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FORMAT OF REVISED SAFETY STANDARDS FOR INFRARED LASER EXPOSURES--ETC(U)
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This technical report has been reviewed and is approved for publication.

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A thermal model has been normalized to experimental damage threshold data for corneal injury (minimum epithelium lesions) from infrared lasers. Subsequent damage threshold predictions (as a function of exposure duration and absorption coefficient) are approximated by general equations and threshold curves. The formulated equations are adapted to indicate the wavelength dependence of infrared laser damage. A revised format for the ANSI Z136.1-1976 laser safety standard is proposed on the basis of these analyses.

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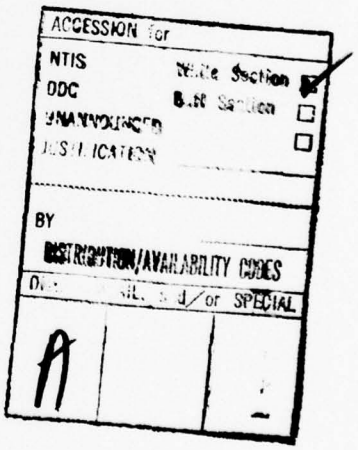
PREFACE

The author expresses appreciation for the excellent support of the Laser Effects Branch, Radiation Sciences Division, USAF School of Aerospace Medicine. Assistance from R. G. Allen, E. O. Richey, J. Taboada, G. W. Mikesell, Jr., K. L. Schepler, and K. A. Toth was particularly significant. I am indebted to D. E. Egbert of Air Force Weapons Laboratory for helpful discussions and the use of his unpublished data.



FORMAT OF REVISED SAFETY STANDARDS FOR INFRARED LASER EXPOSURES

INTRODUCTION

Current laser safety standards for infrared (IR) wavelengths between 1400 and 10^6 nm (Table 1) are not specified for individual wavelengths (1, 3, 4, 9), with the exception of the 1540-nm wavelength (3). Permissible exposure for this wavelength is 100 times that for all other wavelengths in this region. Standards for this particular wavelength, however, are defined only for exposure durations of 10^{-9} to 10^{-6} seconds.

TABLE 1: CURRENT ANSI STANDARD

Wavelength, λ (nm)	Exposure duration, t (sec)	Protection standard (J/cm^2)
$1400 < \lambda \leq 10^6$	$10^{-9} \leq t < 10^{-7}$	10^{-2}
	$10^{-7} \leq t < 10$	$0.56xt^{1/4}$
	$10 \leq t \leq 3x10^4$	$0.1xt$
$\lambda = 1540$	$10^{-9} \leq t < 10^{-7}$	1
	$10^{-7} \leq t \leq 10^{-6}$	$56xt^{1/4}$

The extent of IR energy absorption by the cornea depends on the wavelength-dependent corneal absorption coefficient (α). The absorbed energy generates heat, which causes damage if the resultant temperature rise is of sufficient magnitude and duration. Consideration of α vs. wavelength (λ) and of α vs. damage threshold should permit correlation of λ to damage threshold (and subsequently to safety standards).

The absorption spectrum (α vs. λ) of the cornea can be approximated, to a great degree, by that of water (5, 10, 17). In the wavelength region of interest here, the absorption coefficient of water varies from about 5 to 13,000 cm^{-1} (Fig. 1). That the wide variation in λ-dependent energy deposition is not reflected in current safety standards is not surprising, since biological threshold studies have been performed at only a limited number of wavelengths. However, as interest increases in new laser-generated wavelengths (e.g., λ = 1540 nm for the erbium laser),

new standards will be needed to ensure more realistic hazard evaluations and safety control measures while maximizing laser usage.

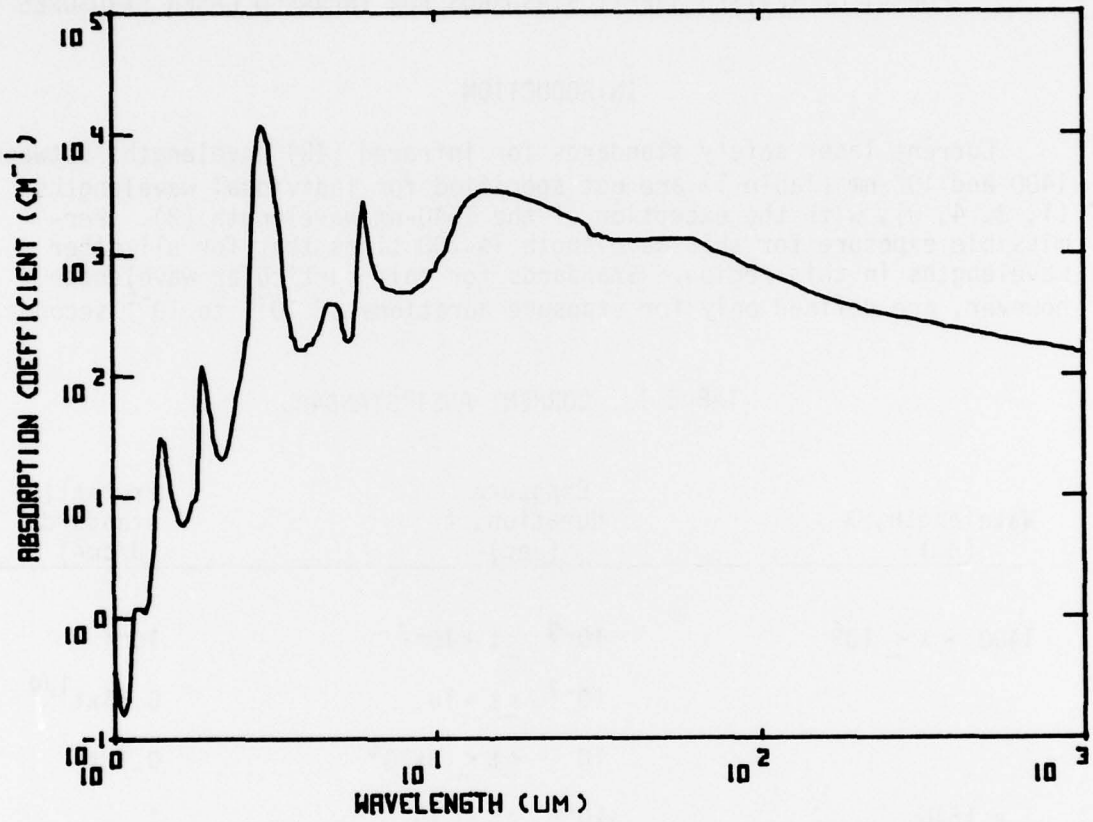


Figure 1. Water absorption spectrum (From Ref. 7, p. 28).

The objective of the current study was to develop an infrared safety standard that would both incorporate λ-dependence and be easily employed by the laser user.

BACKGROUND

The need to experimentally determine damage threshold values can be minimized if a reliable model is used to predict corneal temperature rise and damage. Recently, such a biomathematical model (11, 17) was used by Egbert and Maher (7) to predict the corneal damage threshold from IR laser radiation as a function of α, duration of exposure, beam radius, and damage endpoint criterion. They compared the predictions to experimental data and concluded that the model can be used to provide a broader basis for IR safety standards.

The applied model computes time-varying, three-dimensional temperature distributions (i.e., temperature-rise histories) based on the standard heat-conduction equation in cylindrical coordinates. Details of the approach for using calculated temperature rises to determine thresholds of irreversible tissue damage within the cornea are given by Egbert and Maher (7).

METHODS

Both current and proposed standards are essentially based on minimum epithelial damage thresholds. As detailed by Egbert and Maher (7), consideration has been given also to possible thresholds for stromal deformation and epithelial vaporization. Although this approach was limited by a lack of empirical data with which to normalize the model, comparisons with available data indicate that the proposed standards will safely encompass these other damage endpoints.

Egbert and Maher (7) calculated minimum epithelial lesion damage thresholds using two approaches: (a) the Henrique damage integral, or rate process method, at the beam center, r=0 (termed $H_{\ell di}$); and (b) the average critical peak temperature (CPT) rise method at r=0 (termed $H_{\ell c}$). Both approaches have been normalized to available experimental data; i.e., constants of the damage integral were normalized to predict lesion depths resulting from skin thermal exposures (16), and the CPT was normalized with respect to laser exposures producing a minimal visible epithelial lesion of the cornea (7). For their purposes Egbert and Maher (7) averaged the results of these approaches to produce an average lesion threshold ($H_{\ell a}$). For our effort, however, we selected $H_{\ell c}$, which has been directly normalized to laser threshold studies, as the primary threshold criterion. The constant relationship found (7) between $H_{\ell c}$ and $H_{\ell di}$--such that, on the average, $H_{\ell c} \approx H_{\ell di} \times 1.7$--adds support to the $H_{\ell c}$ findings and further indicates the utility of the more flexible damage integral method for threshold modeling.

The threshold data ($H_{\ell c}$) generated by the thermal model has been approximated by a general equation (A-1, Appendix) that can be broken into three parts to produce a 3-segment, α-dependent threshold curve. Use of such a segmented curve simplifies quantification and calculation of standards. We developed safety standards from this curve (with a designated safety factor of $\simeq$10) after the following three modifications:

First, Egbert and Maher (7) originally made model predictions for a beam radius of .0707 cm (1/e). They reported, however, that larger beam radii yield lower thresholds, presumably due to a limitation of heat diffusion away from the central damage site. For this reason, our final standards were based on a modeled beam radius of 0.5-1.0 cm as the worst case. If much smaller beam radii are used, coupled with exposure durations longer than $\simeq 10^{-2}$ sec, the safety margin set by the proposed standard increases markedly.

Second, we made a correction for the increased reflection (2, 6, 8, 12, 13, 15, 18) from the corneal surface of far IR wavelengths (>50 μm). This correction was used in calculating the constants for the standard in discrete λ-dependent steps. (See Appendix.)

Third, the equation that we developed for the longest exposure durations produced safety standard curves close to the existing standard of $0.1xt$ (J/cm^2). In this region the current standard was retained.

A unique safety standard could be generated for each specific infrared wavelength; however, this is not practical. To simplify use of the standard, we divided the IR wavelength region (1400-10^6 nm) into discrete bands. For each band of wavelengths a maximum, worst-case, α was determined and used to calculate the constants that establish the proposed IR safety standard for that band.

Two main criteria were used in defining these bands. The primary criterion was to divide the spectrum (α vs. λ) with small increments of α, keeping the range of α(ratio: $\alpha_{max}/\alpha_{min}$) within each wavelength band to a factor of $\simeq 2$. This criterion was unnecessary for $\alpha > 1000\text{-}2000\ cm^{-1}$ because the damage threshold becomes independent of α as α increases beyond $\sim 1000\ cm^{-1}$. Several sources were surveyed for appropriate values of α (2, 6, 8, 12, 13, 14, 15, 18), and conservative values were selected. The second criterion was that if a point of division fell on or very near the wavelength of a well-known laser system, the division line was shifted slightly to avoid confusion. Wavelength bands are used only as a simplification for the user. This avoids more complex manipulations of an equation (such as A-2, Appendix) requiring the input of α from some table or graph. The simplification does not preclude applying the standard to particular systems, and any wavelength in the infrared region has a designated standard.

RESULTS

The equations used to calculate the constants for the proposed standard are presented in the Appendix. These equations are modified forms (considering beam radius, possible stromal effects, etc.) of the single equation (A-1, Appendix) originally formulated to approximate the modeled threshold predictions.

Tables 2 and 3 present the format and constants of the proposed standard. Figures 2-4 give a graphic comparison of the proposed standard vs. the current ANSI standard for three selected laser systems. Finally, Table 4 gives a comparison of ANSI and currently proposed standards (with corresponding safety factors) when applied to specific, experimentally determined threshold exposures. For wavelengths with low corneal absorption coefficients, the difference between standards increases, with the current ANSI standard setting excessive safety factors.

TABLE 2. PROPOSED STANDARD

Wavelength, λ (nm)	Exposure duration, t (sec)	Protection standard (J/cm^2)*
$1400 < \lambda \leq 10^6$	$10^{-9} \leq t < T_1$	A
	$T_1 \leq t < T_2$	$Bxt^{1/3}$
	$T_2 \leq t \leq 3x10^4$	0.1xt

*See Table 3 for values of T_1, T_2, A, and B at any λ.

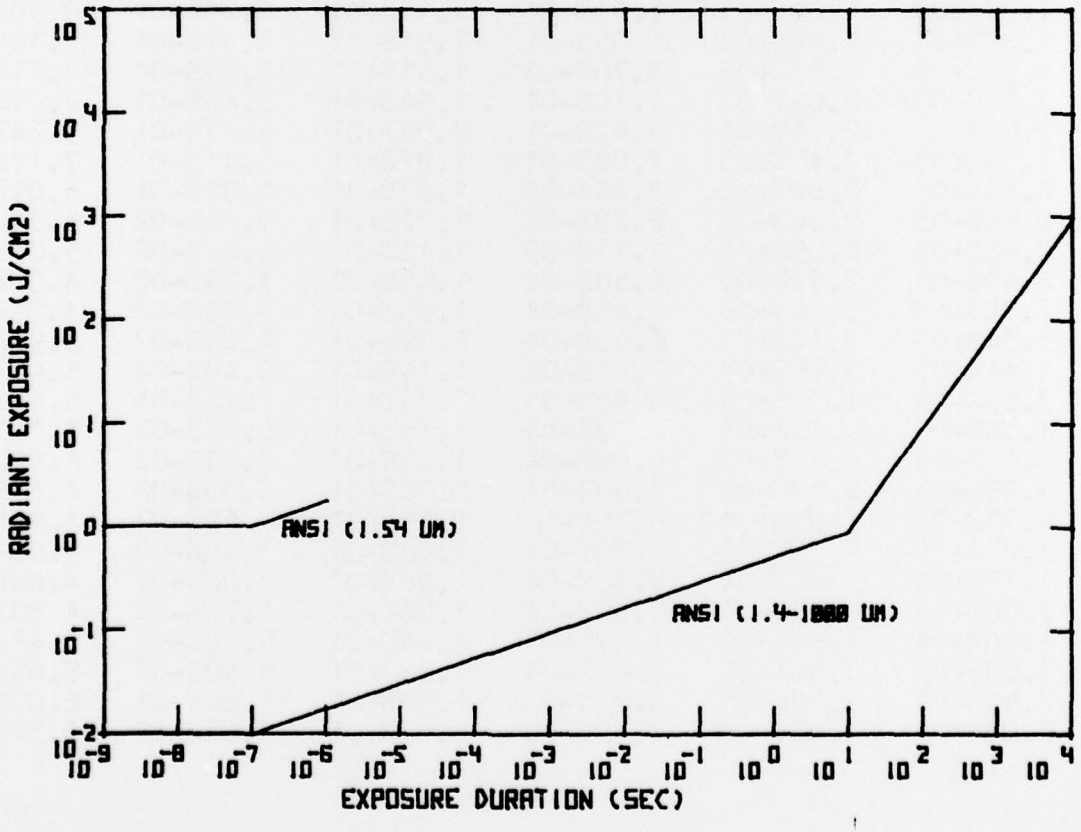


Figure 2. Current ANSI safety standard from 1400-10^6 nm.

TABLE 3: SUBDIVISION OF WAVELENGTH REGION 1400-10^6nm AND APPROPRIATE CONSTANTS FOR SAFETY STANDARD

Instructions:
1. Locate the wavelength band encompassing the experimental wavelength (λ) such that ($\lambda_1 < \lambda \leq \lambda_2$).
2. In the same line as that wavelength band, read values of T_1, T_2, A, & B.
3. Referring to Table 2, use the appropriate constant in conjunction with the known exposure duration (t) to determine the Protection Standard.

λ_1(nm)	λ_2 (nm)	T_1 (sec)	T_2 (sec)	A	B
1.40E+03	1.53E+03	3.39E-01	3.22E+01	7.06E-01	1.01E+00
1.53E+03	1.85E+03	5.03E-01	4.47E+01	1.00E+00	1.26E+00
1.85E+03	1.88E+03	2.91E-01	2.93E+01	6.29E-01	9.49E-01
1.88E+03	1.90E+03	1.05E-01	1.91E+01	3.37E-01	7.14E-01
1.90E+03	2.01E+03	3.78E-02	1.51E+01	2.05E-01	6.11E-01
2.01E+03	2.07E+03	1.10E-01	1.94E+01	3.46E-01	7.21E-01
2.07E+03	2.34E+03	3.02E-01	2.99E+01	6.47E-01	9.64E-01
2.34E+03	2.45E+03	1.08E-01	1.92E+01	3.41E-01	7.17E-01
2.45E+03	2.60E+03	3.25E-02	1.47E+01	1.92E-01	6.01E-01
2.60E+03	2.66E+03	6.28E-03	1.22E+01	9.80E-02	5.31E-01
2.66E+03	2.69E+03	1.73E-03	1.13E+01	6.05E-02	5.04E-01
2.69E+03	2.72E+03	6.60E-04	1.09E+01	4.29E-02	4.92E-01
2.72E+03	3.34E+03	2.46E-04	1.05E+01	3.00E-02	4.79E-01
3.34E+03	3.44E+03	6.60E-04	1.09E+01	4.29E-02	4.92E-01
3.44E+03	3.55E+03	2.01E-03	1.14E+01	6.40E-02	5.07E-01
3.55E+03	4.30E+03	8.98E-03	1.26E+01	1.13E-01	5.42E-01
4.30E+03	5.72E+03	2.39E-03	1.15E+01	6.82E-02	5.10E-01
5.72E+03	5.85E+03	6.60E-04	1.09E+01	4.29E-02	4.92E-01
5.85E+03	6.37E+03	2.39E-04	1.06E+01	3.00E-02	4.83E-01
6.37E+03	1.07E+04	8.19E-04	1.10E+01	4.63E-02	4.95E-01
1.07E+04	1.15E+04	4.20E-04	1.08E+01	3.65E-02	4.88E-01
1.15E+04	3.00E+04	2.40E-04	1.06E+01	3.00E-02	4.82E-01
3.00E+04	9.00E+04	4.56E-04	1.08E+01	3.76E-02	4.89E-01
9.00E+04	1.50E+05	1.07E-03	1.28E+01	5.60E-02	5.48E-01
1.50E+05	2.50E+05	3.45E-03	1.36E+01	8.59E-02	5.69E-01
2.50E+05	5.00E+05	8.98E-03	1.50E+01	1.26E-01	6.07E-01
5.00E+05	1.00E+06	1.55E-02	1.67E+01	1.62E-01	6.52E-01

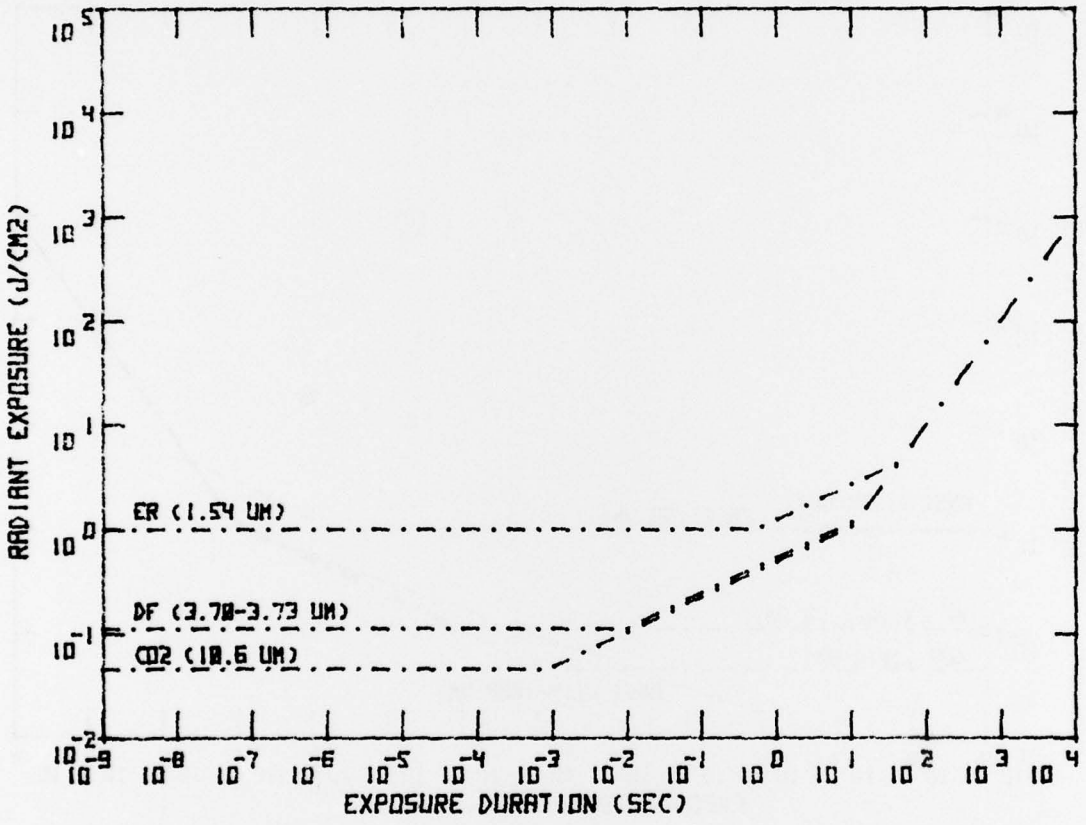


Figure 3. Proposed safety standard as exercised for three laser systems.

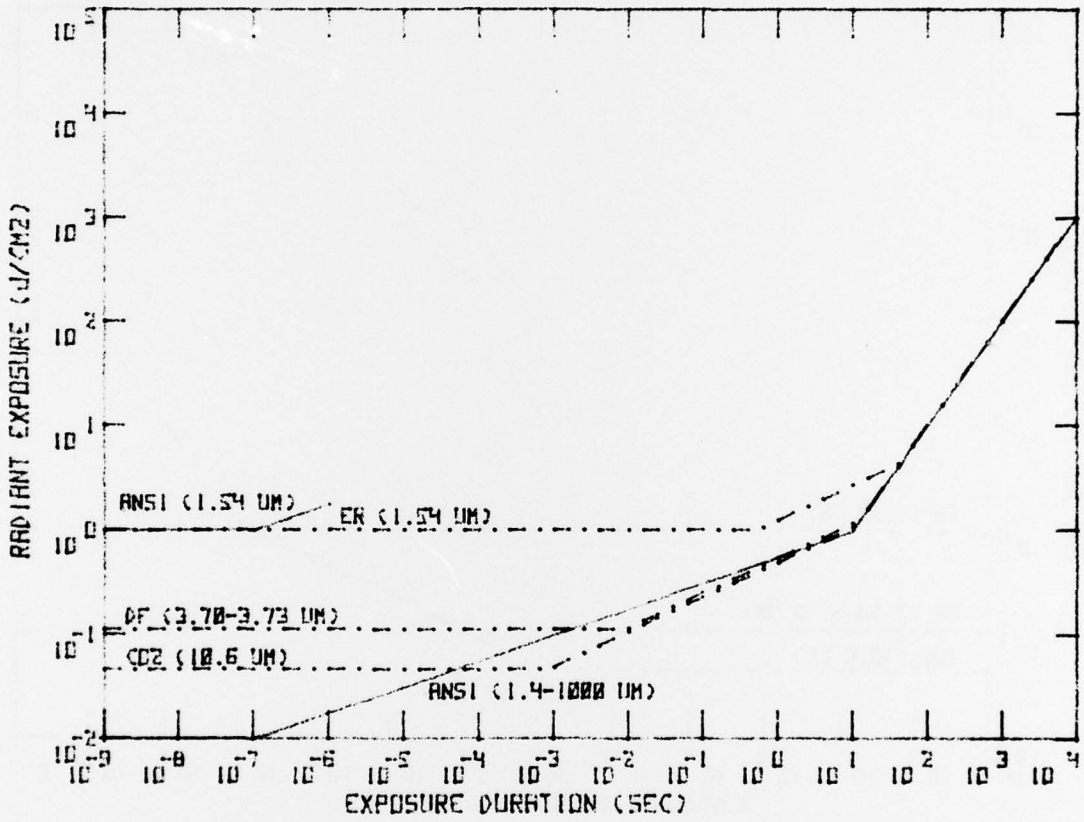


Figure 4. Comparison of ANSI and proposed standards (composite of Figs. 2 and 3).

TABLE 4. COMPARISON OF ANSI AND PROPOSED STANDARDS AS APPLIED TO SPECIFIC EXPERIMENTAL EXPOSURES[a]

A--Epithelial Endpoints

Exposure duration	Wavelength λ (μm)	Experimental[b] threshold $H_{\ell e}$ (J/cm^2)	ANSI standard H_{ANSI} (J/cm^2)	Proposed standard H_{pr} (J/cm^2)	Safety factors $\frac{H_{\ell e}}{H_{ANSI}}$	Safety factors $\frac{H_{\ell e}}{H_{pr}}$
1.4 nsec	10.6	0.2	0.01	0.046	20.0	4.3
45 "	2.61-2.87	0.62	0.01	0.03	62.0	20.7
50 "	1.54	21	1.00	1.00	21.0	21.0
100 "	3.55-3.98	1.51	0.01	0.113	151.0	13.4
100 "	2.9	0.3	0.01	0.03	30.0	10.0
120 "	10.6	0.35	0.01	0.046	35.0	7.6
1 msec	10.6	0.80	0.10	0.050	8.0	16.0
2 "	10.6	0.97	0.12	0.062	8.1	15.6
3.5 "	10.6	0.55	0.14	0.075	3.9	7.3
6 "	10.6	0.9	0.16	0.090	5.6	10.0
10 "	10.6	0.73	0.18	0.107	4.1	6.8
10 "	10.6	0.77	0.18	0.107	4.3	7.3
10 "	2.795	0.86	0.18	0.103	4.8	8.3
25 "	2.727	1.55	0.22	0.140	7.0	11.1
55 "	10.6	1.20	0.27	0.188	4.4	6.4
70 "	10.6	0.68	0.29	0.204	2.3	3.3
100 "	10.6	2.34	0.32	0.230	7.3	10.2
100 "	10.6	2.50	0.32	0.230	7.8	10.9
100 "	10.6	2.57	0.32	0.230	8.0	11.2
100 "	10.6	0.95	0.32	0.230	3.0	4.1
100 "	2.727	2.80	0.32	0.222	8.8	12.6
100 "	2.795	2.06	0.32	0.222	6.4	9.3
125 "	3.70-3.73	4.61	0.33	0.271	14.0	17.0
300 "	10.6	5.64	0.41	0.331	13.8	17.0
500 "	3.70-3.73	7.68	0.47	0.430	16.3	17.9
500 "	10.6	4.69	0.47	0.393	10.0	11.9
500 "	2.727	6.99	0.47	0.380	14.9	18.4
500 "	2.795	4.76	0.47	0.380	10.1	12.5
1 sec	10.6	7.70	0.56	0.495	13.8	15.6
1 "	10.6	3	0.56	0.495	5.4	6.1
1 "	10.6	10.3	0.56	0.495	18.4	20.8
3 "	10.6	11.6	0.74	0.714	15.7	16.2
5 "	10.6	15	0.84	0.846	17.9	17.7
900 "	10.6	220	90.00	90.00	2.4	2.4
1800 "	10.6	360	180.00	180.00	2.0	2.0

B--Stromal Endpoints

1.4 nsec	10.6	>0.2	0.01	0.046	>20.0	>4.3
50 "	1.54	45	1.00	1.00	45.0	45.0
100 "	2.9	>0.3	0.01	0.03	>30.0	>10.0
55 msec	10.6	3.6	0.27	0.188	13.3	19.1
70 "	10.6	1.2	0.29	0.204	4.1	5.9
300 "	10.6	6.9	0.41	0.331	16.8	20.8
500 "	10.6	12	0.47	0.393	25.5	30.5
1 sec	10.6	12.6	0.56	0.495	22.5	25.5
1 "	10.6	15	0.56	0.495	26.8	30.3
1 "	10.6	15	0.56	0.495	26.8	30.3
3 "	10.6	17	0.74	0.714	23.0	23.8
600 "	10.6	228	60	60	3.8	3.8
1800 "	10.6	540	180	180	3.0	3.0

[a]See Ref. 7, Tables 1 and 2, for experimental references and related data.

[b]Confidence limits are not cited in Ref. 7. Our own researchers indicate that 95% confidence limits for corneal ED_{50} values commonly lie 5 to 25% above and below the ED_{50}.

CONCLUSIONS AND RECOMMENDATIONS

The proposed format for infrared laser standards incorporates wavelength dependency into the standards. It covers the entire wavelength region of 1400-10^6 nm and eliminates the need for narrowly defined exceptions (e.g., 1540 nm) to the standard. The format is flexible and subject to easy revision or redivision should either more or less resolution of wavelengths be required. It ensures a more uniform safety factor (Table 4) for laser systems and indicates that a higher safe energy output is possible for lasers operating in many wavelength regions.

Beam size is not considered in the current standard nor the proposed standard. The potential exists, however, for later introduction of a radius-dependent correction factor, which would decrease safety restrictions for laser systems with very small beam radii. Until that time, the proposed standard is conservative with respect to safety in this regard.

The problem of standards for multiple-wavelength exposures deserves more attention. The most conservative treatment is to assume, for the sake of calculations, that all incident energy is derived from the most destructive wavelength present (i.e., the wavelength that has the most restrictive standard). This treatment is no worse than the current standard, which essentially equates all lasers to the high-α CO_2 system. The potential exists, however, for a treatment involving analysis of the energy contributions by each wavelength present. Validation of such an approach would require biological experimentation and more extensive computer modeling, but could be beneficial by substantially liberalizing standards in some areas.

Exploration of possible infrared laser effects on corneal stroma or deeper tissues of the eye (e.g., lens) will require biological experimentation to clarify the mechanisms and magnitude of such damage. Also, further research will be required before the endpoint of the minimum visible epithelial lesion can be replaced by a more "sensitive" endpoint. At this time, the proposed standard utilizes the most sensitive common corneal endpoint and encompasses stromal effects. We were concerned whether at low corneal absorption coefficients sufficient energy might reach the lens to create a cataract. Although we could find no data to indicate such a hazard in this wavelength region, we did increase the safety factor on the wavelength bands with lowest corneal absorption coefficients.

There is a scarcity of chronic laser exposure data with which to verify the proposed standard's segment dealing with the longest exposure durations. This is also true for the current ANSI safety standard since the two are, in this region, identical. This segment can be readily altered (e.g., from 0.1t to 0.01t or $0.1t^{3/4}$) if future experimental studies indicate an increased danger from chronic low-level exposure.

Experimental validation of the proposed standard would ultimately involve selected exposures at various near-IR wavelengths. Either selected lasers or a tunable IR laser would meet the requirements for such biological studies. As pointed out by Egbert and Maher (7), studies of this type to date have produced damage threshold values that support the need for a new infrared safety standard such as the one proposed here.

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APPENDIX

DEVELOPMENT AND CALCULATION OF CONSTANTS FOR PROPOSED STANDARD

The threshold data of $H_{\ell c}$ (J/cm^2) as a function of α and t (provided by Egbert, unpublished data) was fitted with the general equation:

$$H_{\ell c} = \underbrace{(200\alpha^{-1} + 0.25)}_{\text{but} \geq 0.3} + (110\alpha^{-1} + 2.2)t^{1/3} + (35\alpha^{-1} + 3.3)t \quad \text{(A-1)}$$

where α is the estimated corneal absorption coefficient in cm^{-1}, and
t is the exposure duration in seconds.

This equation is applicable only for a 1/e beam radius of .0707 cm. It was modified to predict damage thresholds for a beam radius of ≈1 cm (considered worst case conditions), and a safety factor of ≈10 was incorporated. Subsequently, it was altered slightly to coincide with the current ANSI safety standard curve in the region of longest exposure durations. The general equation of the proposed safety standard, H_{pr} (maximum permissible exposure, in J/cm^2), is:

$$H_{pr} = \underbrace{(17\alpha^{-0.944} + 0.02)R}_{\text{but} \geq 0.03R} + (16\alpha^{-1} + 0.478)Rt^{1/3} + 0.1t \quad \text{(A-2)}$$

where R = a correction factor for the reflectivity of the tear layer, detailed later.

A graphic presentation of Equation A-2 for three specific laser systems is given in Figure A-1.

For ease of quantification and calculation of standards, the safety standard curve was divided into 3 straight-line segments (Figs. 3 and A-2). The constants of these segments (see Tables 2 and 3) are calculated as below:

$$A = (17\alpha^{-0.944} + 0.02)R, \text{ but} \geq 0.03R \quad \text{(A-3)}$$

Equation A-3 is used as the safety standard (i.e., A, in J/cm^2) for exposure durations of $10^{-9} \leq t < T_1$.

$$B = (16\alpha^{-1} + 0.478)R \quad \text{(A-4)}$$

Equation A-4 is used to calculate the safety standard (i.e., $Bt^{1/3}$, in J/cm^2) for exposure durations of $T_1 \leq t < T_2$.

$$C = 0.1 \qquad \text{(A-5)}$$

Equation A-5 is used to calculate the safety standard (i.e., 0.1t, in J/cm^2) for exposure durations of $T_2 \leq t \leq 3x10^4$. This segment is identical to the current ANSI standard for long exposure durations.

The times T_1 and T_2 are the points at which $A = Bt^{1/3}$ and $Bt^{1/3} = Ct$, respectively. Thus,

$$T_1 = \left(\frac{A}{B}\right)^3 \qquad \text{(A-6)}$$

$$\text{and, } T_2 = \left(\frac{B}{C}\right)^{1.5}$$

The values of λ_1, λ_2, and α for discrete wavelength bands (see Table 3) were selected as described in the text. For each band of $\lambda_1 - \lambda_2$ the corresponding α is used to solve for A and B. Correction factors (R) for the reflectivity of the tear layer were as follows (with λ_1 in μm):

FOR: $\lambda_1 < 50$, R = 1.00

$50 \leq \lambda_1 < 70$, R = 1.06

$70 \leq \lambda_1 < 200$, R = 1.10

$200 \leq \lambda_1 < 350$, R = 1.12

$350 \leq \lambda_1 < 450$, R = 1.14

$450 \leq \lambda_1 < 600$, R = 1.16

$600 \leq \lambda_1 < 750$, R = 1.18

$750 \leq \lambda_1 < 900$, R = 1.20

$900 \leq \lambda_1 \leq 1000$, R = 1.22

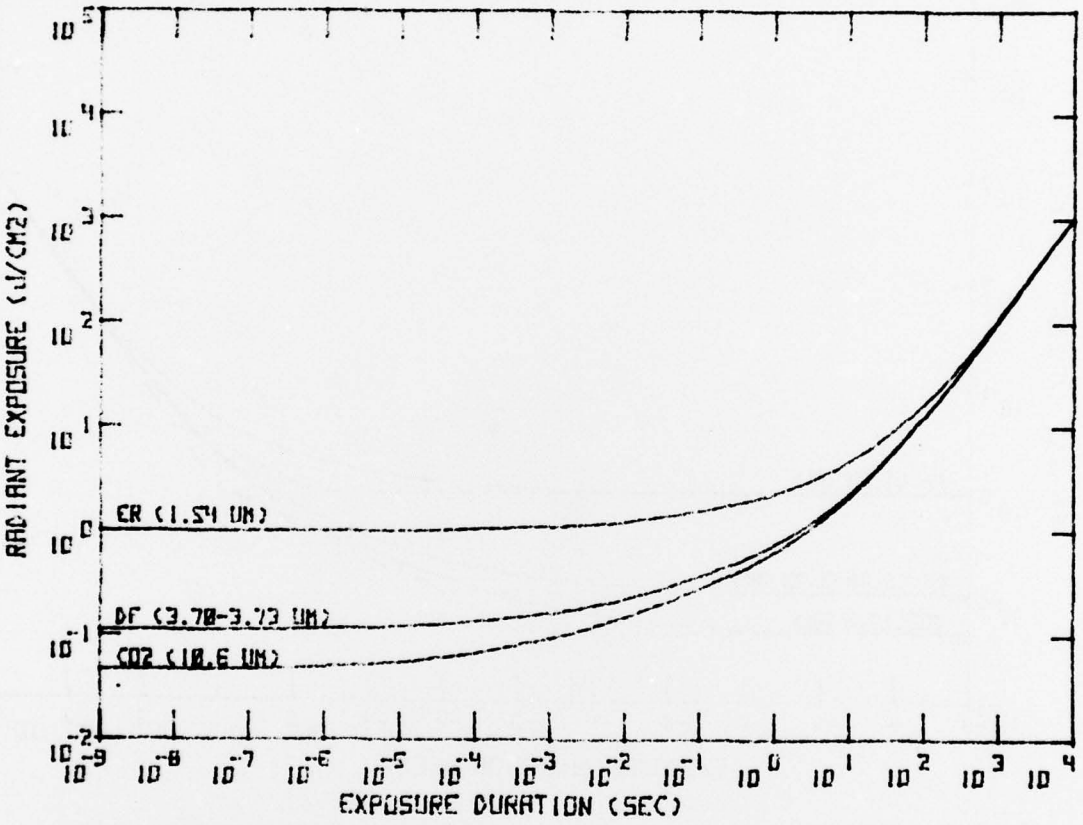

Figure A-1. General equation for safety standard as exercised for three laser systems.

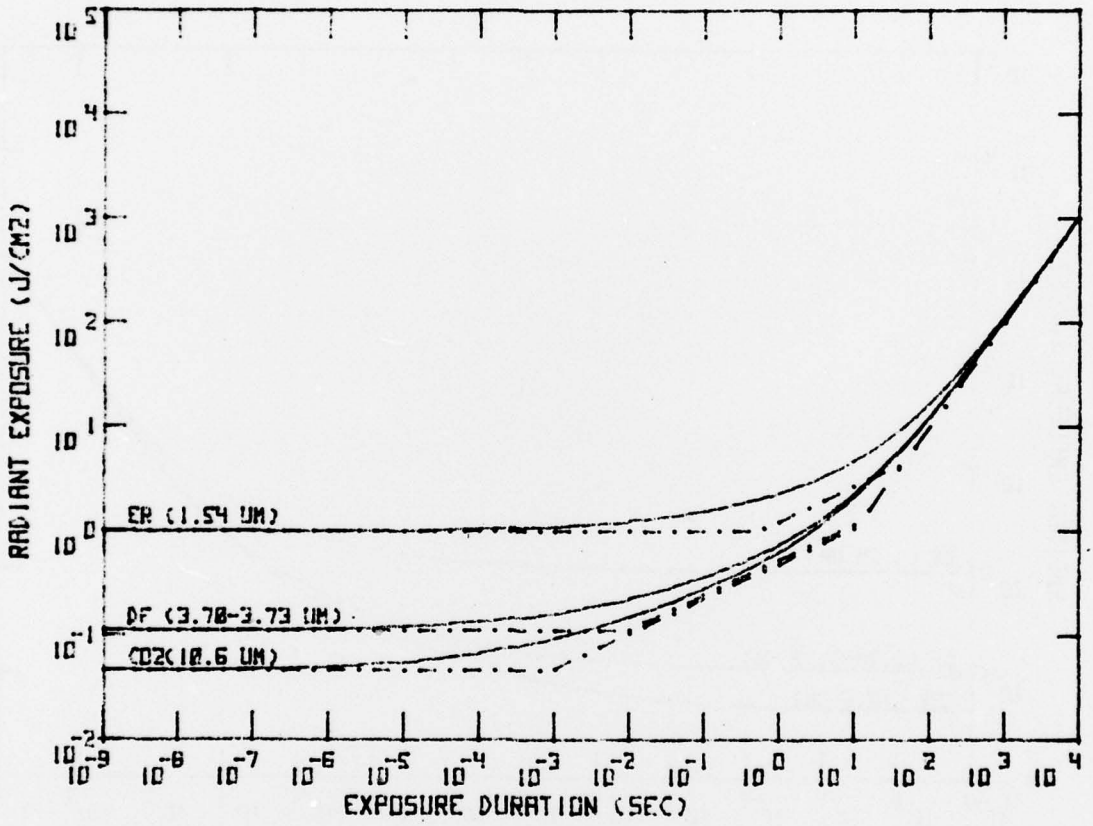

Figure A-2. General equation for safety standard, and segmented approximation, as exercised for three laser systems.