New Challenges in Laser Safety

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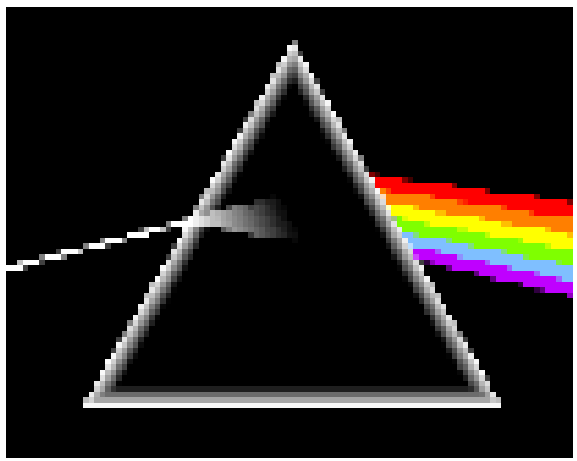
USACHPPM
Readiness thru Health

Topics of Lecture

- **Intro to Lasers & Biological Effects**
- **New Standard – New Classes**
- **Increased Numbers/Applications of Lasers**
- **Commercial-Off-The-Shelf (COTS) Systems**
- **“Dazzlers”**
- **New Parameters – hard to evaluate**
- **Questions?**

Non-ionizing Radiation

- **Non-ionizing radiation** does not have enough energy to create ion pairs.
- Examples of **non-ionizing radiation** include:
  - Microwaves
  - Radio waves
  - Optical Radiation (UV, Visible, IR)



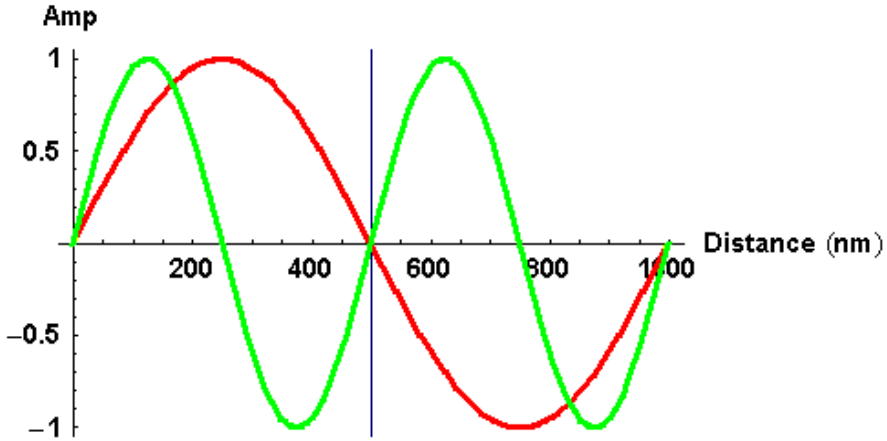
Basic Parameters of Electromagnetic Radiation

Wavelength λ

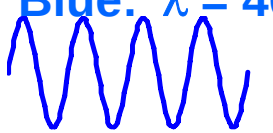
The length of one complete wave pattern.

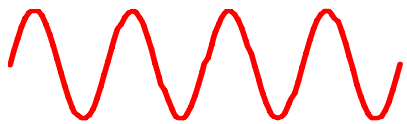
[The distance between any two points at corresponding positions on successive repetitions in the wave shape].

Different wavelengths in the visible spectrum are seen by the eye as different colors.



Blue: λ = 400 nm



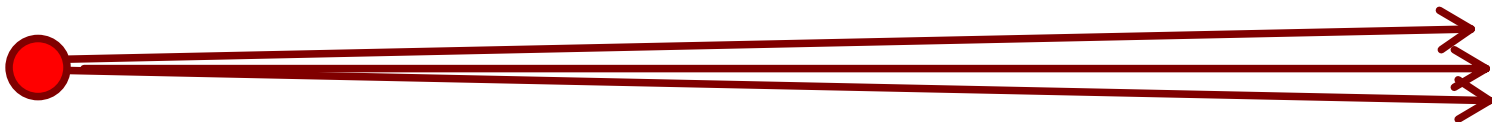


Red: λ = 700 nm

$$c = \lambda \cdot \nu$$
$$E = h \cdot c / \lambda$$
$$E = h \cdot \nu$$

Point Source Laser

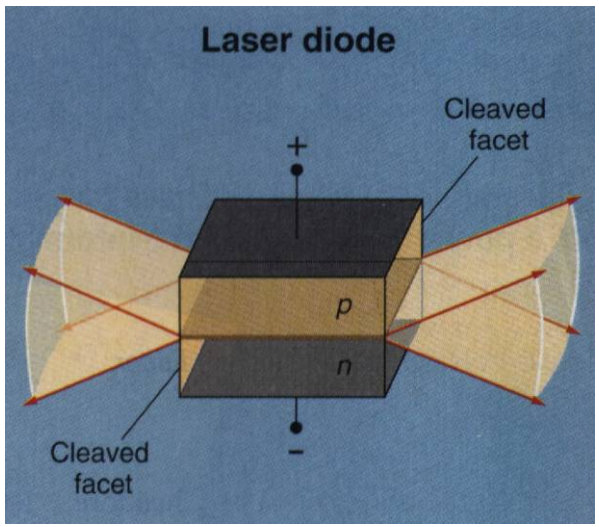
- Emission from a laser or laser system can be considered to originate from a tiny dimensionless "***point source***"
- Theoretical construct

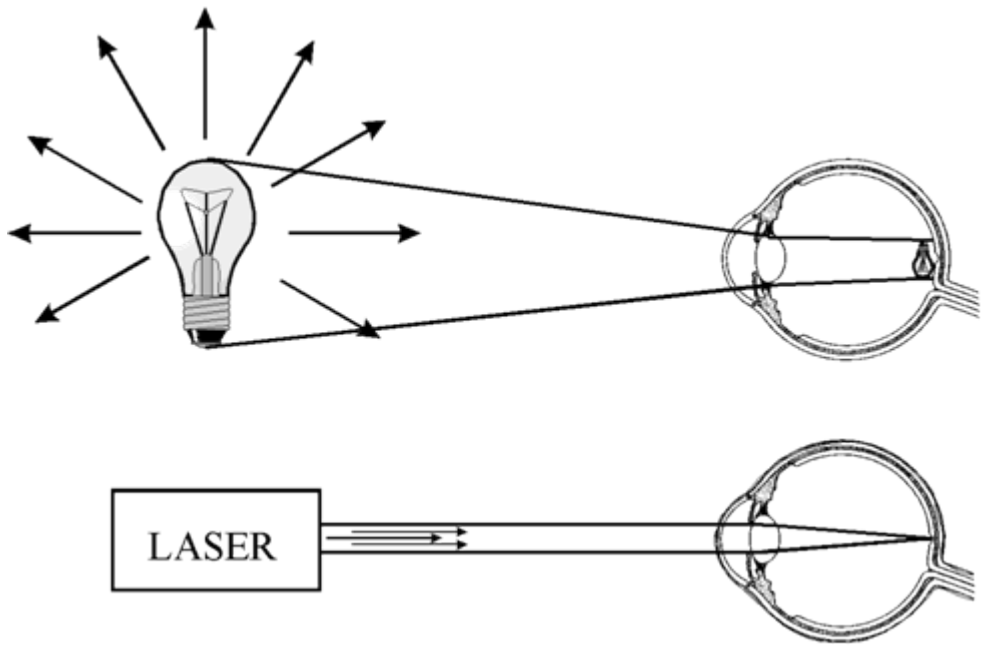


- Focusing of optical radiation in the retinal hazard region (400-1400 nm) by the eye causes an increase in irradiance by a factor of approximately 100,000

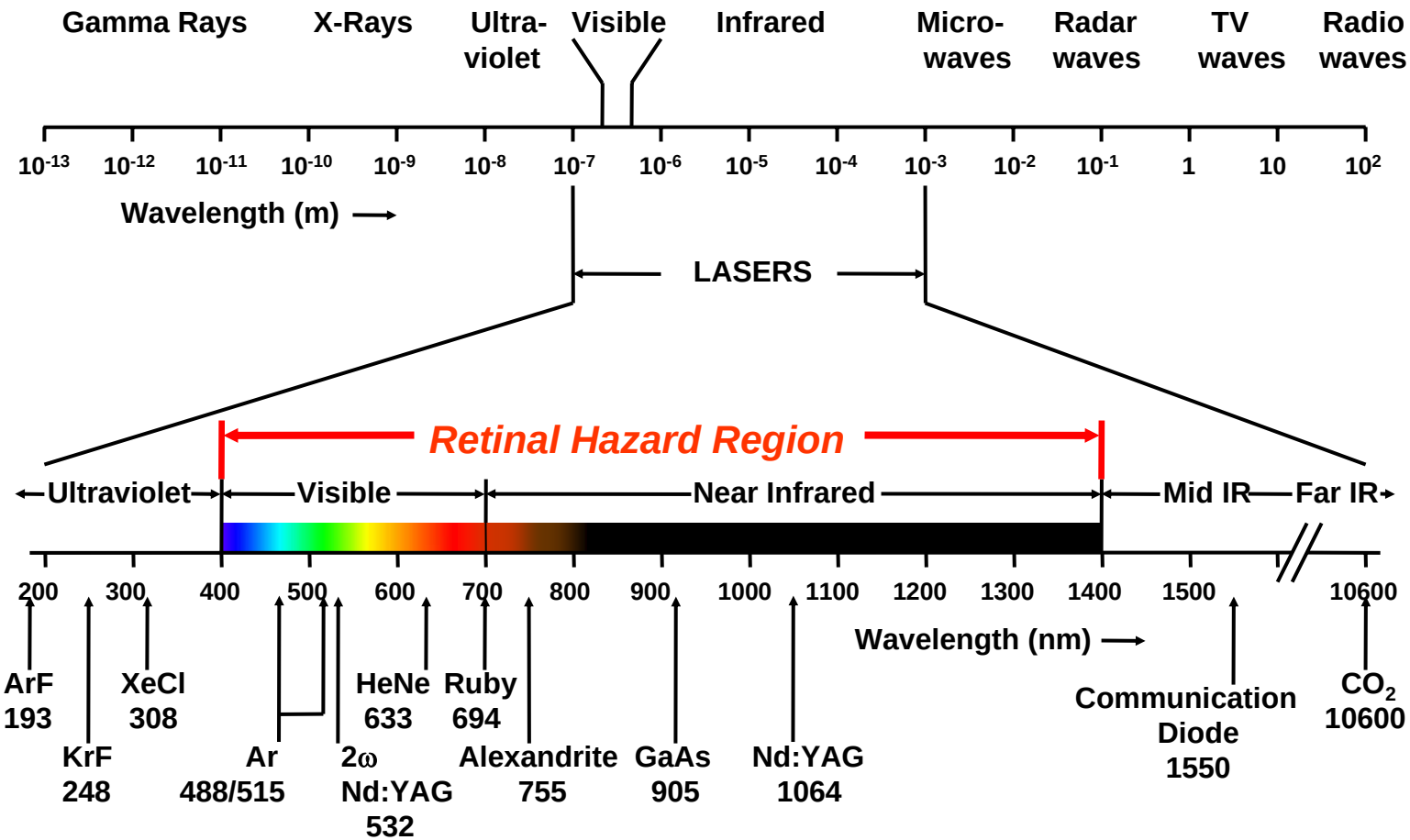
Extended Source Laser

- Actual source, finite sized.
- Can be viewed as an array of continuous or discrete point sources.
- Examples: Laser diode arrays and diffuse reflections





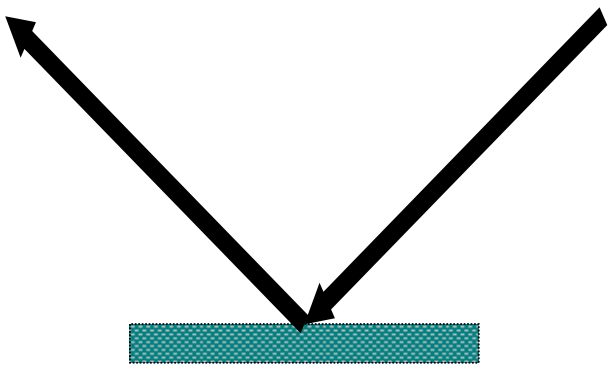
Electromagnetic Spectrum

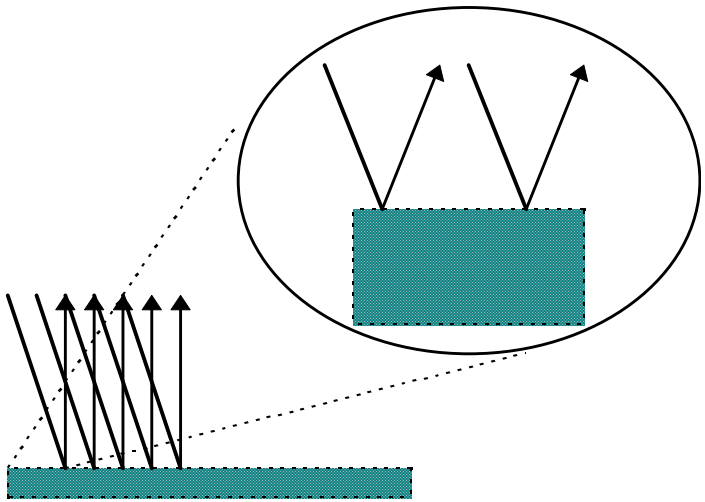


Specular Reflections

- Specular or mirror-like reflections can occur when the size of surface irregularities or roughness is less than the wavelength of the incident radiation.
  - Identify and be aware of specular reflectors
  - Consider unanticipated reflections
  - Retro-reflectors

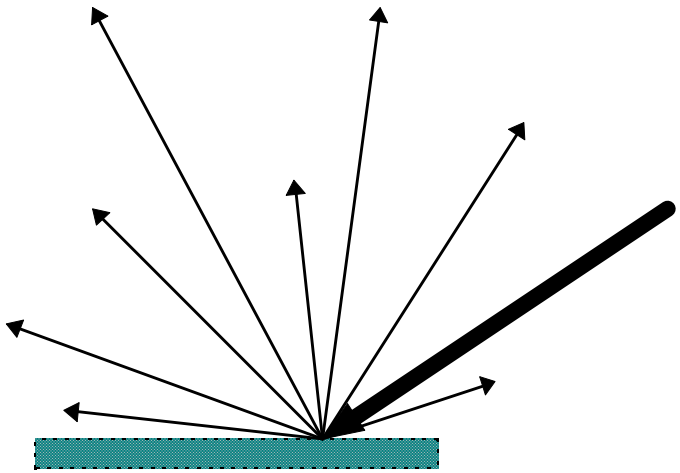
- Angle of incidence = angle of reflection
- Example: A good mirror.

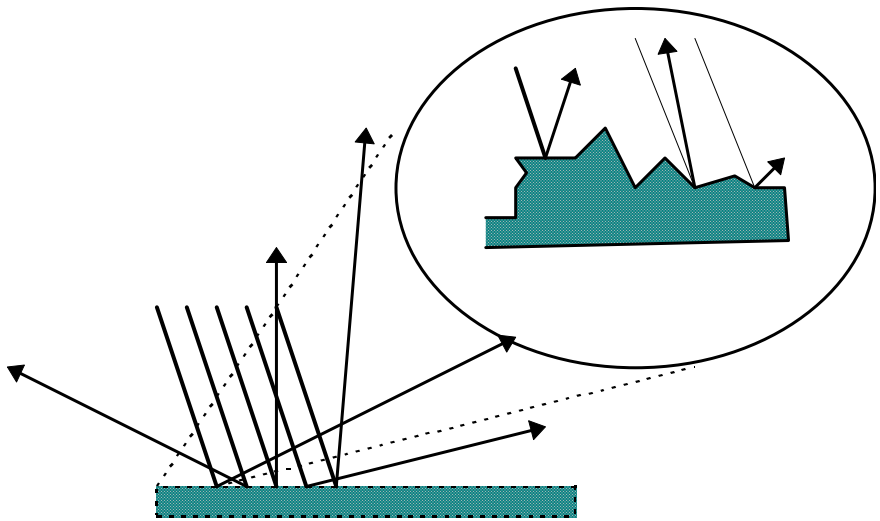




Diffuse (Lambertian) Reflections

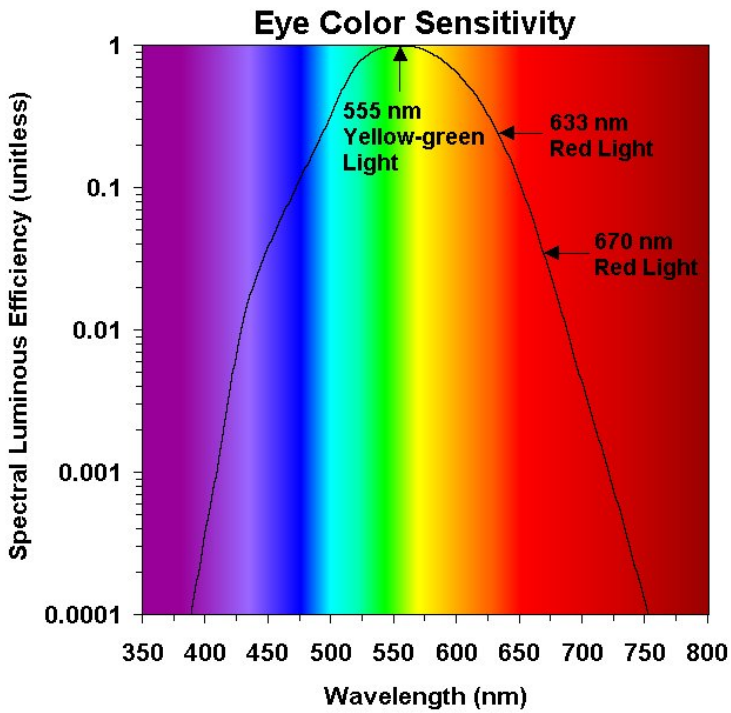
- Diffuse reflection occurs when the surface irregularities are randomly orientated and are much greater than the scale of the wavelength of the incident radiation.
  - Diffuse reflections greatly reduce the hazard
- Examples: light reflected from a road surface or tree leaves.





Radiometric vs. Photometric

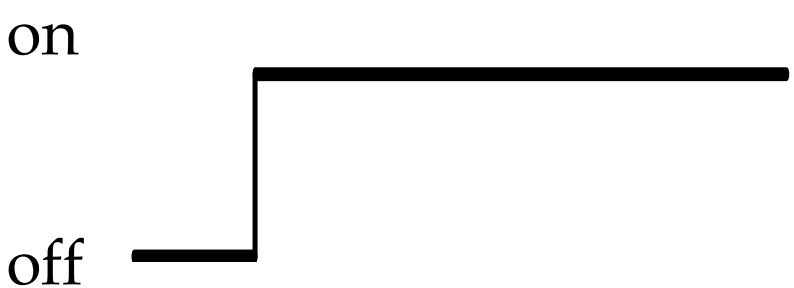
- **<u>Radiometric:</u>**
- Absolute measurements of radiation
  - eg: Irradiance
  - eg: Radiant Intensity
- **<u>Photometric:</u>** related to visual response of the eye.
  - eg: Illuminance
  - eg: Luminance

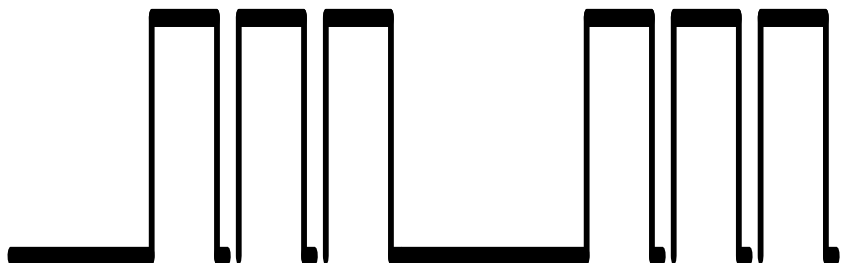


Laser Notes

- Continuous Wave (CW) lasers are generally considered to be lasers that work “continuously” for more than 1 second

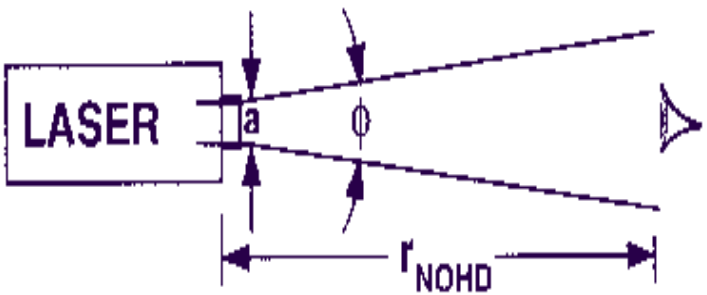
- Pulsed lasers are lasers that work in an on/off mode
- Pulsed laser have an associated Pulse Repetition Frequency (PRF) and Duty Cycle





Why is this information useful?

- Classifies lasers and identify laser hazards
- Used to determine what safety measures are needed when working with lasers



$$r_{NOHD} = \frac{1}{\phi}\left[\left(\frac{4\Phi}{\pi MPE}\right) - a^2\right]^{1/2}$$

MPE and AEL

- Maximum Permissible Exposure (MPE): “The level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin.” MPEs are based on biological injury data, the ED50, with a safety factor. [J/cm^2 or W/cm^2]

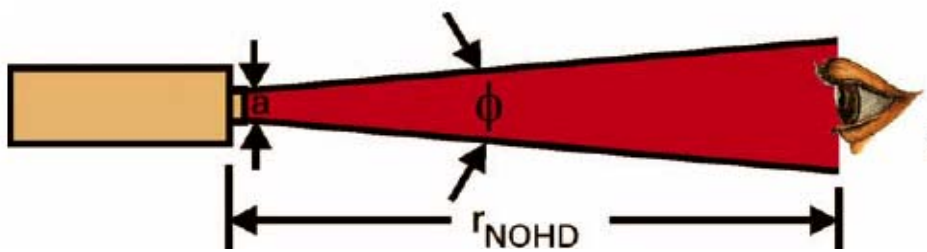
- Accessible Emission Limit (AEL): “The maximum accessible emission level permitted within a particular class.” Class 1 AEL = MPE x Area of limiting aperture [J or W]

Wavelength (nm)	Exposure Duration, t (s)	MPE ($J \cdot cm^{-2}$)	MPE ($W \cdot cm^{-2}$)
Visible and Near Infrared			
400 to 700	10^{-13} to 10^{-11}	1.5×10^{-8}	
400 to 700	10^{-11} to 10^{-9}	$2.7\ t^{0.75}$	
400 to 700	10^{-9} to 18×10^{-6}	5.0×10^{-7}	
400 to 700	18×10^{-6} to 10	$1.8\ t^{0.75} \times 10^{-3}$	
400 to 450	10 to 100	1×10^{-2}	
450 to 500	10 to T_1		1×10^{-3}
450 to 500	T_1 to 100	$C_B \times 10^{-2}$	
400 to 500	100 to 3×10^4		$C_B \times 10^{-4}$
500 to 700	10 to 3×10^4		1×10^{-3}
700 to 1050	10^{-13} to 10^{-11}	$1.5\ C_A \times 10^{-8}$	
700 to 1050	10^{-11} to 10^{-9}	$2.7\ C_A\ t^{0.75}$	
700 to 1050	10^{-9} to 18×10^{-6}	$5.0\ C_A \times 10^{-7}$	
700 to 1050	18×10^{-6} to 10	$1.8\ C_A\ t^{0.75} \times 10^{-3}$	
700 to 1050	10 to 3×10^4		$C_A \times 10^{-3}$
1050 to 1400	10^{-13} to 10^{-11}	$1.5\ C_C \times 10^{-7}$	
1050 to 1400	10^{-11} to 10^{-9}	$27.0\ C_C\ t^{0.75}$	
1050 to 1400	10^{-9} to 50×10^{-6}	$5.0\ C_C \times 10^{-6}$	
1050 to 1400	50×10^{-6} to 10	$9.0\ C_C\ t^{0.75} \times 10^{-3}$	
1050 to 1400	10 to 3×10^4		$5.0\ C_C \times 10^{-3}$

Definitions from ANSI Z136.1 - 2000

NOHD

- Nominal Ocular Hazard Distance (NOHD): "The distance along the axis of the unobstructed beam from a laser to the human eye beyond which the irradiance or radiant exposure during operation is not expected to exceed the appropriate MPE; that is, the safe distance from the laser."
- Nominal Ocular Hazard Distance-Magnifying (NOHD-M): The NOHD when viewing with optical aids.

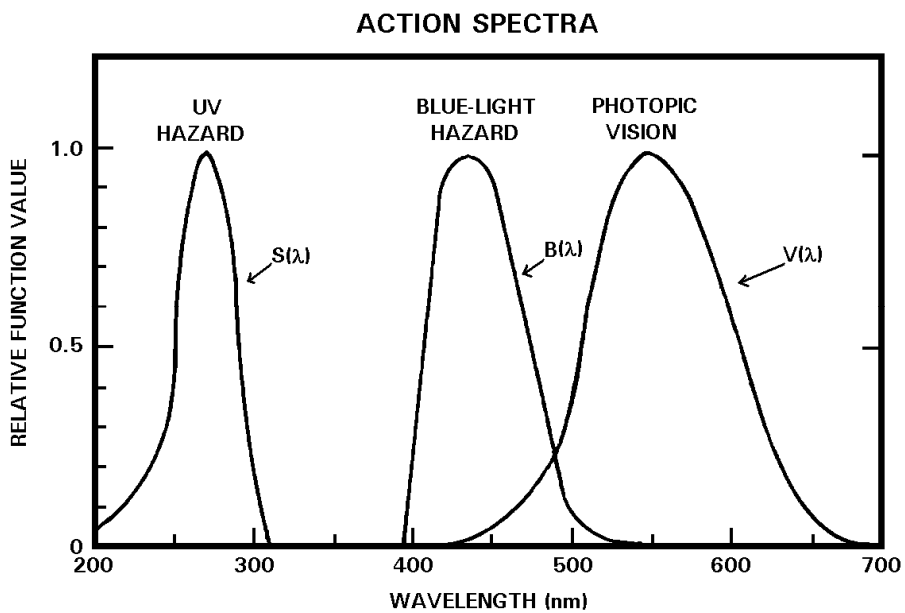


$$r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{4\Phi}{\pi\ MPE} - a^2}$$

Definitions and illustration from TB MED 524 January 2006

Action Spectra

- Action Spectra -- Relative spectral effectiveness of optical radiation.
- Higher Photon Energy ≠ Greater Damage to Eyes/Skin
  - 4ω Nd Laser (266 nm) vs.
    ArF excimer (193 nm)



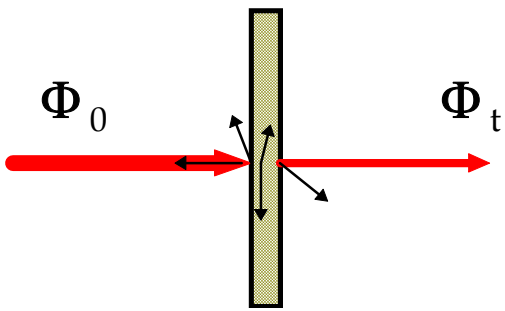
CIE, *International Lighting Vocabulary*, CIE Publication No.17.4, IEC 50846,Vienna, CIE, 1987

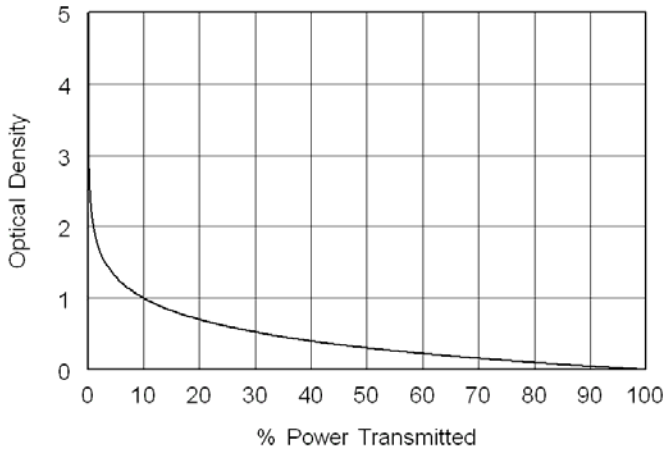
Optical Density

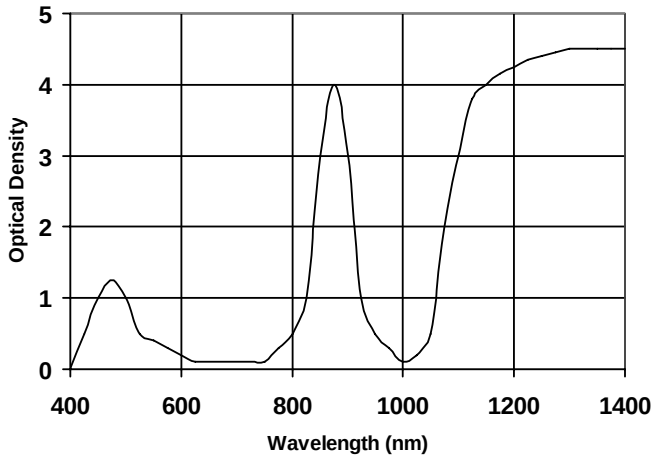
- When radiant energy strikes an object (such as a glass surface), some of the light is transmitted, some is reflected, and some is absorbed.
- The light stopping power of the object (such as a glass surface) is measured in terms of its optical density (depends on wavelength).
- OD = Log (Φ_0/ Φ_t)

  Φ_0 = INCIDENT POWER

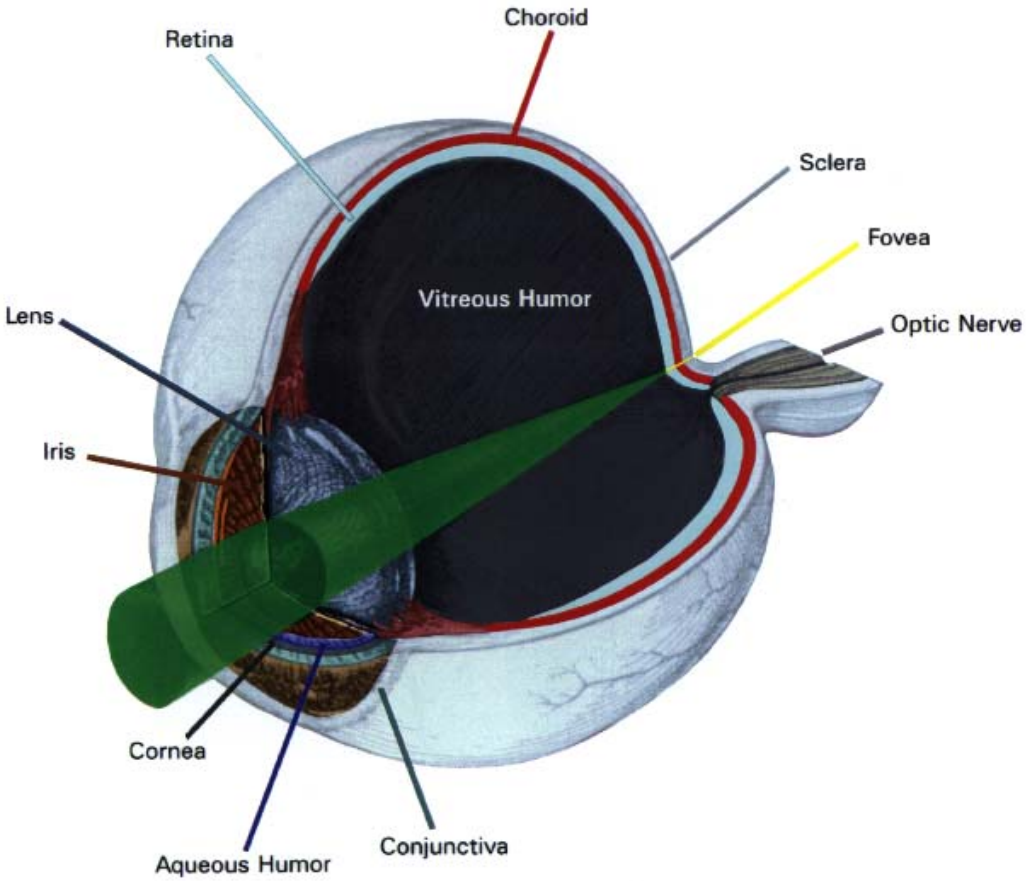
  Φ_t = TRANSMITTED POWER







THE EYE

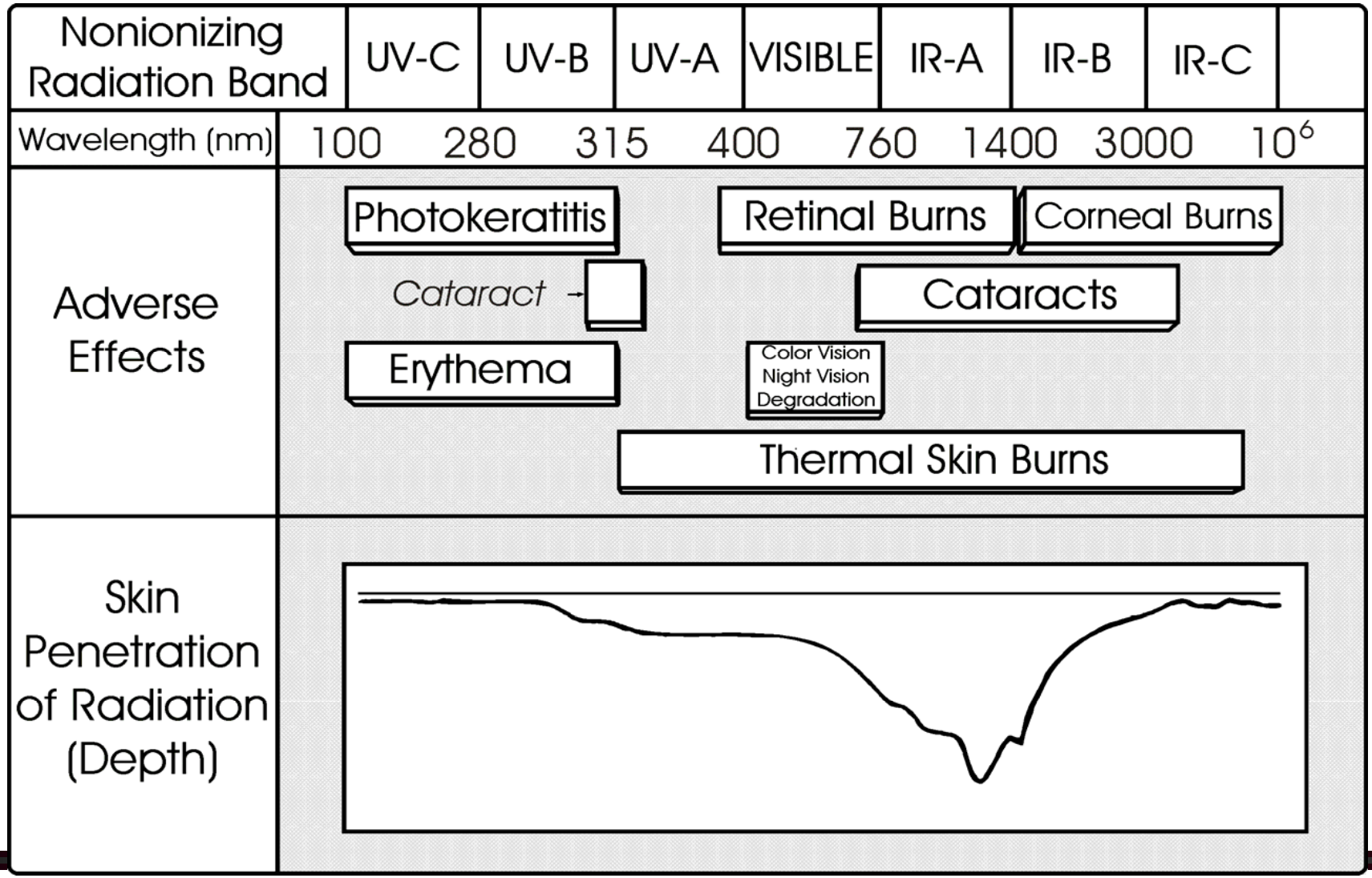

Retina
Choroid
Sclera
Fovea
Vitreous Humor
Optic Nerve
Lens
Iris
Cornea
Aqueous Humor
Conjunctiva

PHYSIOLOGY OF THE EYE

- **CORNEA**:
- Vulnerable to mid/far IR and shorter wavelength UV radiation
- LENS: Vulnerabilities to far IR and shorter UV similar to Cornea

- **Retina:**
- During normal vision, images are formed on the retina; signals are sent to the brain from photosensitive cells; and vision occurs.
- During laser exposure, no image is formed; all the energy is simply focused to a pinpoint.

λ vs. Penetration Depth



PHYSIOLOGY OF THE EYE
Retinal Components

- **Macula**: A small region on the retina about the size of the head of a pin.
- The density of photoreceptor cells in this region is much higher than other parts of the retina
- **Fovea**: An even smaller region within the Macula.
- From this small region, all detailed vision takes place.
- A laser induced lesion on this area would be catastrophic

LASER DAMAGE MECHANISMS

- THERMAL: Thermal damage occurs when energy incident on the retina exceeds the ability of the eye's capillary action to dissipate heat
- PHOTCHEMICAL: Photochemical damage is the result of photons incident upon the molecular structure of biological tissue. The interaction and energy transfer result in rearrangement of the molecular structure.

New Standard – New Classes

Classify lasers based on:

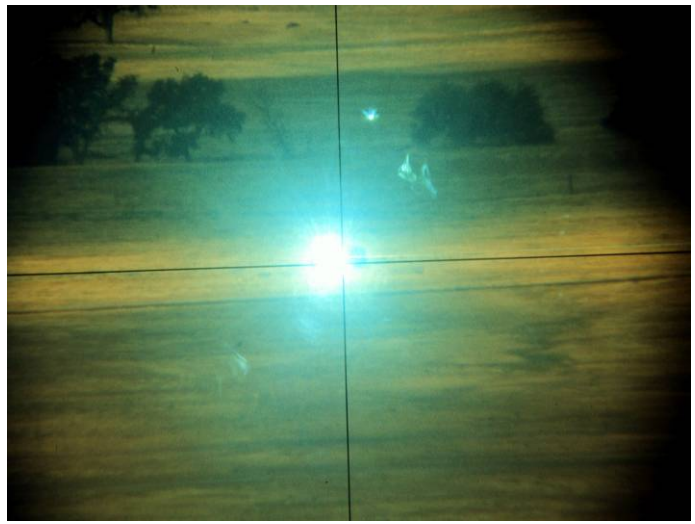
- Capability of injuring personnel
- Use

Laser Hazard Classes:

Old System

Class 1 => least hazardous
Class 2 (visible beams only)
Class 3a, 3b
Class 4 => most hazardous

New System (2007)



Justification:

- Standardization
- Guidelines for use and protection
- Control measures

Classification Procedure

- Compare the Following:
  - Laser parameters
  - Accessible emission limit (AEL)
    - ANSI Z136.1
    - TB MED 524

Laser Parameters

- Wavelength(s)
- Beam size and shape
- Divergence
- Exposure duration
- For pulsed lasers:
  - Total energy per pulse
  - Pulse duration
  - Pulse repetition frequency

- For cw lasers:
  - Average power output
- For extended source lasers:
  - Viewing angle subtended by the source

Hazard Classification

- Class 1
  - No hazards
- Class 1M (NEW!)
  - Hazardous only when viewed through magnifying optics
- Class 2
  - Visible
  - Blink reflex protection
- Class 2M (NEW!)
  - Visible
  - Hazardous only when viewed through magnifying optics
- Class 3
  - Class 3R and 3B (3a and 3b) (NEW NAMES!)
  - Direct viewing hazard
  - Specular viewing hazard
- Class 4
  - Direct viewing & skin hazard
  - Specular viewing hazard
  - Possible diffuse viewing hazard
  - Potential fire and plasma hazards
  - May produce laser generated air contaminants (LGAC)

Class 1

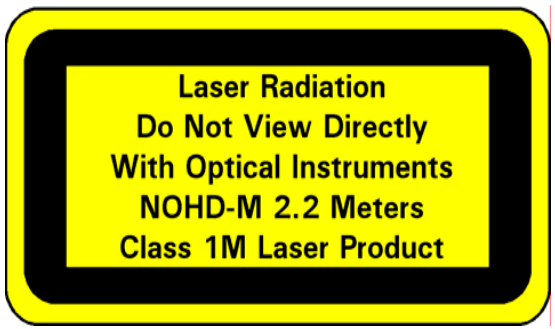
- Incapable of producing damaging radiation
- Cannot exceed the AEL for the maximum possible exposure duration inherent in the design or intended use of the laser
- Includes laser systems with enclosed beam paths
- No control measures required
- Example include some MILES

  & some Rangefinder

Class 1
1540 nm laser energy emitted from this aperture

Class 1M

- Incapable of producing damaging radiation under normal operation unless beam is viewed with an optical instrument (7 x 50 binoculars)
- Exempt from control measures other than preventing intra-beam viewing with optical instruments
- Cannot exceed the Class 3B AEL

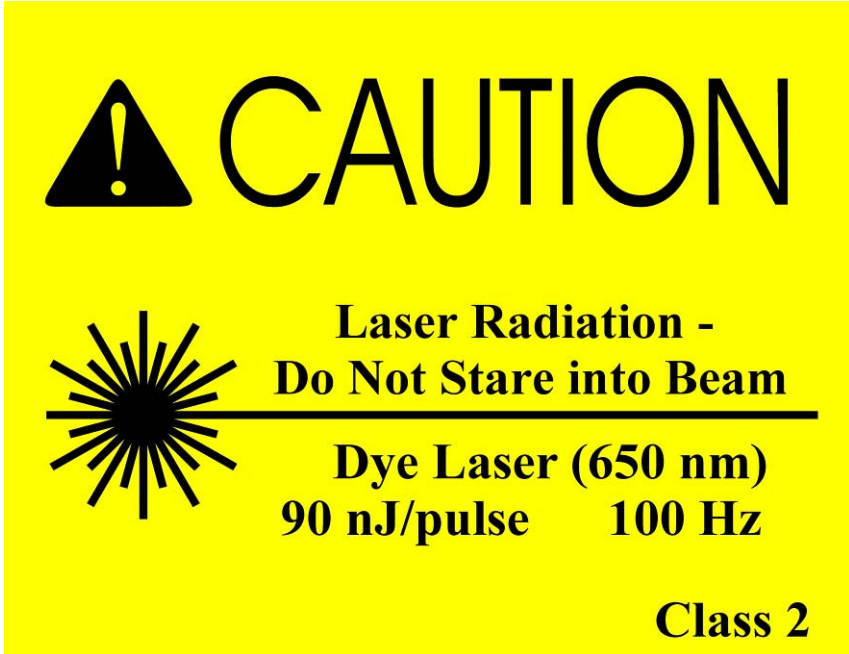


Class 2

- Visible portion of spectrum
- Eye protection is normally afforded by the aversion response (0.25 sec for visible)
- Hazards comparable to projectors or the sun
- "Caution" signs

Class 2 parameters

- CW visible lasers: Cannot exceed 1 mW
- Repetitively pulsed lasers: Cannot exceed the AEL for 0.25 sec exposure



Class 2M

- Visible portion of spectrum
- Eye protection is normally afforded by the aversion response (0.25 sec) for unaided viewing
- Potentially hazardous if viewed with optical instruments (7 x 50 binoculars)
- Max exposure duration ≤ 0.25 s
- Cannot exceed the Class 3B AEL

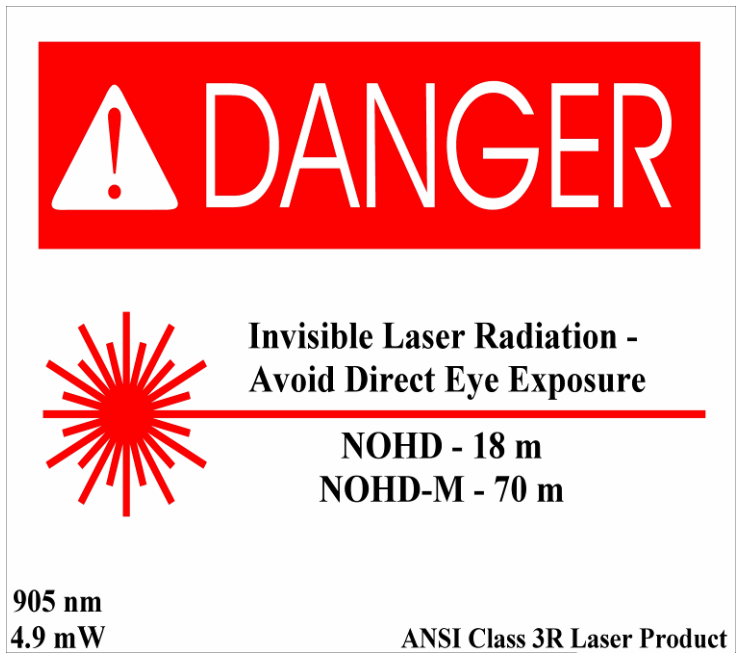
Class 3

- Two subclasses: 3R (3a) and 3B (3b)
- Direct and specular reflection viewing hazards
- Diffuse reflection usually not a hazard
- Danger signs

Class 3R

- Probability of injury is small
- Visible lasers: Cannot exceed 5 times the Class 2 AEL
- Other lasers: Cannot exceed 5 times the Class 1 AEL
- Example:

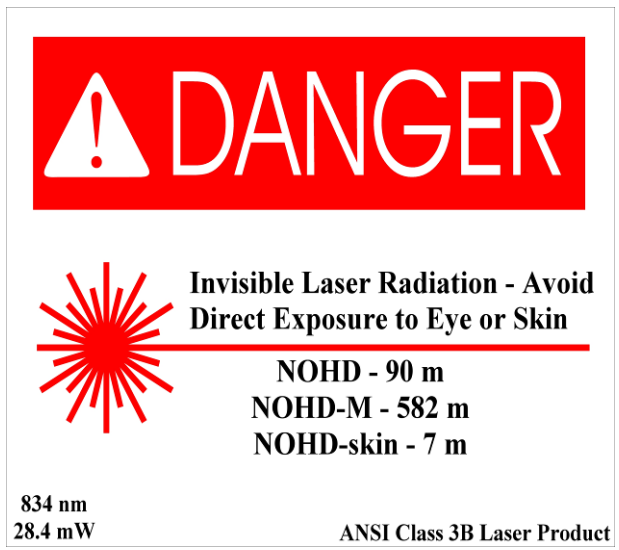
  Classroom pointer < 5 mW



Class 3B

- Visible or NIR (700-1400 nm) lasers: Cannot exceed 0.5 W for $t \geq 0.25$ sec and cannot produce radiant energy > $0.03C_A$ J

- Other wavelength lasers: Cannot exceed 0.5 W for $t \geq 0.25$ sec and cannot produce radiant energy > 125 mJ within $t < 0.25$ sec



Class 3B Control Measures

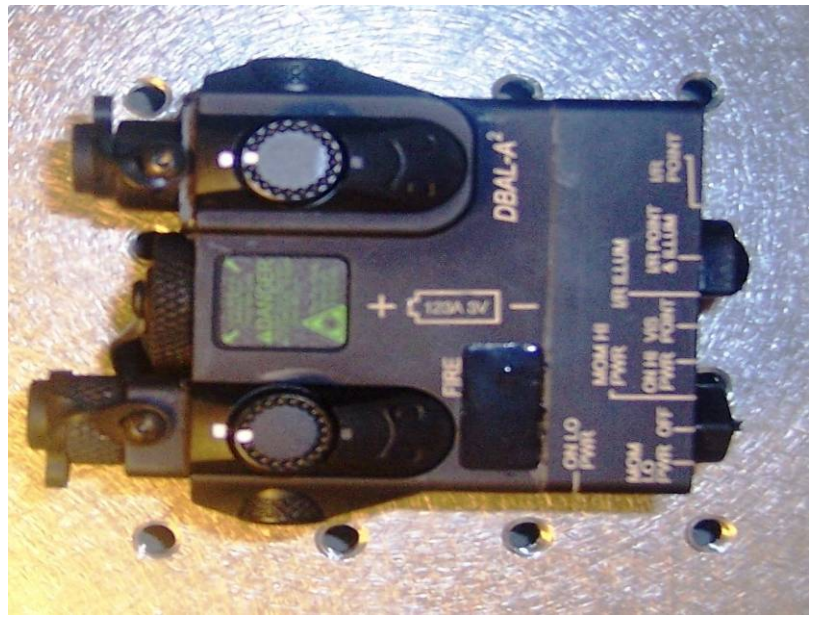
- Should have Key control – master switch should be controlled by a removable key or coded access
- LSO establishes nominal hazard zones (NHZ) – area within which the direct, reflected or scattered radiation exceeds the appropriate MPE
- Should have beam stop – permanently attached beam stop or attenuator shall prevent access to laser radiation in excess of the appropriate MPE when laser output isn't required such as during laser warm-up

Class 3b Control Measures (cont)

- Should have activation warning – audible alarm, visible warning light, or verbal “countdown” command indicating laser is operating
- Laser controlled area – proper warning signs posted, limited access to area, no specularly reflective materials near beam path, proper eye protection where needed
- Medical surveillance for Class 3b
- Class 3B military laser systems may be granted an exemption from required control measures

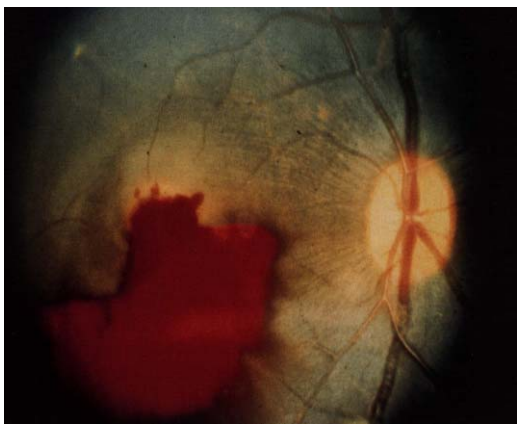
Class 3b Examples

- MIPIM
- DBAL-A^2



Class 4

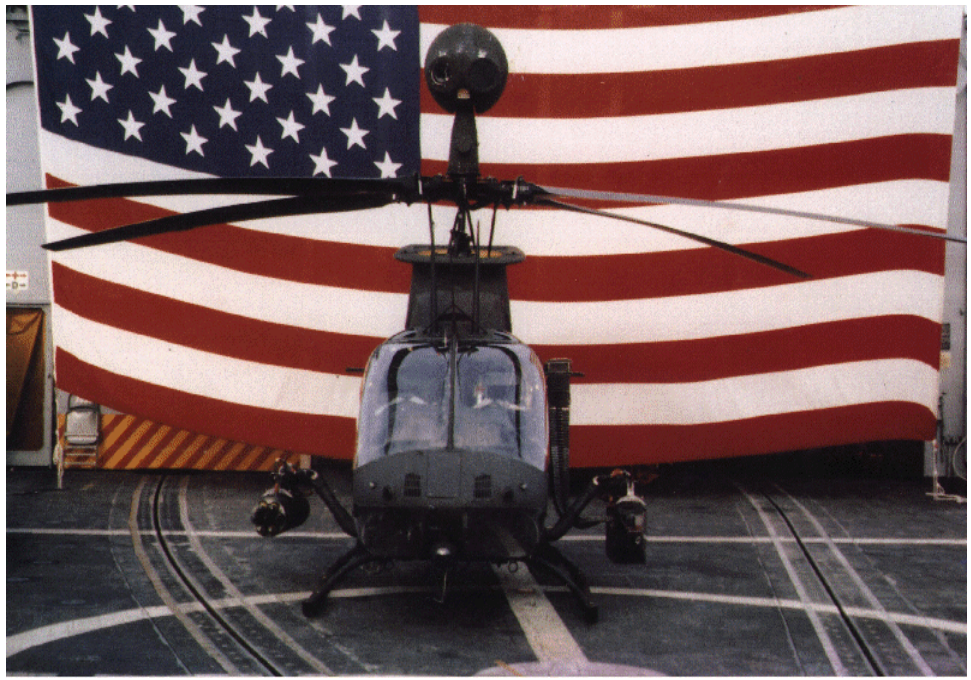
- Class 4 Lasers – Output greater than the Class 3B AEL
  - Direct and specular reflection viewing hazards
  - Diffuse reflection may present a hazard
  - May pose a fire hazard
  - May generate hazardous airborne contaminants and plasma radiation



Class 4 Examples

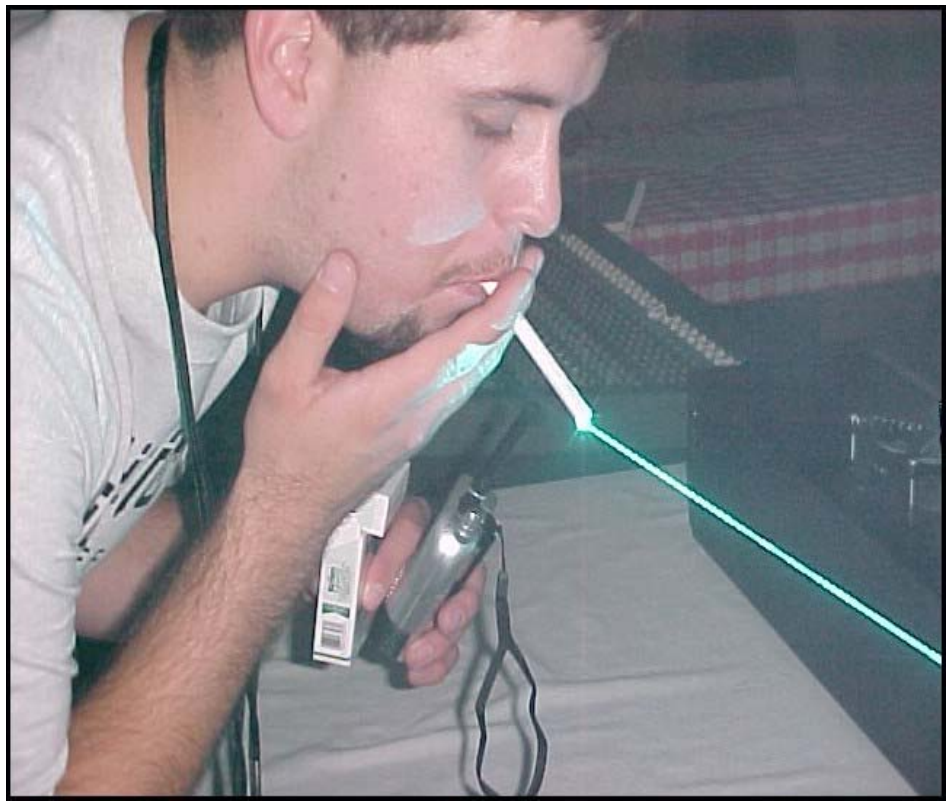
- AH-64 TADS

- OH-58 D - MMS



Class 4 Examples

- Cigarette Lighters



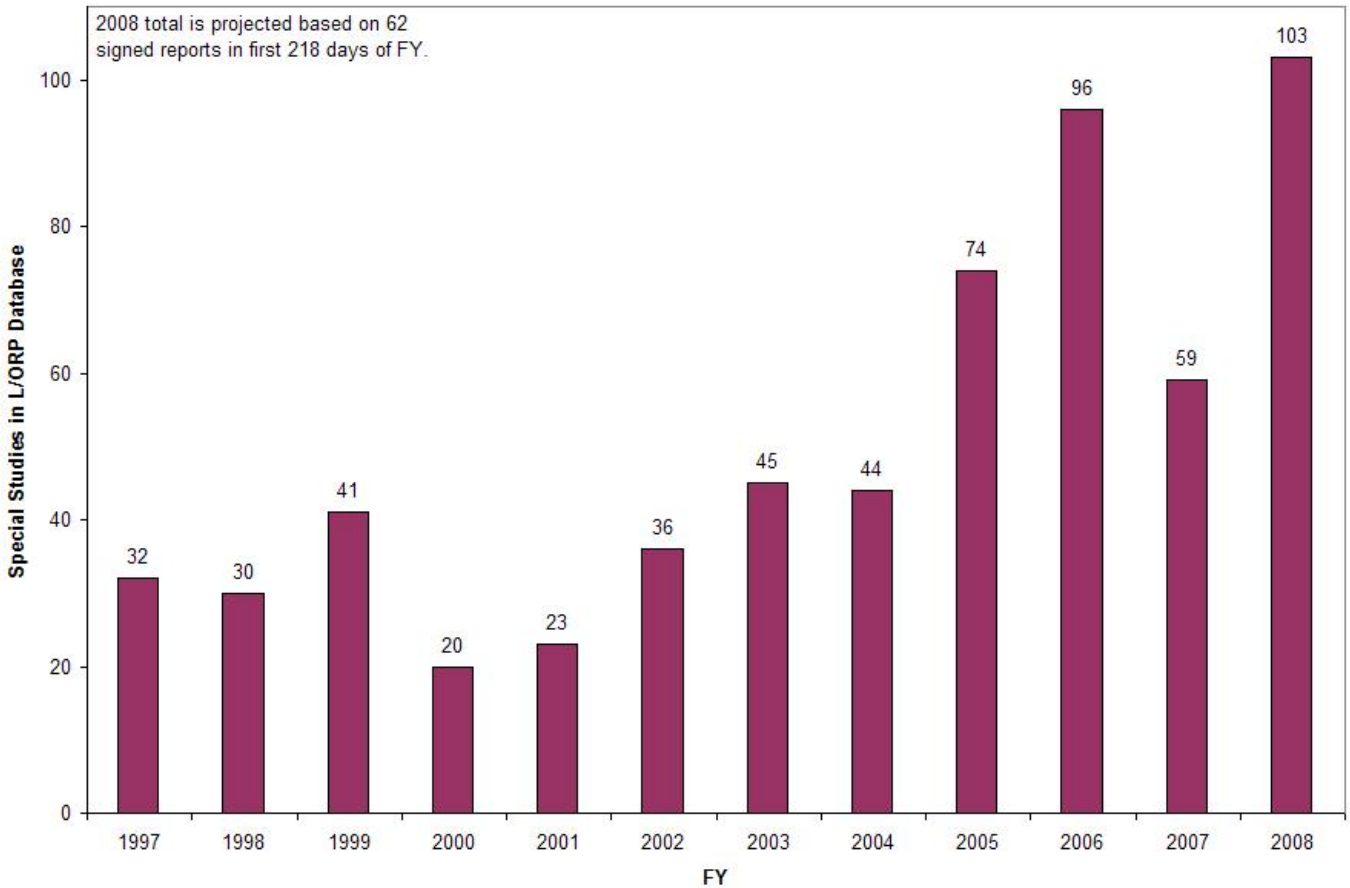
Class 4 Control Measures

- Key control
- LSO establish NHZ
- Beam stop
- Activation warning
- Laser controlled area
- Emission Indicator – warning system indicating the laser is firing.
- Remote interlock connector – interlock connector that connects to an emergency disconnect switch, or an entryway or room interlock
- Medical surveillance for Class 4

- Class 4 military laser systems may be granted an exemption from required control measures

INCREASED NUMBERS/ APPLICATIONS OF LASERS

- Great increase in lasers developed during GWOT.
- Novel Applications



INCREASED NUMBERS/ APPLICATIONS OF LASERS

- Large number of multifunction weapon mounted lasers being fielded:
  - Replacements for the AN/PEQ-2A
  - Aiming/pointing devices – IR & Visible lasers, Flashlight
    - AN/PEQ-15 ATPIAL
    - AN/PEQ-15A DBAL-A^2
    - AN/PEQ-16A MIPIM

INCREASED NUMBERS/ APPLICATIONS OF LASERS

AN/PEQ-2A Aiming Light

https://peosoldier.army.mil

AN/PEQ-16A MIPIM

https://peosoldier.army.mil

AN/PEQ-15A DBAL-A2

https://peosoldier.army.mil

AN/PEQ-15 ATPIAL

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INCREASED NUMBERS/ APPLICATIONS OF LASERS

- Small Tactical Optical Rifle Mounted (STORM) Micro-Laser Rangefinder (MLRF)
  - LRF
  - IR Aiming, Illuminating
  - MILES

COTS LASERS

- Large numbers of COTS systems being deployed or purchased in theater
- Reluctance for CHPPM testing
- Why must it be tested by CHPPM if it is commercially available?
  - Manufacturers self-certify compliance with FDA CDRH Title 21 CFR 1040
    - Devices are sometimes measured or classified incorrectly
    - Inconsistent output
  - System may be used in situation other than intended by manufacturer

COTS LASERS

- Labeled incorrectly
  - Nov 07: Pointer specified as Class 1, measured at Class 3R power level

COTS LASERS

- Measured/Classified Incorrectly
  - July 06: LRF specified as Class 1,

    ns pulses were 10x the Class 1 limit.
  - Sept 06: Infrared Illuminator – manufacturer classified as Class 1, output was >6000 x higher than Class 1 limit

COTS LASERS

- Quality Assurance Issues
  - Jan 06: Laser warning device specified at 150 mW, delivered 20-105 mW
  - June 07: Laser warning device specified at 250 mW, delivered 128-195 mW
  - June 07: Laser warning device output varied from 110 mW to 155 mW, no spec, extra beams
  - Dec 07: Device to be used for EOF specified as Class 3R (< 5mW) measured at Class 3B power level (6 & 8 mW)

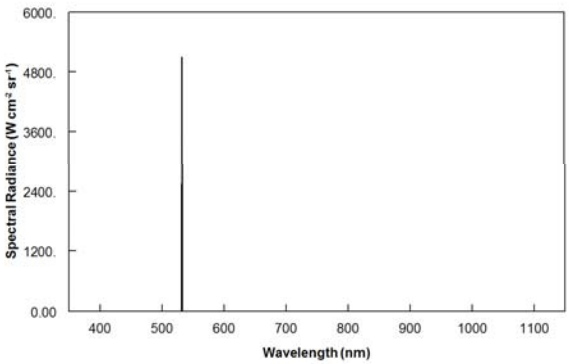
DAZZLERS

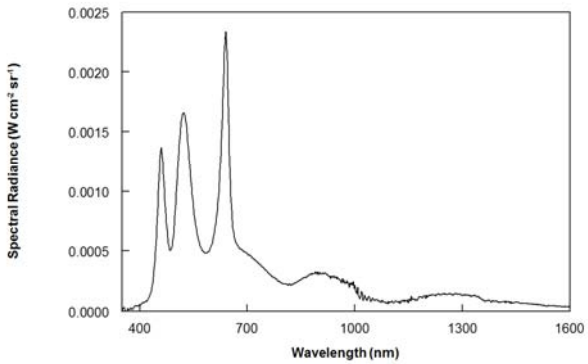
- “The REF reports that green lasers have enabled a 60% to 80% drop in aggressive driving at checkpoints.” Business Week, July 2007

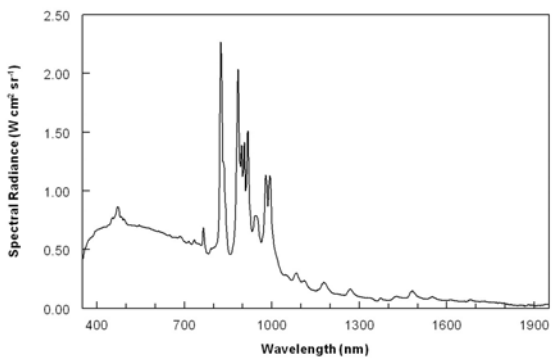
- “New” application for lasers
  - Exposure criteria not well defined
  - Inconsistent output makes effective ranges and NOHD information unreliable

DAZZLERS

- Application of broadband and LED sources
  - Must consider biological effects from a range of wavelengths (up to 7 biological damage mechanisms)
  - Different equipment and measurements are necessary







DAZZLERS

- LSSWG (tri-service) working on guidance for requirements, effective output levels, etc.

DAZZLERS

- Threats to force
  - Friendly “fire” incidents
    - Lasers can cause injury at ranges closer than intended use.
  - Enemy Forces
    - Military incidents (ground & air)
    - Commercial Airlines Incidents
      - Incidents range from innocent carelessness to coordinated attacks

FUTURE CHALLENGES

- Modulated frequency & amplitude
- Femto/picosecond pulses
  - Biological experiments have not been performed to set exposure levels for all of these cases-reasonable limits have been set
  - Equipment to measure laser parameters is expensive, fragile, highly specialized

New Challenges in Laser Safety

Presented by: Chris Brumage

Physicist, Laser/Optical Radiation Program

U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM)

Questions? Comments?

USACHPPM

Readiness thru Health

Additional Useful Information

Useful References

General Military System Safety	TB MED 524, Control of hazards to health from laser radiation
Specific Military System Safety	TB 43–0133, Hazard Controls For Cecom Radiofrequency And Optical Radiation Producing Equipment
CBRNE for Field	USACHPPM Tech Guide 244, The Medical NBC Battlebook
Lasers - Exposure Limits, Control Measures	ANSI Z136 series
Lamps - Exposure Limits, Control Measures	ANSI/IESNA RP-27 series
Internationally Accepted Terms & Units	*International Lighting Vocabulary*, CIE Publication No. 17.4, IEC 50846,Vienna, CIE, 1987 (next edition in 2007)
Optical Radiation Safety	D. H. Sliney and M. L. Wolbarsht, *Safety with Lasers and Other Optical Sources*, (Plenum Publishing Corp, New York), (1980).

Spectral Band Definitions

optical radiation - Electromagnetic radiation at wavelengths between the region of transition to X rays ($\lambda \approx 1$ nm) and the region of transition to radio waves ($\lambda \approx 1$ mm). [i.e. wavelengths that effect the eye]

light **-** 1. Perceived light, or 2. Visible radiation.

Note. – The world *light* is sometimes used in sense 2 for optical radiation extending outside the visible range, but this usage is not recommended.

visible radiation - Any radiation capable of causing a visual sensation directly.

Note. – There are no precise limits for the spectral range of visible radiation since they depend upon the amount of radiant power reaching the retina and the responsivity of the observer. The lower limit is generally taken between 360 nm and 400 nm and the upper limit between 760 and 830 nm.

ultraviolet radiation **-** Optical radiation for which the wavelengths are shorter than those for visible radiation.

Note. – For ultraviolet radiation, the range between 100 nm and 400 nm is commonly subdivided into:

UV-A	315	400 nm
UV-B	280	315 nm
UV-C	100	280 nm

infrared radiation - Optical radiation for which the wavelengths are longer that those for visible radiation.

Note. – For infrared radiation, the range between 780 nm and 1 mm is commonly subdivided into:

IR-A	780	1400 nm
IR-B	1.4	3 µm
IR-C	3 µm	1 mm

From: Commission International de l'Eclairage (CIE), *International Lighting Vocabulary*, CIE Publication No. 17.4, IEC 50846,Vienna, CIE, 1987

Scientific Notation

Equivalent Numbers

1000	$1 \times 10 \times 10 \times 10$	1×10^{3}
3000	$3 \times 10 \times 10 \times 10$	3×10^{3}
42380	$4.238 \times 10{,}000$	4.238×10^{4}
1	1×1	1×10^{0}
0.1	$1/\ 10$	1×10^{-1}
0.0023	$2.3/\ 1000$	2.3×10^{-3}
0.000006328	$6.328/\ 1{,}000{,}000$	6.328×10^{-6}

Prefixes

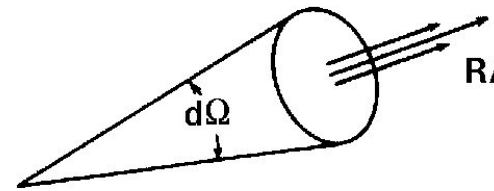
Unit Prefix	*Unit Abbreviation*	*Power*
centi	c	1×10^{-2}
milli	m	1×10^{-3}
micro	μ	1×10^{-6}
nano	n	1×10^{-9}
pico	p	1×10^{-12}
kilo	k	1×10^{3}
mega	M	1×10^{6}
giga	G	1×10^{9}
tera	T	1×10^{12}

Quantities

Quantity	*Symbol*	*Unit*	*Abbrev.*
Frequency	f,ν	hertz	Hz
Wavelength	λ	nanometers	nm
Power	Φ	watts	W
Energy	Q	joules	J
Time	t	seconds	s

Term	Symbol	Definition	Unit and abbreviation
Radiant Energy	Q	Energy emitted, transferred, or received in the form of radiation	joule (J)
Radiant Power	Φ	Radiant Energy per unit time	watt (W) defined as J/s
Radiant Exposure (Dose in Photobiology)	H	Energy per unit area incident upon a given surface	joules per square centimeter ($J \times cm^{-2}$)
Irradiance or Radiant Flux Density (Dose Rate in Photobiology)	E	Power per unit area incident upon a given surface	watts per square centimeter ($W \times cm^{-2}$)
Integrated Radiant Intensity	I_P	Radiant Energy emitted by a source per unit solid angle	joules per steradian ($J \times sr^{-1}$)
Radiant Intensity	I	Radiant Power emitted by a source per unit solid angle	watts per steradian ($W \times sr^{-1}$)
Integrated Radiance	L_P	Radiant Energy emitted by a source per unit solid angle per source area	joules per steradian per square centimeter ($J \times sr^{-1} \times cm^{-2}$)
Radiance	L	Radiant Power emitted by a source per unit solid angle per source area	watts per steradian per square centimeter ($W \times sr^{-1} \times cm^{-2}$)
Optical Density	OD	A logarithmic expression for the attenuation produced by a medium	unitless

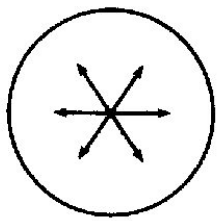
DESCRIBING A SOURCE



POINT SOURCE

RADIANT INTENSITY, I[W/sr]

$dI = d\Phi/d\Omega$

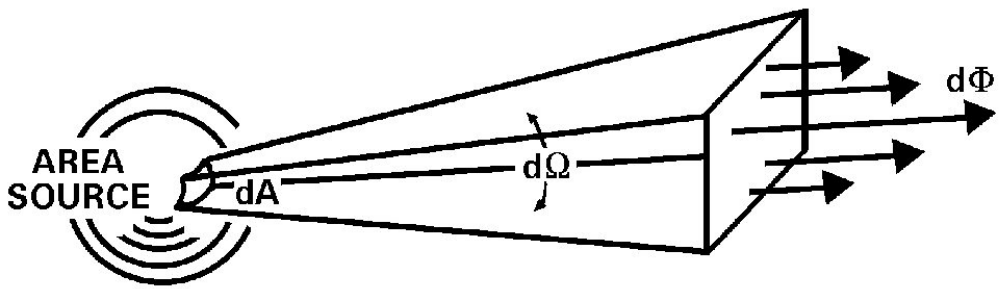


SOURCE

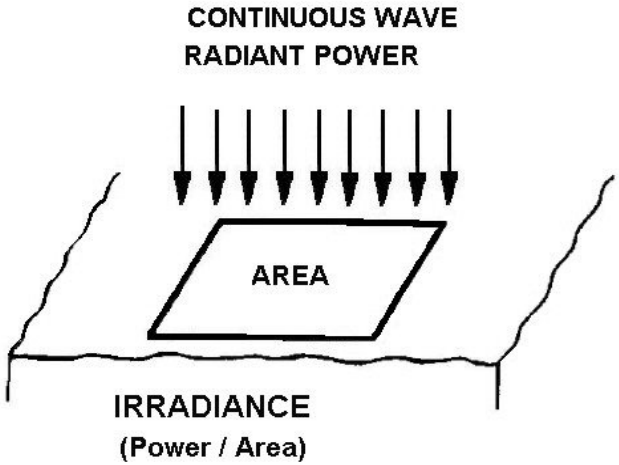
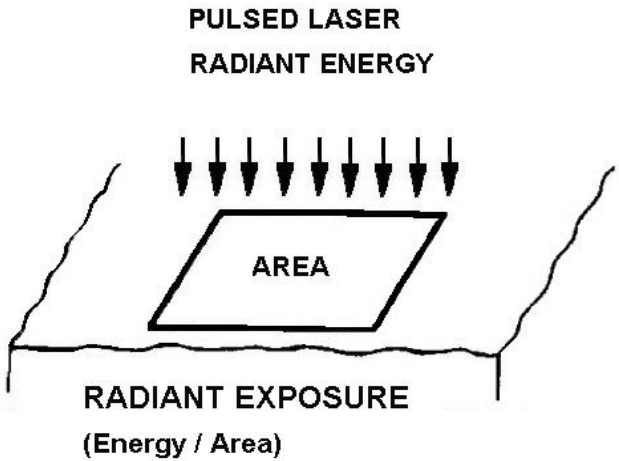
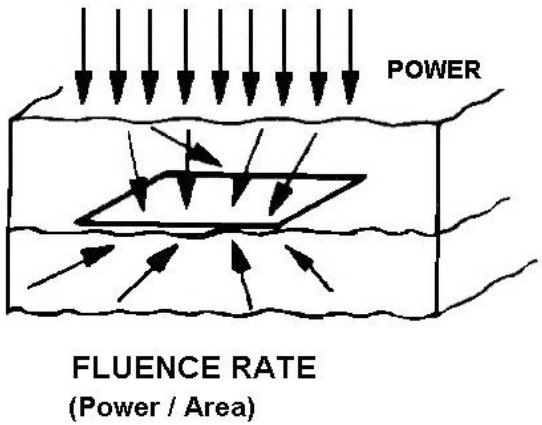
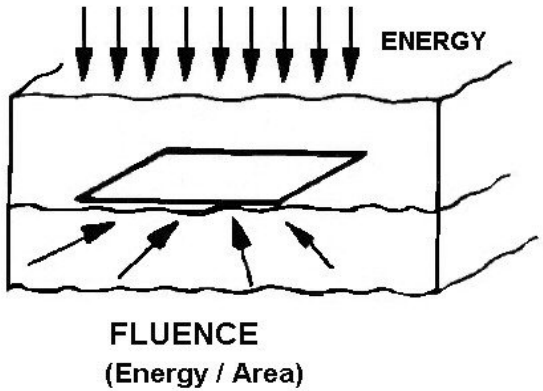
RADIANT POWER, Φ[W]

RADIANT ENERGY, Q(J)

Total power or energy
collected in an integrating sphere



RADIANCE, L[$W/cm^2 \cdot sr$]

$dL = d\Phi/dA\, d\Omega_{\Phi}$

Describing an Irradiated Surface