CHAPTER 28

NON-IONIZING RADIATION

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INTRODUCTION

Current Interest in the Non-Ionizing Radiations

Interest in the public health aspects of the non-ionizing radiations has increased many fold due to the expanded production of electronic products which use or emit radiation, e.g., lasers, microwave ovens, radar for pleasure boats, infrared inspection equipment and high intensity light sources. All such sources generate so-called "non-ionizing" radiation, a term which is defined in the section entitled "Nature of Electromagnetic Energy." Because of the proliferation of such electronic products as well as a renewed interest in electromagnetic radiation hazards, the Congress recently enacted Public Law 90-602, the "Radiation Control for Health and Safety Act of 1968."

PL 90-602 has as its declared purpose the establishment of a national electronic product radiation control program which includes the development and administration of performance standards to control the emission of electronic product radiation. The most outstanding feature of the Act is its omnibus coverage of all types of both ionizing and non-ionizing electromagnetic radiation emanating from electronic products, i.e., gamma, X rays, ultraviolet, visible, infrared, radiofrequencies (RF) and microwaves. Performance standards have already been issued under the Act for TV sets and microwave ovens; preparations are underway for the issuance of a laser standard. In similar fashion, the recent enactment of the federal "Occupational Safety and Health Act of 1970" gives due attention to the potential hazards of non-ionizing radiations in industrial establishments.

For the purposes of this chapter more formal treatment is given to ultraviolet radiation, lasers, and microwave radiation than to the visible and infrared (IR) radiations. However, the information on visible and IR radiation presented in the section on "Laser Radiation" is generally applicable to noncoherent sources.

Nature of Electromagnetic Energy

The electromagnetic spectrum extends over a broad range of wavelengtths, from less than 10^{-12} cm to greater than 10^{10} cm. The shortest wavelengths are generated by cosmic and X-rays; the longer wavelengths are associated with microwave and electrical power generation. Ultraviolet, visible and infrared radiations occupy an intermediate position. Radio frequency waves may range from 3×10^{10} μm to 3×10^{2} μm; infrared rays, from 3×10^{2} μm to about 0.7 μm; the visible spectrum, from approximately 0.7 μm to 0.4 μm; ultraviolet, from approximately 0.4 μm to 0.1 μm; and gamma and x radiation, below 0.1 μm (see Fig. 28-1). The photon energies of electromagnetic radiations are proportional to the frequency of the radiation and inversely proportional to wavelength. Hence, the higher energies, e.g., 10^{8} electron volts (eV) are associated with X-ray and gamma radiations, and the lower energies (e.g., 10^{-8} eV) with RF and microwave radiations.

Whereas the thermal energy associated with molecules at room temperature is approximately 1/30 eV, the binding energy of chemical bonds is roughly equivalent to a range of <1 to 15 eV. The nuclear binding energies of protons may be equivalent to 10^{6} eV and greater. Since the photon energy necessary to ionize atomic oxygen and hydrogen is of the order of 10-12 eV it seems in order to adopt a value of approximately 10 eV as a lower limit in which ionization is produced in biological material. Hence, those electromagnetic radiations that do not cause ionization in biological systems may be presumed to have photon energies less than 10-12 eV and, therefore, may be termed "nonionizing." An extremely important qualification however is that non-ionizing radiations may be absorbed by biological systems and cause changes in the vibrational and rotational energies of the tissue molecules, thus leading to possible dissociation of the molecules or, more often, dissipation of energy in the form of fluorescence or heat.

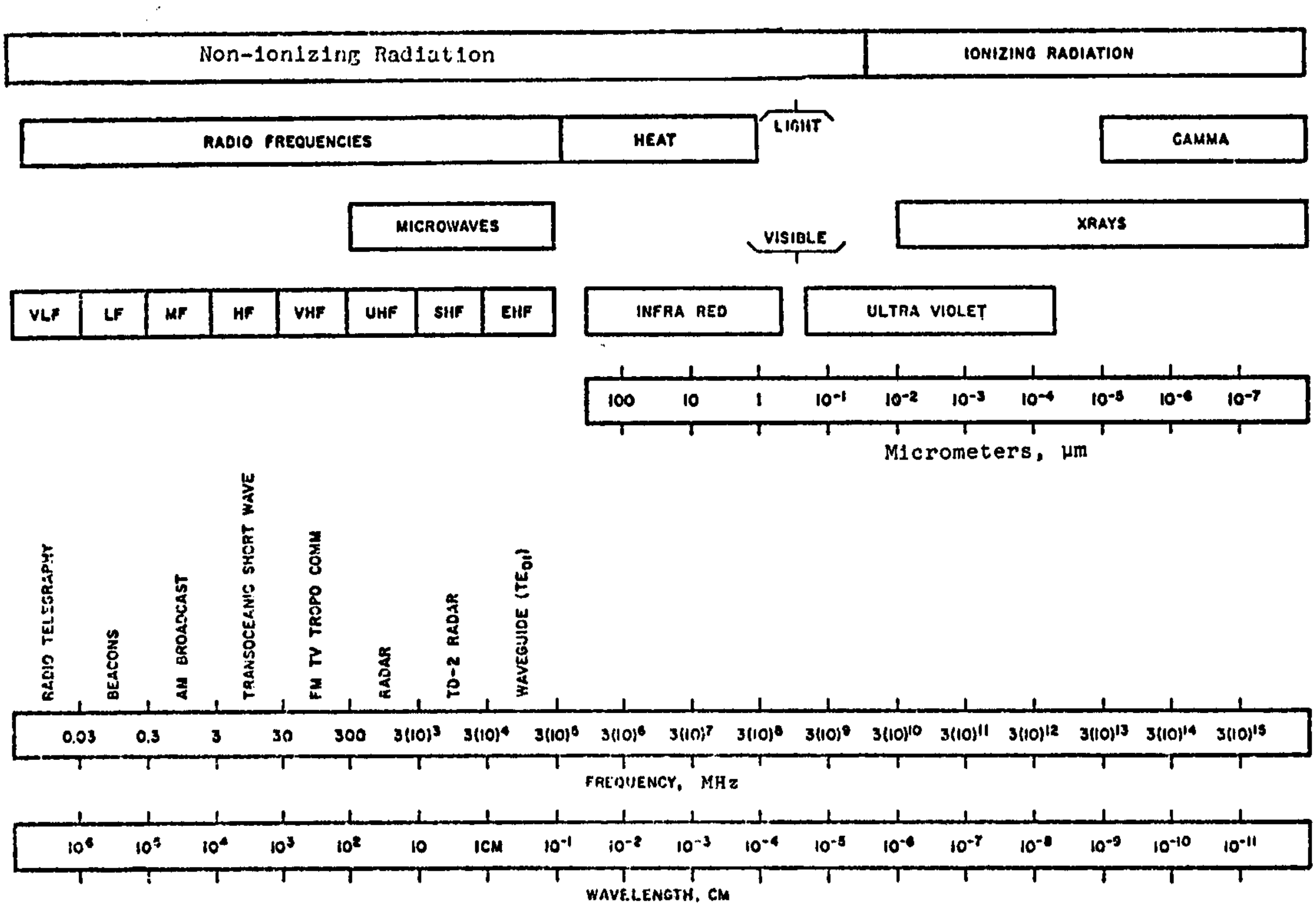
In conducting research into the bioeffects of the nonionizing radiations the investigator has had to use several units of measurement in expressing the results of his studies. For this reason Appendix A, containing definitions of many useful radiometric terms has been included. Appendix B provides a simple means for expressing radiant exposure and irradiance units in a number of equivalent terms.

Since the eye is the primary organ at risk to all of the non-ionizing radiations, Appendix C has been added to provide the reader with a general scheme of absorption and transmission of electromagnetic radiations within the human eye.

ULTRAVIOLET RADIATION

Physical Characteristics of Ultraviolet Radiation

For the purpose of assessing the biological effects of ultraviolet radiation the wavelength range of interest can be restricted to 0.1 μm to 0.4 μm. This range extends from the vacuum ultraviolet (0.1 μm) to the near UV (0.4 μm). A useful breakdown of the ultraviolet region is as follows:[1]



Mumford WW: Some Technical Aspects of Microwave Radiation Hazards. Proc. IRE 49:427-47, 1961.

Figure 28-1. **The Electromagnetic Spectrum.**

UV Region	—Range, μm.	Photon Energy (electron volts)
Vacuum	<0.16	>7.7
Far	0.16-0.28	7.7-4.4
Middle	0.28-0.32	4.4-3.9
Near	0.32-0.4	3.9-3.1

The photon energy range for wavelengths between 0.1 μm and 0.4 μm is 12.4 to 3.1 electron volts respectively. Certain transmission, absorption and reflectance characteristics of ultraviolet radiation are given in Tables 28-1 and 28-2.

Representative Sources of Ultraviolet Radiation

The major source of ultraviolet radiation is the sun, although absorption by the ozone layer permits only wavelengths greater than 0.29 μm to reach the surface of the earth. Low and high pressure mercury discharge lamps and welding and plasma torches constitute significant man-made sources. In low pressure mercury vapor discharge lamps over 85% of the radiation is usually emitted at 0.2537 μm. At the lower pressures (fractions of an atmosphere) the characteristic mercury lines predominate whereas at higher pressures (up to 100 atmospheres) the lines broaden to produce a radiation continuum. In typical quartz lamps the amount of energy at wavelengths below 0.38 μm may be 50% greater than the radiated visible energy, depending upon the mercury pressure. Other man-made sources include xenon discharge lamps, lasers and relatively new types of fluorescent tubes which emit radiation at wavelengths above 0.315 μm reportedly at an irradiance less than that measured outdoors on a sunny day.

TABLE 28-1

Transmission, Absorption Characteristics of Ultraviolet Radiation

λ range, μm	Transmission, Absorption Properties
0.3-0.4	Transmits through air — Partially transmits through ordinary glass, quartz, water.
0.2-0.32	Transmits through air, quartz. Absorbed by ordinary window glass. Ozone layer absorbs sun's radiation at λ less than 0.29 μm. Absorbed by epithelial layers of skin and cornea.
0.16-0.2	Poorly transmitted through air and quartz.
<0.16	Air and quartz completely absorb these λ. Radiations can exist only in vacuum.

Biological Effects of Ultraviolet Radiation

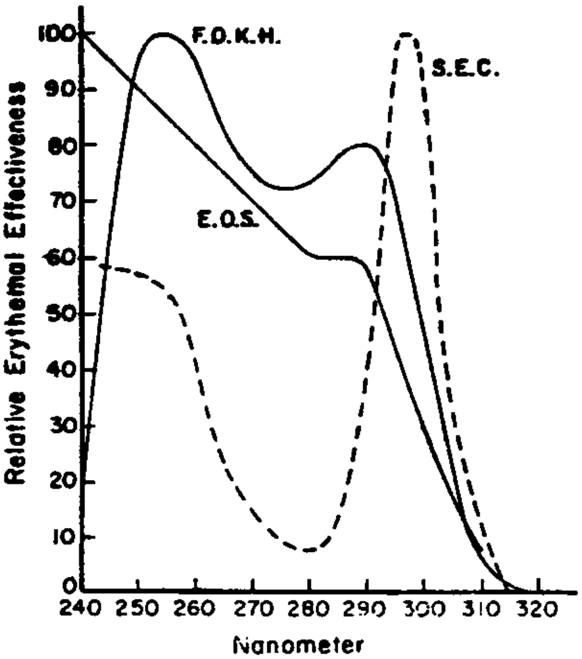
The biological action spectrum for erythema (reddening) produced by ultraviolet radiation of the skin has been the subject of investigation for many years. The most recent data show that a maximum erythemal effect is produced at 0.260 μm with the secondary peak at approximately

TABLE 28-2

Reflectance of 0.2537 μm Radiation From Various Surfaces

Material	% Reflectance*
Aluminum, etched	88
Aluminum foil	73
Chromium	45
Nickel	38
Stainless Steel	20-30
Silver	22
Tin-plated steel	28
White wall plaster	40-60
White paper	25
White cotton	30
White oil paints	5-10
White porcelain enamel	5
Glass	4
Water paints	10-30

*Values obtained at normal incidence. The percentage reflectance increases rapidly at angles greater than 75%. Reprinted from American Industrial Hygiene Journal, 3:1964, Akron, Ohio.



Industrial Hygiene Highlights, vol. 1, p. 145.

Figure 28-2. Comparison of Standard Erythemal Curve (S.E.C.) with Relative Erythemal Curve (S.E.C.) with Relative Erythemal Effectiveness Curves of Everett, Olsen and Soyer (E.O.S.) and Freeman, Owens, Knox and Hudson (F.O.K.H.)

0.290 μm.[2,3] Erythemal response to wavelengths above 0.32 μm is predictably poor (see Fig. 28-2). The greatly increased air absorption of wavelengths below 0.25 μm and the difficulty in obtaining monochromatic radiations in this region probably account for the lack of definitive bioeffects data. This may change with the increase in the number of UV lasers available for research and study.

Wavelengths between 0.28 μm and 0.32 μm penetrate appreciably into the corium or dermis; those between 0.32 μm and 0.38 μm are absorbed primarily in the epidermis, while those below 0.28 μm appear to be absorbed almost completely in the stratum corneum of the epidermis.

Depending upon the total UV dose, the latent period for erythema may range from two to several hours; the severity may vary from simple erythema to blistering and desquamation with severe secondary effects. A migration of melanin granules from the basal cells to the malpighian cell layers of the epidermis may cause a thickening of the horny layers of the skin. The possible long-term effects of the repeated process of melanin migration is not completely understood. The available data seem to support the contention that some regions of the ultraviolet may produce or initiate carcinogenesis in the human skin. The experiments which have supported this contention indicate that the biological action spectrum for carcinogenesis is the same as that for erythema (see Fig. 28-3). Cases of skin cancer have been reported in workers whose occupation requires them to be exposed to sunlight for long periods of time. The reportedly high incidence of skin cancer in outdoor workers who are simultaneously exposed to chemicals such as coal tar derivatives, benzpyrene, methyl cholanthrene and other anthracene compounds raises the question as to the role played by ultraviolet radiation in these cases. It is a matter of common knowledge that significant numbers of workers who routinely expose themselves to coal tar products while working outdoors experience a photosensitization of the skin.

Abiotic effects from exposure to ultraviolet radiation occur in the spectral range of 0.24 to 0.31 μm. In this part of the spectrum, most of the incident energy is absorbed by the corneal epithelium at the surface of the eye. Hence, although the lens is capable of absorbing 99% of the energy below 0.35 μm only a small portion of the radiation reaches the anterior lenticular surface.

Photon-energies of about 3.5 eV (0.36 μm) may excite the lens of the eye or cause the aqueous or vitreous humor to fluoresce thus producing a diffuse haziness inside the eye that can interfere with visual acuity or produce eye fatigue. The phenomenon of fluorescence in the ocular media is not of concern from a bioeffects standpoint; the condition is strictly temporary and without detrimental effect.

The development of photokeratitis usually has

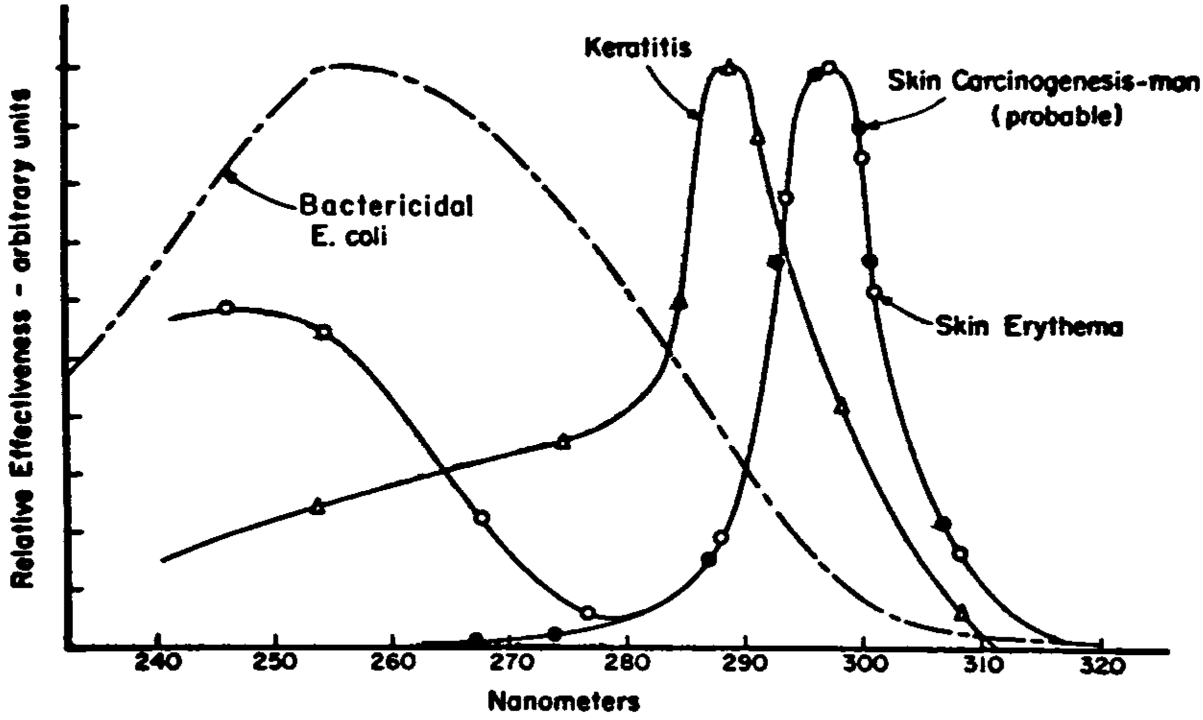


Figure 28-3. Action Spectra: Bactericidal, Hollaender; Keratitis, Cogan and Kinsey; Erythemal, I.E.S. Lighting Handbook, 4th Ed.; Carcinogenesis, Rusch, Kline and Baumann.

a latency period varying from 30 minutes to as long as 24 hours depending upon the severity of the exposure. A sensation of "sand in the eyes" accompanied by varying degrees of photophobia, lacrimation and blepharospasm is the usual result. Blepharospasm is a reflex protective mechanism characterized by an involuntary tight closing of the lids, usually over a damaged cornea.

Exposure Criteria

The biological action spectrum for keratitis peaks at 0.28 μm. At this wavelength, the threshold for injury has been determined to be approximately 0.15×10^6 ergs.[4] It has been suggested that the corneal reaction is due primarily to selective absorption of UV by specific cell constituents; for example, globulin.

Verhoeff and Bell[5] gave the first quantitative measurement of the ultraviolet energy necessary for threshold damage as 2×10^6 ergs/cm^2 for the whole UV spectrum. More recent data by Pitts et al.,[6,7] using 10 nm bands of radiation produced a threshold of approximately 0.5×10^5 ergs per square centimeter in rabbit eyes.

The exposure criteria adopted by the American Medical Association based on erythemal thresholds at 0.2537 μm radiation are as follows: 0.5×10^{-6} W/cm^2 for exposure up to seven hours; 0.1×10^{-6} W/cm^2 for exposure periods up to and exceeding 24 hours.[8] Although these criteria are generally thought to be very stringent, they are nevertheless in common use.

The American Conference of Governmental Industrial Hygienists[9] has published a "Notice of Intent" to establish Threshold Limit Values for ultraviolet radiation. The Notice states that the total irradiance of the unprotected skin or eye by ultraviolet energy in the 0.32 to 0.4 μm wavelength range should not exceed 10^{-3} W/cm^2 for a period of 16 minutes. For ultraviolet in a range from 0.2 μm to 0.315 μm, the radiant exposure should not exceed values which vary from 0.1 J/cm^2 to 1.0 J/cm^2, respectively.

Measurement of Ultraviolet Radiation

Various devices have been used to measure ultraviolet radiation; e.g., photoelectric cells, photoconductive cells, photovoltaic cells and photochemical detectors. It is common practice to employ the use of selective filters in front of the detecting device in order to isolate that portion of the ultraviolet spectrum of interest to the investigator.

A commonly used detector is the barrier or photovoltaic cell. Certain semiconductors such as selenium or copper oxide deposited on a selected metal develop a potential barrier between the layer and the metal. Light falling upon the surface of the cell causes the flow of electrons from the semiconductor to the metal. A sensitive meter placed in such a circuit will record the intensity of radiation falling on the cell.

Ultraviolet photocells take advantage of the fact that certain metals have quantitative photoelectric responses to specific bands in the UV spectrum. Therefore, a photocell may be equipped with metal cathode surfaces which are sensitive to certain UV wavelengths of interest. One of the drawbacks of photocells is solarization or deterioration of the envelope, especially with long usage or following measurement of high intensity ultraviolet radiation. This condition requires frequent recalibration of the cell. The readings obtained with these instruments are valid only when measuring monochromatic radiation, or when the relationship between the response of the instrument and the spectral distribution of the source is known.

A desirable design characteristic of ultraviolet detectors is to have the spectral response of the instrument closely approximate that of the biological action spectrum under consideration. However, such an instrument is unavailable at this time. Since available photocells and filter combinations do not closely approximate the UV biological action spectra, it is necessary to standardize (calibrate) each photocell and meter. Such calibrations are generally made at a great enough distance from a standard source that the measuring device is in the "far field" of the source. Special care must be taken to control the temperature of so called standard mercury lamps because the spectral distribution of the radiation from the lamp is dependent upon the pressure of the vaporized mercury.

A particularly useful device for measuring ultraviolet is the thermopile. Coatings on the receiver elements of the thermopile are generally lamp black or gold black to simulate black body radiation devices. Appropriate thermopile window material should be selected to minimize the effects of air convection, the more common windows being crystal quartz, lithium fluoride, calcium fluoride, sodium chloride and potassium bromide. Table 28-3 shows the sensitivity, impedance and response time of certain junction detectors.[10] Low intensity calibration may be made by exposing the thermopile to a secondary standard (carbon filament) furnished by the National Bureau of Standards.

TABLE 28-3

Sensitivity, Impedance and Response Time of Junction Detectors

Type (Circular)	Sensitivity μV/μW cm^{-2}	Impedance OHM	Response Time (1/e) sec
1-junction:			
Const-Mang	0.005	2	0.1
4-junction:			
Cu-Const	0.025	5	0.5
4-junction:			
Bi-Ag	0.05	5	0.5
8-junction:			
Bi-Ag	0.10	10	1.0
16-junction:			
Bi-Ag	0.20	25	2.0
(linear)	0.05	10	0.5)
12-junction:			
Bi-Ag	0.05	10	0.5

Reprinted from Bulletin No. 3 (1964), p. 5, Eppley Laboratory, Inc., Newport, Rhode Island.

Other UV detection devices include: 1) photodiodes, e.g., silver, gallium arsenide, silver zinc sulfide and gold zinc sulfide (peak sensitivity of these diodes is at wavelengths below 0.36 μm; the peak efficiency or responsivity is of the order of 50-70%); 2) thermocouples, e.g., Chromel-Alumel; 3) Golay cells; 4) superconducting bolometers; and 5) zinc sulfide Schottky barrier detectors.[11]

Care must be taken to use detection devices having the proper rise time characteristics (some devices respond much too slowly to obtain meaningful measurements). Also, when measurements are being made special attention should be given to the possibility of UV absorption by many materials in the environment; e.g., ozone or mercury vapor, thus adversely affecting the readings. The possibility of photochemical reactions between ultraviolet radiation and a variety of chemicals also exists in the industrial environment.

Control of Exposure

Because ultraviolet radiations are so easily absorbed by a wide variety of materials, appropriate attenuation is accomplished in a straight forward manner. The exposure criteria given in the section entitled "Exposure Criteria" should be used for the specification of shielding requirements. In the case of ultraviolet lasers no firm bioeffects criteria are available; however, the data of Pitts[6, 7] may be used because of the narrow band UV source used in his experiments to determine thresholds of injury to rabbit eyes. In using the data in the section "Exposure Criteria" it is important to remember that photosensitization may be induced in certain persons at levels below the suggested exposure criteria.

LASER RADIATION

Sources and Uses of Laser Radiation

The rate of development and manufacture of devices and systems based on stimulated emission of radiation has been truly phenomenal. Lasers are now being used for a wide variety of purposes, including micromachining,welding, cutting, sealing, holography, optical alignment, interferometry, spectroscopy, surgery, and as communications media.

Generally speaking, lasing action has been obtained in gases, crystalline materials, semiconductors and liquids. Stimulated emission in gaseous systems was first reported in a helium neon mixture in 1961.[12] Since that time lasing action has been reported at hundreds of wavelengths from the ultraviolet to the far infrared (several hundred micrometers). Helium neon (He-Ne) lasers are typical of gas systems where stable single frequency operation is important. He-Ne systems can operate in a pulsed mode or continuous wave (CW) at wavelengths of 0.6328 micrometers (μm), 1.15 μm or 3.39 μm, depending upon resonator design. Typical power for He-Ne systems is of the order of 1-500 mW. The carbon dioxide gas laser system operates at a wavelength of 10.6 μm in either the continuous wave, pulsed or Q-switched modes. A Q switch is a device for enhancing the storage and dumping of energy to produce extremely high power pulses. The power output of CO_2-N_2 systems may range from several watts to greater than 10 KW. The CO_2 laser is attractive for terrestrial and extraterrestrial communications because of the low absorption window in the atmosphere between 8 μm and 14 μm. Of major significance from the personal hazard standpoint is the fact that enormous power may be radiated at a wavelength which is invisible to the human eye. The argon ion gas system operates predominantly at wavelengths of 0.488 μm and 0.515 μm in either a continuous wave or pulsed mode. Power generation is greatest at 0.488 μm, typically at less than 10 watts.

Of the many ions in which laser action has been produced in solid state crystalline materials, perhaps neodymium ($Nd^{3}+$) in garnet or glass and chromium ($Cr^{3}+$) in aluminum oxide are most noteworthy (see Table 28-4). Garnet (yttrium aluminum garnet) or YAG is an attractive host for the trivalent neodymium ion because the 1.06 μm laser transition line is sharper than that in other host crystals. Frequency doubling to 0.530 μm using lithium niobate crystals may produce power approaching that available in the fundamental mode at 1.06 μm. Also through the use of electro-optic materials such as KDP, barium-sodium niobate or lithium tantalate, "tuning" or scanning of laser frequencies over wide ranges may be accomplished.[13] The ability to scan rapidly through wide frequency ranges requires special consideration in the design of protective measures.

Perhaps the best known example of a semiconductor laser is the gallium arsenide types operating at 0.840 μm; however, semiconductor materials have operated in a range of approximately 0.4 to 5.1 μm. Generally speaking, the semiconductor laser is a moderately low-powered (milliwatts to several watts) CW device having relatively broad beam divergence thus tending to reduce its hazard potential. On the other hand, certain semiconductor lasers may be pumped by multi kilovolt electron beams thus introducing a potential ionizing radiation hazard.[14]

TABLE 28-4

Certain Ions Which Have Exhibited Lasing-Action

Active ion	Wavelength μm
$Nd^{3}+$	0.9-1.4
$Ho^{3}+$	2.05
$Er^{3}+$	1.61
$Cr^{3}+$	0.69
$Tm^{3}+$	1.92
$U^{3}+$	2.5
$Pr^{3}+$	1.05
$Dy^{2}+$	2.36
$Sm^{2}+$	0.70
$Tm^{2}+$	1.12

Biological Effects of Laser Radiation

The body organ most susceptible to laser radiation appears to be the eye; the skin is also susceptible but of lesser importance. The degree of risk to the eye depends upon the type of laser beams used, notably the wavelength, output power, beam divergence and pulse repetition frequency. The ability of the eye to refract long ultraviolet, visible and near infrared wavelengths is an additional factor to be considered in assessing the potential radiation hazard.

In the case of ultraviolet wavelengths (0.2 to 0.4 μm) produced by lasers the expected response is similar to that produced by noncoherent sources; e.g., photophobia accompanied by erythema, exfoliation of surface tissues and possibly stromal haze. Absorption of UV takes place at or near the surface of tissues. The damage to epithelium results from the photochemical denaturization of proteins (see section entitled "Ultraviolet Radiation").

In the case of infrared laser radiation, damage results exclusively from surface heating of the cornea subsequent to absorption of the incident energy by tissue water in the cornea. Simple heat flow models appear to be sufficiently accurate to explain the surface absorption and damage to tissue.

In the case of the visible laser wavelengths (0.4 to 0.75 μm) the organ at risk is the retina and more particularly the pigment epithelium of the retina. The cornea and lens of the eye focus the incident radiant energy so that the radiant exposure at the retina is at least several orders of magnitude greater than that received by the cornea. Radiant exposures which are markedly above the threshold for producing minimal lesions on the retina may cause physical disruption of retinal tissue by steam formation or by projectile-like motion of the pigment granules.[15, 16] In the case of short transient pulses such as those produced by Q-switched systems, acoustical phenomena may also be present.[15]

There are two transition zones in the electromagnetic spectrum where bio-effects may change from one of a corneal hazard to one of a retinal hazard. These are located at the interface of the ultraviolet-visible region and the visible near infrared region. It is possible that both corneal and retinal damage, as well as damage to intermediate structures such as the lens and iris, could be caused by devices emitting radiation in these transitional regions.

Figures 28-4 and 28-5 show the percent transmission of various wavelengths of radiation through the ocular media and the percent absorption in the retinal pigment epithelium and choroid, respectively. These graphs illustrate why the retina

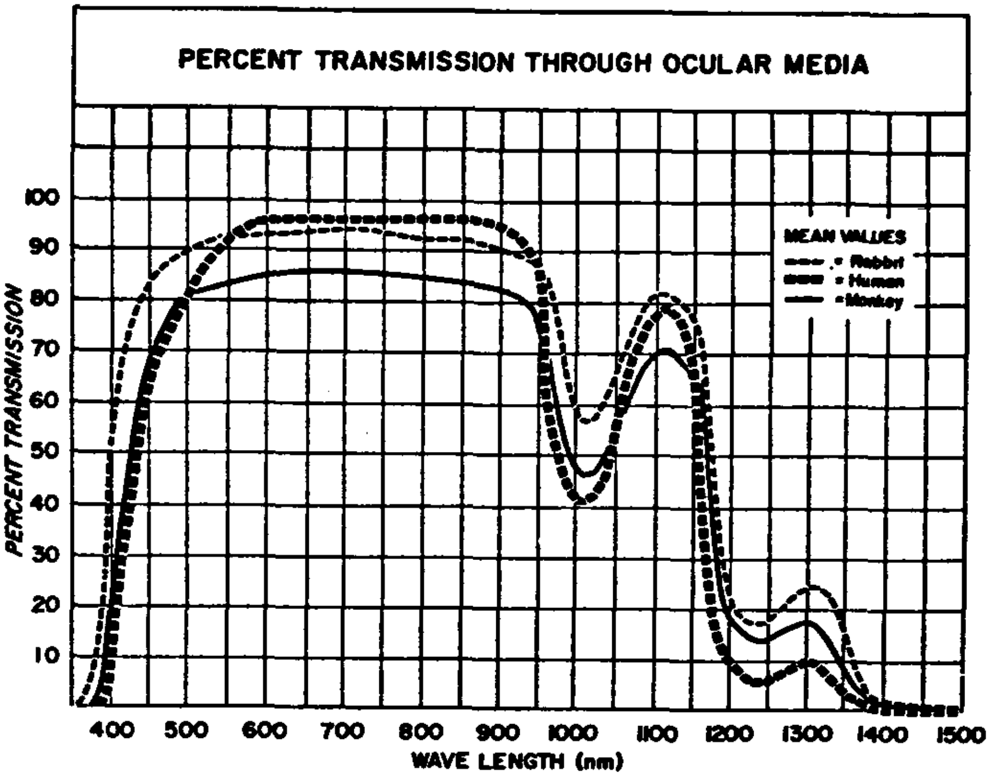


Figure 28-4. Percent Transmission through Ocular Media. Percent transmission for light of equal intensity through the ocular media of human, monkey (rhesus), and rabbit eyes. From Geeraets, W. J. and Berry, E. R., Amer. J. Ophthal., 66, 15, 1968.

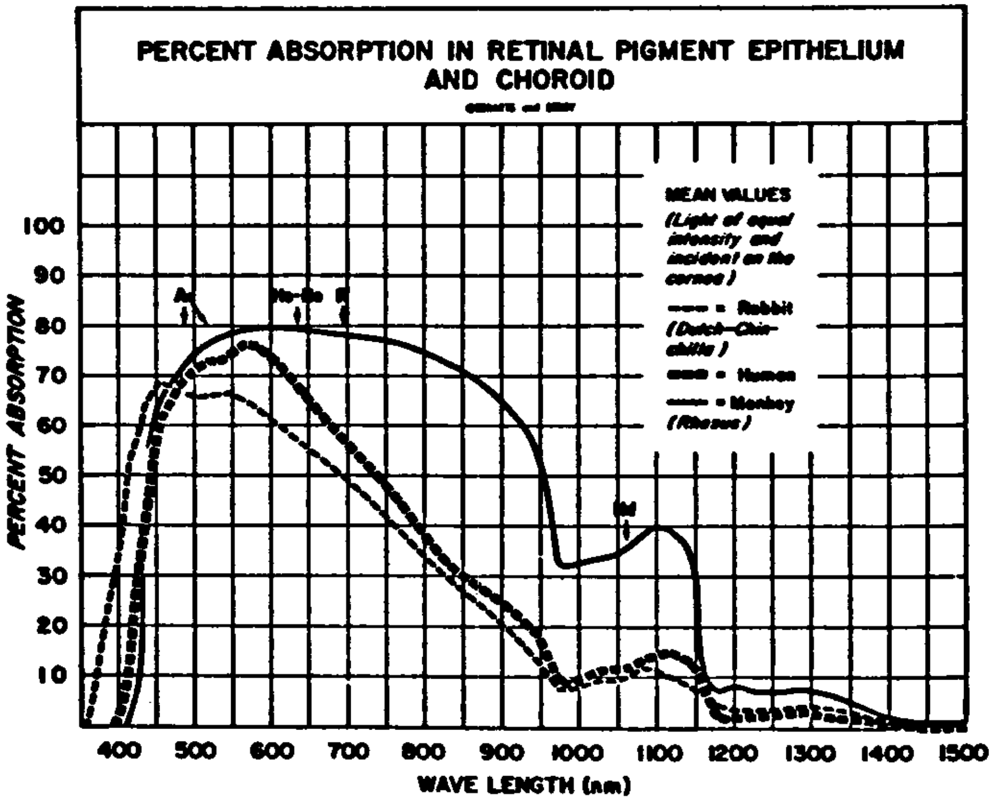


Figure 28-5. Percent Absorption in Retinal Pigment Epithelium and Choroid. Percent absorption of light of equal intensity at the cornea in the retinal pigment epithelium and choroid for rabbits, monkey, and man. Redrawn to include correction for reflection from Figure 2 of Geeraets, W. J. and Berry E. R., Amer. J. Ophthal. 66, 15, 1968.

is the organ at risk with visible wavelength-radiation whereas the cornea and skin surfaces are at risk with infrared and ultraviolet radiation. Several investigators [17, 18] noticed irreversible changes in electroretinograms, with attendant degeneration of visual cells and pigment epithelium, when albino and pigmented rats were exposed to high illumination environments.

The biological significance of irradiating the skin with lasers is considered to be less than that caused by exposure of the eye since skin damage is usually repairable or reversible. The most common effects on the skin range from erythema to blistering and charring depending upon the wavelength, power and time of exposure to the radiation. Depigmentation of the skin and damage to underlying organs may occur from exposure to extremely high powered laser radiation, particularly Q-switched pulses. In order that the relative eye/skin hazard potential be kept in perspective, one must not overlook possible photosensitization of the skin caused by injection of drugs or use of cosmetic materials. In such cases the maximum permissible exposure (MPE) levels for skin might be considerably below the currently recommended values.

Exposure Criteria

Permissible levels of laser radiation impinging upon the eye have been derived from studies of short term exposure and an examination of damage to eye structures as observed through an ophthalmoscope. Some investigators[19] have observed irreversible visual performance changes at exposure levels as low as 10% of the threshold determined by observation through an ophthalmoscope. McNeer and Jones [19, 20] found that at 50% of the ophthalmoscopically determined threshold, the ERG B wave amplitude was irreversibly reduced. Davis and Mautner[21] reported severe changes in the visually evoked cortical potential at 25% of the ophthalmoscopically determined threshold. Since most if not all of the so-called laser exposure criteria have been based on ophthalmoscopically-determined lesions on the retina, the findings of irreversible functional changes at lower levels cause one to ponder the exact magnitude of an appropriate safety factor which should be applied to the ophthalmoscope data in order to derive a reasonable exposure criterion.

There is unanimous agreement that any proposed maximum permissible exposure (MPE) or threshold limit value (TLV) does not sharply divide what is hazardous from what is safe. Usually any proposed values take on firm meaning only after years of practical use. However, it has become general practice in evaluating a laser exposure to:

1. Measure the radiant exposure (J/cm^2) or irradiance (W/cm^2) in the plane of the cornea rather than making an attempt to calculate the values at the retina. This simplifies the measurements and calculations for the industrial hygienists and radiation protection officers.
2. Use a 7 mm diameter limiting aperture (pupil) in the calculations. This assumes that the largest amount of laser radiation may enter the eye.
3. Make a distinction between the viewing of collimated sources; (e.g., lasers) and extended sources (e.g., fluorescent tubes or incandescent lamps). The MPE for extended source viewing takes into account the solid angle subtended at the eyes in viewing the light source; therefore, the unit is Watts/cm^2.sr (Watts per square centimeter and steradian).
4. Derive permissible levels on the basis of the wavelength of the laser radiation; e.g., the MPE for neodymium wavelength (1.06 μm) should be increased; i.e., made less stringent by a factor of approximately five than the MPE for visible wavelengths.
5. Urge caution in the use of laser systems that emit multiple pulses. A conservative approach would be to limit the power or energy in any single pulse in the train to the MPE specified for direct irradiation at the cornea. Similarly the average power for a pulse train could be limited to the MPE of a single pulse of the same duration as the pulse train. More research is needed to precisely define the MPE for multiple pulses.

Typical exposure criteria for the eye proposed by several organizations are shown in Table 28-5 and Table 28-6. These data do not apply to permissible levels at ultraviolet wavelengths or to the skin. A few supplementary comments on these factors are in order. There appears to be general agreement on maximum permissible exposure levels of radiation for the skin; e.g., the MPE values are approximately as follows: for exposure times greater than 1 sec., an MPE of 0.1 W/cm^2; exposure times 10^{-1} to 1 sec., 1.0 W/cm^2; for 10^{-4} to 10 sec., 0.1 J/cm^2 and for exposure times less than 10^{-4} sec., 0.01 J/cm^2. The MPE values apply to visible and infrared wavelengths. For ultraviolet radiations the more conservative approach is to use the standards established by the American Medical Association. These exposure limits (for germicidal wavelengths viz. 0.2537 μm) should not exceed 0.1×10^{-6} W/cm^2 for continuous exposure. If an estimate is to be made of UV laser thresholds, then it is suggested that the more recent work of Pitts[6, 7] be consulted (see section entitled "Ultraviolet Radiation").

TABLE 28-5

Eye Exposure Guidelines for Laser Radiation as Recommended by Various Organizations

Wavelength and Pulse Duration	Air Force*	Army/Navy**	ACGIH***
	Total Energy or Power Entering Eye	Total Energy or Power Over a 7 mm Aperture (Pupil)	Total Energy or Power Over a 7 mm Aperture (Pupil)
Visible (0.4-0.7 μm)			
Q switched	0.5×10^{-6} J	1×10^{-6} W/cm^2	1×10^{-7} J/cm^2 (1 ns to 1 μs)
Long Pulse	1×10^{-6} J	1×10^{-7} J/cm^2	1×10^{-6} J/cm^2 (1 μs to 0.1s)
Continuous Wave	1×10^{-3} W(10-500ms) 2×10^{-3} W(2-10ms)	1×10^{-6} J/cm^2	1×10^{-5} W/cm^2 (>0.1s)
Near Infrared (1.06 μm)			
Q switched (10-100ms)	2.5×10^{-6} J		
Long Pulse (0.2-2ms)	2.0×10^{-5} J		
CW-YAG (2-10ms)	1×10^{-2} W		
CW-YAG (10-500ms)	5×10^{-3} W		
Infrared (10.6 μm)	1 W/cm^2 (50-250ms) 3 W/cm^3 (10-50ms) 8 W/cm^2 (<10ms)	1×10^{-1} W/cm^2	1×10^{-1} W/cm^2

*See Reference 43

**See Reference 44

***See Reference 45

TABLE 28-6

Maximum Permissible Exposure (MPE) for Direct Ocular Intra-beam Viewing for Single Pulses or Exposures (ANSI Z136)*

Wavelength (μm)	Exposure Time (t in seconds)	Maximum Permissible Exposure (MPE)		Notes for Calculation and Measurement
UV				
.200-.302	$10^{-2}-3\times10^{4}$	3×10^{-3}	J·cm^{-2}	I mm limiting aperture.
.303	$10^{-2}-3\times10^{4}$	4×10^{-3}		
.304	$10^{-2}-3\times10^{4}$	6×10^{-3}		In no case shall the total irradiance, over all the wavelengths within the UV spectral region, be greater than 1 watt per square centimeter upon the cornea.
.305	$10^{-2}-3\times10^{4}$	1.0×10^{-2}		
.306	$10^{-2}-3\times10^{4}$	1.6×10^{-2}		
.307	$10^{-2}-3\times10^{4}$	2.5×10^{-2}		
.308	$10^{-2}-3\times10^{4}$	4.0×10^{-2}		
.309	$10^{-2}-3\times10^{4}$	6.3×10^{-2}		
.310	$10^{-2}-3\times10^{4}$	1.0×10^{-1}		
.311	$10^{-2}-3\times10^{4}$	1.6×10^{-1}		
.312	$10^{-2}-3\times10^{4}$	2.5×10^{-1}		
.313	$10^{-2}-3\times10^{4}$	4.0×10^{-1}		
.314	$10^{-2}-3\times10^{4}$	6.3×10^{-1}		
.315-.400	10^{-2} to 10^{3}	1		
.315-.400	$10^{3}-3\times10^{4}$	1×10^{-3}W·cm^{-2}		
Visible and near IR[a]				
.4 − 1.4	$10^{-9}-2\times10^{-5}$	5×10^{-7}J·cm^{-2}		7 mm limiting aperture.
	$2\times10^{-5}-10$	$1.8\times10^{-3}t^{3/4}$J·cm^{-2}		
	$10-10^{4}$	10^{-2}J·cm^{-2}		
	$10^{4}-3\times10^{4}$	10^{-6}W·cm^{-2}		
Far IR[b]				
1.4-10^{3}	$10^{-9}-10^{-7}$	10^{-2}J·cm^{-2}		
	$10^{-7}-10$	$0.56\ t^{1/4}$J·cm^{-2}		
	>10	0.1W·cm^{-2}		

[a] Special Qualifications and Correction Factors Are Given in ANSI Document.

[b] Special Qualifications, Correction Factors and Dimensions of Limiting Apertures Are Given in ANSI Document.

*See Reference 46.

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Measurement of Laser Radiation

The complexity of radiometric measurement techniques, the relatively high cost of available detectors and the fact that calculations of radiant exposure levels based on manufacturers' specifications of laser performance have been found to be sufficiently accurate for protection purposes, have all combined to minimize the number of measurements needed in a protective program. In the author's experience, the output power of commonly used laser systems, as specified by the manufacturers, has never been at variance with precision calibration data by more than a factor of two.

All measurement systems are equipped with detection and readout devices. A general description of several devices and their application to laser measurements follows.

Because laser radiation is monochromatic, certain simplifications can be made in equipment design. For example, it may be possible to use narrow band filters with an appropriate type of detector thereby reducing sources of error. On the other hand, special care must be taken with high powered beams to prevent detector saturation or damage. Extremely short Q-switched pulses require the use of ultrafast detectors and short time-constant instrumentation to measure power instantaneously. Photoelectric detectors and radiation thermopiles are designed to measure instantaneous power, but they can also be used to measure total energy in a pulse by integration, provided the instrumental time-constants are much shorter than the pulse lengths of the laser radiation. High current vacuum photo-diodes are useful for measuring the output of Q-switched systems and can operate with a linear response over a wide range.

Average power measurements of CW laser systems are usually made with a conventional thermopile or photo-voltaic cells. A typical thermopile will detect signals in the power range from 10 μ watts to about 100 milliwatts. Because thermopiles are composed of many junctions the response of these instruments may be nonuniform. The correct measure of average power is therefore not obtained unless the entire surface of the thermopile is exposed to the laser beam. Measurements of the CW power output of gas lasers may also be made with semiconductor photocells.

The effective aperture or aperture stop of any measurement device used for determining the radiant exposure (J/cm^2) or irradiance (W/cm^2) should closely approximate if not be identical to the pupillary aperature. For purposes of safety the diameter should correspond to that of the normal dark-adapted eye; i.e., 7 mm. The response time of measurement systems should be such that the accuracy of the measurement is not affected, especially when measuring short pulse durations or instantaneous peak power.

Many calorimeters and virtually all photographic methods measure total energy, but they can also be used for measuring power if the time history of the radiation is known. Care should be taken to insure that photographic processes are used within the linear portion of the film density versus log radiant exposure (gamma) curve.

Microammeters and voltmeters may be used as read-out devices for CW systems; microvoltmeters or electrometers coupled to oscilloscopes may be used for pulsed laser systems. These devices may be connected in turn to panel displays or recorders, as required.[22,23]

Calibration is required for all wavelengths at which the instrument is to be used. It should be noted that tungsten ribbon filament lamps are available from the National Bureau of Standards as secondary standards of spectral radiance over the wavelength region from approximately 0.2 to 2.6μm. The calibration procedures using these devices permit comparisons within about 1% in the near ultraviolet and about a half percent in the visible. All radiometric standards are based on the Stefan-Boltzmann and Planck laws of blackbody radiation.

The spectral response of measurement devices should always be specified since the ultimate use of the measurements is a correlation with the spectral response of the biological tissue receiving the radiation insult.

Control of Exposure

It stands to reason that certain basic control principles apply to many laser systems: (1) the need to inform appropriate persons as to the potential hazards, the procedures and engineering control measures required to prevent injury, the electrical hazard, particularly with the discharge of capacitor banks associated with solid state Q-switched systems; and (2) the need to rely primarily on engineering controls rather than procedures; e.g., enclosures, beam stops, beam enlarging systems, shutters, interlocks and isolation of laser systems, rather than sole reliance on memory or safety goggles. The "exempt" laser system is an exception to these measures. In all cases, particular attention must be given to the safety of unsuspecting visitors or spectators in laser areas.

"High powered" systems deserve the ultimate in protective design: enclosures should be equipped with interlocks. Care should be taken to prevent accidental firing of the system and where possible, the system should be fired from a remote position. Controls on the high powered systems should go beyond the usual warning labels; e.g., an integral warning system such as a "power on" audible signal or flashing light which is visible through protective eye wear should be installed.

Infrared laser systems should be shielded with fireproof materials having an appropriate optical density (O.D.) to reduce the irradiance below MPE values. The main hazard of these systems is absorption of excessive amounts of IR energy by human tissue or by flammable or explosive chemicals.

Before protective eye wear is chosen, one must determine as a minimum the radiant exposure or irradiance levels produced by the laser at the distance where the beam or reflected beam is to be viewed; one must know the appropriate MPE value for the laser wavelength; and finally one must determine the proper optical density of protective eyewear in order to reduce levels below the MPE. Likewise, the visible light transmission characteristics should be known because sufficient transmission is necessary for the person using the device to be able to detect ordinary objects in the immediate field of vision. The minimum optical density required of protective eyewear is shown in Table 28-7. Table 28-8 lists the characteristics of most laser protective eyewear now available on the American market.[24]

TABLE 28-7

Minimum Optical Densities Required of Protective Eyewear

($OD_{min} = \log_{10} H_o/MPE$ or $\log_{10} E_o/MPE$)

E_o/MPE or H_o/MPE	OD_{min}
$1 = 10^0$	0
$10 = 10^1$	1
$100 = 10^2$	2
$1000 = 10^3$	3
$10000 = 10^4$	4
$100000 = 10^5$	5
$1000000 = 10^6$	6

Where H_o is equal to the emergent beam radiant exposure in Joules per square centimeter and E_o is equal to the emergent beam irradiance in Watts per square centimeter.

TABLE 28-8

Laser Eye Protection Goggles Based on Manufacturers' Information†

$$\text{OPTICAL DENSITY} = \log_{10} \frac{1}{\text{Transmittance}}$$

Manufacturer or Supplier	Catalogue Number	Argon 4880 Å	HeNe 6328 Å	Ruby 6943 Å	GaAs 8400 Å	Nd 10600 Å	CO₂ 10.6 µ	UV <4000 Å >3000 Å	Coated Filter	Approx. Cost $	No. of glass filters & thickness of each	Visible Light transmission	Useful Range Å
American Optical Co.	SCS—437,*	0.15	0.20	0.36	1	5	High	No	No	55	1, 3.5 mm	90 %	10600
	SCS—440												10600
	580, 586*	0.2	2	3.5	4	2.7	—	>0.2	No	35, 25*	1, 3.5 mm	27.5%	—
	581, 587*	0.6	4.1	6.1	5.5	3	—	>1.6	No	35, 25*	1, 3.5 mm	9.6%	6328
	584	0	1	5	13	11	High	>0.6	No	55	2, 2 mm	46 %	10600
	585	0.3	2	8	21	17	High	>0.6	No	55	2, 2 mm	35 %	6943-10600
	598*	13	0	0	0	—	—	>14	No	25*	1, 3 mm	23.7%	4550-5150
	599	11	0	0	0	—	—	>14	No	35	1, 2.5 mm	24.7%	4550-5150
	680	0	0	0	0	0	50	No	No	35	1, 2.7 mm	92 %	10600
	698	13	1	4	11	8.5	High	>14	No	55	2, 2&3mm	5 %	10600 and 5300
Bausch & Lomb	5W3754	15	0.2	0	0	0	⋚35	20	Yes	39	1, 7.9 mm	4.3%	3300-5300
	5W3755	4	0	0	0	0.1	⋚35	10	Yes	39	1, 7.9 mm	57 %	4000-4600
	5W3756	0.8	12	15	5.6	4.8	⋚35	3	Yes	39	1, 6.4 mm	6.2%	6000-8000
	5W3757	0.9	4.5	7.7	12	5.7	⋚35	2	Yes	39	1, 7.1 mm	4.7%	7000-10000
	5W3758	1.9	1.8	2.2	4.8	7.5	⋚35	2	Yes	39	1, 7.6 mm	3 %	10000-11500
Control Data Corp.	TRG-112-1	—	5	12	30	30	—	No	No	50	1, 6 mm	22 %	6943
	TRG-112-2	10	0	0	0	0	—	No	No	50	1, 6 mm	31 %	4880
	TRG-112-3	5	2	6	15	15	—	No	No	50	2, 3 mm	5 %	6943-4880
	TRG-112-4	—	—	—	—	—	High	No	No	50	1, 5 mm	92 %	106000
Fish-Schurman Corp.	FS650AL/18	0.34	3.8	10	>10	>10	—	No	No	30	1, 6 mm	30 %	6943, 8400, 106000
Glendale Optical Co.	NDGA**	1	0.5	2	16	16	High	>20	No	25	Plastic	60 %	8400, 10600
	R**	0.4	2.2	6.3	0.4	0.0	High	5	No	25	Plastic	19 %	6943
	NH**	0.4	5	2.5	0.6	0.5	High	>10	No	25	Plastic	19 %	6328
	A**	15	0	0	0	0	High	>12	No	25	Plastic	59 %	4880, 5143
	NN**	0	0	0	0	0	High	>12	No	25	Plastic	70 %	3320, 3370
Spectrolab	—	8	5	9	13	12	0	8	Yes	115	2, 3.2 mm	<5 %	Broadband

*Spectacle Type. †See reference 24.

**Available in goggles or spectacle type.

CAUTION

1. Goggles are not to be used for viewing of laser beam. The eye protective device must be designed for the specific laser in use.
2. Few reliable data are available on the energy densities required to cause physical failure of the eye protective devices.
3. The establishment of engineering controls and appropriate operating procedures should take precedence over the use of eye protective devices.
4. The hazard associated with each laser depends upon many factors, such as output power, beam divergence, wavelength, pupil diameter, specular or diffuse reflection from surfaces,

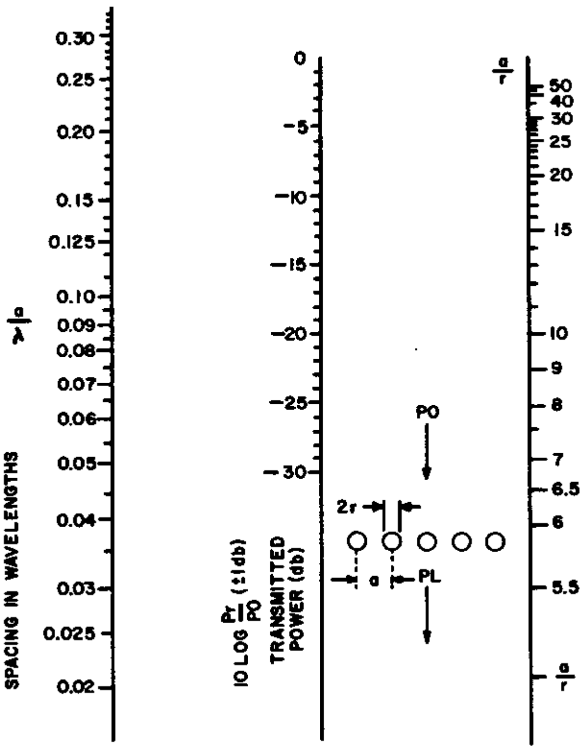
MICROWAVE RADIATION

Physical Characteristics of Microwave Radiation

Microwave wavelengths vary from about 10 meters to about one millimeter; the respective frequencies range from 30 MHz to 300 GHz. Certain reference documents,[25] however, define the microwave frequency range as 10 MHz to 100 GHz. The region between 10 MHz and the infrared is generally referred to as the RF, or radiofrequency, region. Reference may be made to Figure 28-1 to determine the position occupied by microwaves relative to other electromagnetic radiations. Certain bands of microwave frequencies have been assigned letter designations by industry (see Table 28-9); others, notably the ISM (Industrial, Scientific, Medical) frequencies have been assigned by the Federal Communications Commission for industrial, scientific and medical applications (see Table 28-10). For a more complete classification of microwave frequency ranges, including a comparison of American and Soviet designations, reference should be made to Table 28-11.

Sources of Microwave Radiation

Microwave radiation is no longer of special interest only to those involved with communications and navigational technology. Because of the growing number of commercial applications of microwaves; e.g., microwave ovens, diathermy, materials drying equipment, there is widespread interest in the possible new applications as well as an increased awareness of potential hazards. Typical sources of microwave energy are klystrons, magnetrons, backward wave oscillators and semiconductor transit time devices (IMPATT diodes). Such sources may operate continuously as in the case of some communications systems or intermittently as in microwave ovens, induction heating equipment and diathermy equipment, or in the pulsed mode



Mumford, W.W.: Some Technical Aspects of Microwave Radiation Hazards. Proc. IRE 49:427-47, 1961.

Figure 28-6. Transmission through a Grid of Wires of Radius r and Spacing a.

TABLE 28-9
Letter Designation of Microwave Frequency Bands

Band	Frequency — MHz
L	1,100- 1,700
LS	1,700- 2,600
S	2,600- 3,950
C	3,950- 5,850
XN	5,850- 8,200
X	8,200-12,400
Ku	12,400-18,000
K	18,000-26,500
Ka	26,500-40,000

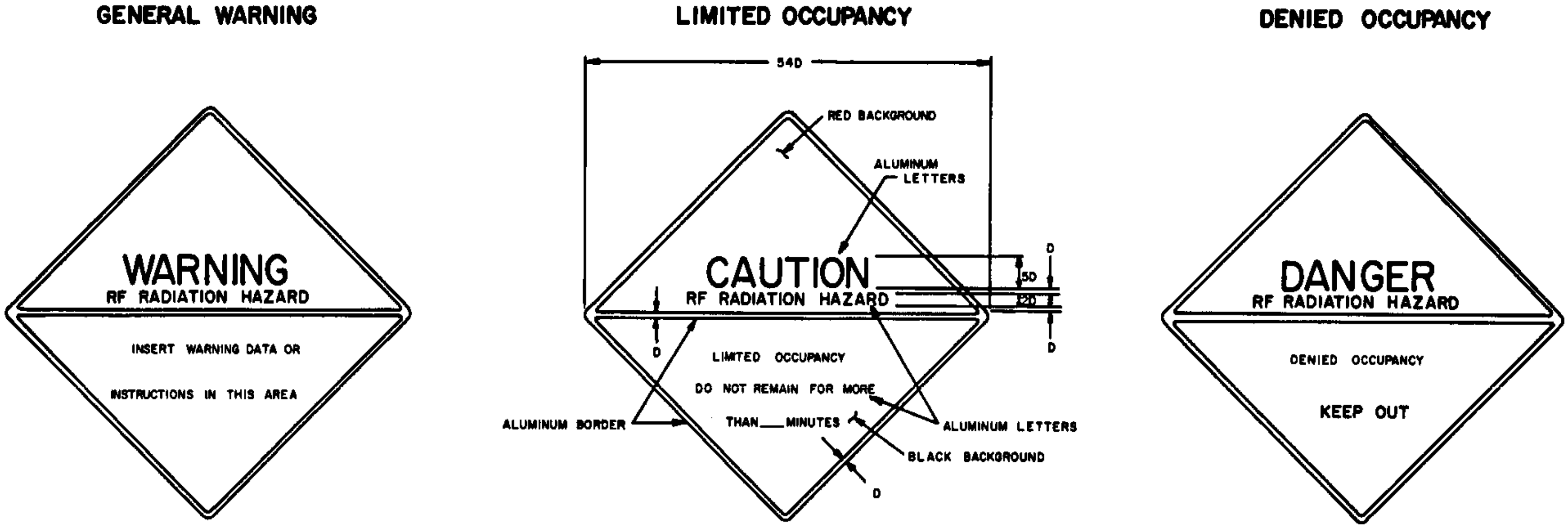
TABLE 28-10
Industrial, Scientific, and Medical (ISM) Uses. ISM Frequencies Assigned by the FCC

13.56 MHz ± 6.78 kHz
27.12 MHz ± 160 kHz
40.68 MHz ± 20 kHz
915 MHz ± 25 MHz
2,450 MHz ± 50 MHz
5,800 MHz ± 75 MHz
22,125 MHz ± 125 MHz

TABLE 28-11
Radiofrequency and Microwave Band Designations

	Band Designations					
	USA	USSR		Wavelengths	Frequencies	Typical Uses*
Radiofrequency Bands	Low frequency (LF)	Long	VCh (HF)	10^4-10^3m	30-300 KHz	Radionavigation, radio beacon
	Medium frequency (MF)	Medium		10^3-10^2m	0.3-3 MHz	Marine radiotelephone, Loran, AM broadcast
	High frequency (HF)	Short	UHF	10^2-10m	3-30 MHz	Amateur radio, world-wide broadcasting, medical diathermy, radio astronomy
Microwave Bands	Very high frequency (VHF)	Ultra-short (meter)		10-1m	30-300 MHz	FM broadcast, television, air traffic control, radionavigation
	Ultra high frequency (UHF)	Decimeter	Super HF (SHF)	1-0.1m	0.3-3 GHz	Television, citizens band, microwave point-to-point, microwave ovens, telemetry, tropo scatter and meteorological radar
	Super high frequency (SHF)	Centimeter		10-1 cm	3-30 GHz	Satellite communication, airborne weather radar, altimeters, shipborne navigational radar, microwave point-to-point
	Extra high frequency (EHF)	Millimeter		1-0.1 cm	30 GHz-300 GHz	Radio astronomy, cloud detection radar, space research, HCN (hydrogen cyanide) emission

*Modified after Table 1 in Reference 26



1. PLACE HANDLING AND ROUTING INSTRUCTIONS ON REVERSE SIDE.
2. D=SCALING UNIT.
3. LETTERING RATIO OF LETTER HEIGHT TO THICKNESS OF LETTER LINES.

UPPER TRIANGLE: 5 to 1 LARGE
6 to 1 MEDIUM
LOWER TRIANGLE: 4 to 1 SMALL
6 to 1 MEDIUM

4. SYMBOL IS SQUARE, TRIANGLE ON RIGHT-ANGLE ISOSCALES

Derived from an ANSI C95.2 Standard. American National Standards Institute, New York, New York.

Figure 28-7. Radio Frequency Signs.

in radar systems. Natural sources of RF and microwave energy also exist. For example, peak field intensities of over 100 volts per meter (V/m) are produced at ground level by the movement of cold fronts. Solar radiation intensities range from 10^{-18} to 10^{-17} watts per square meter per Hz (Wm^{-2} Hz^{-1}); however, the integrated intensity at the earth's surface for the frequency range of 0.2 to 10 GHz is approximately 10^{-8} mW/cm². This value is to be compared with an average value of 10^2 mW/cm² on the earth's surface attributable to the entire (UV, visible IR and microwave) solar spectrum.[26]

Biological Effects of Microwave Radiation

The photon energy in RF and microwave radiation is considered to be too low to produce photochemical reactions in biological matter. However, microwave radiation is absorbed by biological systems and ultimately dissipated in tissue as heat. Irradiation of the human body with a power density of 10 mW/cm² will result in the absorption of approximately 58 watts[27] with a resultant body temperature elevation of 1°C, a value which is considered acceptable from a personal hazard standpoint. By way of comparison, the human basal metabolic rate is approximately 80 watts for a person at rest; 290 for a person engaged in moderate work.

Microwave wavelengths less than 3 centimeters are absorbed in the outer skin surface, 3 to 10 centimeter wavelengths penetrate more deeply (1 mm to 1 cm) into the skin and at wavelengths from 25 to 200 centimeters, penetration is greatest with the potential of causing damage to internal body organs. The human body is thought to be essentially transparent to wavelengths greater than about 200 centimeters. Above 300 MHz the depth of penetration changes rapidly with frequency, declining to millimeter depths at frequencies above 3000 MHz. Above 10 GHz the surface absorption of energy begins to approach that of infrared radiation.

Carpenter and Van Ummersen[28] investigated the effects of microwave radiation on the production of cataracts in rabbit eyes. Exposures to 2.45 GHz radiation were made at power densities ranging from 80 mW/cm² to 400 mW/cm² for different exposure times. They found that repeated doses of 67 J/cm² spaced a day, a week or two weeks apart produced lens opacities even though the single threshold exposure dose at that power density (280 mW/cm²) was 84 J/cm². When the single exposure dose was reduced to 50 J/cm², opacities were produced when the doses were administered one or four days apart, but when the interval between exposures was increased to seven days, no opacification was noted even after five such weekly exposures. At the low power density of 80 mW/cm² (dose of 29 J/cm²) no effect developed, but when administered daily for 10 or 15 days, cataracts did develop. The conclusion is that microwaves may exert a cumulative effect on the lens of the eye if the exposures are repeated sufficiently often. The interval between exposures is an important factor in that a repair mechanism seems to act to limit lens damage if adequate time has elapsed between exposures.

Certain other biological effects of microwave radiation have been noted in literature. One of these is the so-called "pearl chain effect" where particles align themselves in chains when subjected to an electric field. There is considerable disagreement as to the significance of the pearl chain effect.

Investigators at the Johns Hopkins University[29] have suggested a possible relationship between mongolism (Down's Syndrome) in offspring and previous exposure of the male parent to radar. This suggested relationship was based on the finding that of two hundred sixteen cases of mongolism, 8.7 percent of the fathers having mongol offspring versus 3.3 percent of the control fathers (no mongol offspring) had contact with radar while in military service. This possible association must be regarded with extreme caution because of many unknown factors including the probability of a variety of exposures to environmental agents (including ionizing radiation) while in military service.

Soviet investigators claim that microwave radiation produces a variety of effects on the central nervous system with and without a temperature rise in the organism.[30–33] Claims are also made for biochemical changes, specifically a decrease in cholinesterase and changes in RNA at power density levels of approximately 10 mW/cm². The reported microwave effects on the central nervous system usually describe initial excitatory action; e.g., high blood pressure followed by inhibitory action, e.g., low blood pressure over the long term.[30] Electroencephalographic data have been interpreted as indicating the presence of epileptiform patterns in exposed subjects. Other reported effects ranged from disturbances of the menstrual cycle to changes in isolated nerve preparations.

What is often overlooked in any description of the biological effects of microwave radiation is that such radiations have produced beneficial effects. Controlled or judicious exposure of humans to diathermy or microthermy is widely practiced. The localized exposure level in diathermy may be as high as 100 milliwatts per square centimeter.

Exposure Criteria

Schwan[34] in 1953 examined the threshold for thermal damage to tissue, notably cataractogenesis. The power density necessary for producing such changes was approximately 100 mW/cm² to which he applied a safety factor of 10 to obtain a maximum permissible exposure level of 10 milliwatts per square centimeter. This number has been subsequently incorporated into many official standards. The current American National Standards Institute C95 standard[25] requires a limiting power density of 10 milliwatts per square centimeter for exposure periods of 0.1 hour or more; also an energy density of 1 milliwatt-hour per square centimeter (1 mWh/cm²) during any 0.1 hour period is permitted. The latter criterion allows for intermittency of exposure at levels above 10 mW/cm², on the basis that such intermittency does not produce a temperature rise in human tissue greater than 1 degree centigrade. More recently, Schwan[35] has suggested that the permissible exposure levels be expressed in terms of current density rather than power density, especially when dealing with measurements in the near or reactive field where the concept of power density loses its meaning. He suggests that a permissible current density of approximately 3 milliamps per square centimeter be accepted since this value is comparable to a far field value of 10 mW/cm². At frequencies below 100 KHz this value should be somewhat lower and for frequencies above 1 GHz it can be somewhat higher.

The new performance standard for microwave ovens specifies a level of 1 milliwatt per square centimeter at any point 5 centimeters or more from the external oven surfaces at the time the oven is fabricated by the manufacturer. Five milliwatts is permitted throughout the useful life of the oven.

Because Soviet investigators believe that effects on the central nervous systems (CNS) are more appropriate measures of the possibly detrimental effects of microwave radiation than are thermally induced responses, their studies have reported "thresholds" which are lower than those reported in Western countries. Soviet permissible exposure levels are several orders of magnitude below those in Western countries.

The Soviet Standards for whole body radiation are as follows: 0.01 milliwatts per square centimeter for five hours per day exposure, 0.1 milliwatts per square centimeter for two hours exposure per day and 1 milliwatt per square centimeter for a 15 to 20 minute exposure provided protective goggles are used. These standards apply to frequencies above 300 MHz.

There appears to be no serious controversy about the power density levels necessary to produce thermal effects in biological tissue. The nonthermal CNS effects reported by the Soviets are not so much controversial as they are a reflection of the fact that Western investigators have not used the conditioned reflex as an end point in their investigations.

Measurement of Microwave Radiation

Perhaps the most important factor underlying some of the controversy over biological effects is the lack of standardization of measurement techniques used to quantify results. Unfortunately, there seems to be little promise that such standardization will be realized in the near future.

The basic vector components in any electromagnetic wave are the electric field (E) and the magnetic field (H). The simplest type of microwave propagation consists of a plane wave moving in an unbounded isotropic medium where the electric and magnetic field vectors are mutually perpendicular to each other and both are perpendicular to the direction of wave propagation. Unfortunately, the simple proportionality between the E and H fields is valid only in free space or in the so-called "far field" of the radiating device. The far field is the region which is sufficiently removed from the source to eliminate any interaction between the propagated wave and the source. The energy or power density in the far field is inversely proportional to the square of the distance from the source and in this particular case the measurement of either E or H suffices for their determination.

Plane-wave detection in the far field is well understood and easily obtained with equipment which has been calibrated for use in the frequency range of interest. Most hazard survey instruments have been calibrated in the far field to read in power density (mW/cm²) units. The simplest type of device uses a horn antenna of appropriate size coupled to a power meter.

To estimate the power density levels in the near field of large aperture circular antennas, one can use the following simplified relationship:[36]

$$W = \frac{16P}{\pi D^2} = \frac{4P}{A} \quad \text{(near field)}$$

where P is the average power output, D is the diameter of the antenna, A is the effective area of the antenna and W is power density. If this computation reveals a power density which is less than a specified limit (e.g., 10 mW/cm²), then no further calculation is necessary because the equation gives the maximum power density on the microwave beam axis. If the computed value exceeds the exposure criterion then one assumes that the calculated power density exists throughout the near field. The far field power densities are then computed from the Friis free space transmission formula:

$$W = \frac{GP}{4\pi r^2} = \frac{AP}{\lambda^2 r^2} \quad \text{(far field)}$$

where λ is the wavelength, r is the distance from the antenna and G is the far field antenna gain, and W, P, and A are as in the equation above.

The distance from the antenna to the intersection of the near and far fields is given by:

$$r_1 = \frac{\pi D^2}{8\lambda} = \frac{A}{2\lambda}.$$

These simplified equations do not account for reflections from ground structures or surfaces; the power density may be four times greater than the free space value under such circumstances.

Special note should be made of the fact that microwave hazard assessments are made on the basis of the average, not the peak power of the radiation. In the case of radar generators, however, the ratio of peak to average power may be as high as 10^5.

Most microwave measuring devices are based on (1) bolometry, (2) calorimetry, (3) voltage and resistance changes in detectors and (4) radiation pressure on a reflecting surface. The latter three methods are self-explanatory. Bolometry measurements are based upon the absorption of power in a temperature sensitive resistive element, usually a thermistor, the change in resistance being proportional to absorbed power. This method is one of the most widely used in commercially available power meters. Low frequency radiation of less than 300 MHz may be measured with loop or short whip antennas. Because of the larger wavelengths in the low frequency region, the field strength in volts per meter (V/m) is usually determined rather than power density.

One troublesome fact in the measurement of microwave radiation is that the near field (reactive field) of many sources may produce unpredictable radiative patterns. Energy density rather than power density may be a more appropriate means of expressing hazard potential in the near field.[37, 38] In the measurement of the near field of microwave ovens, it is desirable that the instrument have certain characteristics; e.g., the antenna probe should be electrically small to minimize perturbation of the field, the impedance should be matched so that there is no backscatter from the probe to the source, the antenna probe should behave as an isotropic receiver, the probe should be sensitive to all polarizations, the response time should be adequate for handling the peak to average power of the radiation and the response of the instrument should be flat over a broad band of frequencies.

In terms of desirable broad band characteristics of instruments it is interesting to note that one manufacturer has set target specifications for the development of a microwave measurement and monitoring device as follows: frequency range 20 KHz to 12.4 GHz and a power density range of 0.02 to 200 mW/cm^2 ± 1 dB. Reportedly,[39] two models of this device will be available: one a hand-held model with complete meter readout, the other a lapel model equipped with audible warning signals if excessive power density levels develop.

Control Measures

The installation of engineering controls is usually the most satisfactory means for controlling exposures to microwave radiation. The engineering measures may range from the restriction of azimuth and elevation settings on radar antennas to complete enclosures of magnetrons in microwave ovens. The use of personnel protective devices has its place, but is of much lower priority importance to engineering controls. Various types of microwave protective suits, goggles and mesh have been used for special problems. In this connection Figure 28-6 showing the transmission loss through a wire grid may prove useful.[40] Similarly, the general order of attenuation provided by various types of material (Table 28-12) may be of use in designing shields or enclosures.[41]

It has been shown recently[42] that cardiac pacemakers, particularly those of the demand type, may have their function seriously compromised by microwave radiation. Furthermore, the radiation levels which cause interference with the pacemaker may be orders of magnitude below levels which cause detrimental biological effects. The most effective method of reducing the susceptibility of these devices to microwave interference seems to be improved shielding. Manufacturers of cardiac pacemakers are engaged in a major program to minimize such interference.

The judicious use of appropriate signs and labels may prove useful in alerting people to the presence of dangerous microwave sources. Figure 28-7 illustrates the RF and microwave warning signs adopted by the American National Standards Institute C95 committee.

TABLE 28-12

Attenuation Factors (Shielding)

	Frequency			
Material	1-3 GHz	3-5 GHz	5-7 GHz	7-10 GHz
60 × 60 mesh screening	20 dB	25 dB	22 dB	20 dB
32 × 32 mesh screening	18 dB	22 dB	22 dB	18 dB
16 × 16 window screen	18 dB	20 dB	20 dB	22 dB
¼″ mesh (hardware cloth)	18 dB	15 dB	12 dB	10 dB
Window Glass	2 dB	2 dB	3 dB	3.5 dB
¾″ Pine Sheathing	2 dB	2 dB	2 dB	3.5 dB
8″ Concrete Block	20 dB	22 dB	26 dB	30 dB

Presented at Am. Ind. Hyg. Conf., 1967: Palmisano, W., U. S. Army Environmental Hygiene Agency, Edgewood Arsenal, Md.

Research Needs

A major need is to conduct intermediate and long term bioeffects research at low ($\leq$ 10 mW/cm^2) radiation levels. In this connection it is desirable to replicate certain of the Soviet work on CNS effects. Perhaps of greater importance is the need to standardize or at least coordinate all such research, particularly the measurement techniques used in the investigations.

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APPENDIX A
USEFUL RADIOMETRIC AND RELATED UNITS

Term	Symbol	Description	Unit and Abbreviation
Radiant Energy	O	Capacity of electromagnetic waves to perform work	Joule (J)
Radiant Power	P	Time rate at which energy is emitted	Watt (W)
Irradiance or Radiant Flux Density (Dose Rate in Photobiology)	E	Radiant Flux Density	Watt per square meter ($W \cdot M^{-2}$)
Radiant Intensity	I	Radiant Flux or Power Emitted per solid angle (steradian)	Watt per steradian ($W \cdot sr^{-1}$)
Radiant Exposure (Dose in Photobiology)	H	Total Energy Incident on Unit Area in A Given Time Interval	Joule per square meter ($J \cdot m^{-2}$)
Beam Divergence	Φ	Unit of Angular Measure. One Radian ≈ 57.3° 2π Radians = 360°	Radian

APPENDIX B
Conversion Factors
A-Radiant Energy Units

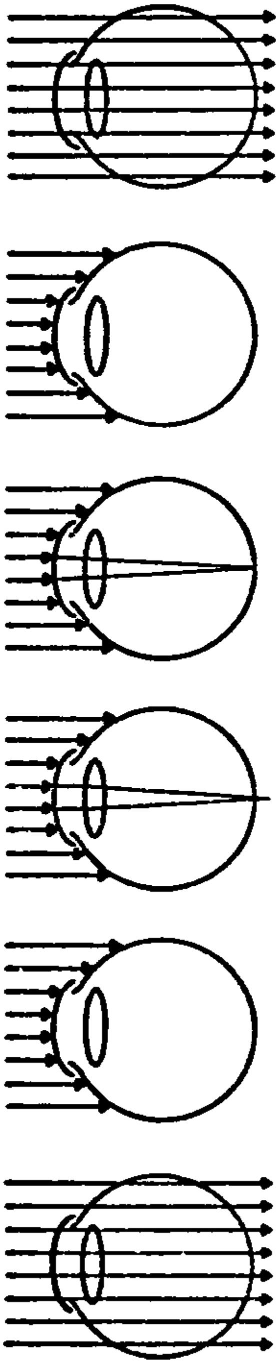
	erg	joule	W sec	μW sec	g-cal
erg =	1	10^{-7}	10^{-7}	0.1	2.39×10^{-8}
joule =	10	1	1	10^{6}	0.239
W sec =	10^{7}	1	1	10^{4}	0.239
μW sec =	10	10^{-6}	10^{-6}	1	2.39×10^{-7}
g-cal =	4.19×10^{7}	4.19	4.19	4.19×10^{6}	1

B-Radiant Exposure (Dose) Units

	erg/cm²	joule/cm²	W sec/cm²	μW sec/cm²	g-cal/cm²
erg/cm² =	1	10^{-7}	10^{-7}	0.1	2.39×10^{-8}
joule/cm² =	10^{7}	1	1	10^{6}	0.239
W sec/cm² =	10^{7}	1	1	10^{6}	0.239
μW sec/cm² =	10	10^{-6}	10^{-6}	1	2.39×10^{-7}
g-cal/cm² =	4.19×10^{7}	4.19	4.19	4.19×10^{6}	1

C-Irradiance (Dose Rate) Units

	erg/cm²•sec	joule/cm²•sec	W/cm²	μW/cm²	g-cal/cm²•sec
erg/cm²•sec =	1	10^{-7}	10^{-7}	0.1	2.39×10^{-8}
joule/cm²•sec =	10^{7}	1	1	10^{6}	0.239
W/cm² =	10^{7}	1	1	10^{6}	0.239
μW/cm² =	10	10^{-6}	10^{-6}	1	2.39×10^{-7}
g-cal/cm²•sec =	4.19×10^{7}	4.19	4.19	4.19×10^{6}	1



HIGH ENERGY X-RAYS, GAMMA RAYS; 99% PASS COMPLETELY THRU THE EYE, 1% ABSORBED.

SHORT UV; ABSORPTION PRINCIPALLY AT CORNEA. (INTERMEDIATE UV; ABSORPTION AT CORNEA AND LENS.)

LONG UV, VISIBLE; TRANSMITTED THRU EYE AND FOCUSED ON RETINA.

NEAR IR; PARTIALLY ABSORBED BY LENS, IRIS, AND MEDIA, PARTIALLY FOCUSED AT RETINA.

FAR IR; ABSORPTION LOCALIZED AT CORNEA FOR SHARP H_2O ABSORPTION WAVELENGTHS, OTHER WAVELENGTHS ABSORBED ALSO BY LENS AND IRIS.

MICROWAVE; GENERALLY TRANSMITTED WITH PARTIAL ABSORPTION IN ALL PARTS OF THE EYE.

Figure also appears in Bell Laboratories: Policies and Practices for Personnel Using Laser Devices. Murray Hill, New Jersey.

Appendix C. General Absorption Properties of the Eye for Electromagnetic Radiation.