Are Open Optical Fiber Less Hazardous than MPEs Suggest?

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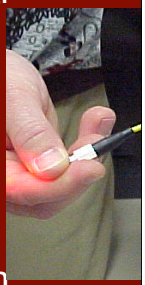
Issue Comes from IEC TC76 Committee –

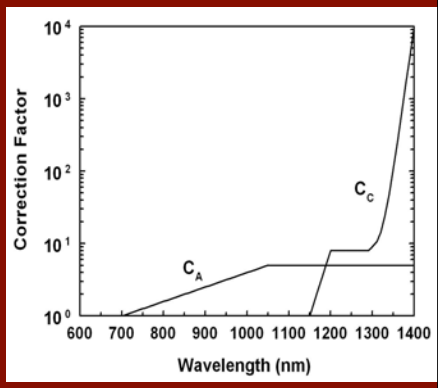
"How can Class 1 AEL be higher than Class 3B AEL!?"

- But are the AELs higher, and what prompted question?
- Two key fiber-optical communication wavelength bands correspond with deeply penetrating wavelengths in skin and eye and where ocular exposure limits are highest.
  - C-Band: 1530 nm – 1565 nm (e.g., 1550 nm)
  - O-Band: 1260 nm – 1360 nm (e.g., 1320 nm)
- *Past limits have been overly restrictive when compared to eye/skin injury thresholds*
- Revision in 2013/2014 MPEs led to increase in AELs which helped in the O-Band (1260-1360 nm)



Concerns in Laser Telecommunication Committees about Result of new Laser MPEs for Wavelengths between 1300-1400 nm

- The 2013-2014 revision of laser MPEs & AELS increased spectral C_C (C_7 in IEC) more in O-Band
  - The ocular MPE for viewing a CW (or OFCS modulated) "point"-source at 1350 nm would now be 50 W·cm^{-2} if not limited by a corneal protection factor, which differs between ANSI Z136.1 and IEC 60825-1.
  - The AEL for Class 1 would be 19.5 W, except that this emission value is limited to the AEL for Class 3B, which is only 500 mW CW.



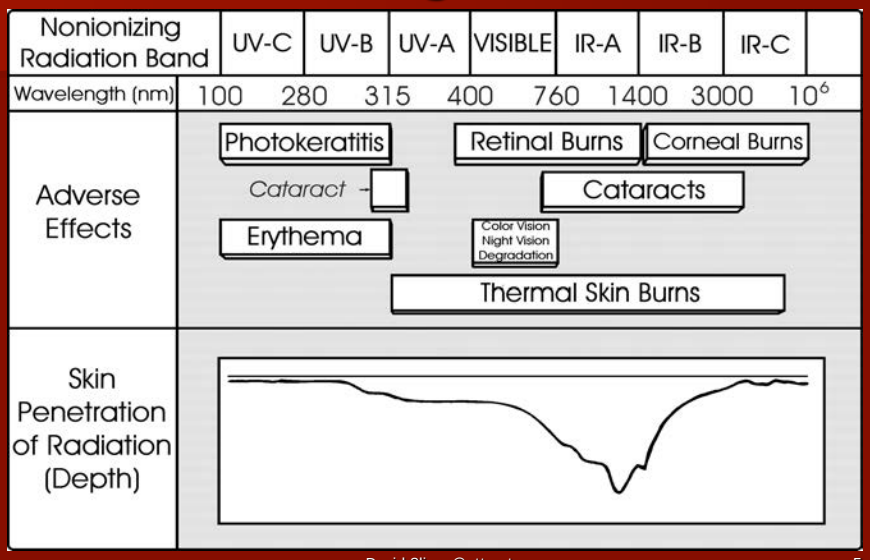
Source: ACGIH TLVs for 2017

The Limits in the 1.55 µm Band

- At 1550 nm the CW AEL is still only ~10 mW
  - But penetration depth and tissue-absorption volume is greatest at 1.55 µm compared to other wavelengths in the IR-B spectral band
  - This low power cannot be sensed by touch!
  - If you cannot sense heat there cannot be a risk!
- ***The limits are very clearly overly restrictive if compared to eye- and skin- injury thresholds A***
  - Reason – Same CW MPE for all IR-B and IR-C wavelengths
  - Limits are now being reviewed with an eye toward increases
  - The 3.5-mm limiting aperture for lengthy periods may also be too restrictive

Biological Effects in Relation to CIE Photobiological Bands

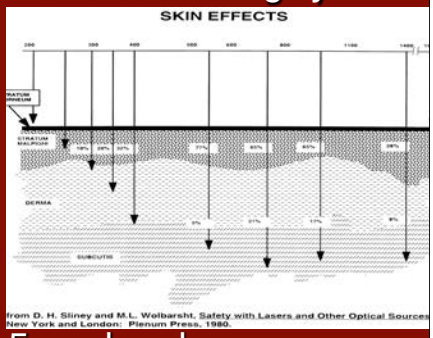
Photobiological Effects



Skin MPEs and Penetration Depths

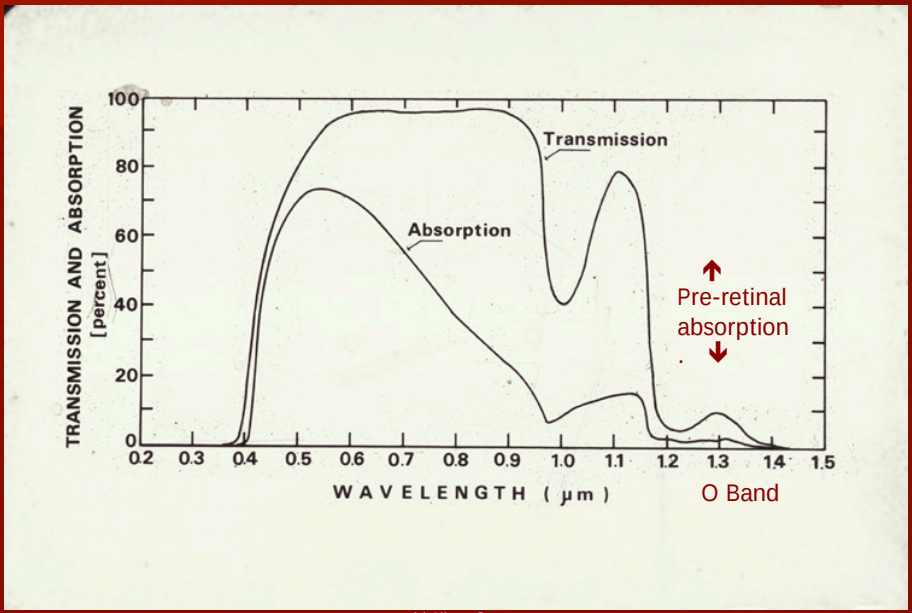
IR-A Wavelengths have the greatest absorption depth/volume

- The skin MPEs were set circa 1975 based largely on Rockwell-Goldman (1974)
  - Nd:YAG, CO_2, Ruby, etc.
  - 1.2 – 2 µm band not tested
  - Melanin absorption was the basis of C_A (C_4) in skin & eye
- Depth (volume) absorption was not considered and new higher MPEs at 1.3 µm and 1.5 µm bands are now strongly needed!
- CW IR-B & C Class 1 AELs should be >> 10 mW!



from D. H. Sliney and M.L. Wolbarsht, Safety with Lasers and Other Optical Sources New York and London: Plenum Press, 1980.

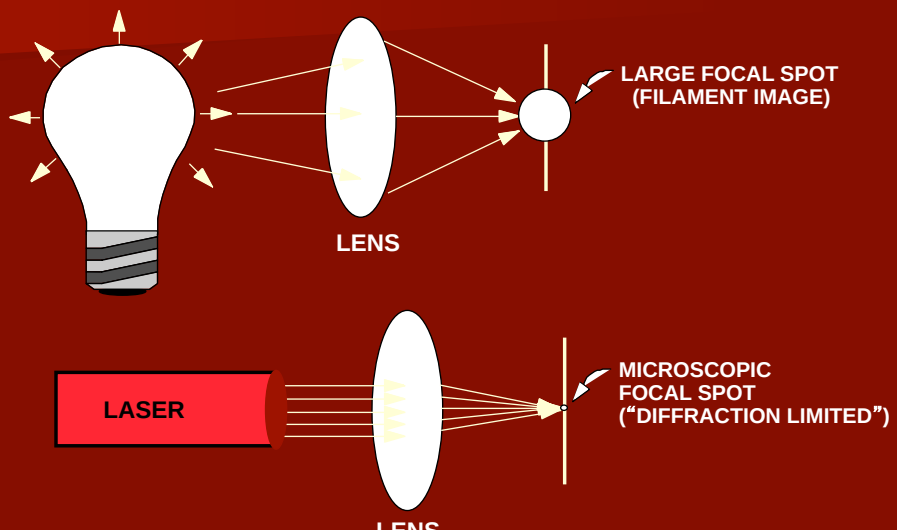
The "Retinal Hazard Region" ~ 400 to 1400 nm



The ocular media strongly absorb energy at the 1.3 μm & 1.5 μm bands

- Transparent ocular media:
  - the cornea – IR-C heating
  - the aqueous, lens and vitreous heating
- Most IR-B (e.g., 1.55 μm) is absorbed in cornea & aqueous at > 1200 nm
- IR-A - λ penetrates deeply
  - trace amount to retina
  - C_C (C_7) reflects this!
- Deep penetration = high MPEs

Eye loupe magnifiers create a hazard because of laser radiance – But what averaging area is relevant?



From Sliney DH and Trokel, S, 1993

Ocular Hazards: Infrared Laser Wavelengths

- Three Spectral Bands -- Three Ocular Hazards
- Near-Infrared Ga-As diode family (850 - 910 nm):
  - Chorioretinal thermal injury hazard
- Near-Infrared IR-A transition band (1300-1350 nm):
  - Retinal (but also lens and corneal) thermal injury hazard
- Mid-Infrared IR-B band (1.5-1.6 μm 1500 - 1600 nm):
  - Corneal thermal injury hazard (full-thickness absorption), often referred to as "eye-safe" wavelengths, but really should be referred to as "retinal-safe" wavelengths

Our natural aversion response to skin heating protects from most conventional sources rich in Infrared – but avoidance not considered in AEL!

All of us are familiar with deeply penetrating IR-A

IR-A Heat lamps used in physical therapy are incandescent lamps with red filter to block the surface-absorbing visible wavelengths

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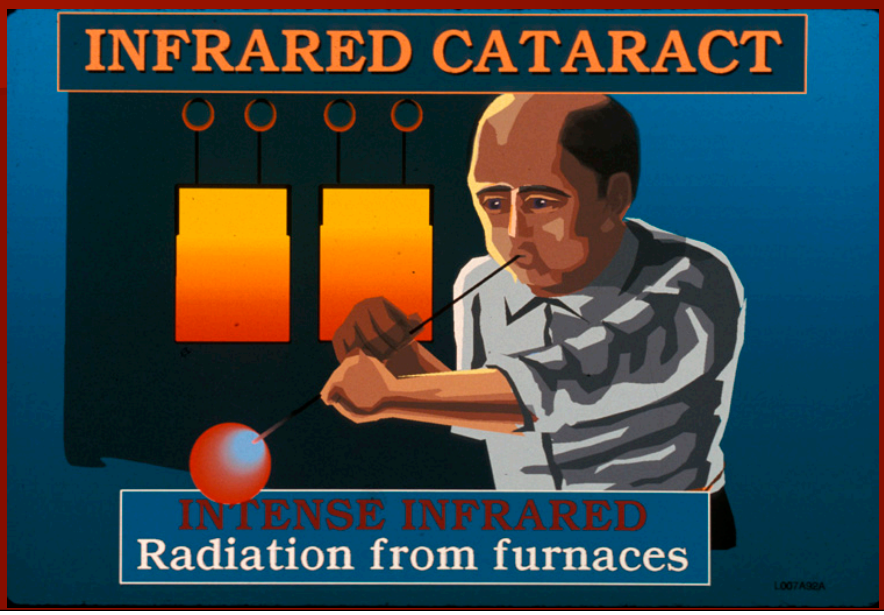
Chronic Exposure Not a Laser Issue



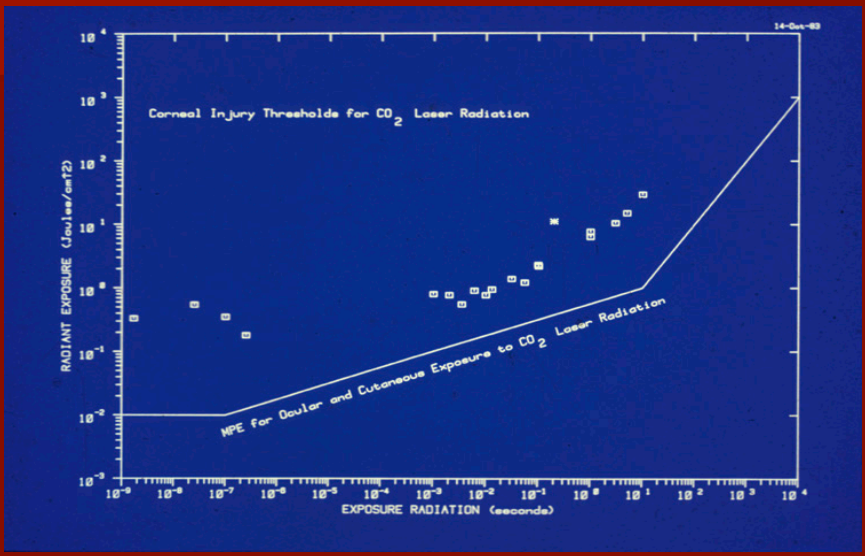
Corneal Thermal Injury

Implications for MPEs and AELS

- Thermal photocoagulation of the cornea and conjunctiva (outer surfaces of the eye) $W \cdot cm^{-2}$
- Penetration Depth in the corneal tissue is critically important on the risk of thermal injury from pulsed lasers because of the differing absorption volumes, e.g. 1540 nm (1.54 µm) penetrates deeply.
- For CW lasers – It was *believed* there was little difference with wavelength, but data at 10.6 µm was applied throughout IR-B & IR-C spectral bands
  - Aversion to warmth not considered (Class 2 not extended)
  - Only 3.5-mm averaging aperture – overly conservative
  - What is a reasonable reaction time base?

Corneal Thermal Injury Thresholds

Is such a large reduction (safety) factor needed?

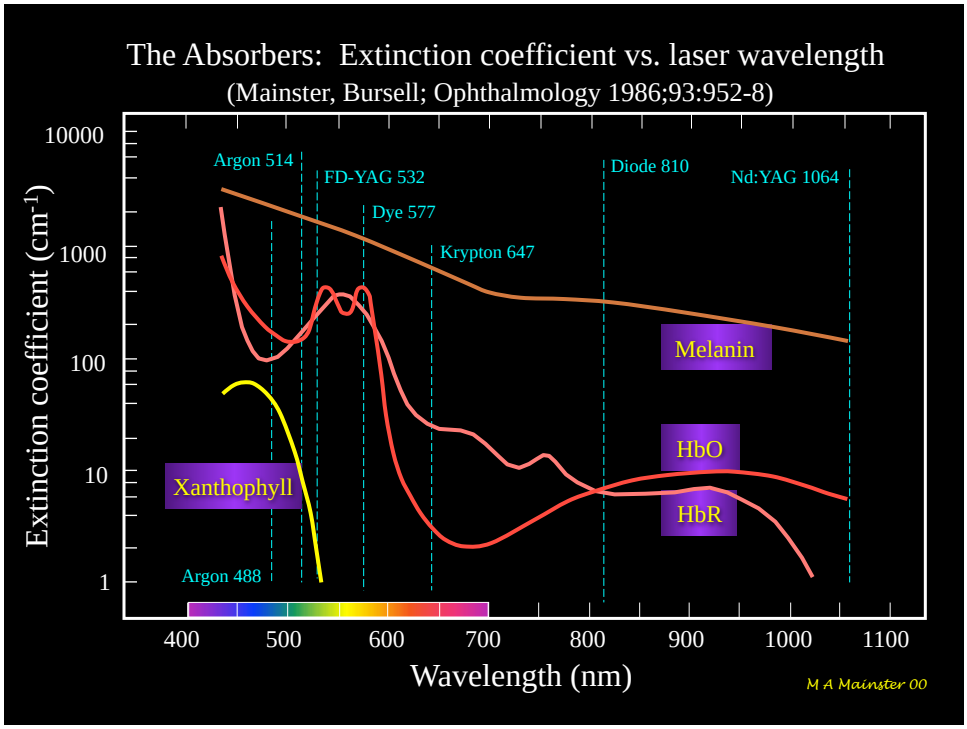


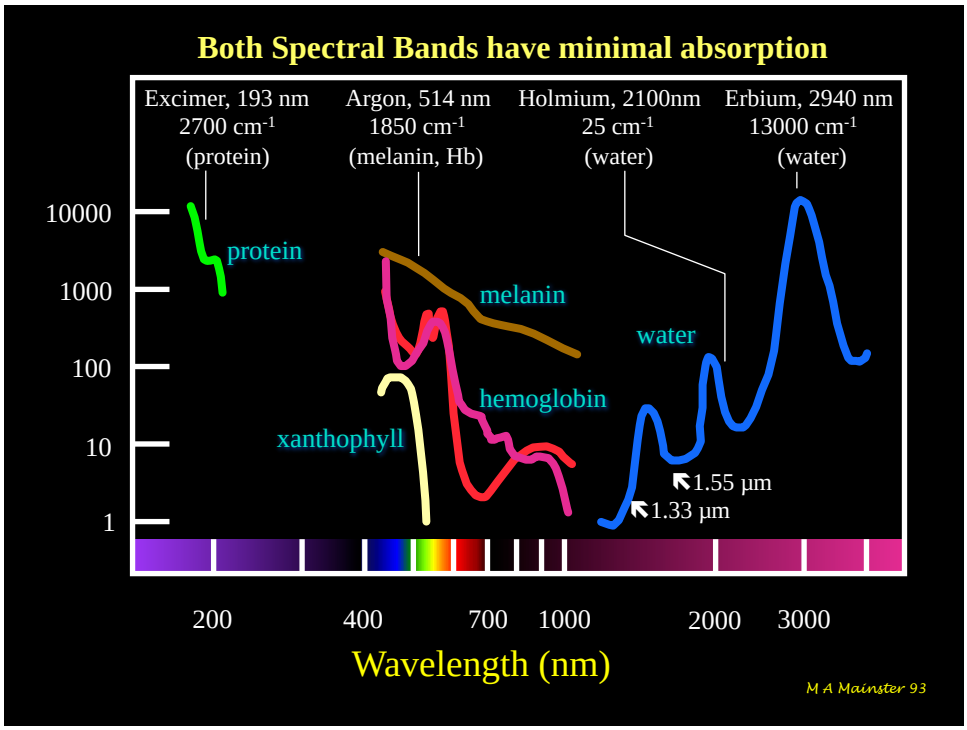
Biological Uncertainties—IR-B/C

- The thermal sensation may limit duration of exposure, but little is really known above 40 mW/cm^2
- Actual thresholds for 10.6 μm radiant energy are rather well established and 0.1 W/cm^2 has an order-of-magnitude safety factor, but the safety factor varies with corneal spot size and duration
- Thermal heat-stress issue for large beam diameter

Current Laser Exposure Guidance

- International Commission on Non-Ionizing Radiation (ICNIRP) last revised laser guidelines in *Health Physics, 79(4):431-440,2013*
- International Electrotechnical Commission Standard IEC 60825-1-2014 (same limits)
- ANSI Z136.1 – 2014 -- Maximum Permissible Exposure (MPE) limits for sub-ns pulse exposure for the first time.
- ACGIH – 2017 also contains revised Laser TLVs for large-source and IR-A lasers (otherwise the same MPEs); ICNIRP following this direction

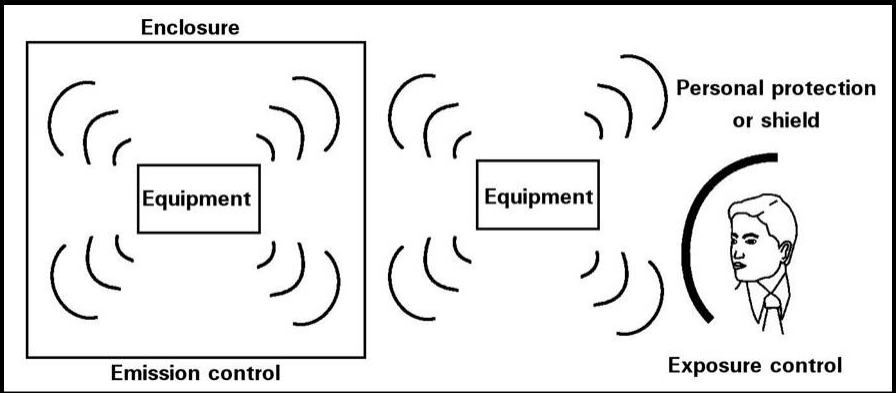

The Absorbers: Extinction coefficient vs. laser wavelength
(Mainster, Bursell; Ophthalmology 1986;93:952-8)
Extinction coefficient (cm-1)
10000
1000
100
10
1
Argon 514
FD-YAG 532
Dye 577
Krypton 647
Diode 810
Nd:YAG 1064
Melanin
HbO
HbR
Xanthophyll
Argon 488
400
500
600
700
800
900
1000
1100
Wavelength (nm)
M A Mainster 00


Both Spectral Bands have minimal absorption
Excimer, 193 nm
2700 cm-1
(protein)
Argon, 514 nm
1850 cm-1
(melanin, Hb)
Holmium, 2100nm
25 cm-1
(water)
Erbium, 2940 nm
13000 cm-1
(water)
10000
1000
100
10
1
protein
melanin
water
hemoglobin
xanthophyll
1.55 µm
1.33 µm
200
400
700
1000
2000
3000
Wavelength (nm)
M A Mainster 93

TWO TYPES OF STANDARDS:

Product Safety Standards Control *Emissions* (AELs), but

Occupational Safety Standards Control *Exposures* (MPEs)



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Engineering

- Positioning of equipment so that the beam height is not at eye level when a person is standing or sitting down.
- Installing door interlocks on class 4 lasers to preclude unprotected persons from being exposed upon entering a room.
- Installing warning lights on the doors to class 3 and class 4 laboratories to warn personnel

Administrative Control Measures

- Standing operating procedures must be developed and followed for each laboratory. The SOP should have information about the hazards and methods for preventing overexposure.
- Only selected personnel should be allowed to operate the most hazardous laser equipment.
- Laser safety training should be provided to those personnel authorized to use the equipment.

Personal Protection

- Laser goggles
- Laser protective visors
- Protective clothing or gloves

Optical Fiber Communications

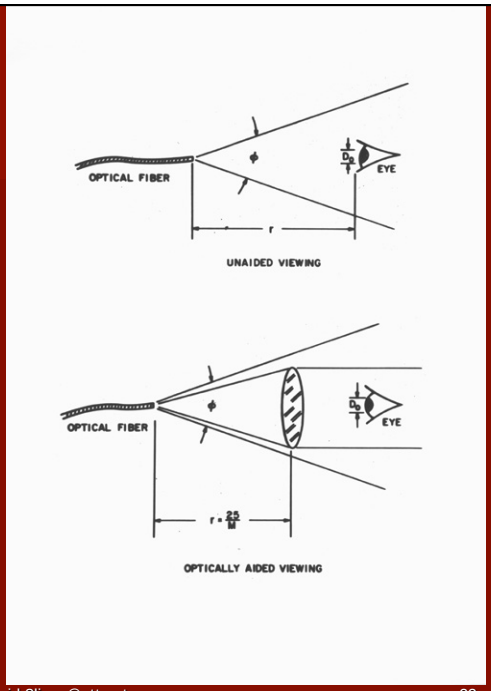
The beam emitted from an optical fiber diverges rapidly

During operation: Class 1

Hazardous exposure of the eye is frequently only possible when viewing the disconnected fiber tip by an eye loupe magnifier

Safety standards for optical fiber communication systems center on assuring that access to Class 3B is limited to service and that eye loupes used by servicing persons have laser safety filters.

The use of MPEs to determine hazardous conditions may occur



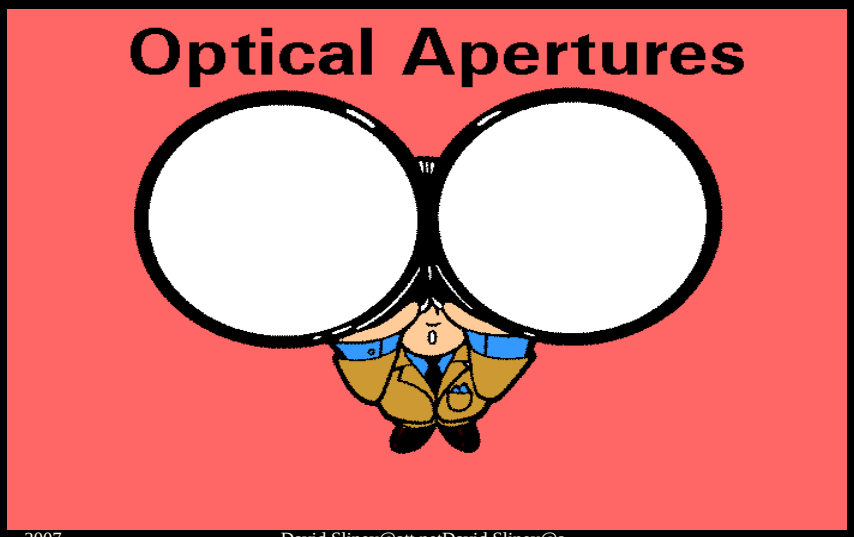
RELATIVE RISKS

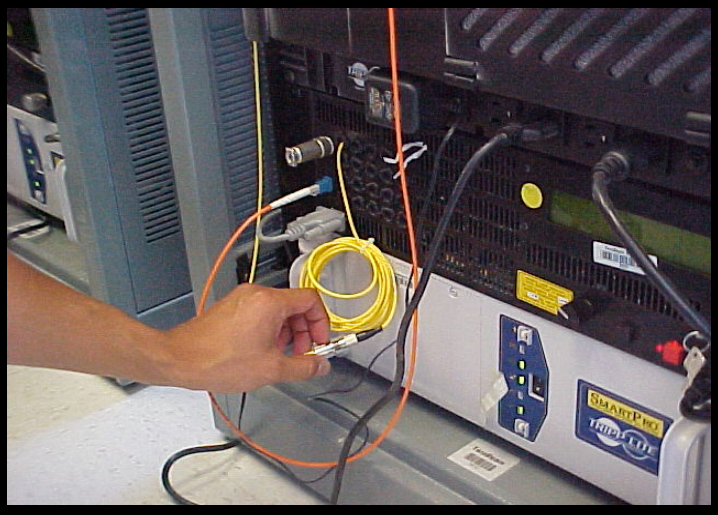
•Risk Perceptions….

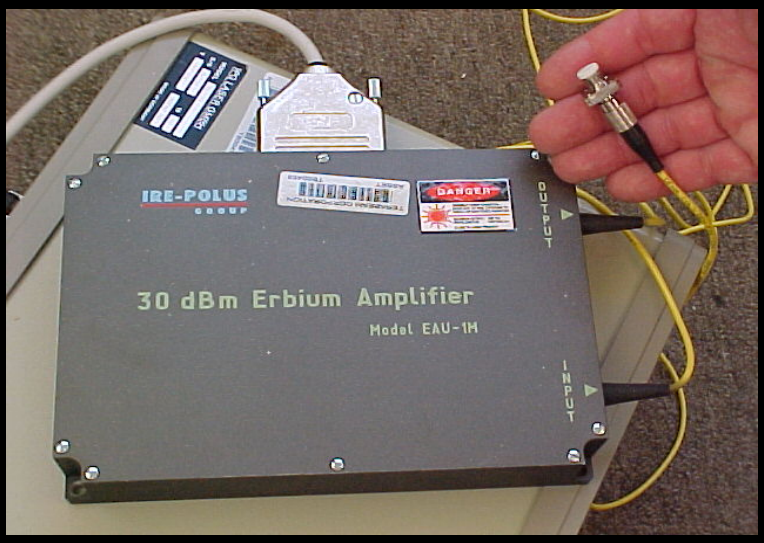
•Class 2 M and Class 3R lasers used for alignment in pipe laying, but the beam is not at eye level

•Although the worker here is exposed to fatal risks from cave-ins of the un-shored trench wall, and a 3-ton shovel is within 50 cm of his head, he was concerned about the 2 mW, Class 2M laser striking his boot! (~1972)

Measurements for Safety Class







- During servicing, one may have access to an open fiber at potentially hazardous levels
- At 1.54-1.57 μm and 1.6-1.63 μm, the MPE is 100 mW/cm^2 for continuous viewing (t > 10 s) and higher for shorter durations (e.g., 1.6 W/cm^2 at 0.25 s).
- The NA is 0.16 for a high-index fiber, which means the beam diverges in a tight cone and creates a 10 s Nominal Hazard Zone (NHZ) up to 1.8 m at 2 W.

The importance of specifying measurement apertures

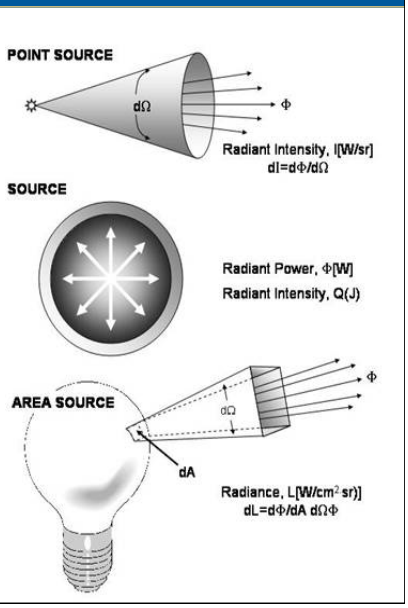
- In laser safety and in some applications in material processing and surgery, the measurement aperture should be specified.
- Laser safety standards always specify measurement apertures for averaging irradiance and radiant exposure. Laser safety classification requires the measurement of power through a fixed aperture; e.g., a 7-mm aperture to simulate the eye's pupil diameter

CONCLUSIONS ABOUT LASERS

- Laser exposures represent an acute hazard in almost all cases of potentially hazardous exposure.
- Low probability of exposure to hazardous beams
- Chronic exposure from scattered UV an exception, but exposure dwarfed by solar UV

CIE Standardized Radiometric Terms

- Provided in the CIE International Lighting Vocabulary (e-ILV) and ISO and IEC standards
- Radiometric quantities, units and symbols are standardized
- Retinal irradiance is directly proportional to *radiance*
- Radiant Intensity is useful for highly diverging beams
  - $E = I/r^2$ is very simple calc.
  - What is the worst-case unaided viewing distance of fiber tip?

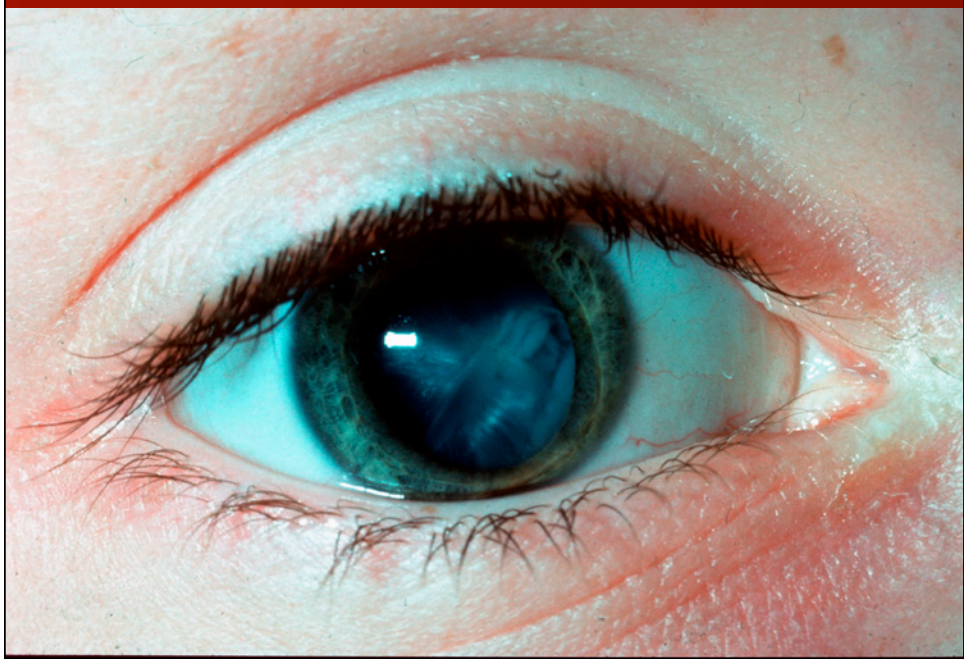
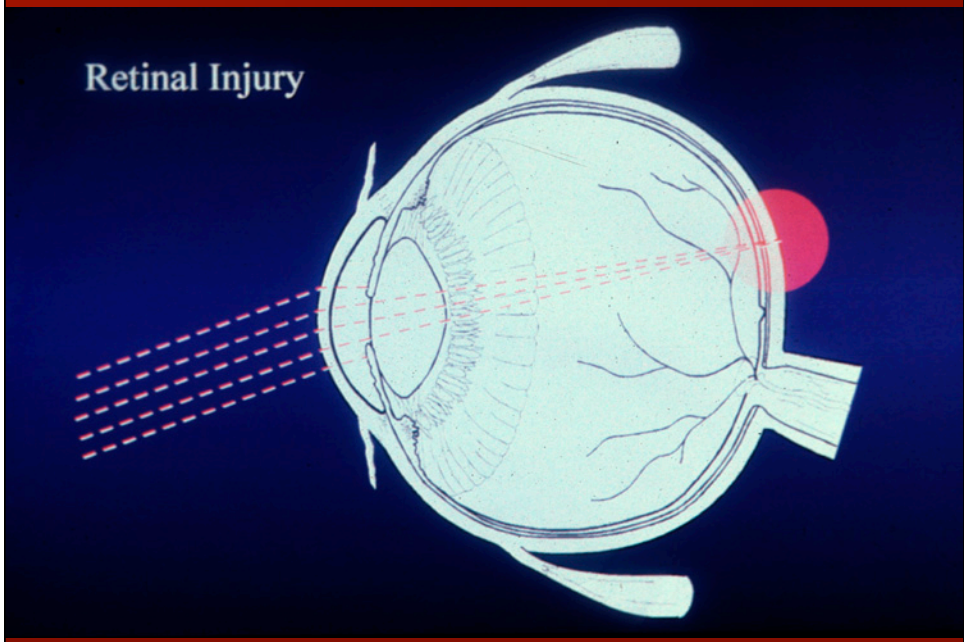


How to deal with Classification and OFCS 'Hazard Level'?

- Classes 1M & 2M concern telescopic optically aided viewing
- IEC 60826-2 includes "Condition 2" measure

- Eye-loupe Viewing
  - Concerns about eye-loupe viewing of diverging-beam lasers were finally resolved in TC76. ANSI had no requirement
  - Significant only for very high-power (>10x) optic clamped to fiber (OFCS)
  - Biggest issue remains at 1.55 µm where focus could pass over the cornea (?)

Cataract (lenticular opacity) - normally a delayed effect



Retinal location of exposure is important—determines long-term consequences