CONSIDERATIONS OF HUMAN EYE SAFETY IN THE DESIGN AND DEVELOPMENT OF A LASER ENGAGEMENT SYSTEM

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ABSTRACT

Laser Engagement Systems (LES) of the type recently developed by Xerox Electro-Optical Systems involve the intentional direction of pulsed laser radiation at humans. Since the hazard of ocular irradiance is obvious, it is imperative that such systems be eye safe to the point of insuring that no permanent retinal damage can be inflicted regardless of the tactical environment. The analysis developed in this paper considers the influence of power levels, pulse duration, multiple pulses, laser beam divergence, distributed and point source characteristics and, finally, the matter of retinal thermal relaxation. The results of this analysis are a series of constraints which must be placed upon the design of an LES system in order to insure human eye safety under all conditions.

SECTION I. INTRODUCTION

It is absolutely imperative that any field equipment involving laser radiation directed at personnel be totally eye safe under all conditions. This is critically important as any retinal damage incurred can result in permanent blindness. We must also realize that the equipment may not always be used in the prescribed manner. For example, there is no tactical reason why a soldier should look directly into the laser tube at one-inch range, but undoubtedly at some time this will occur. We believe it is imperative that the system be unconditionally eye safe - so that in spite of unauthorized or unapproved actions the soldier cannot inadvertently be exposed to a radiation level resulting in permanent blindness.

The philosophy of unconditional eye safety for MILES/LES runs through much of the Xerox Electro-Optical Systems system design. The factors which influence eye safety (viz., laser power, laser beamspread, laser optical aperture) are also the parameters which influence range, "kill" probability, beam size, "near miss" probability, detector spacing, and detector sensitivity. Furthermore, the detector spacing influences the number of detectors and the power level determines the required detector/preamplifier sensitivity. All of the above items influence both performance and cost.

Adopting an overly stringent eye safety requirement (e.g., two orders of magnitude less dosage than the Surgeon General's limit) would force a system with very low power lasers. In order to achieve the desired range it would then be necessary to utilize more sensitive detector/preamplifier combinations. Since the detector/preamplifier costs are a significant portion of the total system cost, overly stringent eye safety requirements would probably:

- Reduce range capabilities
- Increase false alarm rates
- Increase system cost

On the other hand, relaxing the eye safety requirements beyond the Surgeon General's specifications is patently dangerous and invites potentially permanent retinal damage and/or blindness. The responsibility to insure ocular safety of field troops is one we fully appreciate.

The goal of this eye safety analysis is to determine realistic constraints on the laser parameters, consistent with eye safety requirements, with the unaided eye or binoculars, and allowing the best possible system performance at the lowest cost.

SECTION II. EYE SAFETY ANALYSIS

As a result of the recently developed "Beam Goemetry Equation" and the associated digital computer program developed at Xerox Electro-Optical Systems, it is now possible to more accurately establish the irradiance, H(X,r), as a function of axial and radial beam coordinates. Furthermore, advances in both TES and VES accomplished during the ADM program, as well as anticipated EDM requirements, have changed some of the transmitter and detector parameters. For these reasons, this analysis will deal with the eye safety requirements for the proposed EDM versions of TES and VES.

The fundamental concepts involved in the analysis are as follows:

1. We shall utilize the Surgeon General's (see References 1 and 2) eye safety limit of 1 erg/cm^2 incident upon the cornea. This is the eye safe limit

for a pulsed, near IR laser which is imaged as a point source by a fully dark adapted human eye;

2. In the near IR the eye is sufficiently transparent that retinal rather than corneal damage is the dominant concern. (Reference 1);

3. That a point source will be imaged on a single 10μ diameter retinal element;

4. That the Surgeon General's eye safety limits used in concert with distributed sources can only be applied at those range values such that the point source approximation is again valid;

5. That the eye shall be characterized by a corneal-to-retinal magnification factor, for $\lambda = 9040Å$, of 6×10^5. That is, the retinal irradiance shall be greater than the point source/corneal irradiance by a factor of 6×10^5. (Reference 3);

6. The laser energy shall be assumed to be uniformly spread over the laser aperture;

7. The aperture of the laser transmitter is assumed to have a diameter of 2.5 cm for both TES and VES;

8. The laser pulse width is small compared to retinal thermal relaxation times so that the adiabatic heating limit is closely approached by the retinal tissue.

9. Continued viewing of multiple pulses will have a negligible effect since the thermal relaxation process, while slow relative to a single laser pulse width, is fast relative to the period between messages. We shall, however, assume the effects of multiple pulses per message (i.e., coded kill or miss bits, words and messages) are cumulative. Thus a single coded message consisting of three active bits in a 5-bit word, with 4 words per message results in 12 laser pulses per 38 millisecond time period. Since 38 milliseconds is comparable to or smaller than the thermal relaxation time of retinal tissue, we shall conservatively assume the effects to be directly cumulative. Hence, we shall consider the effective energy entering the cornea to be $E = 12\varepsilon$ where ε is the energy entering the cornea per pulse.

10. The laser pulse width shall be approximated to be 200 nanoseconds.

11. The kill and near-miss laser beams are superimposed in the kill region. Since the near miss beamspread is greater than the kill beamspread in all cases, the additional irradiance is thereby given by this geometry ratio times the ratio of the near miss to kill beam power levels. We may write the general superposition of the kill and near miss irradiance as follows:

$$H_{tot} = H_{Kill} + H_{Near\text{-}miss}$$

$$= \frac{P_{Kill}}{\pi\theta_K^2 x^2} + \frac{P_{NM}}{\pi\theta_{NM}^2 x^2}$$

or

$$H_{tot} = H_{Kill}\left[1 + \left(\frac{\theta_K}{\theta_M}\right) \frac{P_{NM}}{P_K}\right]$$

<u>For the TES System</u>:

$P_K = 1$ W $\quad \theta_K = 2 \times 10^{-3}$ rad

$P_{NM} = 5$ W $\quad \theta_M = 8 \times 10^{-3}$ rad

Thus, the superposition bracket becomes

$$\left[1 + \left(\frac{2 \times 10^{-3}}{8 \times 10^{-3}}\right)^2 \left(\frac{5}{1}\right)\right] = \left[1 + \frac{5}{16}\right]$$

$$= \frac{21}{16}$$

<u>For the VES System</u>:

$P_K = 5$ W $\quad \theta_K = 1 \times 10^{-3}$ rad

$P_{NM} = 5$ W $\quad \theta_{NM} = 4 \times 10^{-3}$ rad

Hence, the superposition bracket for the VES becomes

$$\left[1 + \left(\frac{1 \times 10^{-3}}{4 \times 10^{-3}}\right)^2 \left(\frac{5}{5}\right)\right] = \left[1 + \frac{1}{16}\right]$$

$$= \frac{17}{16}$$

Thus the inclusion of kill beam and near-miss beam superposition has a very small effect upon the Xerox EOS ADM VES, but does contribute approximately one-third additional irradiance to the worst case TES.

The power out of the laser is assumed constant during the effective pulse width τ. Thus the energy out of the laser is $E = P\tau$ and the total energy per "kill" message (i.e., individual firing of the trigger) is $E = 12\ P\tau$. The irradiance resulting from superposition of the kill and near-miss beams is 21/16 times that of the kill beam for TES, and 17/16 for VES. Hence, we shall consider the extremely conservative assumption that all individual pulses are directly cumulative, and that the kill and near-miss beams are superimposed, which gives,

$$E_{Max},\ TES = 15.75(P\tau)_{TES}$$

and

$$E_{Max},\ VES = 12.75\ (P\tau)_{VES}$$

Further, we shall assume the viewer is located directly on the centerline of the beam distribution, that the beam shape is Gaussian about the centerline in a cylindrical coordinate system. Thus if we assume the irradiance at any axial location is $H(X_o,r) = H_o\ e^{-(r/a)^2}$ then the total power in the beam at this station is simply,

$$P_{tot} = \int H dA = \int H_o\ e^{-(r/a)^2}\ 2\pi r dr$$

$$= 2\pi H_o \int_o^\infty e^{-(r/a)^2} r dr$$

$$= 2\pi H_o \left(\frac{a^2}{2}\right) \int_o^\infty e^{-u} du$$

$$= \pi a^2 H_o$$

Thus the total energy in the beam is given by

$$\pi a^2 H_o$$

where H_o is the centerline, peak irradiance, and "a" is the Gaussian e-folding width. Since it can be shown from conservation principles (see Reference 4) that

$$a(X) = \frac{D}{2} + \frac{\beta X}{2}$$

where,

D = aperture diameter of laser

β = laser total beamspread

X = range from laser aperture

We must now evaluate $a(X)$ at $X = X^*$. The critical point source range, X^*, is defined as that range at which the laser aperture is first perceived as a point source by the human eye. From Reference 5 we find that the minimum angular subtense which can be resolved by the human eye is approximately

$$\theta_{crit} = 0.5 \text{ arc-minute}$$

for a healthy human eye under good ocular conditions. Since 1 degree corresponds to $\pi/180$ radians or 17.5 milliradians, then 1 minute of arc corresponds to 17.5/60 or 0.292 milliradians. Thus

$$\theta_{crit} = 1.46 \times 10^{-4} \text{ radian}$$

and

$$X^* = \frac{D}{\theta_{crit}}$$

$$= \frac{2.5 \times 10^{-2} \text{ meter}}{1.46 \times 10^{-4} \text{ radian}}$$

$$= 171 \text{ meters}$$

Therefore,

$$a(X^*) = \frac{2.5}{2} + \frac{1 \times 10^{-3} \times 171 \times 10^2}{2}$$

$$= 1.25 + 8.55 = 9.8 \text{ cm}$$

Thus, the value of the <u>maximum centerline irradiance</u> can be computed from the simple expression, P_{tot}

$$P_{tot} = \pi a^2 H_{Max}$$

provided the values of $a(X^*)$ given above for TES and VES are employed.

Hence,

$$H_{Max_{TES}} = \frac{15.75(P\tau)TES}{\pi(18.35\ cm)^2}$$

and

$$H_{Max_{VES}} = \frac{12.75(P\tau)VES}{\pi(9.8)^2}$$

Substituting

$$(P\tau)_{TES} = 1 \text{ watt} \times 2 \times 10^{-7} \text{sec}$$

$$= 2 \times 10^{-7} \text{joules}$$

we find, for the ADM, TES system

$$H_{Max_{TES}} = \frac{15.75 \times 2 \times 10^{-7}}{3.14 \times 3.37 \times 10^{2}}$$

$$= 3 \times 10^{-9} \text{joules/cm}^2$$

This number may now be compared to Table 1 below.

Table 1

Non-Q-Switched Laser Safety Levels*

Daylight 3mm pupil	5.0×10^{-7} joules/cm^2
Laboratory 5mm pupil	2.0×10^{-7} joules/cm^2
Night 7mm pupil	1.0×10^{-7} joules/cm^2

* Prescribed by the Surgeon General. See Reference 1.

Since the lowest eye safety limit is 1×10^{-7} joules/cm^2, then the worst possible TES case is eye safe by a factor of 33. Note that this calculation assumed complete superposition of kill and near-miss irradiance levels and viewing on centerline. Off centerline viewing will result in even smaller levels.

Turning now to the VES system we find,

$$H_{Max_{VES}} = \frac{12.75 \times 5 \times 2 \times 10^{-7}}{3.14 \times (9.8)^2} \text{ j/cm}^2$$

$$= 4.39 \times 10^{-8} \text{ joules/cm}^2$$

Thus the VES system is still eye safe by over a factor of 2 in the worst possible case involving:

- Nighttime, dark adapted eye
- Viewing directly towards the laser exactly on the centerline
- Viewing at precisely the range at which the source is first perceived as a point source
- Complete cumulative addition of all 12 laser pulses in a message, with zero relaxation or dissipation of the thermal energy between pulses
- Superposition of the kill and near-miss beams

The VES (most powerful) ADM laser code is shown graphically in Figure 1. From this figure, it can be seen that the total energy density is 4.39×10^{-8}joules/cm^2 or a safety factor of better than 2:1 under theoretical worst case conditions.

SECTION III. <u>THERMAL RELAXATION OF RETINAL TISSUE</u>

The original analysis for eye safety assumed adiabatic heating of retinal tissue. In actuality, the eye does, of course, have a finite relaxation time. Riggs (Reference 6) suggests that thermal energy deposited on the retina will dissipate with a characteristic e-folding time of approximately 100 milliseconds. Thus an amount of energy, ϵ_1, deposited at the time t_1 will have dissipated to

$$\epsilon = \epsilon_1 e^{-(t-t_1)/\tau}$$

where τ = 100 milliseconds. We may now calculate, in a serial-chain fashion, the actual non-adiabatic retinal energy residual at the end of a 38-millisecond superimposed kill/near-miss message.

We shall consider the VES case. The energy per cm^2 for the near-miss pulse, $H_{VES_{NM}}$ is

$$\epsilon_{VES_{NM}} = \frac{5 \text{ watts}}{\pi \times (4)^2 \times (9.8)^2 \text{cm}^2} \times 2 \times 10^{-7} \text{sec}$$

$$= 0.021 \times 10^{-8} \text{joules/cm}^2$$

(note that the divergence of the near-miss beam is 4 times as great as the "kill" beam) while for the VES system "kill" beam

$$\epsilon_{VES_{Kill}} = 16\epsilon_{VES_{NM}} = 0.33 \times 10^{-8} \text{j/cm}^2$$

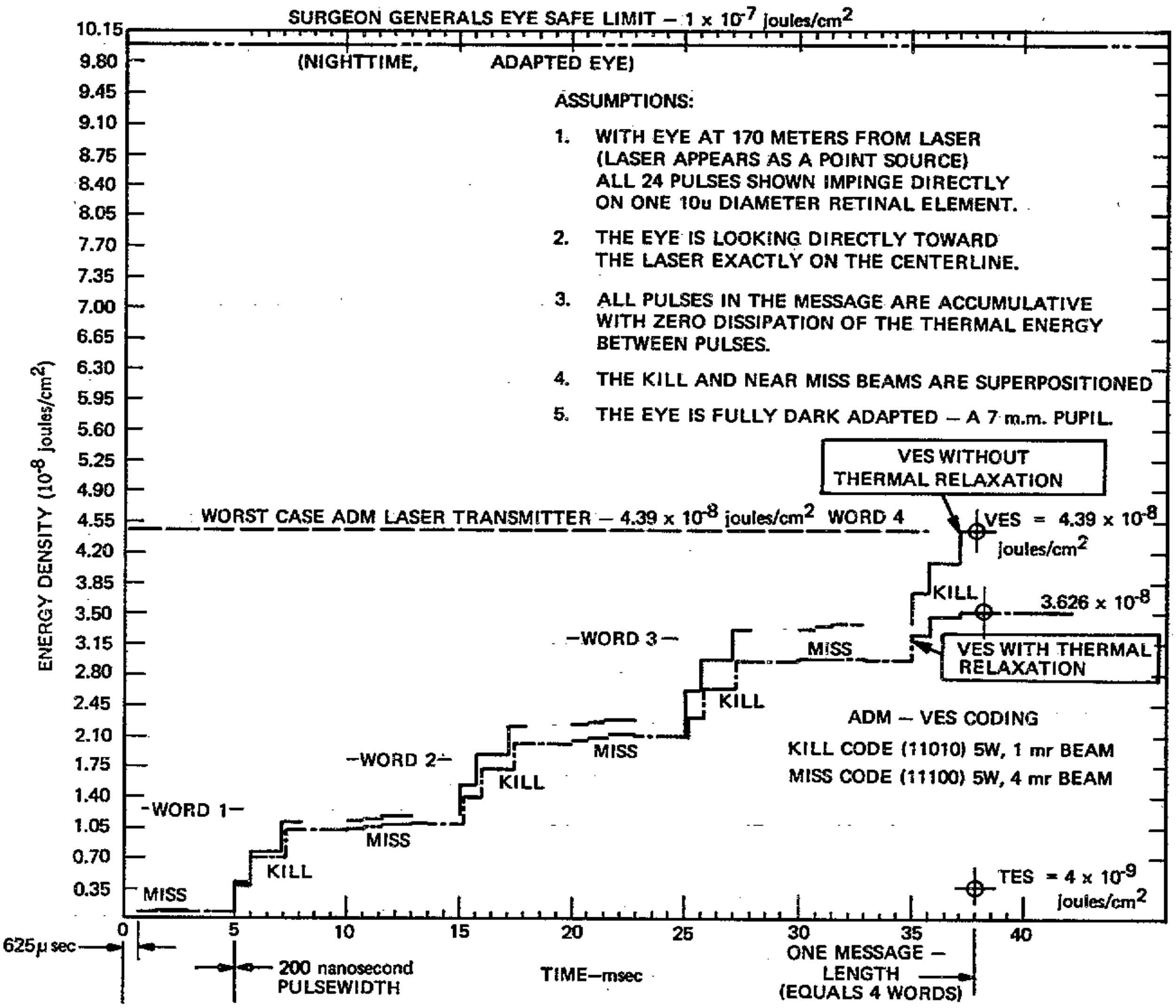

Figure 1. Maximum Retinal Energy Impingement, ADM System

TABLE 2

THERMAL RELAXATION HISTOGRAM

Event	t_i (milliseconds)	Δt_i (milliseconds)	$e^{-\Delta t_i/100}$	ϵ_i	$\epsilon_{residual}$
First Miss Word	1	37	0.69	0.06×10^{-8} j	0.042×10^{-8} j
First Kill Word	7	31	0.73	1.0×10^{-8} j	0.730×10^{-8} j
Second Miss Word	12	26	0.77	0.06×10^{-8} j	0.046×10^{-8} j
Second Kill Word	17	21	0.81	1.0×10^{-8} j	0.810×10^{-8} j
Third Miss Word	22	16	0.85	0.06×10^{-8} j	0.051×10^{-8} j
Third Kill Word	27	11	0.90	1.0×10^{-8} j	0.900×10^{-8} j
Fourth Miss Word	32	6	0.94	0.06×10^{-8} j	0.057×10^{-8} j
Fourth Kill Word	37	1	0.99	1.00×10^{-8} j	0.990×10^{-8} j
				TOTAL	3.626×10^{-8} j

Since the near miss code consists of 3 bits followed by two spaces, we can closely approximate a miss word by taking $\epsilon_{MISS\ WORD}$

$$\epsilon_{MISS\ WORD} = 3\epsilon_{VES_{NM}} = 0.06 \times 10^{-8} j/cm^2$$

at the time of the central pulse.

The kill code is given by 2 bits, a space, a bit and a space. Again, we may approximate this by taking,

$$\epsilon_{KILL,\ WORD} = 3\epsilon_{VES_{KILL}}$$

$$= 1 \times 10^{-8}\ j/cm^2$$

at the time of the second pulse.

Table 2 describes the event, central time of the event (per above discussion), time interval remaining to the end of the message, thermal relaxation factor, and remaining residual energy at the end of the message due to this particular portion of the message.

Figure 2 is a logarithmic energy plot of some of the more important values pertinent to the eye safety question. The levels are as follows:

1. At the lowest level, 1×10^{-9} joule, we find the entire VES near miss code word energy level incident to on the retina. Here we have assumed that all energies in the near miss code are directly additive.

2. The second level, 3.3×10^{-9}, represents an <u>individual</u> "kill code" <u>VES pulse</u>.

3. At 4×10^{-9} we find the entire kill and near miss <u>TES message</u>.

4. At 1.0×10^{-8} joule is the 3-active bit, <u>VES kill word</u>.

5. At about 4.4×10^{-8} joules is the VES "kill" message (i.e., $4 \times 1 \times 10^{-8}$) plus the VES miss message ($4 \times 1 \times 10^{-9}$). This value is realized in the limit of complete adiabatic heating of the retina. If one allows for finite thermal relaxation of retinal tissue, a value of 3.6×10^{-8} joules is realized.

6. At 1×10^{-7} joules we find the Surgeon General's eye safety limit for fully dark adapted (7 mm diameter pupil) human eyes. At 2×10^{-7} and 5×10^{-7} joules we find the levels for a normal 5 mm pupil (indoor lighting) and for a 3 mm pupil in bright sunshine.

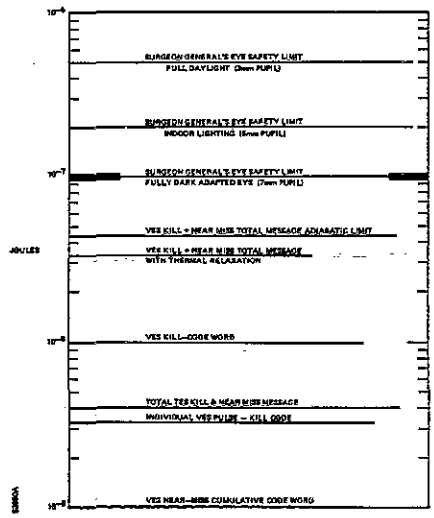

Figure 2. ADM Retinal Energy Absorption Versus Eye Safety Limits

The point of this figure is to show graphically that even the worst case EDM VES situation (i.e., maximum laser power, minimum beamspread, centerline, zero atmospheric absorption, cumulatively added "kill" and near miss laser pulses) is still eye safe by a factor of three against a worst case, fully dark adapted eye. In the daytime, the system is eye safe by over an order of magnitude.

SECTION IV. <u>MAXIMUM ALLOWABLE EYE SAFE LASER POWER LEVELS</u>

The inclusion of retinal thermal relaxation results in an effective cumulative total energy per message of 3.626×10^{-8} joules, as shown in Figure 1. Since the Surgeon General's eye safety limit for a fully dark adapted eye corresponds to 10×10^{-8} joule, this corresponds to a safety factor of 2.76.

SECTION V. CONCLUSIONS

1. The present Xerox EOS LES system is eye safe at all ranges.

2. The unaided human eye represents the most critical retinal damage case. Binoculars will decrease the hazard at all range values (see Reference 7). An extended object viewed through binoculars will always seem less bright than when viewed with the unaided eye. Only when the object appears as a point source is the brightness increased. For seven power optics, the point source range is approximately 1200 meters. At this range the laser beam has spread sufficiently that the irradiance is reduced to the point that no eye hazard exists. Further, atmospheric transmission losses and optical system transmission losses will provide the observer additional safety.

3. At close ranges (i.e., less than 170 meters for the unaided human eye) the source is a distributed source and the radiant energy is spread over more than 1 retinal element. The increased corneal irradiance is exactly cancelled by the increased retinal focal area. The retinal irradiance does not increase as the observer moves closer to the laser.

4. Modifications to either the laser output power, laser pulse width, code structure or beamspread must be carefully studied in order to insure eye safe operation for all LES conditions.

5. Calculations indicate that significant increases in TES laser output are allowable within eye safety limits.

6. Calculations indicate that only modest increases in the VES kill laser output are allowable within eye safety limits

7. The effects of thermal relaxation of retinal tissue for imaged point source, produce a modest reduction in accumulated LES retinal energy density relative to the adiabatic limit.

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