wavelength will not provide a natural aversion response such as a visible wavelength laser would, assume a 10 s exposure duration (T_{max}) for this particular laser application.

From Table 6a or Figure 8a, the wavelength correction factor C_A is 2.57 at 905 nm. The *MPE/pulse* is the most conservative (i.e., lowest value) MPE.

Rule 1. Single Pulse limit. The MPE from Table 5c for a single 100 ns pulse is:

$$MPE_{SP} = 2\ C_A \times 10^{-7}\ \text{J}\cdot\text{cm}^{-2}$$
$$= 5.1\times10^{-7}\ \text{J}\cdot\text{cm}^{-2}$$

Rule 2. Average Power Limit. First, consider two pulses in a train of pulses separated by 1 ms. The MPE for a 1.0 ms exposure is:

$$MPE : H_{group} = 1.8\times10^{-3} C_A t_p^{0.75}\,\text{J}\cdot\text{cm}^{-2} = (1.8\times10^{-3}) \times 2.57 \times (1\times10^{-3})^{0.75} = 2.6 \times 10^{-5}\ \text{J}\cdot\text{cm}^{-2}$$

This value is much more than twice the MPE for a single pulse. The *MPE/pulse* is half the above value.

Second, consider the MPE for a 10 s exposure:

$$MPE{:}E_{group} = (1.8\times10^{-3}) \times (2.57) \times (10)^{0.75} = 2.6 \times 10^{-2}\ \text{J}\cdot\text{cm}^{-2}$$

The *MPE/pulse* based on a 10 s exposure (T) is:

$$MPE/pulse = \frac{2.6\times10^{-2}\,\text{J}\cdot\text{cm}^{-2}}{10^{4}\ \text{pulses}}$$
$$= 2.6\times10^{-6}\ \text{J}\cdot\text{cm}^{-2}$$

Resultant MPE (Example 11):

Rule 1 provides the *MPE/pulse* since it is the most conservative (i.e., lowest value) calculation.

Hence, the MPE expressed as a cumulative exposure for the duration of the entire pulse train is:

$$MPE{:}H_{group} = T \times F \times MPE/pulse \qquad \text{(B.9)}$$
$$= (10\ \text{s})(10^{3}\ \text{Hz})(5.1\times10^{-7}\ \text{J}\cdot\text{cm}^{-2})$$
$$= 5.1\times10^{-3}\ \text{J}\cdot\text{cm}^{-2}$$

This may also be expressed in terms of average irradiance,

$$MPE : E = \frac{MPE : H_{group}}{T} = \frac{5.1\times10^{-3}\,\text{J}\cdot\text{cm}^{-2}}{10\ \text{s}} = 5.1\times10^{-4}\ \text{W}\cdot\text{cm}^{-2}$$

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Example 12. **Low-PRF, Long-Pulse, Repetitive-Pulse Near IR Laser. Determine the MPE for a 1319 nm laser where T_{max} = 10 s, pulse width $t = 10^{-3}$ s, and F = 100 Hz. The beam is Gaussian, a point source, with a diameter of 1.0 cm at the 1/e peak of irradiance points, and pulses are each 1.0 mJ, corresponding to an average power of 100 mW.**

Solution. Both retinal and corneal effects need to be considered. The total number of pulses in the 10 s exposure is $n = \text{F}\times T$ equals 1000.

Start, with *retinal* hazards:

Rule 1. Single-Pulse Limit. From Table 5c or Figure 4, and Table 6a or Figure 8c, the MPE for a single 1 ms pulse is:

$$\begin{aligned} MPE_{SP} &= (9\times10^{-3}) \times C_C \times t^{0.75}\ \text{J}\cdot\text{cm}^{-2} \\ &= (9\times10^{-3})\ (8 + 10^{0.04(1319\text{-}1250)})\ (5.62\times10^{-3})\ \text{J}\cdot\text{cm}^{-2} \\ &= (9\times10^{-3})\ (583)\ (5.62\times10^{-3})\ \text{J}\cdot\text{cm}^{-2} \\ &= 2.95 \times 10^{-2}\ \text{J}\cdot\text{cm}^{-2} \end{aligned}$$

This MPE in terms of average irradiance for Rule 1 is:

$$\begin{aligned} MPE{:}E &= MPE/\text{pulse} \times F \\ &= 2.95 \times 10^{-2}\ \text{J}\cdot\text{cm}^{-2} \times 100\ \text{Hz} = 2.95\ \text{W}\cdot\text{cm}^{-2} \end{aligned}$$

Rule 2. Average-Power Limit. The MPE found using Rule 2 is found from Table 5c for an exposure duration of T_{max}:

$$\begin{aligned} MPE{:}H_{\text{group}} &= (9\times10^{-3}) \times C_C \times (T_{max})^{0.75}\ \text{J}\cdot\text{cm}^{-2} \\ &= (9\times10^{-3}) \times (583) \times (10^{0.75})\ \text{J}\cdot\text{cm}^{-2} \\ &= 29.5\ \text{J}\cdot\text{cm}^{-2} \end{aligned}$$

for all the pulses in the train.

In terms of average irradiance, the MPE is found from:

$$MPE{:}E = \frac{MPE{:}H_{\text{group}}}{T_{\text{max}}} = 2.95\,\text{W}\cdot\text{cm}^{-2}$$

This result is the same as Rule 1 (a coincidence).

Rule 3. Multiple-Pulse Correction Factor. The MPE for Rule 3 is the same as Rule 1 because (from Table 6c), the multiple-pulse correction factor C_P =1.0 for point sources.

Corneal Limit:

Rule 1. Single-Pulse Limit. From Table 5c and Table 6a, or Figure 4, the corneal MPE for a single 1-ms pulse is:

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$MPE_{SP} = 0.3\ K_\lambda$ J·cm^{-2}
= 0.3 ($10^{0.01(1400-1319)}$)
= (0.3) (6.46)
= 1.94 J·cm^{-2} per pulse.

This MPE in terms of average irradiance for Rule 1 is:

$MPE{:}E = MPE_{SP} \times F$

= 1.94 J·cm^{-2} × 100 Hz = 194 W·cm^{-2}

Rule 2. Average Power limit. From Table 5c and Table 6a, or Figure 4, the corneal MPE for a 10 s exposure is:

$MPE{:}H_{group}$ = (0.3 K_λ + 0.7) J·cm^{-2}

= (1.94 + 0.7) J·cm^{-2}

= 2.64 J·cm^{-2}

$$MPE\,/\,pulse = \frac{2.64\ \mathrm{J\cdot cm^{-2}}}{1000\ \mathrm{pulses}} = 2.64\ \mathrm{mJ\cdot cm^{-2}}$$

In terms of average irradiance, the MPE is found from:

$$MPE:E = \frac{MPE:H_{group}}{T_{max}} = \frac{2.64\,\mathrm{J\cdot cm^{-2}}}{10\,\mathrm{s}} = 264\,\mathrm{mW\cdot cm^{-2}}$$

For corneal exposure, the MPE considering Rule 2 provides a much lower MPE than Rule 1 and a much lower MPE than when considering retinal exposure.

Resultant MPE (Example 12):

Although corneal exposure appears to produce the lower MPE, the MPE that is applied, when two different limiting apertures are involved, corresponds to the calculation that results in the largest ratio of irradiance (or radiant exposure) to the corresponding MPE (either retinal or corneal). This constraint makes it necessary to determine the amount of energy or power per pulse that is transmitted by the applicable limiting aperture and then calculating irradiance or radiant exposure averaged over the limiting aperture. This average irradiance is calculated by dividing the power transmitted by the aperture by the area of that aperture. The appropriate limiting aperture, D_f, is found in Table 8a. The area of the aperture (πD_f^2) can be found in Table 8b.

The limiting aperture diameter for either the retina or cornea is determined from Table 8a based on the wavelength, and the exposure duration for the applicable rule. The areas of the various apertures are provided in Table 8b. The limiting aperture for the retina is given as a value of D_f = 7.0 mm for all exposure durations. For an exposure duration of 1 ms (Rule 1),

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the limiting aperture for the cornea is D_f = 1 mm. For an exposure duration of 10 seconds (Rule 2), the limiting aperture for the cornea is given as D_f = 3.5 mm.

The energy per pulse transmitted by the limiting aperture, Q_f, for a laser with a diameter, D_L, at the 1/e peak of irradiance points and a Gaussian profile, with pulses of energy, Q_0, is determined by:

$$Q_f = Q_0\left(1 - e^{-\frac{D_f^2}{D_L^2}}\right)$$

For this example, the beam diameter is 1 cm. Each of our rules produce the following exposures:

Rule 1 and Rule 2, Retina.

$$Q_f = \left(1\times10^{-3}\ \mathrm{J}\right)\times\left(1 - \mathrm{e}^{-\frac{(0.7)^2}{(1.0)^2}}\right)$$

$$Q_f = 0.39 \times 10^{-3}\ \mathrm{J}$$

The radiant exposure, H, that is compared with the MPE for retinal exposure is then,

$$H = \frac{Q_f}{\text{area of } D_f} = \frac{0.39\times10^{-3}\ \mathrm{J}}{\left(0.385\,\mathrm{cm}^2\right)} = 1.01\times10^{-3}\ \mathrm{J\cdot cm^{-2}}$$

The irradiance, E, that is compared with *MPE:E* is then,

$$E = H \times F = 1.01\times10^{-3}\ \mathrm{J\cdot cm^{-2}} \times 100\,\mathrm{Hz}$$
$$= 0.101\ \mathrm{W\cdot cm^{-2}}$$

$$\text{ratio} = \frac{101\times10^{-3}\ \mathrm{W\cdot cm^{-2}}}{2.95\,\mathrm{W\cdot cm^{-2}}} = 0.034$$

Rule 1, Cornea. For a 1-ms pulse, a 1-mm limiting aperture found in Table 8a is used.

$$Q_f = \left(1\times10^{-3}\ \mathrm{J}\right)\times\left(1 - \mathrm{e}^{-\frac{(0.1)^2}{(1.0)^2}}\right)$$

$$Q_f = 9.95 \times 10^{-6}\ \mathrm{J}$$

The area of the limiting aperture (πD_f^2) can be found in Table 8b. The radiant exposure, H, that is compared with the MPE for Rule 1 corneal exposure is then,

$$H = \frac{Q_f}{\text{area of } D_f} = \frac{9.95\times10^{-6}\ \mathrm{J}}{\left(7.85\times10^{-3}\ \mathrm{cm}^2\right)} = 1.27\times10^{-3}\ \mathrm{J\cdot cm^{-2}}$$

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The irradiance, E, that is averaged over a 1 mm aperture and compared with *MPE:E* for Rule 1 for corneal exposure is about 27% higher than what was used for retinal exposure.

$$E = H \times F = 1.27 \times 10^{-3}\ \mathrm{J \cdot cm^{-2}} \times 100\ \mathrm{Hz}$$

$$= 0.127\ \mathrm{W \cdot cm^{-2}}$$

For Rule 1 corneal exposure, the ratio of the irradiance to the MPE can be computed,

$$\text{ratio (Rule 1)} = \frac{E}{MPE:E} = \frac{127 \times 10^{-3}\ \mathrm{W \cdot cm^{-2}}}{194\ \mathrm{W \cdot cm^{-2}}} = 6.5 \times 10^{-4}$$

Rule 2, Cornea. For the 10-second exposure, the limiting aperture diameter is 3.5 mm as found in Table 8a, with area defined in Table 8b.

$$Q_\mathrm{f} = \left(1 \times 10^{-3}\ \mathrm{J}\right) \times \left(1 - e^{-\frac{(0.35)^2}{(1.0)^2}}\right)$$

$$Q_\mathrm{f} = 1.15 \times 10^{-4}\ \mathrm{J}$$

The radiant exposure, H, that is compared with the MPE for Rule 2 corneal exposure is then,

$$H = \frac{Q_\mathrm{f}}{\text{area of } D_\mathrm{f}} = \frac{1.15 \times 10^{-4}\ \mathrm{J}}{\left(9.6 \times 10^{-2}\ \mathrm{cm^2}\right)} = 1.20 \times 10^{-3}\ \mathrm{J \cdot cm^{-2}}$$

The irradiance, E, that is compared with *MPE:E* is then,

$$E = H \times prf = 1.20 \times 10^{-3}\ \mathrm{J \cdot cm^{-2}} \times 100\ \mathrm{Hz}$$

$$= 120\ \mathrm{mW \cdot cm^{-2}}.$$

$$\text{ratio (Rule 2)} = \frac{E}{MPE{:}E} = \frac{120\ \mathrm{mW \cdot cm^{-2}}}{264\ \mathrm{mW \cdot cm^{-2}}} = 0.45$$

The MPE found using Rule 2 for 10 s for the corneal limit is the correct MPE (264 $\mathrm{mW \cdot cm^{-2}}$) to apply, because it has the largest ratio of E compared with the MPE. The MPE therefore corresponds to 264 $\mathrm{mW \cdot cm^{-2}}$ and the appropriate irradiance to use for the comparison is 120 $\mathrm{mW \cdot cm^{-2}}$ averaged over a limiting aperture of 3.5 mm in diameter.

***Example 13.* A xenon chloride excimer laser operating at 308 nm is used in a medical facility. The laser emits pulses that are 20 ns in length at a PRF of 200 Hz. What is the MPE for this laser for a 10 s exposure duration?**

Solution. The MPE for ultraviolet lasers is based on a dual limit of photochemical effects and thermal effects. The MPE for 308 nm is 40 $\mathrm{mJ \cdot cm^{-2}}$ for exposure durations from 1 ns to 30,000 s. This MPE is based on photochemical effects on the eye or skin. In addition, the MPE of $0.56t^{\,0.25}$ also cannot be exceeded. This latter MPE is based on thermal effects. In fact it is the same MPE that is used for middle and far-infrared wavelengths for exposures

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lasting more than a few ns. The MPE can be computed by applying both thermal and photochemical effects.

Rule 1. Single-Pulse Limit. For this laser, the thermal MPE limit for a single pulse is:

$$MPE_{SP} = 0.56\times(20\times10^{-9})^{0.25}\ \text{J}\cdot\text{cm}^{-2}$$
$$= 0.56\times1.19\times10^{-2}\ \text{J cm}^{-2} = 6.66\ \text{mJ}\cdot\text{cm}^{-2}$$

For the photochemical limit, the MPE for a single pulse is the same as for the entire exposure (40 mJ·cm^{-2}). Therefore, the MPE for Rule 1 is based on the thermal limit.

$$MPE_{SP}\ \text{(Rule 1)} = 6.66\ \text{mJ}\cdot\text{cm}^{-2}$$

Rule 2. Average Power Limit. For thermal effects, the MPE is 0.56 $t^{0.25}$ J·cm^{-2}, where t is now the total duration of the exposure, T_{max}, which is 10 s.

Thermal *MPE* (Rule 2) = $0.56\times(10)^{0.25}$ J·cm^{-2} = 0.56×1.78 J·cm^{-2} = 1.0 J·cm^{-2}

In a 10 s exposure, an individual could be exposed to 200×10 = 2000 pulses. The thermal MPE for each pulse is then

$$1.0\ \text{J}\cdot\text{cm}^{-2}/2000 = 0.5\ \text{mJ}\cdot\text{cm}^{-2}$$

The MPE based on photochemical effects for an accumulated exposure over a 10 s duration is 40 mJ·cm^{-2}. Therefore, the *MPE/pulse* based on photochemical effects is:

Photochemical *MPE/pulse* (Rule 2) = 40 mJ·cm^{-2}/2000 = 20 μJ·cm^{-2}

Since the photochemical MPE is much less than the thermal MPE, the MPE is:

$$MPE/pulse\ \text{(Rule 2)} = 20\ \mu\text{J}\cdot\text{cm}^{-2}$$

Rule 3. Multiple Pulse Correction. No correction (C_P) needs to be applied for this example since the pulses are less than t_{min} in length and the source is not extended.

Resultant MPE (Example 13):
The lowest *MPE/pulse* is 20 μJ·cm^{-2} or an average irradiance of 4 mW·cm^{-2}

B3.4 MPEs for Repetitive-Pulse, Pulse-Groups.
Example 14. **Pulse Group for Short-Pulse Laser. Find the MPE for a 694.3 nm Q-switched ruby laser that has an output of three 200 ps pulses, each separated by 100 ns.**

Solution. This is not a repetitive-pulse laser in the usual sense (that is, one having a continuous train of pulses lasting of the order of 0.25s or more with the pulses being reasonably equally spaced).

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Rule 1. Single Pulse Limit. From Table 5b, the MPE for a single pulse is:

$$MPE_{SP} = 2\times10^{-7}\ \mathrm{J\cdot cm^{-2}}$$

Rule 2. Average Power Limit. The duration of the pulse train is 200 ns (which is still less than t_{min} of 5 µs). The $MPE{:}H_{group}$ is therefore 2×10^{-7} J·cm^{-2} for the three pulses:

$$MPE\,/\,pulse = \frac{2\times10^{-7}\ \mathrm{J\cdot cm^{-2}}}{3\ \mathrm{pulses}} = 6.7\times10^{-8}\ \mathrm{J\cdot cm^{-2}}$$

Rule 3. Multiple Pulse Correction. No correction, C_P, needs to be applied for this example since the pulse group is less than t_{min} in length and the source is not extended.

Resultant MPE (Example 14):

Rule 2 provides the lowest MPE. Therefore, the *MPE/pulse* for this laser is 6.7×10^{-8} J·cm^{-2}.

Example 15. **Repetitive-Pulse, Pulse Groups. Find the MPE for a mode-locked Nd:YAG, frequency-doubled laser (532 nm) used in a pulse-code-modulated (PCM) communications link. The laser presents 10^4 "words" per second (that is, 10^4 pulse groups per second) and each word consists of five hundred 2-ps pulses spaced at coded intervals such that the average pulse separation is 100 ns. The laser is a small source when viewed from within the beam. Compute the MPE for a 0.25 s exposure.**

Solution.

Rule 1. Single Pulse Limit. The MPE_{SP} for a pulse less than 10 ps from Table 5b is:

$$MPE_{SP} = 1.0\times10^{-7}\ \mathrm{J\cdot cm^{-2}} \qquad \text{(B.10)}$$

Rule 2. Average Power Limit. Several iterations are required for this method since the pulses are in groups.

First, consider the pulses contained within t_{min}, which is 5 µs. The average PRF for exposure less than or equal to the word length is the inverse of 100 ns, which is 10 MHz. The number of pulses within 5 µs is therefore 5×10^{-6} s $\times$ 10^7 Hz = 50 pulses. The number of pulses in a word is 50×10^{-6} s $\times$ 10^7 Hz = 500 pulses.

For t_{min}, the MPE is the same as it is for 10 ps

$$MPE{:}H_{(t_{min})} = 2\times10^{-7}\ \mathrm{J\cdot cm^{-2}}$$

The MPE for each pulse is then,

$$MPE/pulse = \frac{2\times10^{-7}\ \mathrm{J\cdot cm^{-2}}}{50} = 4.0\times10^{-9}\ \mathrm{J\cdot cm^{-2}}$$

Second, consider one word, a group of 500 pulses, which lasts 50 µs.

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