

COMMONWEALTH DEPARTMENT OF HEALTH



# **Australian Radiation Laboratory**

**Non-Ionizing Radiation Measurements and Protection.**

**VOLUME 1**

**Lecture notes from a course conducted at the  
Australian Radiation Laboratory.**

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## PREFACE

The use of non-ionizing radiation (NIR) sources in the scientific, medical, industrial and domestic areas is becoming increasingly widespread. Concern has been expressed of the increased possibility of exposure of employees and of the public to NIR. Regulatory authorities have the role of ensuring that all organisations using NIR sources keep the exposure of all persons below prescribed limits.

The Australian Radiation Laboratory is frequently asked to provide expert advice on NIR devices in terms of radiation levels, hazard evaluations and personnel protection. To assist Radiation Protection Officers and personnel associated with regulatory authorities, hospitals and private organisations, ARL is offering a three day course on non-ionizing radiation measurement and protection. The course is designed with mornings devoted to lectures and afternoons to practical work.

The lecture notes which are reproduced in this report draw together the basic information on NIR protection including essential quantities and units, biological interactions, protection standards, measurement techniques and personnel protection.

The practical work is performed under the supervision of ARL staff and is directly related to topics covered in the lectures. A list of experiments and staff involved is included.

The skill and patience of Miss Judy Evans and Mrs Rhonda Austin in typing this report is gratefully acknowledged.

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## PRACTICAL SESSIONS

### Radiofrequency and Microwave Radiation

(K.H. Joyner and M. Bangay)

1. Broadband measurements of radiofrequency radiation:  
The use of broadband monitors for surveying microwave ovens, RF heaters and shortwave diathermy units will be investigated. Measurement errors and compliance with standards will be discussed.
2. Spectral measurements of radiofrequency radiation:  
The spectrally resolved emission from a VDT will be determined using a calibrated spectrum analyser with E- and H-field detectors.

### Laser Radiation

(W.A. Cornelius and V. Delpizzo)

3. Measurement of the output of a pulsed and scanned lasers:  
Thermal and quantum detectors will be used to determine the safety classification of a high power, low repetition rate laser and of a lower power, cw scanned laser.
4. Measurement of the output of a cw laser product:  
A thermopile will be used to determine the protective measures needed for a high power laser. Photographic techniques will be used to evaluate the infrared output from a fiber light guide coupled to a laser diode.

### Ultraviolet Radiation

(H.P. Gies, G. Elliott, C.R. Roy and F.J. Wilkinson)

5. Broadband measurements of ultraviolet radiation:  
Radiometry and the radiometer, optical filters, instrument calibration, measurement of ultraviolet radiation emissions, errors and compliance with standards.
6. Spectral measurements of ultraviolet radiation:  
Spectroradiometry and the spectroradiometer, monochromator characteristics, measurement system calibration, spectral measurements of ultraviolet radiation emissions, errors, biological response weighting and compliance with standards.

## LECTURE 1

### NON-IONIZING ELECTROMAGNETIC RADIATION

M H Repacholi

Royal Adelaide Hospital

#### ABSTRACT

Non-ionizing electromagnetic radiation (NIR) incorporates all radiations of the electromagnetic spectrum that do not normally have enough energy to produce ionization in matter. This radiation has an energy per photon less than 12.4eV, wavelengths longer than 100nm and frequencies lower than 3000THz. Included in the NIR part of the spectrum are optical radiation (ultraviolet (UV), visible, infrared (IR), lasers), radiofrequency (RF) (including microwaves), extremely low frequency (ELF) fields and static electric and magnetic fields.

This paper provides some basic information on the physical characteristics, mechanisms of interaction and biological effects of all NIR except lasers, which will be covered in a separate paper. With the imminent introduction of medical resonance imaging (MRI) into Australia, details will be provided on magnetic fields.

#### INTRODUCTION

Human and other life forms have evolved in a complex milieu of electromagnetic fields spanning the spectrum (see Figure 1) from near-zero frequency (atmospheric electric fields, geomagnetic fields) to high-energy regions associated with radiation occurring naturally in the environment (cosmic and ionizing radiation from natural radioisotopes). Man has long been aware of the role that radiation of visible and other optical radiations play in life processes. The effects of gamma, X, and ultraviolet radiation on genetic material are examples of phenomena in which the mechanisms of effect are direct and fairly well understood. In other parts of the NIR electromagnetic spectrum there is an incomplete understanding of the evolutionary necessity, the biological significance, and the mechanisms of interaction of these fields with living matter.

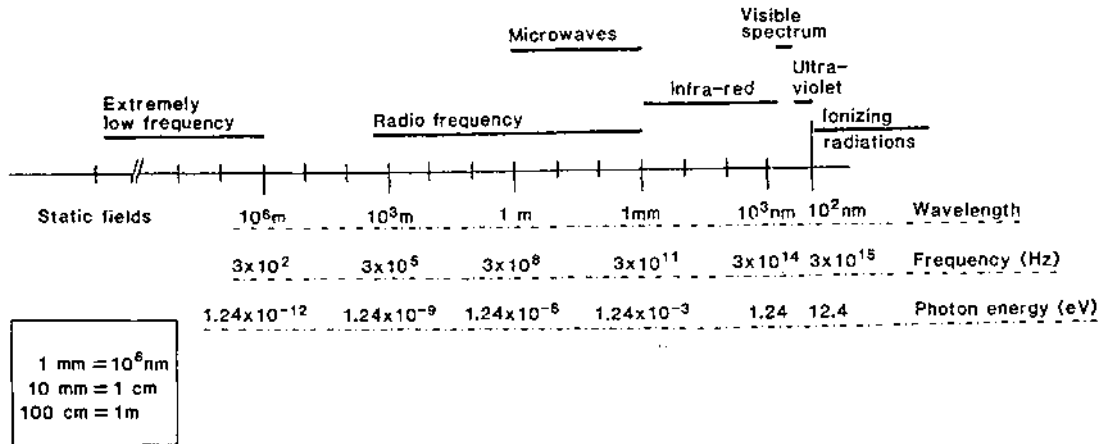


Figure 1: The spectrum of non-ionizing electromagnetic radiation.

Over the past few decades man has drastically altered the environmental electromagnetic fields so that both the likelihood and the level of exposure of many life forms have increased by many orders of magnitude. These increases have resulted from numerous sources in industry, commerce, medicine, research and the home.

Questions have been raised as to whether adequate measures are being taken to guard the user and the general public from the possible adverse effects of NIR. In contrast to ionizing radiation, radiation of longer wavelengths is intrinsically less energetic and usually interacts with human tissue primarily by generating heat.

Nonionizing radiation pervades the entire environment but, except for the narrow spectrum of visible radiation, it is unperceived by any of the human senses unless its intensity becomes so great that it is felt as heat. Differences in wavelengths, even within a single type of radiation, are particularly important when evaluating hazards from exposure to NIR. The ability of the radiation to penetrate into the human body and the sites of absorption differ from one type of radiation to another.

## DIVISION OF THE NIR SPECTRUM

The basic divisions of the NIR spectrum are shown in Table 1 (from WHO, 1982). This table gives the ranges of frequency, wavelength and energy per photon of NIR. Many of the subdivisions are arbitrary, such as those for ultraviolet - extreme (vacuum), far and near. The terms far and near refer to subdivisions of UV and IR and are used to denote "distance" from the visible part of the spectrum. It is common now to refer to the UV-A, UV-B, UV-C and IR-A, IR-B and IR-C subdivisions where the "A" subdivision is closest to the visible region.

TABLE 1  
RANGES OF FREQUENCY, WAVELENGTH AND ENERGY FOR SOME TYPE OF  
ELECTROMAGNETIC RADIATION (WHO, 1982)

Type of radiation	Frequency range <sup>a, b</sup>	Wavelength range <sup>d</sup>	Energy range per photon <sup>a, b</sup>
Ionizing	> 3000 THz	< 100 nm	> 12.40 eV
Ultraviolet (UV) (nonionizing part)	3000 - 750 THz	100 - 400 nm	12.40 - 3.10 eV
extreme (vacuum)	$3 \times 10^3$ to 30 000 - 1580	1 to 10 - 190	1240 to 124 - 6.53
far	1580 - 1000	190 - 300	6.53 - 4.13
near	1000 - 750	300 - 400	4.13 - 3.10
UV-C <sup>c</sup>	3000 - 1070	100 - 280	12.40 - 4.43
UV-B <sup>c</sup>	1070 - 952	280 - 315	4.43 - 3.94
UV-A <sup>c</sup> ("black light")	952 - 750	315 - 400	3.94 - 3.10
Visible light <sup>d</sup>	750 - 385 THz	400 - 780 nm	3.10 - 1.59 eV
Infrared (IR)	385 - 0.3 THz	0.78 - 1000 $\mu$ m	1590 - 1.24 meV
IR-A <sup>c</sup>	385 - 214	0.78 - 1.4	1590 - 886
IR-B <sup>c</sup>	214 - 100	1.4 - 3	886 - 413
IR-C <sup>c</sup>	100 - 0.3	3 - 1000	413 - 1.24
near	385 - 100	0.78 - 3	1590 - 413
middle	100 - 10	3 - 30	413 - 41.33
far	10 - 0.3	30 - 1000	41 - 1.24
Lasers	1500 - 15	0.2 - 20	6200 - 62
Class 1 - non-risk laser devices			
Class 2 - low-risk, low-power laser devices			
Class 3a - low-risk, medium-power laser devices			
Class 3b - moderate-risk, medium-power laser devices			
Class 4 - high-risk, high-power laser devices			
Microwave (MW)	300 - 0.3 GHz	1 - 1000 mm	1240 - 1.24 $\mu$ eV
EHF (extremely high frequencies)	300 - 30	1 - 10	1240 - 124
SHF (super-high frequencies)	30 - 3	10 - 100	124 - 12.40
UHF (ultra-high frequencies)	3 - 0.3	100 - 1000	12 - 1.24
Radar	56 - 0.23	5.4 - 1300	230 - 0.95
Radiofrequency (RF)	300 - 0.1 MHz	1 - 3000 m	1240 - 0.41 neV
VHF (very high frequencies)	300 - 30	1 - 10	1240 - 124
HF (high frequencies)	30 - 3	10 - 100	124 - 12.4
MF (medium frequencies)	3 - 0.3	100 - 1000	12 - 1.24

<sup>a</sup> The ranges given are only approximations, since no precise limits can be defined.

<sup>b</sup> The figures given here have generally been rounded up or down to the third significant digit.

<sup>c</sup> Radiation bands of biological significance designated by the International Commission on Illumination (CIE)

<sup>d</sup> The visibility limits of the human eye vary among individuals between about 380-400 nm and 750-780 nm.

Radiofrequency fields incorporate the microwave region and have been subdivided into frequency bands. It should be noted that the divisions within the NIR spectrum have evolved by convention rather than with thought of different biological effects or interaction mechanisms.

### QUANTITIES AND UNITS

A detailed review of the concepts, quantities, units and terminology for NIR protection is given in INIRC/IRPA (1985).

For optical radiation (UV, visible and IR) two systems of quantities and units are used, the radiometric and photometric systems. Table 2 (from WHO/IRPA, 1982) gives the most commonly used quantities and units in these systems. The radiometric system is used for all the optical radiations while the photometric system is limited to describing visible light. The more commonly used radiometric units are radiance and irradiance, and it is important to know the distinction between them. The radiance at a point on a surface and in a given direction is the radiation intensity of an element of the surface divided by the area of the orthogonal projection of this element on a plane perpendicular to the given direction. Radiance is expressed in watts per steradian per square metre ( $\text{W}/\text{sr}/\text{m}^2$ ). Irradiance is the radiant flux onto a unit area of surface and is expressed in watts per square metre ( $\text{W}/\text{m}^2$ ). Other quantities that will be used in this course are the integrated radiance (i.e. radiance integrated over a given time interval, measured in joules per steradian per square metre), spectral radiance (radiance restricted to a narrow wavelength band), and integrated spectral radiance, (integrated radiance restricted to a narrow wavelength band).

When radiofrequency (RF) energy is absorbed in a medium, the most obvious effect is heating, so the radiation intensity can be determined calorimetrically. In SI terminology this radiant intensity, irradiance or more commonly "power density" is expressed in watts per square metre ( $\text{W}/\text{m}^2$ ). The associated electric (E) and magnetic (H) field strengths can be equally valid expressions of radiant energy flow. Their units are volt per metre (V/m) and ampere per metre (A/m) respectively. In the far field (at distances generally greater than one wavelength from the source), either V/m or A/m can be used to describe the intensity of energy flow since there is a constant phase relationship between E and H ( $E/H=120\pi$ ). Their product  $\text{VA}/\text{m}^2$  may be expressed as  $\text{W}/\text{m}^2$ , or the power density derived from  $E^2/120\pi$  or  $H^2 \times 120\pi$ . The source can be regarded as a point where the inverse square law holds.

However, in the near field, at points normally less than one wavelength from the source, there is not a constant phase relationship between E and H and so both the electric and magnetic field strengths must be given to properly express the intensity of the field. In the near field, the inverse square law does not hold.

TABLE 2  
USEFUL CIE RADIOMETRIC AND PHOTOMETRIC QUANTITIES AND UNITS (a,b)  
(WHO/IRPA, 1982)

RADIOMETRIC				
Term	Symbol	Defining equation	Quantity applicable <sup>c</sup>	SI units & abbreviations
Radiant energy	$Q_e$		S, R	joule (J)
Radiant energy density	$W_e$	$W_e = \frac{dQ_e}{dV}$	F	joule per cubic metre (J/m <sup>3</sup> )
Radiant power (radiant flux)	$\Phi_e$	$\Phi_e = \frac{dQ_e}{dt}$	S, R	watt (W)
Radiant exitance	$M_e$	$M_e = \frac{d\Phi_e}{dA}$ $= \int L_e \cos \theta d\Omega$	S	watt per square metre (W/m <sup>2</sup> )
Irradiance or flux density (dose rate in photobiology)	$E_e$	$E_e = \frac{d\Phi_e}{dA}$	R	watt per square metre (W/m <sup>2</sup> )
Radiant intensity (W/sr')	$I_e$	$I_e = \frac{d\Phi_e}{d\Omega}$	S	watt per steradian
Radiance <sup>d</sup>	$L_e$	$L_e = \frac{d^2\Phi_e}{d\Omega dA \cos \theta}$	S, F, R	watt per steradian and per square metre (W/sr/m <sup>2</sup> )
Radiant exposure (dose in photobiology)	$H_e$	$H_e = \frac{dQ_e}{dA}$	R	joule per square metre (J/m <sup>2</sup> )
Radiant efficiency <sup>e</sup> (of a source)	$\eta_e$	$\eta_e = \frac{P}{P_i}$	S	unitless
Optical	$D_e$	$D_e = -\log_{10} \tau_e$	R	unitless
PHOTOMETRIC				
Term	Symbol	Defining equation		SI abbreviations & units
Quantity of light	$Q_v$	$Q_v = \int \Phi_v dt$		lumen-second (lm·s)
Luminous energy density	$W_v$	$W_v = \frac{dQ_v}{dV}$		lumen-second per cubic metre (lm·s/m <sup>3</sup> )
Luminous flux	$\Phi_v$	$\Phi_v = 680 \int \frac{d\Phi_e}{dW(\lambda)d\lambda}$		lumen (lm)
Luminous exitance	$M_v$	$M_v = \frac{d\Phi_v}{dA}$ $= \int I_v \cos \theta d\Omega$		lumen per square metre (lm/m <sup>2</sup> )
Illuminance (luminous density)	$E_v$	$E_v = \frac{d\Phi_v}{dA}$		lumen per square metre (lm/m <sup>2</sup> )

TABLE 2 (Continued)

Luminous intensity (candlepower)	$I_v$	$I_v = \frac{d\Phi_v}{dr}$	lumen per steradian (lm/sr) or candela (cd)
Luminance $\frac{d}{d}$	$L_v$	$L_v = \frac{d^2\Phi_v}{dr^2 dA \cos\theta}$	candela per square metre (cd/m <sup>2</sup> )
light exposure	$H_v$	$H_v = \frac{dQ_v}{dA}$ $= \int E_v dt$	lux-second (lx s)
Luminous efficacy (of radiation)	$K$	$K = \frac{\Phi_v}{\Phi_e}$	lumen per watt (lm/W)
Luminous efficiency (of a broad band radiation)	$V(\lambda)$	$V(\lambda) = \int \frac{K}{K_m} = \frac{K}{680}$	unitless
Luminous efficacy $\xi$	$n_v$	$n_v = \frac{\Phi_v}{P_i}$	lumen per watt (lm/W)
Optical density $\frac{f}{f}$	$D_v$	$D_v = -\log_{10} \tau_v$	unitless
Retinal illuminance (in trolands)	$E_t$	$E_t = L_v \cdot S_p$	Troland (td) = luminance of 1 cd/m <sup>2</sup> times pupil area in mm <sup>2</sup>

<sup>a</sup> The quantities may be altered to refer to narrow spectral bands, in which case the term is preceded by the word spectral, and the unit is then per unit of wavelength and the symbol has a subscript  $\lambda$ . For example, spectral irradiance  $H_{\lambda}$  has units of W/(m<sup>2</sup>m) or more often, W/(cm<sup>2</sup>nm).

<sup>b</sup> While the metre is the preferred unit of length, the centimetre is still the most commonly used unit of length for many of the above terms and the nm or  $\mu$ m are most commonly used to express wavelength.

<sup>c</sup> Some radiometric quantities refer only to the source, field, or receiver. This noted in this column.

<sup>d</sup> At the source,  $L = \frac{dM}{d\Omega \cos\theta}$ ; at a receptor,  $L = \frac{dE}{d\Omega \cos\theta}$

<sup>e</sup>  $P_i$  is electrical input power in watts.

<sup>f</sup>  $\tau$  is the transmission;  $D_v$  is also abbreviated as O.D.

When describing extremely low frequency (ELF) fields, with frequencies up to about 300Hz, the wavelengths are of the order of hundreds to thousands of kilometres, and so you are virtually always in the near field. Thus both the E and H fields must be given.

The fundamental vector quantities describing a magnetic field are the field strength (H) and the flux density (B) (or equivalently, the magnetic induction). B is defined in terms of the force F exerted on a charge q moving with a velocity v:

$$\underline{F} = q (\underline{v} \times \underline{B})$$

where the term in the brackets is the cross product of the vectors  $\underline{v}$  and  $\underline{B}$ . B is expressed in tesla (T) where  $1\text{T} = 1\text{V}\cdot\text{s}/\text{m}^2 = 1\text{Wb}/\text{m}^2$ . Wb is the symbol for the unit called the Weber.

The relationship between B and H is given by

$$\underline{B} = \mu \underline{H}$$

where  $\mu$  = magnetic permeability of the medium.

The CGS unit for magnetic field strength is oersted, and for magnetic induction is gauss. The SI and CGS conversion factors are:

SI	CGS	Term
1A/m	$= 4\pi/10^3$ oersted	field strength (H)
1T	$= 10^4$ gauss	flux density (B)

In the CGS system, for biological materials where the permeability in free space equals 1, B can be set numerically equal to H as a close approximation.

#### BIOLOGICAL ACTION OF NIR

A review of the biological effects and mechanisms of NIR interaction with living tissues has been the subject of a number of reviews (WHO/IRPA, 1979, 1981, 1982, 1984; WHO, 1982; NCRP, 1981, Repacholi, 1984). In this section, each of the NIR are dealt with separately and summaries of the interaction mechanisms, biological effects data and human health risk are given.

#### Optical Radiations

The ability of optical radiation to damage the skin and eyes depends on their transmission and absorption in the critical organ. Figure 2 shows the penetration of the optical radiation into the skin and figure 3 shows the absorption of UV in the eye.

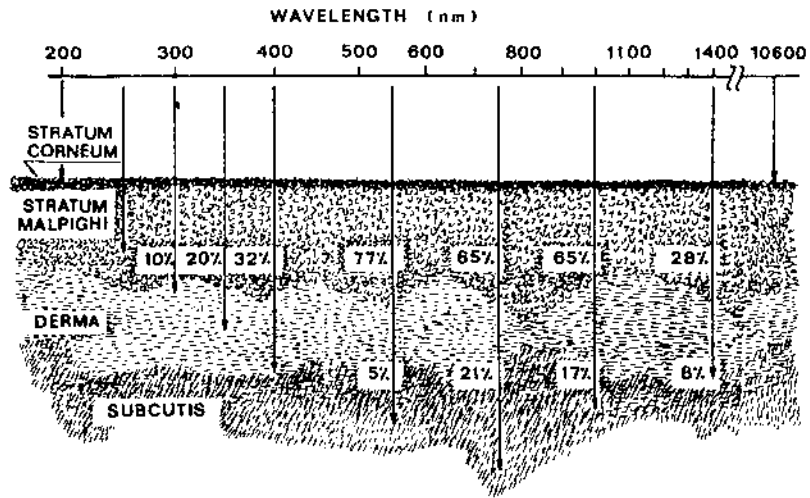


Figure 2: Penetration of optical radiations into the skin.

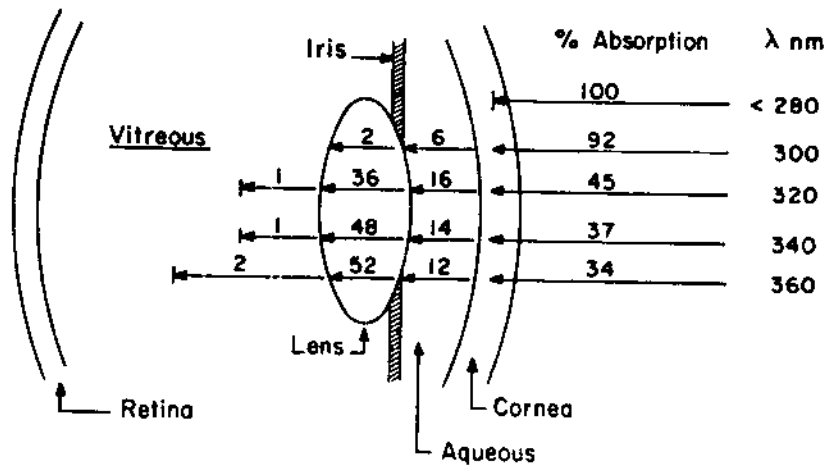


Figure 3: Absorption of UV radiation into the eye.

### Mechanisms of Action

The biological effects of exposure to all optical radiation are mainly to the skin and eyes and can be divided into three major categories; thermal (including thermo-mechanical), photochemical, and direct electric field effects.

The latter effect is a special case which relates to the exposure to picosecond (ps) pulses producing non linear effects in the tissue. It is believed that certain biological effects can be explained as an action of the direct electric field of the incident photons. This effect will not be dealt with further in this text. Most primary biological effects can be related to the thermal and photochemical mechanisms of injury.

Thermal injury mechanisms require radiant energy to be absorbed by the tissue, sufficiently fast to create a substantial increase above normal tissue temperature (typically 10-25°C above normal temperature within periods of a minute or less). There is no dependence on the photon energy except that the energy must be absorbed - so the distribution of energy absorption will be wavelength dependent. Heat will be conducted away from the area, so presence of blood vessels and the size of the irradiated volume, as well as spectral absorption will influence the injury threshold. For very short, high intensity exposures, microexplosions or thermo-mechanical effects may become important.

Photochemical reactions take place when single photons have sufficient quantum energy to convert individual molecules to one or more different molecules. This is demonstrated when a reciprocity relationship between irradiance (dose-rate) and exposure duration exists. That is, a constant radiant exposure (dose) is required to elicit the response over a wide variation of exposure durations. There are times for which biological repair comes into play. In some instances both photochemical and thermal mechanisms may contribute to the final biological effect, and may enhance one another.

### Biological Effects

The principal injuries to the skin and eye from the various optical radiations are summarised in Table 3. Optical radiation effects on the eye vary significantly with wavelength. The effects of UV are generally photochemical, on the lens and cornea. Visible and IR-A present a hazard to the retina because of the imaging characteristics of the eye.

Table 3. Summary of injuries produced in humans exposed to optical radiations

Radiation	Skin	Eye
UV	Erythema Aging Skin Cancer Photosensitive reaction	Photokeratitis Conjunctivitis Cataract Corneal oedema
Visible	Photosensitive reactions Burn	Retinal injury
Near Infrared	Burn Heat stress	Cataract Retinal injury Corneal injury
Far Infrared	Burn Heat stress	Corneal injury

The cornea and conjunctiva are tissues with sensory receptors that serve as triggers of protective reflexes for mechanical and thermal agents. Epithelial cells have a life span of only 2-5 days. If this death rate increases (as with exposure to UV producing photokeratitis) and if replacement is not in step with the loss, small erosions will develop that elicit a pain sensation. Disturbances of the corneal epithelium, especially the inner cell layer (endothelium) will result in oedema. This can reduce the transparency of the cornea or even make it opaque.

UV-B and UV-C are absorbed in the cornea and conjunctiva and at sufficiently high doses will cause keratoconjunctivitis. The UV causes damage to the epithelial cells which would normally be repaired in a day or so. Severe exposures may cause scars, seen as a milky appearance, or sometimes induce an invasion of the cornea by blood vessels. High doses of IR-B and IR-C can also cause damage to the cornea.

The lens, like the cornea, is not optically homogeneous, but it is transparent in the visible range of the spectrum. Lens fibres or ribbon-like cells are quite sensitive to injury, as injury to any single fibre will, in time, extend throughout the entire fibre cell.

A disturbance of cell elements or the fibre will cause hydration of the fibre, resulting in an increase in light scattering. Extensive damage of this nature will cause the lens to have milky appearance (a cataract). The lens has much the same sensitivity to UV as the cornea, although with exposure to UV-A, there is a substantial transmission in the cornea and higher absorption in the lens. UV-B appears strongly effective in causing lenticular opacities, although there is evidence that UV-A can induce photosensitized oxidation of the lens.

The retina is particularly vulnerable to optical radiation in a special domain known as the "retinal hazard region". This region incorporates both visible and near infrared radiation. Because of the refractive power of the cornea and the lens to this radiation, there is a dramatic increase in irradiance between the cornea and the retina. Typically retinal injury results in a blind spot (a scotoma) within the irradiated area. If the scotoma is located in the fovea (most sensitive area of the retina for direct viewing), a severe visual handicap results. The size of the scotoma depends on the irradiance above a threshold level, the angular extent of the source, and the extent of accommodation.

As shown in Table 3, injuries to the skin are wavelength dependent. At high enough intensities both visible and IR produce burns. IR can also produce whole body heat stress. Visible light can induce photosensitising reactions similar to those produced by UV. The main injuries caused by UV are accelerated aging and skin cancer.

Erythema (e.g., the reddening of the skin in sunburn) is the most commonly observed effect on skin after exposure to UV. Erythema is a photochemical response of the skin normally resulting from overexposure to wavelengths in the UV-C and UV-B regions (180-315nm). Exposure to UV-A alone can produce erythema, but only at very high radiant exposures ( $>10^5$  J/m<sup>2</sup>). UV-A exposure prior to UV-B exposure may slightly intensify the erythematous response. This additive effect is known as photoaugmentation. Erythema induced by the longer UV-B wavelengths (295-315nm) is more severe and persists for a longer period than induced by shorter wavelengths.

The increased severity and time course of the erythema may result from the deeper penetration of these wavelengths into the epidermis. In general it is accepted that UV releases a number of diffusing mediators, which in turn carry the inflammatory effect into deeper skin layers. Action spectra for different grades of erythema are quite different. For the most severe grade of erythema maximum sensitivity occurs between 290 and 300nm. The minimal erythema doses (MED) for untanned, lightly pigmented skin range from 60 to 300 J/m<sup>2</sup>. Skin pigmentation and "conditioning" (thickening of the stratum corneum and tanning) may result in an increase of the MED by at least one order of magnitude.

Chronic exposure to sunlight, especially the UV-B component, accelerates the skin aging process and increases the risk of developing skin cancer. Exact quantitative dose-response relationships have not yet been established although fair-skinned individuals, especially of Celtic origin, are much more prone to develop skin cancer. Only a few quantitative studies have examined work populations chronically exposed to artificial sources of UV-B to determine whether there is an increased skin cancer risk in the occupational environment. Squamous cell carcinoma is the most common type. This is localized at exposed sites (e.g., hands and back of the neck).

The use of certain drugs can enhance an individual's sensitivity to UV. This enhanced sensitivity is used successfully in the treatment of psoriasis; UV-A activates the molecules of psoralen, a drug ingested by the patient before exposure. This action leads to a reduction in skin-cell proliferation in the areas exposed to UV. However, an inadvertent increase in sensitivity to UV can occur with such drugs as

- . sulfas,
- . diuretics (drugs which rid the body of excess fluid) and drugs for the treatment of high blood pressure containing diuretics (e.g., hydrochlorothiazide),
- . certain antibiotics (e.g., tetracyclines),
- . estrogens (used for the treatment of menopause and other gynaecological problems),
- . tranquilizers containing phenothiazine derivatives,
- . griseofulvin (for treatment of ringworm), and
- . sulfonyleurea-containing drugs or oral hypoglycemic agents used in treatment of diabetes.

Cosmetic ingredients (in perfumes, deodorants, soaps) may react with UV to produce photoallergic or phototoxic effects (e.g., redness, itching, hives, blistering, or uneven pigmentation). It is wise not to apply these products to the exposed skin before tanning.

Some fruits and vegetables, such as carrots and parsnips, also contain sensitizing chemicals.

#### Human Health Risk

The International Non-Ionizing Radiation Committee of the International Radiation Protection Association has recently completed a review of the scientific literature on biological effects of optical radiation (WHO/IRPA, 1982) and used this as a basis for the development of standards for UV and lasers (INIRC/IRPA, 1985a). Since there are wide variations in threshold values and exposure history (conditioning) among individuals, some margin of safety was incorporated in the IRPA guidelines (INIRC/IRPA, 1985a) for UV to protect all but the most sensitive individuals. However, the exposure limits may not provide adequate protection for photosensitive individuals or for normal individuals exposed concomitantly to chemicals, pharmaceuticals or photosensitizers, and special precautions must be taken for such cases.

Compliance with the exposure limits in the IRPA guidelines should reduce the risk of chronic skin effects by preventing acute effects and limiting life-long UV exposure.

In addition to the direct UV effects, very intense UV-C sources may also produce hazardous concentrations of ozone and nitrous oxides from the air and of phosgene gas in the presence of degreasers.

#### Radiofrequency and Microwaves

##### Absorption of Energy

When a biological organism is exposed to radiofrequency or microwave radiation, electric and magnetic fields are induced within it. A perfect dielectric absorbs no energy from the electromagnetic field, and the field is propagated through the medium unattenuated. A lossy dielectric, by definition, has finite conductivity and there is motion of free ions (conduction loss), and molecular rotation (dielectric loss). Both processes result in energy transfer from the field to the medium. This absorbed energy

will be the source of any work (electrical, mechanical, chemical, etc.) and a temperature rise results.

The total power absorbed and its spatial distribution within a human body are functions of the following:

- (i) Electromagnetic field frequency, with the maximum total absorption in the whole body occurring at a certain ratio of the body dimensions to the wavelength; when the long body axis is parallel to the electric field, the maximum (resonant) absorption occurs for a ratio of body length to wavelength equal to about 0.4, while in other orientations (the long body axis parallel to the direction of propagation or the magnetic field) the maximum absorption is for a body length approximately equal to the wavelength.
- (ii) Field polarisation.
- (iii) Body to radiation source configuration; far-field versus near-field exposure conditions.
- (iv) Exposure environment; presence of other objects in the vicinity of the source and/or the exposed body.
- (v) Electrical properties (dielectric constant and conductivity) of the tissue. These depend critically on the water content and on relative amounts of free and bound water present. Higher absorption levels and lower penetration depths are found in biological media with a relatively high dielectric constant such as brain, muscle, skin and other tissue of high water content, whereas lower absorption levels and greater penetration depth are found in biological media with a low dielectric constant such as bone and fat.

Knowing the electrical and geometrical characteristics of the irradiated body and the external exposure conditions, it is possible (in principle) to calculate the internal fields and the rate at which energy is absorbed throughout the interior of the irradiated tissue. An exact mathematical determination of the internal fields is possible only for objects having a simple geometry such as a plane, sphere, or cylinder, exposed to incident radiation which can be well characterised. Power absorption can be estimated

in more realistic geometries by calculations using numerical methods. Even the best theoretical models are relatively crude because of various limitations in the methods. Experimental measurements of the magnitude and distribution of the specific absorption rate (SAR, expressed in W/kg) in the bodies of exposed animals and models of man can be made. The total amount of energy absorbed by an exposed animal and the distribution of that energy within the animal will vary greatly (up to several orders of magnitude) depending on frequency, animal size, and orientation.

Exposure of biological systems to radiofrequency or microwave energy leads to temperature elevation when the rate of energy absorption exceeds the rate of heat dissipation. Whether the resultant temperature elevation is to the whole body or confined to specific anatomical sites, depends on:

- (a) the distribution of the electric field (SAR) within the body, and
- (b) the passive and active thermoregulatory mechanisms available to the particular biological entity.

Passive thermoregulatory mechanisms consist of heat radiation, conduction, convection and evaporative cooling. In fur-bearing animals and clothed humans, heat loss by radiation and evaporative cooling is poor. The efficacy of heat convection between a body and its immediate environment is a function of the environmental conditions. By way of example, convective heat loss is less in still air than in an environment with moderate air flow.

Active thermoregulatory mechanisms potentiate passive heat transfer mechanisms by employing internal circulating fluids (such as blood) to transfer heat from internal regions to external regions where passive heat radiation and convection are more effective. In some fur-bearing animals, an efficient mechanism is the movement of internally-warmed blood to the lungs; heat in the lungs is then transferred to the inspired air by convection and expired into the environment. Another mechanism (especially in man) is cutaneous vasodilation, resulting in the transfer of internal heat to the skin where it can be radiated and convected into the surrounding environment. Sweating from the skin of humans and the paws and snout of fur-bearing animals provides a means of heat transfer; evaporation of the fluid permits rapid heat loss into the environment.

The possibility of local internal 'hot spots' exists if:

- (a) the rate of energy absorption is relatively high compared to the vascular heat transfer capacity of the local region (i.e., lens of the eye, necrotic centre of tumour, etc.), and
- (b) the rate of energy absorption is relatively uniform throughout the region, but the vascular perfusion patterns are such that confluence or pooling occurs (i.e., venous system in the splanchnic region and above the spinal cord).

In order to extrapolate observations in animals to predict results that might be obtained during human exposures, some method of scaling must be employed. The best method available at present, albeit fraught with over-simplifications, is frequency scaling. This scaling method has been used in the development of a number of exposure standards (INIRC/IRPA, 1984, ANSI, 1982; Australia, 1985). This approach equates the biological response of exposure to shorter wavelengths (higher frequencies) for smaller animals and with longer wavelengths (lower frequencies) for larger animals.

#### Biological Effects in Experimental Animals

The exposure of animals to high levels of radiation has caused various injuries, ranging from local lesions and necrosis to gross thermal stress from hyperthermia. Death from hyperthermia was found to occur following exposure to power densities of a few hundred to several thousand watts per square metre ( $W/m^2$ ), depending mainly on the size of the animal and the radiation frequency. Lesions found in the internal organs of animals exposed for prolonged periods, during which there was no significant rise in rectal temperature, have been attributed to non-uniform energy deposition. Furthermore, such animals may not show any overt signs of distress.

Acute exposures may cause injury to the eye. The cornea and crystalline lens are particularly susceptible to injury within the frequency range of 1-300GHz. The cornea is at greatest risk between 10GHz and 300GHz and the crystalline lens between 1GHz and 10GHz. Exposure within the range of 1.5-2  $kW/m^2$ , lasting from a few hours to 24 hours, or for a few hours per day repeated for a few days per week, can induce cataract formation. The formation of retinal lesions is also possible.

Microwave and radiofrequency radiation exposures of animals can produce transient changes in hormone levels, probably as a result of thermal stimulation of a particular endocrine gland. Effects have also been reported on the blood-forming and immunocompetent cells.

Genetic effects, effects on development, and teratogenic effects have been observed in animals and plants. Numerous reports have indicated that at sufficiently high intensities, microwave and RF exposure may induce chromosomal aberrations, and also disturbances in somatic cell division (mitosis), germ cell development (meiosis), and spermatogenesis. The intensity levels required to produce these effects seem to indicate that a thermal mechanism may be responsible.

Probably one of the most sensitive effects that has been established is on behaviour. Work stoppage, work decrement, decreased endurance, and convulsive activity have been observed in small animals exposed to fields producing SARs above 4W/kg. Both the ANSI (1982) and INIRC/IRPA (1984) considered this behavioural sensitivity to be the "lower limit" of harm from exposure to radiofrequency fields and based their exposure limits on these effects.

#### Health Effects in Man

Studies on the health effects in man from microwave exposure are entirely inadequate. Surveys of the health status of personnel occupationally exposed to microwaves have been conducted, but their results are difficult to interpret because of the existence of one or more of the following shortcomings: insufficient numbers to obtain statistically significant results; lack of proper dosimetry to determine the exposure levels to which personnel have been subjected; and either the absence of a control group or the use of unmatched controls, thus preventing valid comparisons with effects found in the exposed group.

Early studies conducted in Czechoslovakia, Poland, and the Soviet Union reported subjective complaints in individuals exposed to unspecified levels of microwaves. Such complaints consisted of headaches, irritability, sleep disturbance, weakness, decrease in sexual activity (libido), and generally poorly defined feelings of ill health. However, in later studies in Poland and the United States of America, in which better developed measurement techniques and epidemiology were used, no relationship was found between occupational exposure (up to 60 W/m<sup>2</sup>) and the incidence of functional disturbances, morbidity, reproductive performance, and health in children.

Epidemiology surveys of lenticular effects in workers exposed to microwaves have been performed in a number of different countries; no statistically significant increases in the number of cataracts were observed in any of the surveys. Individuals having confirmed microwave-induced cataracts had been exposed to power densities exceeding ( $1 \text{ kW/m}^2$ ), which is in agreement with the experimental data for rabbits.

Following a detailed study of the literature and a health risk assessment, the International Non-Ionizing Radiation Committee of IRPA has published guidelines on limits of exposure to RF fields. The health risk assessment and exposure limits can be found in INIRC/IRPA (1984). The Australian Standard (Australia, 1985) was based on this standard.

#### Extremely Low Frequency (ELF)

An in-depth review of the interaction mechanisms, biological effects and health risk assessment of ELF electric fields has recently been published (WHO/IRPA, 1984). Other reviews have been made by Repacholi (1984, 1985). A brief summary is given here.

The most prevalent source of ELF electric fields in our environment is from power generation, distribution and use, at frequencies of 50 and 60Hz.

Naturally occurring ELF electric fields arise from the electric charge occurring between the atmosphere and the ground. Variations in the intensity of the electric fields are due to atmospheric disturbances such as thunderstorms. At the power frequencies of 50 and 60Hz the natural electric field is about  $10^{-4} \text{ V/m}$ . This is very weak compared to the fields introduced into the home by the current flowing through electric wiring and operation of various appliances. These fields can be between  $10^3 - 10^6$  stronger than the natural fields. Under high voltage transmission lines and in high voltage substations the electric fields can be of the order of  $10^8$  times stronger.

#### Mechanisms of Action

A human or animal body located in an ELF electric field causes perturbations of the field, resulting in an uneven distribution of the field around the body. Both the electric and magnetic fields induce electric currents in the exposed body. The electric fields at the body surface and currents induced in man and animals are quite different, even when exposed to the same unperturbed field strength.

In the region of strong ELF electric fields, three interactions are known to occur:

- (a) large surface fields are produced particularly at highly curved regions, and may stimulate surface body receptors, producing sensations;
- (b) small currents are induced in the body by the large surface electric fields; their magnitude is very small in comparison with the currents that flow when contact is made with charged conductors. The associated internal electric field is some  $10^5$  to  $10^7$  times smaller than the applied external electric field.
- (c) spark discharges occur when objects, at significantly different potentials, approach contact.

The mechanisms by which a weak ELF field may interact with biomolecular systems and tissues are incompletely understood. However, from in vitro studies, there is now evidence of field-induced interactions, including the phenomena of ionic interactions within the cell and on membrane surface macromolecules, which appear to involve coupling of the cell interior to signals from neurotransmitters, hormones, antigens and antibodies.

These studies have included examination of interactions using tissue culture methods, cell biochemistry, neurophysiology, and growth of bone tissue. Electric fields were reported to affect endocrine gland secretion, response to hormonal stimulation, brain calcium ion exchange, immunoreactivity of lymphocytes, electrical excitability of neuronal tissue, and tissue growth rates.

Some of these studies have revealed ELF field effects occurring within certain "windows" in frequency and amplitude. That is to say, only within a specific frequency range and certain field strengths, but not above or below.

#### Studies in Animals

ELF research on animals has focused predominantly on effects involved with the central nervous system including physiological, ultrastructural and biochemical alterations; changes in blood composition; behaviour; reproduction and development. Studies have been conducted almost exclusively on small

laboratory animals, except for a few studies carried out with cattle, miniature swine and monkeys. One of the most serious shortcomings of these studies on small animals results from the difficulty in making extrapolations to human beings because of uncertainty about applying the mechanisms proposed for the effects so far. In particular, it is difficult to cite equivalent human exposure because of vast differences in the distribution of surface electric field strengths and internal current densities between human beings and animals, and because there are no data on the species dependency of effects.

Studies with small animals exposed to electric fields up to 100kV/m have revealed effects on components of the nervous system, including synaptic transmission, on circadian rhythms, and on the biochemical properties of brain tissue. Results of behavioural studies suggest that the nervous system may be affected by an ELF electric field that is far too weak to stimulate synaptic function or cell firing, although in vivo studies often do not exclude the possible role of tactile sensory phenomena.

Field effects on peripheral blood compositions and biochemistry have been studied by numerous investigators, with inconsistent results. Generally, the changes in blood picture involve small deviations from individual norms, but the values usually remain within physiological norms. The majority of studies on the influence of ELF fields on immunocompetence in whole animals do not show any effect. Studies on swine exposed to 30kV/m and rodents exposed to 65kV/m for up to 18 months have revealed evidence of teratological effects.

These data are not conclusive and do not prove the teratogenic potential of ELF fields in general. Many studies on genetic effects and effects on cardiovascular function have been reviewed and the conclusion reached that such effects have not been convincingly demonstrated.

#### Human Studies

Existing surveys of the state of health of high voltage (HV) substation workers and HV line maintenance crews have been based on small populations and have produced conflicting results. Soviet authors noted an increased incidence of subjective complaints attributable to effects on the nervous system and shifts in blood biochemistry. Other authors have not reported such observations. Differences in method often make comparison difficult, if not impossible. Field strengths to which personnel were exposed were only estimated, and only approximate data on the duration of exposure to fields in a given strength range were available.

Some studies on volunteers exposed to electric fields up to 20kV/m for short periods (days), under laboratory conditions, confirmed the existence of slight changes (within the normal physiological range) in populations of peripheral blood cells and biochemistry, similar to those observed in experimental animal studies. However, no other effects have been reported.

Several recent epidemiological reports have presented data suggesting an increase in the incidence of cancer among children and adults living in homes exposed to magnetic fields from various types of electric power lines, transformers, or other electrical wiring configurations, and among workers in electrotechnical occupations. These studies have a number of deficiencies and do not establish a causal relationship between exposure to electric or magnetic fields and cancer induction. They indicate a need for further research in this area.

Epidemiological studies have been performed on linemen and switch-yard workers, the groups considered to be subjected to the highest electric field exposure levels. However, the exposure levels to which these people are subjected have been found to be remarkably low. Slight increases in genetic defects or abnormal pregnancies have been reported in one study. However, the preliminary nature of the epidemiological findings, the small numbers contained within the studies, the low levels of exposure, and the relative small increment in the reported incidence of any effects, suggest that, though the epidemiological data cannot be dismissed, there must be considerable study before they can serve as useful inputs for risk assessment.

No specific pathological effects resulting from ELF field exposure have been established. However, thresholds for perception, startle, let-go, respiratory tetany, and fibrillation due to contact currents (electric shocks) have been quantified.

#### Conclusions on Health Risk

Following a careful review of laboratory studies and analysis of results obtained on human subjects, the Task Group (WHO/IRPA, 1984) drew the following conclusions about the health risks of exposure to ELF electric fields.

- (i) Adverse human health effects from exposure to ELF electric fields normally encountered in the environment or the workplace have not been established.

- (ii) Some human beings feel spark discharges in electric fields of about 3kV/m and perceive the fields between 2-10kV/m. At present, there are no significant data that suggest that perceiving a field produces an adverse pathological effect.
- (iii) Whilst it would be prudent in the present state of scientific knowledge not to make unqualified statements about the safety of intermittent exposure to electric fields, there is no need to limit access to regions where the field strength is below about 10kV/m. Even at this field strength, some individuals may experience uncomfortable secondary physical phenomena such as spark discharge, shocks, or stimulation of the tactile sense.
- (iv) It is not possible from present knowledge to make a definitive statement about the safety or hazard associated with long-term exposure to sinusoidal electric fields in the range of 1-10kV/m. In the absence of specific evidence of particular risk or disease syndromes associated with such exposures, and in view of experimental findings on the biological effects of exposure, it would be prudent to limit exposure, particularly for members of the general population.
- (v) In principle, electric and magnetic field interference with implanted cardiac pacemakers can lead to reversion to a fixed rate, but cessation of stimulation is possible. Direct interference has not been reported in fields below 2.5kV/m. Although body currents produced by contact with a vehicle in a weaker field may cause interference, the risk of pacemaker reversion is believed to be slight.

#### Magnetic Fields

A magnetic field is always linked to electric currents. A static magnetic field is formed in the case of direct current, and a time-varying magnetic field is induced in the vicinity of alternating current sources. The animal or human body does not appreciably affect an external magnetic field. Varying magnetic fields induce eddy currents within the body.

The term "dosimetry" is used to quantify exposure. Due to a poor understanding of interaction mechanisms, dosimetric concepts have not been developed for magnetic fields. In practical radiation protection it is useful

to consider time-varying and static magnetic field separately. For time-varying magnetic fields, the evaluation may be based on the electric eddy current density in critical organs. Derived protection limits may be expressed as exposure to external magnetic fields, whereby field strength, pulse shape and frequency, orientation of the body and duration of the exposure need to be specified. In case of static magnetic fields, the protection limits tend to be stated primarily in terms of the external field strength and the duration of exposure.

Occupational exposure to magnetic fields is encountered predominantly in industrial processes involving high electric current equipment, in new technologies for energy production and storage, and in people near research facilities. Around various types of welding machines, furnaces, induction heaters etc, the magnetic flux densities at the operator location range from about  $1\mu\text{T}$  to more than  $10\text{mT}$ , depending on the magnetic field frequency and the distance from the coil. Compared to devices operating at high frequencies, lower frequency induction heaters expose operators to higher magnetic flux densities. At operator-accessible locations in industries using electrolytic processes, the mean field level is about  $10\text{mT}$ .

The static magnetic flux densities near systems used in thermonuclear magnetic fusion, magnetohydrodynamic systems etc., in areas accessible to operations personnel are up to  $50\text{mT}$ . Near special research facilities, e.g., bubble chambers, similar field strengths occur. Typical values for the magnetic flux density at working places near 50 or 60Hz overhead transmission lines and in power stations are  $0.02$  to  $0.05\text{mT}$ .

In medical practice, exposure to magnetic fields results mainly from the use of magnetic resonance (MR) imaging or spectroscopy methods for diagnostic purposes or from devices generating magnetic field pulses for therapeutic purposes. In MR-devices the patient is exposed to stationary magnetic fields with intensities up to  $2\text{T}$  and to time-varying magnetic fields of up to  $20\text{T/s}$  during the examinations. Most patients however are not exposed to time varying fields exceeding  $1.5\text{T/s}$ .

The local exposure of the patient caused by therapeutic magnetic devices is of the order of  $0.1$  to  $2.5\mu\text{T}$ . The increasing use of magnetic fields producing equipment in industrial processes, research facilities, energy production and distribution, new transportation technologies, consumer

products and medical practice, increases the possibility of human exposure to magnetic fields. Although up to now occupational and population exposure to magnetic fields was generally kept at low levels, some new technologies, e.g. magnetically-levitated trains, might result in exposure of the public to levels comparable to the highest ones now in some working environments. Therefore, new technologies involving the production of magnetic fields should be carefully evaluated with respect to their potential health risk.

#### Interaction Mechanisms

There are three established physical mechanisms through which static and ELF magnetic fields interact with living matter (Tenforde, 1984, 1985a,b).

- (i) **Magnetic induction.** This mechanism is relevant to both static and time-varying fields, and originates through the following types of interaction:

Electrodynamic interactions with moving electrolytes where both static and time-varying fields exert Lorentz forces on moving ionic charge carriers, and thereby give rise to induced electric fields and currents. This interaction is the basis of magnetically-induced blood flow potentials that have been studied with both static and time-varying ELF fields. It is also the physical basis of the weak induced potentials that provide sensory directional cues to elasmobranch fish (sharks, skates and rays) as they swim through the static geomagnetic field.

Time-varying magnetic fields induce currents in living tissues in accordance with the Faraday law of induction. Available evidence suggests that this mechanism may underlie the visuosensory stimulation that produces magnetophosphenes. In addition, indirect evidence suggests that rapidly time-varying magnetic fields may exert effects on a variety of cellular and tissue systems of inducing local currents that exceed the naturally occurring levels. This effect may be the basis for the wide spectrum of biological perturbations that have been observed with pulsed magnetic fields such as those used clinically for bone fracture reunion.

- (ii) Magnetomechanical effects. The two types of mechanical effects that a static magnetic field exerts on biological objects are the following:

In a uniform static field, both diamagnetic and paramagnetic molecules experience a torque and orient in a configuration that minimizes their free energy within the field. This effect has been well studied for assemblies of diamagnetic macromolecules with differing magnetic susceptibilities along the principal axes of symmetry. Included among this class of macromolecules are the arrays of photopigments in retinal rod disc membranes.

Spatial gradients of static magnetic fields produce a net force on paramagnetic and ferromagnetic materials that leads to translation motion. Because of the limited amount of magnetic materials in most living objects, the influence of this effect on biological functions is negligible.

- (iii) Electronic interactions. Certain classes of chemical reactions involve radical electron intermediate states in which the Zeeman interaction with a low-intensity static magnetic field produces an effect on electronic spin states. An example of this effect is the primary charge transfer reaction in bacterial photosynthesis, in which the yield of triplet state product is decreased in the presence of a static magnetic field. This magnetic field effect, however, occurs only when the ultimate electron acceptor molecules are chemically reduced thereby extending the lifetime of the radical electron intermediate state. Because this condition does not occur in nature, the effect of weak magnetic fields on electronic spin states under normal in vivo conditions has not been demonstrated. It is probable, however, that the usual lifetime of biologically relevant electron intermediate states is sufficiently short that magnetic field interactions exert only a small, and perhaps negligible, influence on the yield of chemical reaction products.

In addition to the mechanisms of magnetic field interactions for which there is direct experimental evidence, other mechanisms have been proposed on theoretical grounds in an effort to explain various biological effects that have been reported to occur in static and ELF fields of very low intensity, but have not been subjected to direct experimental tests.

### Biological Effects

A number of low organisms and aquatic mammals have been demonstrated to possess sensitivity to static magnetic fields with low intensities comparable to that of the geomagnetic field ( $50\mu\text{T}$ ). Phenomena for which there is substantial experimental evidence of sensitivity to the earth's field include:

- . direction finding by elasmobranch fishes;
- . orientation and swimming direction of magnetotactic bacteria;
- . kinetic movements of mollusks;
- . migratory patterns of birds; and
- . waggle dance of bees.

In addition, a number of in vitro demonstrations have been made of magnetic orientation in assemblies of macromolecules, including retinal rod outer segments, muscle fibres, photosynthetic systems (chloroplast grana, photosynthetic bacteria, and Chorella cells), halobacteria purple membranes, and various synthetic liquid crystals and gels. Certain classes of chemical reactions which involve a radical electron intermediate state may also be sensitive to static magnetic fields of moderate intensity ( $<10\text{mT}$ ).

The available experimental information on the response of higher organisms, including land-dwelling mammalian species, to static and ELF magnetic fields indicates that three biological effects can be regarded as established phenomena:

- . the induction of electrical potentials within the circulatory system;
- . magnetophosphene induction by pulsed and ELF magnetic fields with a time rate of change exceeding  $2\text{T/s}$ ; and
- . the induction by time-varying fields of a wide variety of cellular and tissue alterations when the induced current density exceeds  $10\text{mA/m}^2$ ; many of these effects appear to be the consequence of magnetic field interactions with cell membrane components.

### Health Risk Assessment

For static magnetic fields with flux densities less than  $2\text{T}$ , there exists a significant body of experimental data which indicates the absence of any measurable effect on many major developmental, behavioural, and physiological parameters in higher organisms. Broadly summarized, the presently available evidence suggest that the following biological functions are not affected by

static magnetic fields at levels up to 2T; cell growth; reproduction; pre- and post-natal development; bioelectric activity of isolated neurons; behaviour; cardiovascular functions (acute exposures); vision; haematology; immune system functions; physiological regulation and circadian rhythms.

For time-varying magnetic fields in the ELF frequency range, fewer systematic studies have been carried out to define the threshold field characteristics for producing significant perturbations of biological functions. Nevertheless, the presently available evidence suggests that ELF magnetic fields must induce current densities in tissues and extracellular fluids that exceed  $10\text{mA/m}^2$  in order to produce significant alterations in the development, physiology, and behaviour of higher organisms.

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LECTURE 2

LASERS AND LASER HAZARDS

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INTRODUCTION

The laser was only about four years old when it began to get a bad reputation for itself as spectators in movie theatres around the world saw it slice through a steel table and threaten James Bond's life in the movie "Goldfinger". Twenty years later the thin red light beam scans across milk cartons at the local supermarket, but at the same time there is talk of "star war" defence strategies. So the question is often asked: just how dangerous are lasers? The answer of course is: it depends. In fact it depends on so many factors that the laser protection standards that have been adopted in various countries, including Australia, are extremely complicated.

TABLE 1  
COMMERCIAL LASERS AND THEIR AREAS OF APPLICATION\*

			APPLICATION SECTOR												
TYPE	DATE DISCOVERED/ DATE COMMERCIALIZED	INDUSTRIAL		COMMERCIAL				MEDICAL		RESEARCH		MILITARY			
		Material Processing	Align. Measure and Control	Graphic Arts	Communications	Information Processing	Entertainment and Display	Treatment	Diagnosis	Spectroscopy	Studies of Basic Processes	Remote Sensing and Targeting	Simulation	Weapons Development	
Gas	Carbon dioxide	1964/1966													
	• low power (<100 W)		•					•		•	•				
	• medium power (0.1-1 kW)		•							•	•				
	• high power (>1 kW)		•							•	•				•
	Chemical (HF, DF)	1967/1977								•	•				•
	Excimer (ArF, KrF, XeCl, XeF)	1975/1976	•						•		•	•			•
	Far infrared (laser pumped and direct discharge)	1963/1969								•	•				
	Helium neon	1962/1962		•	•		•	•			•				
	Iodine photodissociation	1964/1983	•							•	•				
	Ion (argon; krypton; xenon)	1964/1966	•	•	•		•	•	•	•	•				
	Metal vapor														
	• helium cadmium	1968/1970		•	•		•			•	•				
	• copper vapor	1966/1981	•							•	•				
• gold vapor	1978/1982							•							
Nitrogen	1966/1969								•	•					
Liquid	Continuous-wave dye	1970/1971						•		•	•				
	Pulsed dye	1966/1969						•		•	•				
Solid (resistor)	Alexandrite	1977/1981	•							•	•				
	Color center	1965/1977								•	•				
	Neodymium glass	1961/1968	•							•	•			•	
	Neodymium garnet (YAG)	1964/1965								•	•				
	• continuous-wave (including mode locked)		•		•			•	•	•	•				
• pulsed		•					•	•	•	•	•				
Ruby	1960/1963	•	•						•	•					
Solid (semiconductor)	Single-frequency diode	1962/1965								•	•				
	• GaAs			•	•		•							•	
	• GaAlAs			•	•	•	•								
	• InGaAsP					•									
	Tunable diode (lead salt)	1964/1975		•						•					

\* G.K. Klauminzer, Laser Focus, 20, p. 54, December 1984

The range of laser products potentially within reach of the public is enormous and Table 1 is only meant to give an example of common lasers and their applications. Lasers can be classified according to different criteria, e.g. the duration of their emission, the wavelength range, the engineering design. Each of these classes may entail different risks and require different protection measures.

#### PRINCIPLES OF LASER OPERATION

All lasers have three basic components: the active medium, the pumping system and the optical cavity:

- The active medium is the substance that is responsible for the emission of laser light. It usually gives the name to the laser (e.g. ruby laser, helium-neon laser etc.) and it determines most of the emission properties. For a substance to be suitable as a laser medium a particular electron energy level structure is required. The simplest possible model consists of a lower level and an upper level which must be metastable. This means that if the electron is brought to that level, it must remain in it for a relatively long time (a few milliseconds).

- The pumping system supplies the atoms (or molecules) of the active medium with the energy required to achieve laser action. This can be achieved, for example, by means of an electrical discharge through the active medium if this is a gas, or by irradiating the active medium with a strong light of a wavelength shorter than the desired laser wavelength. In some cases another laser is used.

- The optical cavity consists of two mirrors placed at either end of the active medium and facing each other. One of the mirrors is partially transmitting so that a fraction of the light generated by the active medium may leave the cavity (Fig. 1).

To achieve laser action the pumping system must deliver energy to the active medium at a rate fast enough to have more molecules in the excited state than in the non-excited state. This condition is called "population inversion" because it is the opposite of the normal distribution of energy in the medium. A molecule in the excited state will release its excess energy by emitting a photon whose wavelength is inversely proportional to the energy difference between the excited and the non-excited state. If the photon, as it travels through the medium, collides with a molecule in the non-excited

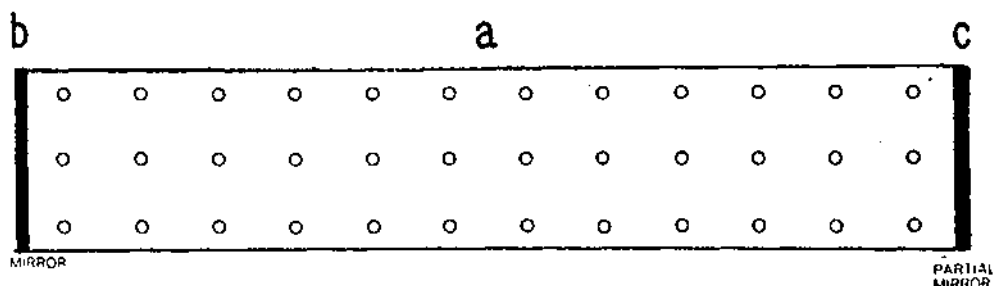


Figure 1: (a) laser medium; (b) totally reflecting mirror; (c) partially reflecting (output) mirror. The open dots represent atoms (or molecules) in the non-excited

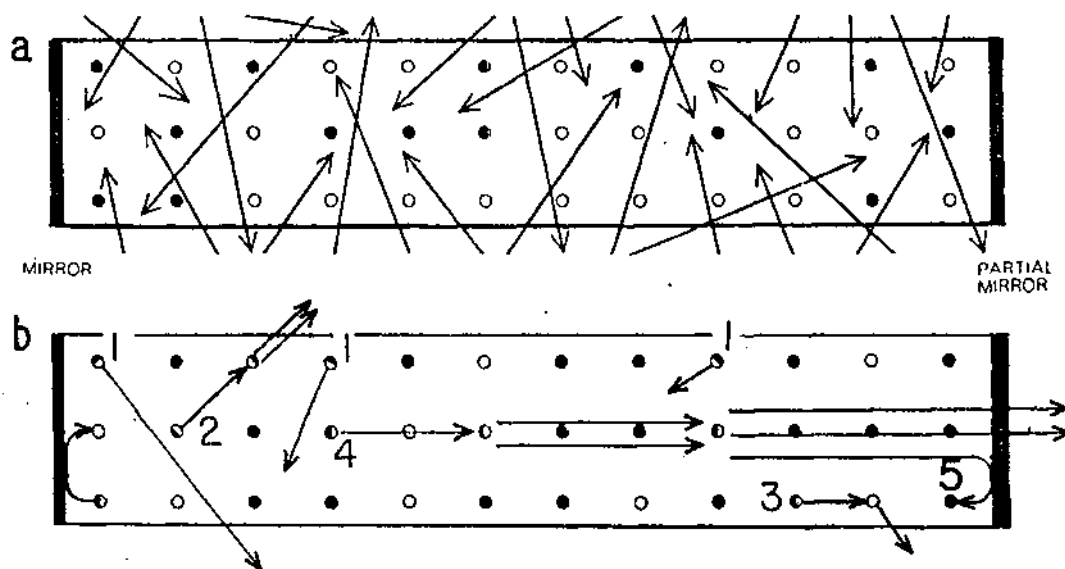


Figure 2: (a) energy from the pump (arrows) raise most of the atoms to an excited metastable state (black dots); (b) excited atoms fall back to the ground state with the emission of photons: (1) spontaneous emission in a non-axial direction (lost); (2) spontaneous emission stimulating further emission in a non-axial direction (both lost); (3) spontaneous emission in the axial direction being absorbed by a non excited atom which subsequently emits a photon in a non-axial direction (lost); (4) spontaneous emission in the axial direction stimulating further emission. Part of this is reflected back to stimulate the emission of more photons in the axial direction; (5) and part emerge from the partially transparent mirror as part of the laser output.

state it is absorbed, (Fig. 2), but, if a population inversion has been achieved in the medium, it is more probable that the photon will collide with an excited molecule. In this case it will stimulate the emission of an identical photon. Most of the photons thus emitted will escape from the laser medium and be lost, but a few, travelling along the axis of the optical cavity, will hit one of the mirrors and be reflected straight back into the laser medium and will stimulate the emission of more photons, all identical, i.e. having the same wavelength, phase and direction of propagation. As one of the mirrors forming the optical cavity is only partially reflective, some of these photons travelling back and forth inside the laser escape in the form of a well collimated monochromatic beam.

These two properties, collimation and monochromaticity, are also termed coherence. A coherent light wave exhibits a predictable correlation between the amplitude and phase of the wave at any one point and at any other point. Consider the analogy of a large group of marchers in a parade. Ideally, knowing the position of one marcher we can predict the presence of another one three feet ahead, one three feet to the right and so on.

Consider now the case where each line of marchers followed its leader without taking into consideration the direction of march of the others. An observer standing at the side of the parade could still predict that a marcher would pass by him every two seconds, but could not make any prediction on the positions of the marchers across the row. This is analogous to the situation of a monochromatic, non collimated beam where it is possible to correlate the amplitude and phase of a "ray" of light since all the photons have the same wavelength and phase, but no correlation is possible between different points of the wavefront. (Fig. 3).

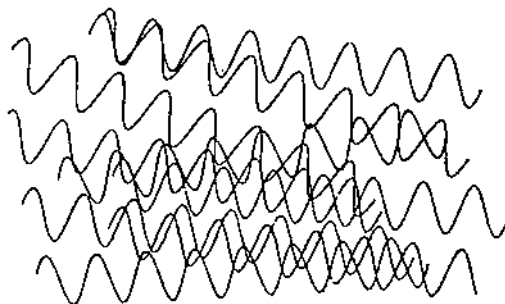


Figure 3: Non collimated, monochromatic light.

In this case the light (and the marchers) exhibit temporal coherence, but not spatial coherence. Note however that if the lines of marchers diverge not because of incompetence but in order to execute a well planned drill (Fig. 4) there would still be spatial coherence because the position of each

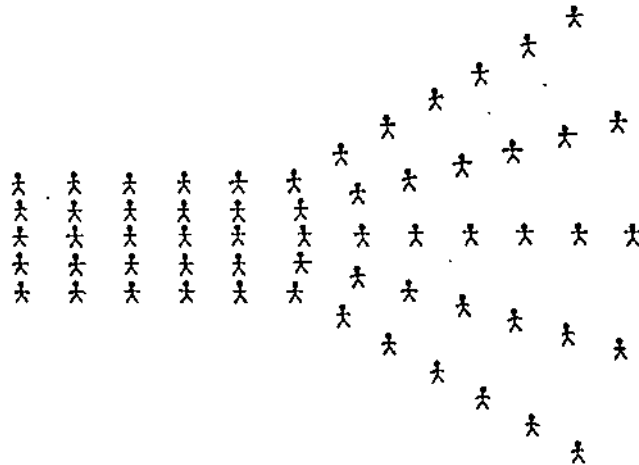


Figure 4: Rows of marchers diverging but maintaining a predictable position with respect to each other.

marcher along each row is still correlated to the position of the others by a precise rule. In the case of light this means that there is a major difference between lack of spatial coherence and divergence. A spherical wavefront can be easily collimated using a spherical lens (Fig. 5) while an incoherent beam cannot (Fig. 6). It follows that a coherent beam can be focussed to a diffraction limited spot.

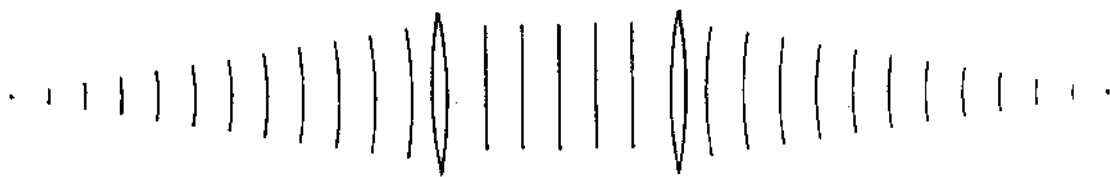


Figure 5: A spatially coherent beam can be collimated and focussed to a diffraction limited spot.

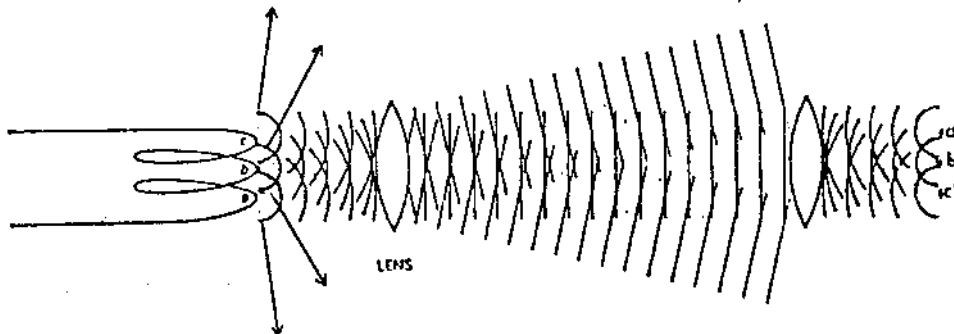


Figure 6: An incoherent beam cannot be well collimated and cannot be focussed to a diffraction limited spot.

A collimated, spatially coherent beam containing photons of different wavelengths is not temporally coherent because there is no predictable correlation between the amplitude of a wave at a given point in space and that of the wave at the same point some time later. In our analogy this corresponds to the case where the marchers maintain a correct alignment but, because their steps are not of the same length, the rate at which they pass a particular spectator is not predictable.

In practice the processes mentioned above may be achieved in a number of different ways depending on the properties of the laser medium and on the application for which the laser is intended. Population inversion is achieved with more or less difficulty depending, among other factors, on the position of the laser levels with respect to the other electron energy levels of the molecule.

#### Cavity Modes

So far we have regarded the laser light as consisting of photons; however to explain other properties of the laser beam it is necessary to take into consideration the wave nature of light. First we must emphasize that in practice the light emitted within the laser medium is not perfectly monochromatic.\* The light waves travelling back and forth between the two mirrors interfere with each other cancelling out when they are out of phase and reinforcing each other when they are in phase. This rapidly leads to the establishment of standing waves (Fig. 7). Only light whose half wavelength is an integer submultiple of the cavity length can exist between the two mirrors. The "permitted" wavelengths are called the longitudinal modes of the cavity.

In addition to light propagating exactly along the axis of the cavity, i.e. perpendicularly to the surface of the mirrors, there will be a number of waves propagating in a slightly off-axis direction that may also re-enter the cavity upon reflection by one of the mirrors and be amplified a number of times, depending on the geometrical design of the laser. Therefore the complete wave pattern will consist of a superposition of a large number of waves, each travelling in a slightly different direction, but all approximately near-axial. Once again, all these waves will interfere with each other and the basic requirement for the waves to reinforce each other is

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There are several reasons for this. The interested reader is referred to Lengyel (1971) pg 22 or other basic laser text books.

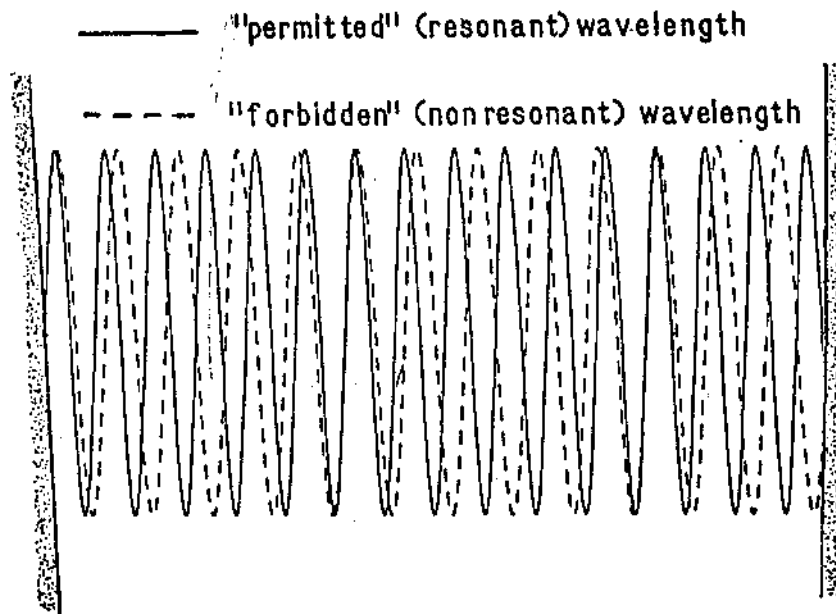


Figure 7: Only light whose wavelength is a semi integer submultiple of the cavity length will reinforce each other upon round trip reflection.

that the wave distribution replicate itself upon round trip reflection by the mirrors. These wave patterns are called the transverse electromagnetic modes (TEM) of the cavity (the name is derived from microwave terminology). Unlike the case of the axial modes, unfortunately, it is not easy to determine these field distributions, but this can be done through an application of diffraction theory. However the transverse modes of a laser beam can be easily identified experimentally by expanding the laser beam with a diverging lens. Different transverse modes will appear as different intensity distribution patterns (Fig. 8). The intensity distribution is an important

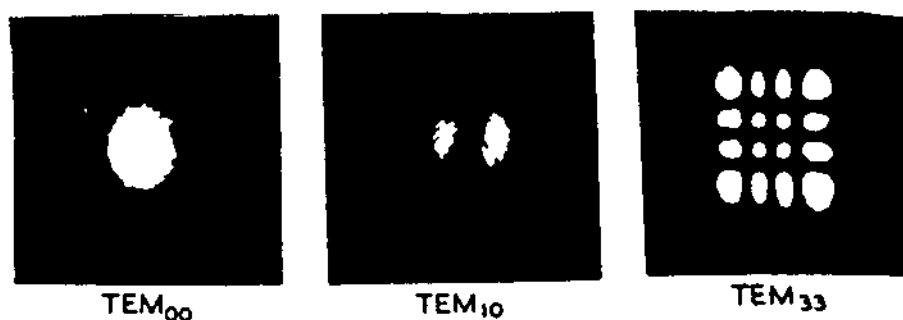


Figure 8: Typical transverse electromagnetic (TEM) mode patterns as revealed in the beam cross-sectional patterns at some distance (i.e. in the far field) from a He-Ne laser (Adapted from: Kogelnik and Li, 1966).

factor in the determination of the safety hazards. Generally lasers are designed to operate in the TEM<sub>00</sub> mode which is characterized by a gaussian intensity distribution across the beam. In some cases it is also possible to achieve lasing in only one axial mode, thus producing an almost absolutely monochromatic and collimated beam.

#### Temporal Properties of the Laser Output

In many cases the "pumping" rate required to maintain population inversion is so high that the laser can only operate in short bursts. In the case of the ruby laser, for example, pumping is accomplished by discharging a capacitor through a flashlamp and this process only lasts a few milliseconds. During this time laser light is emitted in a series of spikes whose intensity and duration varies at random. This can be undesirable in many applications so two techniques are used to make the output more accurately repetitive: Q-switching and mode-locking.

In Q-switching a shutter is placed inside the optical cavity. This stops photons from travelling back and forth, thus preventing further stimulated emission of light. Only when the population inversion is at its peak is the shutter opened. In this way lasing is attained more rapidly and much of the energy stored in the laser medium is released in one pulse whose peak power is orders of magnitude higher than that of the individual pulses emitted in the normal mode of operation.

Mode-locking can be used only in lasers operating in more than one axial mode. This technique relies on the fact that the laser light is not perfectly monochromatic. As photons of slightly different wavelengths interfere with each other, the intensity of the output fluctuates slightly (Fig. 9 and 10). A saturable absorber is placed inside the cavity. This is a substance which absorbs weak light more than intense light. The light peaks, on the other hand, become further amplified as they are reflected back into the laser medium. The two effects combined deepen the troughs and augment the peaks of the laser output which then becomes a train of very short pulses of picosecond duration (Fig. 11c). A single pulse can be isolated from the train using a fast electro-optic shutter (Fig. 11d).

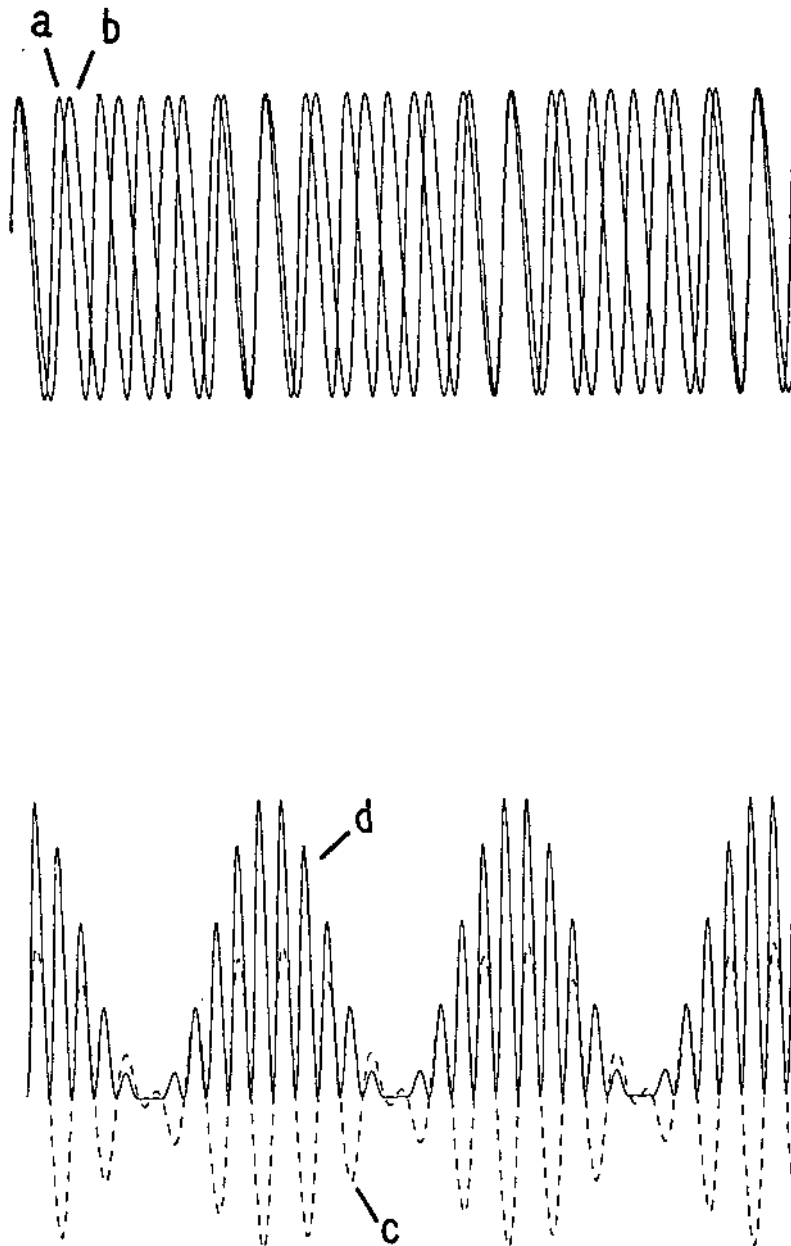


Figure 9: Interference of two light waves of slightly different wavelength (a and b - top) results in a wave whose amplitude varies with time (c) - The intensity of the light (d) is proportional to the square of the amplitude.

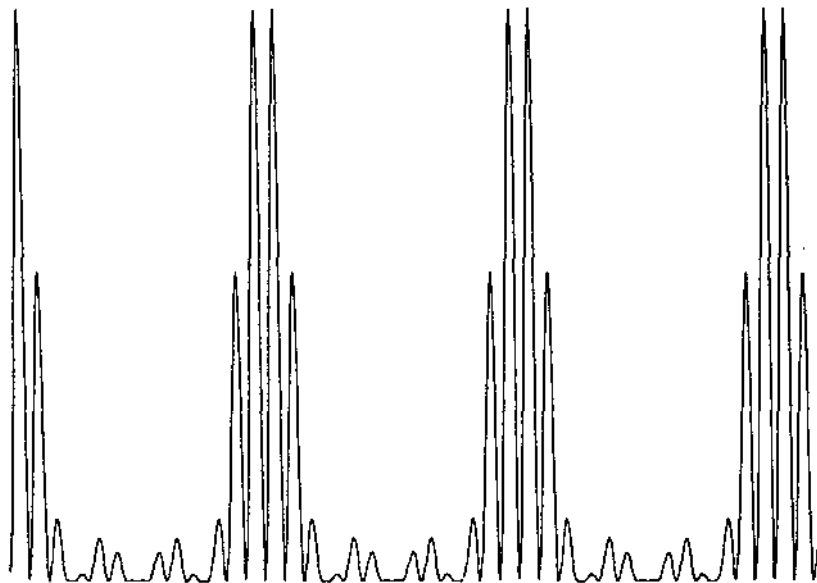
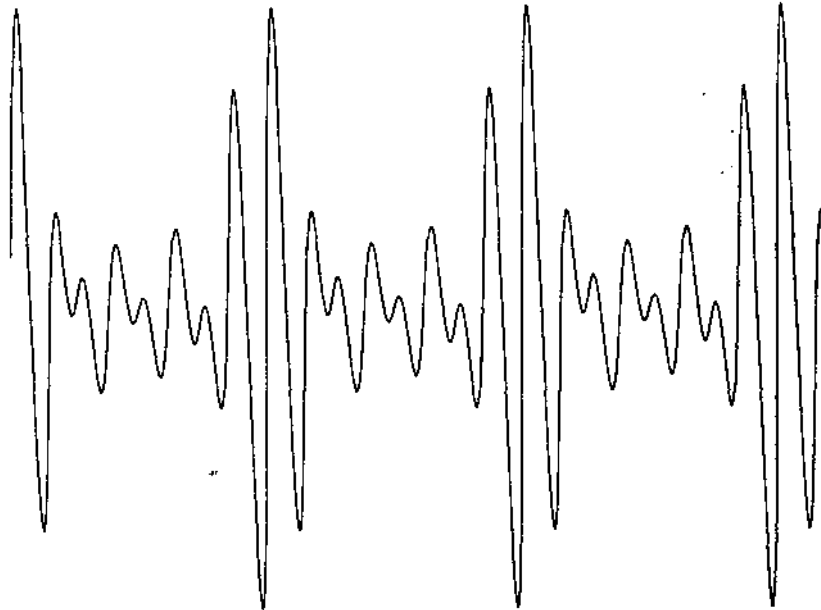


Figure 10: Amplitude (top) and intensity (bottom) of a light wave resulting from the superimposition of four sine waves of slightly different wavelength.

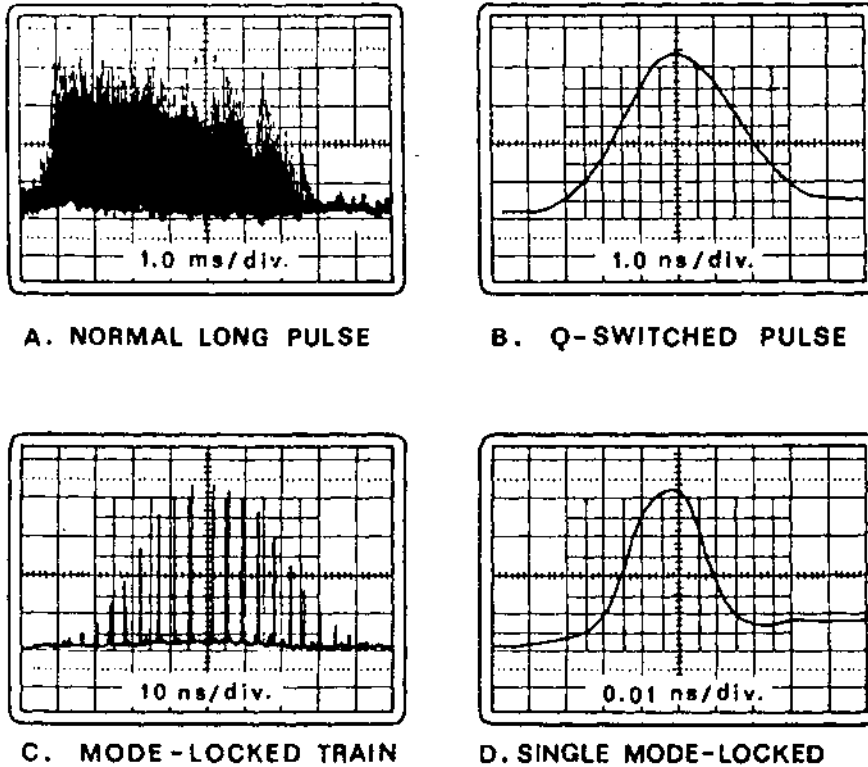


Figure 11: Oscilloscope traces of a long-pulse (normal-pulse) laser (A), a Q-switched pulse (B), and mode-locked laser outputs (C and D) (From: Sliney and Wolbarsht, 1980). Note change in time scales in each trace ( $1 \text{ ms} = 10^6 \text{ ns}$ ).

Both Q-switching and mode-locking result in a loss of energy, but the pulse can then be amplified by passing it through an "amplifier" (Fig. 12) consisting of another laser without the mirrors (the first laser is then called an "oscillator"). The pumping system of the amplifier is timed to fire so that the population inversion is at a maximum when the pulse reaches the amplifier's laser medium. The pulse then stimulates the emission of a large number of photons in a single pass through the amplifier. Some laser systems use a large number of amplifiers of progressively larger size, producing laser pulses having both high peak power and high energy as well as being reproducible in terms of time and amplitude.

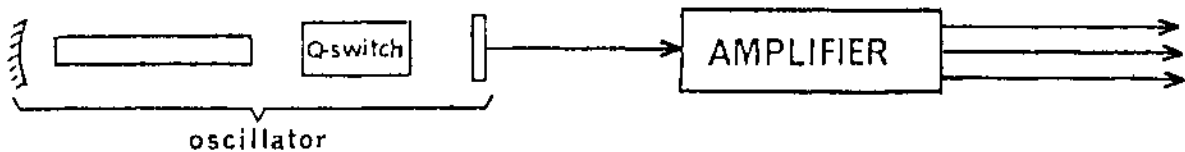


Figure 12: Q-switched laser with amplifier.

In some lasers the pump energy can be delivered at a constant steady rate and the laser operates continuously. These are referred to as cw (continuous wave) lasers.

#### LASER HAZARDS

The biological effects induced by optical radiation are essentially the same for any given wavelength, exposure area and duration, regardless of the nature of the source. Laser light is not, intrinsically, different from light emitted by ordinary sources. If we wanted we could, in principle, generate a beam of light having the same properties of a laser beam using a conventional source, a pinhole aperture, a lens and a filter (Fig 13). However the beam obtained in this manner would contain only an extremely small fraction of the light emitted by the source. A laser is much more efficient.

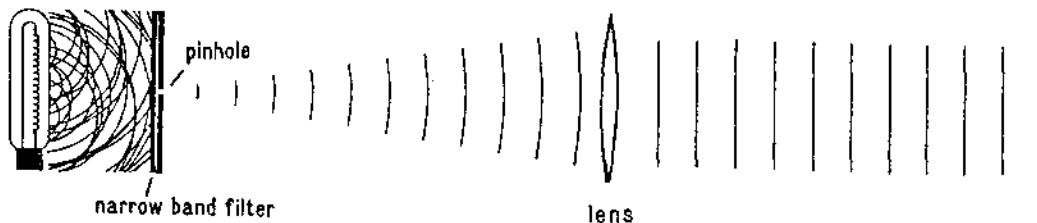


Figure 13: Use of a narrow band filter, a pinhole and a lens, to generate a monochromatic, collimated beam.

### Hazards to the Eye

The main reason why the laser is potentially dangerous lies in its exceptional brightness, i.e. the power emitted per unit area per unit solid angle. A common 1 mW He-Ne laser which is often used in classroom experiments is many times brighter than the sun! Of course the total power irradiated by the sun is infinitely more than 1 mW, but it is emitted in all directions and, even from this distance, the sun appears to us as an extended source, forming an image on the retina approximately 155 microns in diameter. The He-Ne laser, on the other hand, has a typical divergence of only one milliradian and a source area (i.e. the cross section of the beam as it leaves the output mirror) of less than  $0.8 \text{ mm}^2$ . It is quite possible for a person within several metres of the laser to receive the full power of the beam through the pupil of the eye. The image on the retina would be 10-20 microns in diameter (it would be even smaller if not for scattering in the ocular media and corneal aberrations) and have a power density of the order of several hundreds of watts per square centimetre as opposed to less than  $10 \text{ W/cm}^2$  in the case of the sun. The heat generated in the tissues exposed to such an intense radiation could cause irreversible retinal damage in less than one second. The actual damage threshold is quite difficult to define, let alone determine. In fact what constitutes damage is not unequivocally obvious; some changes may not entail any functional alteration, although they may be visible upon an ophthalmic examination; others require histological examination under a microscope. Different researchers may define different threshold levels for each of these types of lesions and different subjects may exhibit slightly different responses to the same exposure. Therefore the dangerous exposure level is determined statistically using probit analysis (Fig. 14). The exposure which causes an ophthalmologically visible lesion in 50% of the cases in an experimental animal (or group of animals) is termed the ED50 dose and is regarded as the minimum level at which a definite hazard exists. Exposure safety levels incorporate a considerable safety margin (typically one order of magnitude) (IRPA 1984).

The mechanism of damage depends on the duration of the pulse. In the case of cw or long pulse lasers, heating originating in the region of highest irradiance spreads to surrounding tissues by conduction and the size of the damaged area increases progressively. The degree of peripheral spread due to conduction is also proportional to the image size as for small images blood circulation is more effective in keeping down the temperature of the irradiated area.



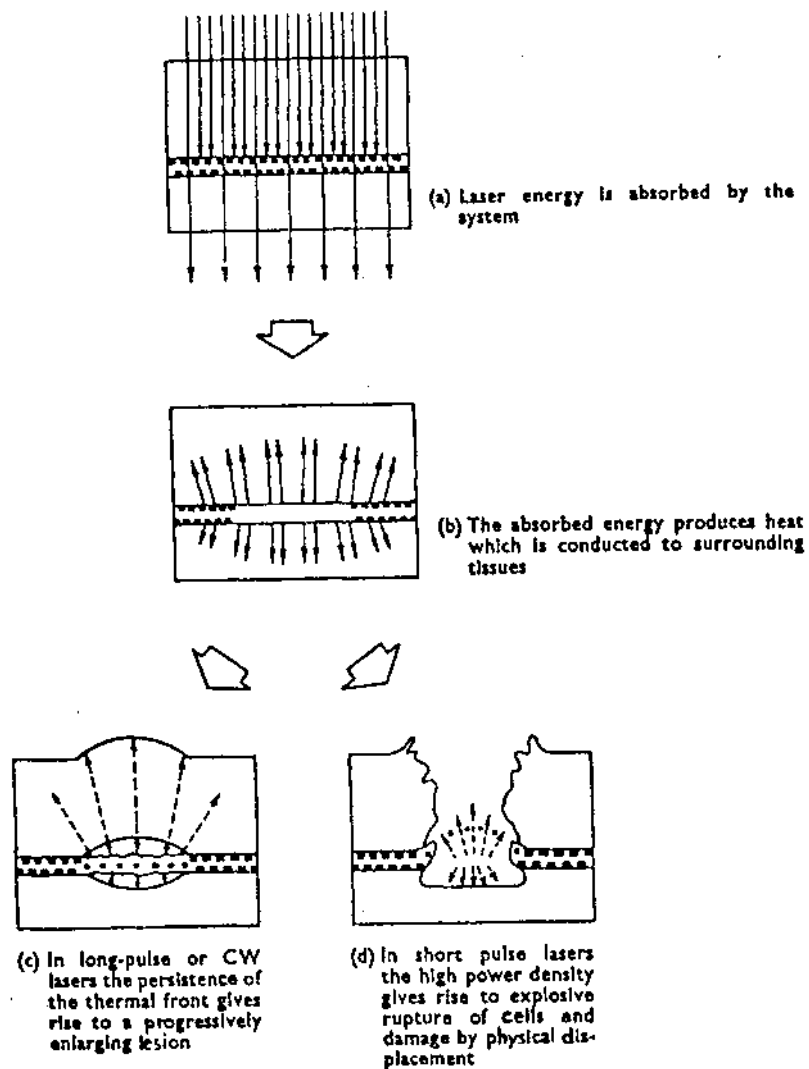


Figure 15: Mechanisms of laser-induced damage (From SAA, 1981).

The retina is not the only organ susceptible to injury. It is the one most at risk because the focusing action of the lens of the eye increases the laser irradiance about 100,000 times from the cornea to the retina. But other parts of the eye can also variously sustain injury, depending on the wavelength of the laser light:

- Ultraviolet B and C is mainly absorbed by the cornea and conjunctiva and this may lead to conjunctivitis and photokeratitis (inflammation of the cornea). Because of the rapid turnover of the corneal epithelial cells damage limited to the outer layer of the cornea is generally temporary.

- Near ultraviolet radiation (UVA) is strongly absorbed by the lens of the eye which is a tissue built up from ribbon-like, transparent cells running completely from the front to the back of the lens. The transparency is a result of a precise relation of the various cell constituents. Damage to any part of a lens fiber will in time extend to the whole fiber which is thicker in the back than in the front. Therefore an injury to the frontal area of the lens will appear to gradually progress to the posterior region and cause a greater visual disturbance as the transparency of the thicker part of the fiber is reduced. The lens cells have a very slow rate of repair and the possibility of damage to this organ must be regarded with great concern as the effects of exposure may not become apparent for many years.

#### Hazard to the Skin

The skin can tolerate a much greater exposure than the eye. However high power lasers may cause effects ranging from a mild erythema to severe blistering. It has also been suggested that under special conditions small regions of human tissue may be sensitized by repeated exposures with the result that the reaction in the tissue is more severe than for normal tissue.

#### Associated Laser Hazards

Beside having the potential for causing injury because of the peculiar qualities of its light output, the laser also poses some of the dangers often associated with the use of any complex instrument handling a large amount of energy.

The greatest risk, which in fact has caused a disturbing number of reported fatalities, is that of electrocution. Almost all lasers have the potential of causing severe and possibly fatal electrical shock. The appropriate standards for electrical safety should be followed when lasers are installed and operated. Research and maintenance personnel are most at risk and should be made familiar with the safety guidelines to prevent electrical shock and with first aid procedures for shock victims.

Chemical hazards arise from the use of toxic substances as the laser media (e.g. halogen gases in excimer lasers) or from the release of airborne contaminants during laser material processing (e.g. fumes produced by laser welding).

Cryogenic coolants used with some types of lasers may create an asphyxiating atmosphere as they evaporate displacing breathable oxygen. Some coolants also pose a fire or explosion hazard.

Other hazards associated with the use of lasers include the following:

- \* possibility of explosions at the capacitor bank or pumping system,
- \* flying particles from the target area during laser welding, cutting or drilling,
- \* high level noise resulting from capacitor discharge or dielectric failure and
- \* production of ozone, uv or ionizing radiation.

It also necessary to remember that eye injury may be caused by radiation emitted from unshielded flash lamps as well as from the laser itself.

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LECTURE 3LASER PROTECTION PRINCIPLES

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INTRODUCTION

Many commercially available lasers are enclosed in a housing that may reduce the risk of exposure to dangerous levels of radiation. Therefore it is more useful to examine the safety characteristics of the 'laser product', meaning a product incorporating a laser, rather than of the laser itself (the definition of laser product will be discussed in detail in lecture 8). The Australian Standard 2211 "Laser Safety" (SAA 1981), which together with that of Japan and a number of European countries is based on the International Electrotechnical Commission guidelines (IEC 1982), defines a system of hazard classification.

Laser products are grouped into one of five categories:

Class 1 laser products are those that are intrinsically safe either because of their low power or because of the safety features incorporated in their enclosure design. These products will not cause eye injury even if the laser output emerging from the product is collected by 80 mm diameter optics and focused into the eye or, in the case of UV or IR lasers, will not cause harm to the eye or the skin at the maximum exposure duration possible during one day of laser operation.

Class 2 laser products are not intrinsically safe but are nevertheless low risk products because sufficient protection is afforded by the natural aversion response to intense light. Obviously a laser product can fall into this class only if the laser output is visible.

Class 3A laser products are also low risk products. They differ from class 2 products in that they emit a higher power in a beam of larger cross section, so that when the output is directly viewed, the power of the beam entering the eye does not exceed that of a class 2 product (the pupil diameter is assumed to be 7 mm). If the beam is viewed through larger diameter optics (eg through binoculars) class 3A lasers pose a definite hazard.

Class 3B laser products are capable of causing eye injury either because their output is invisible and therefore aversion responses are not activated or because the beam power is such that damage is done in a time shorter than the blink reflect ( 0.25 s). However they are not capable of causing serious skin injury or dangerous diffuse reflections under normal use.

Class 4 laser systems present a high risk of injury and can cause combustion of flammable materials. They may also cause diffuse reflection that are eye hazards and serious skin injury from direct exposure.

## SAFETY PRECAUTIONS

### Maximum Permissible Exposure

The basic concept in laser protection is that of the Maximum Permissible Exposure (MPE), that is, the maximum level of radiation to which the eye or skin can be exposed without suffering adverse effects. The MPE is related to the wavelength, the pulse duration or exposure time, the tissue at risk and, if applicable, the size of the retinal image. The MPEs for the eye and the skin can be calculated using the values and the methods given in Appendix A of AS2211. The values given therein are based on the best available published information and incorporate the collective knowledge generated worldwide by research and experience. Although the MPEs do not represent a clear threshold between safe and unsafe conditions they incorporate a comfortable margin of safety. The object of laser protection is to ensure that nobody is ever exposed to more than the applicable MPE. This can be accomplished either through the appropriate selection of the laser or by reducing the exposure (eg by using attenuating filters or by allowing the beam to expand thereby reducing the energy density) or by preventing access to the beam altogether.

### Laser Classification and Precautionary Measures

We will assume that the laser product leaves the manufacturer's hands complying fully with the Australian Standard, that is, it has been classified and bears the appropriate warning signs. The following precautions must be used for the safe use of laser systems:

#### Class 1

no precautions are necessary, provided that the product is not modified or tampered with, as the accessible emission level is below the MPE.

## Class 2

- (a) lasers should preferably be rigidly mounted when they are in use
- (b) the laser must not be directed towards the eye of any person for longer than 0.25 s: this implies that it is permissible to have a class 2 laser beam scanning an area at eye level provided that the scanning rate is such that the beam can move across the diameter of the human pupil (7mm in the worst case) in no more than a quarter of a second.
- (c) an area warning sign must be displayed. The sign must at least contain the same information displayed on the warning sign affixed to the product. The sign details are specified in the Standard.
- (d) the beam must be terminated at the end of its useful path (eg with a cardboard screen) unless the power density of the beam has fallen to a value below the MPE, due for example, to the normal divergence of the beam.
- (e) a responsible person must be appointed as a Laser Safety Officer to assess and implement the above mentioned controls.

## Class 3A

in addition to the precautions required for class 2 lasers:

- (a) only qualified and trained employees approved by the Laser Safety Officer shall be permitted to operate the laser.
- (b) direct viewing of the beam with optical instruments (eg theodolite) shall not be permitted.

## Class 3B and class 4

in addition to the precautions listed above:

- (a) the laser must be operated only in a area to which access can be controlled and which is adequately labelled. If the laser is operated outdoors, caution must be used to avoid directing the laser toward passing traffic for example or, if the laser is directed into the atmosphere, passing aircraft (in this case the Australian Standard requires that the Air Transport Group of the Department of Transport be advised during the planning stage).
- (b) all specular surfaces must be removed from the path of the beam.

In addition to the measures listed above, common sense precautions must also be taken, such as locating the beam well above or below normal eye level whenever possible, limiting access to the beam to the minimum required, etc. Discretionary precautionary measures play a particular role in the case of class 4 lasers which, although always hazardous, may require vastly different degrees of protection. For example termination of the beam may be accomplished with a light cardboard screen in the case of a single pulse, small  $N_2$  laser but may require firebricks in the case of some industrial  $CO_2$  lasers. The skin protection required may or may not be afforded by normal clothing. Even laser goggles may not be very useful for some lasers.

#### Laser Protective Eyewear

The last point needs to be amplified somewhat. Four elements must be taken into consideration when laser protective eyewear is selected:

- (1) ACCEPTANCE. This is the overriding criterion: protective eyewear is only effective if used regularly. If the operator is going to wear them on the forehead all the time and pull them down only before firing a laser pulse, he is relying on his memory more than on the goggles for his safety. Therefore it is advisable to use spectacles rather than goggles, which are uncomfortable, tend to fog up with perspiration and provide poor side vision. Goggles should only be used by visitors who already wear corrective spectacles. Employees who work routinely in laser environments should be allowed to choose the frame style among the variety of lightweight safety spectacles commercially available. Individuals requiring corrective glasses should be provided with prescription lenses manufactured out of an appropriate filter material. Many of the common high power lasers operate in the UV or in the infrared regions of the spectrum. Radiation in both of these spectral regions can be blocked by suitable clear glasses or plastics and in this case it should be possible to induce the employee to wear safety spectacles during the whole working day, if these are comfortable and visually acceptable
- (2) VISIBILITY. Filters designed to be used with lasers operating in the visible will inevitably block more than just the laser wavelength. As a result the possibility of accidents occurring increases as the coloured glasses reduce visibility (the case of green filters designed to block He-Ne and/or ruby laser

radiation is particularly serious since red warning lights and signs disappear!). Visibility is further reduced by the use of opaque side shielding. Fortunately, as already mentioned, many of the high power lasers in use in industry or in research do not operate in the visible and it is possible to obtain excellent protection using clear plastics and glasses.

- (3) ATTENUATION. A convenient, although not rigorous definition of Optical Density (OD) is:

$$OD = \text{Log} (I_i/I_t)$$

where  $I_i$  is the density of light incident on the filter and  $I_t$  is the intensity of this light transmitted through the filter. If, for example, the goggles are used to protect the operator from accidental intrabeam viewing of a 1 ns, 1 MW ruby laser (wavelength = 6943 nm) the required OD will be calculated thus: the MPE obtained from the Standard (table A3) is  $5 \times 10^6$  W/m<sup>2</sup>, the maximum laser power density is equal to the maximum laser power (1 MW) divided by the minimum beam cross section (let's say 1 cm<sup>2</sup>) i.e.  $10^{10}$  W/m<sup>2</sup>. The ratio between this and the MPE is  $2 \times 10^3$ . So the required OD is:

$$OD = \text{Log} (2 \times 10^3) = 3.3$$

A filter with an optical density of 4 will therefore provide adequate protection, while a higher optical density will actually increase the hazards as the visibility will be lower. It is important to remember that the radiating energy absorbed by the filter may cause it to bleach or to shatter. The damage thresholds of absorbing glasses are 5 to 10 J/cm<sup>2</sup> for 30 ps pulses.

- (4) COST. Some low cost plastic lenses offer excellent protection, but tend to get scratched very easily. They are quite adequate for visitors, but may not be the most cost effective choice if they are meant for use by permanent employees. UV protective lenses are now available from optometrists and are a cost saving alternative to imported UV laser spectacles.

It must be always born in mind that protective eyewear is no substitute for the other prescribed precautions.

### Design of Laser Laboratories

The risk of accidents can be reduced by careful design of the optical layout of the laser laboratory itself. Possible sources of diffused or specular reflection should be identified and, if they cannot be eliminated, they should be screened as far as possible. Partial enclosure of the beam where it poses a greater risk is to be recommended.

The door of a laser laboratory should be interlocked to prevent the entry of non-authorized personnel when lasers are operating. An interlock bypass may be added to allow free entry of authorized personnel. The bypass may be key or code operated.

Physical locking of laser laboratories is to be discouraged, considering the fire and other hazards presented in the area.

One or more "panic switches" to cut off the power to all instruments in the laboratory may be valuable in case of electrical accidents etc.

Room lighting should be as bright as practicable in order to constrict the pupil and also to offer adequate visibility where laser spectacles are worn. For the same purpose the walls should be painted in a light color.

Figure 1 contrasts a badly-designed with a well-designed laser laboratory.

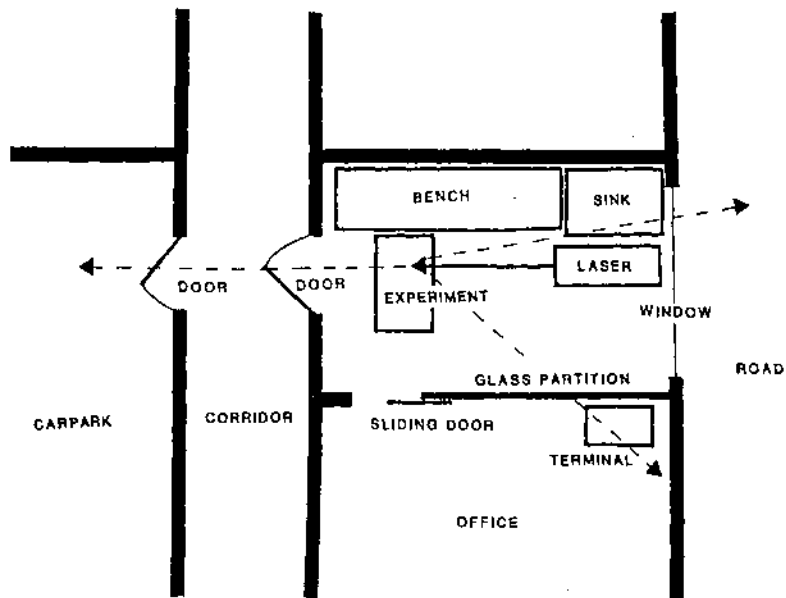
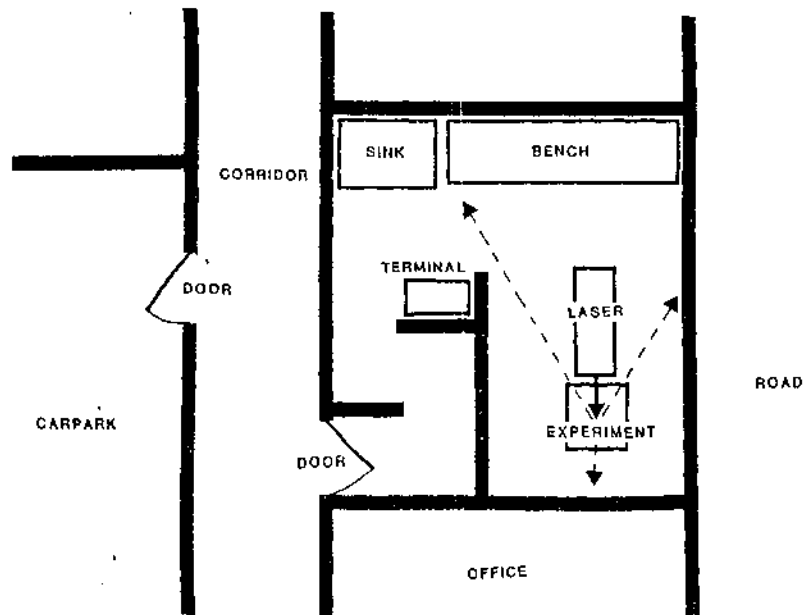


Figure 1: Above: badly designed laboratory - Note

- direct and diffuse laser radiation is not restricted to controlled area.
- location of bench and sink requires crossing the beam path.
- unnecessarily long beam path between laser and target.

Below: careful design obviates the drawbacks encountered above. (Courtesy of W Cornelius).



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IEC (1982). International Electrotechnical Commission. IEC 76 (Central Office) 8, Radiation Safety of Laser Products, Equipment Classification Requirements and Users Guide. Geneva.

SAA (1981). Australian Standard 2211. Laser Safety.

LECTURE 4ULTRAVIOLET RADIATION SOURCES HAZARD EVALUATIONS AND PROTECTION

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INTRODUCTION

The use of ultraviolet radiation (UVR) sources in the scientific, medical, domestic and industrial fields, is becoming increasingly widespread, for example, in sterilization, photopolymerization, photoactivation processes, psoriasis phototherapy and artificial suntanning. UV radiation is also present, as a by-product, in such operations as welding, metal smelting, glass processing and in all processes involving the presence of incandescent materials. These various sources may present a very broad spectrum throughout the UV region. In practice, however, only the radiation in the range between 200 and 400 nm has a direct interaction with living organisms, since at wavelengths shorter than 200 nm the UV radiation is strongly absorbed by oxygen in air (this does, however, produce ozone, the noxious effects of which cannot be disregarded). In this spectral interval, the penetration depth into the human tissues is in the range of 0.1-1 mm; the organs subject to the direct interaction with radiation are the skin and the eyes, on which, as is well known UVR causes short and long-term damage (erythema and carcinoma in regard to the skin, photokeratitis and cataract in regard to the eyes).

The increased spread of UVR sources thus poses the problem of protection (both at the professional and user level) and calls for a set of rules fixing the maximum exposure values for the organs that are subjected to the radiation hazard.

The "American Conference of Governmental Industrial Hygienists" (ACGIH) promulgated, in 1971 (ACGIH, 1981), some criteria for the evaluation of the hazard connected with the use of UVR sources, attributing to the various spectral zones a relative effectiveness varying on the basis of the action spectrum for the production of the most frequent types of damage. The maximum advised exposures correspond within a good approximation, to the threshold values for the production of photokeratitis and cutaneous erythema.

The ACGIH figures are used widely and have been adopted by the US National Institute of Occupational Safety and Health (NIOSH72), the UK National Radiological Protection Board (NRPB, 1977) and are identical to the figures used in the guidelines prepared by the International Radiation Protection Association (IRPA 1985). Following the publication of the IRPA document, it is likely that the National Health and Medical Research Council (NHMRC) will propose its adoption as the Australian ultraviolet exposure standard. Previously the NHMRC recommended the draft IRPA guidelines as an interim standard.

Compliance with the guidelines may cause problems for a number of reasons:

- (a) a strong dependence of the effects (both the short and the long term) on the wavelength;
- (b) variability in the spectral emission of the various sources;
- (c) variability in the skin sensitivity to radiation;
- (d) difficulty in estimating the risk/benefit ratio;
- (e) difficulty of correct dosimetry.

The latter point is shown by the fact that, whilst in the most refined laboratory measurements the radiometric quantities are affected by errors of a few percent, in practical routine measurements such small values are not even approached - the errors being at times as high as 100%.

A number of commonplace UVR sources including various fluorescent lamps, sunlamps discharge lamps, black lights, welding arcs and solar radiation will be investigated. The spectral irradiance in the 200-400 nm will be weighted by the ACGIH spectral sensitivities adopted by ACGIH and IRPA and the total effective irradiance determined.

Where sources are deemed to be potential hazards, protection against overexposure may be achieved by a combination of:

- (a) administrative control measures,
- (b) engineering control measures,
- (c) personal protection.

Emphasis should be placed on administrative and engineering control measures to minimise the need for personal protection. This will be discussed in detail.

GUIDELINES FOR OCCUPATIONAL EXPOSURE TO ULTRAVIOLET RADIATION

The development of an exposure limit (EL) to UVR for workers and the general population must consider the risks of acute and chronic injury to the skin and/or the eye.

## Ultraviolet Effects on the Skin

Exposure to UV-B (280 to 315 nm) and UV-C (200 to 280 nm) radiation results in erythema or reddening of the skin (sunburn). A similar effect can also be obtained with UV-A (315 to 400 nm) but the dose required is much greater. The action spectrum of ultraviolet erythema was initially investigated in the 1920's and 1930's (Coblentz and Stair, 1934). The key findings are generally summarized by a standard action spectrum. The importance of noting the length of time after exposure for the various degrees of erythema to develop and the value of defining the action spectrum at a well-defined degree of redness and not at the just-perceptible erythema was emphasised.

Recent dermatological investigations have found the action spectrum for this just-perceptible erythema to be quite different from the original curve. Erythema thresholds vary significantly with skin pigmentation (over at least one order of magnitude).

In applying an action spectrum to the development of hazard criteria for industrial exposure, one must make a judgement of what exposure limits will result in unwanted acute and chronic effects. Erythema production for a given spectral source is dependent only on the total dose; reciprocity exists between exposure rate and exposure duration over a wide range of exposures (<0.01 sec to several hours).

Chronic exposure to ultraviolet radiation accelerates skin aging and it is now generally felt that such exposure increases the risk of developing certain types of skin cancer. Since UV-B radiation penetrates more deeply into the skin than UV-C radiation, UV-B has been thought to be the most effective in affecting living tissue, as is attested by its capability of producing the more severe grades of erythema. Several epidemiological studies of skin cancer incidence reveal a very strong correlation with terrestrial solar UV-B levels.

A quantitative threshold for carcinogenesis by ultraviolet radiation appears to be very difficult to define, if indeed one exists. Epidemiologic studies correlating solar ultraviolet exposure with skin cancer may shed some light on whether quantitative thresholds exist for human skin cancer.

#### Ultraviolet Radiation and the Eye

The retina responds to near-ultraviolet radiation as to light; however, the lens of the eye is a strong absorber of wavelengths shorter than 400 nm and the resultant spectral sensitivity for vision markedly decreases between 420 nm and 380 nm.

UV-B and UV-C radiation are absorbed in the cornea and conjunctiva, and in sufficient doses will cause keratoconjunctivitis, a painful effect often known as welder's flash. The action spectrum and threshold dosage of ultraviolet keratoconjunctivitis have been investigated by several groups (Pitts et. al., 1977, 1981). General agreement may be found in the results of the different investigators if differences in experimental techniques, instrumentation, and subjects are considered. The peak of the photokeratitis action spectrum was at 265-275 nm and a threshold at that wavelength of approximately  $40\text{J/m}^2$  for both human and primate eyes. These studies did not reveal an action spectrum for conjunctivitis different from keratitis. Unfortunately, this action spectrum, when weighted against the ultraviolet spectrum of indirect daylight to which the eye is daily exposed, would indicate that almost everyone would develop keratoconjunctivitis in a few hours while standing outdoors.

This would indicate that the investigators had experimental difficulties in accurately determining the obviously extreme slope of the action spectrum in the 300-315 nm range. Individuals do develop keratoconjunctivitis from daylight ultraviolet radiation but only after prolonged exposure to ultraviolet reflected from snow (an aspect of snow blindness). Accidental exposures to ultraviolet radiation from germicidal lamps (which emit principally at 253.7 nm) indicate a human threshold for photokeratitis of approximately  $100\text{J/m}^2$ , in reasonable agreement with the data of Pitts.

#### Envelope Action Spectrum

In the UV-B and UV-C regions, an action spectrum curve can be drawn which envelopes the threshold data for exposure doses in the range of reciprocity for acute effects obtained from studies of minimal erythema and keratoconjunctivitis. This EL curve does not differ significantly from the

collective threshold data considering measurement errors and variations in individual response. The curve is also well below the acute UV-B cataractogenic thresholds. Repeated exposure of the eye to potentially hazardous levels of UVR is not believed to increase the protective capability of the cornea as does skin tanning and thickening of the stratum corneum. Thus, this EL is more readily applicable to the eye and must be considered a limiting value for that organ. Any dose accumulation of UV-B and UV-C exposures causing photokeratitis is limited to about 48 hours since the outer corneal epithelial layers are replaced in about 48 hours. The envelope curve and some of the experimental data used for the derivation is given in Figure 1. The safety factor for UV-A EL's is large.

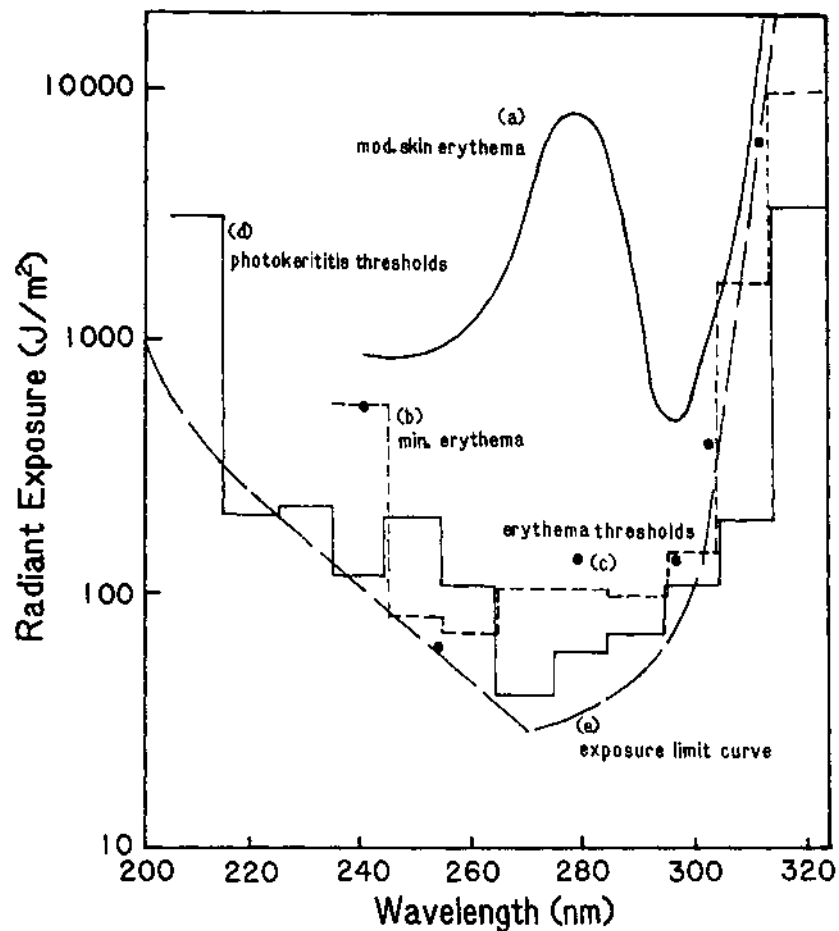


Figure 1: Ultraviolet exposure limit curve. Threshold data of (a) Coblenz and Stair (1934), (b) Freeman et al (1966) and Everett et al (1965), (c) Berger et al (1968), (d) Pitts and Tredici (1971) and (e) ACGIH (1981) and IRPA (1985).

The National Health and Medical Research Council (NHMRC) of Australia has adopted the draft IRPA guidelines as an interim ultraviolet occupational exposure standard. Following the publication of the IRPA document it is expected that NHMRC will recommend its adoption as the Australian Exposure Standard. The exposure limits are given in Appendix 1.

The spectral sensitivity curve used by ACGIH and IRPA is shown in Figure 2. The flat response in the UV-A is quite conservative and a modified version which employs relative UV-A sensitivities (Van der Leun, 1965) has also been used here for comparison.

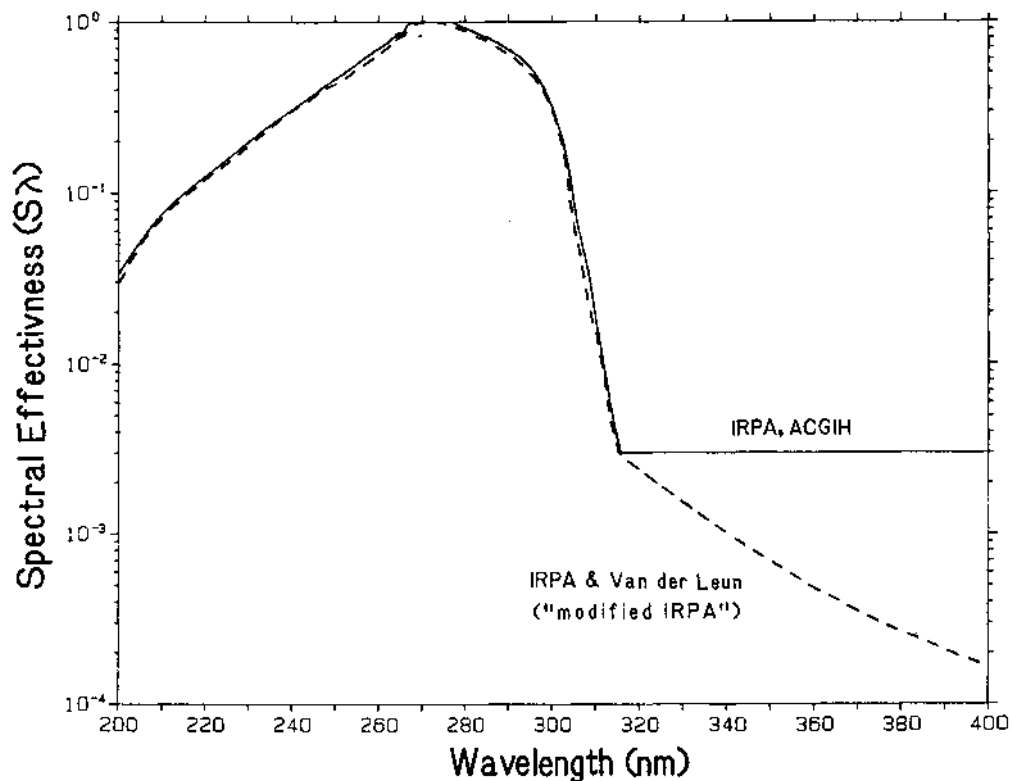


Figure 2: Spectral effectiveness curves used by IRPA and ACGIH.

Because of the wide variations in threshold values and exposure history (conditioning) among individuals, these figures should only be used as a guide for evaluating skin hazards. The envelope guideline has some margin of safety to protect all but the most sensitive individuals. An exact value for this margin cannot be given, but for lightly pigmented persons, the factor varies from about 3 to 20 depending on spectral composition of the radiation. Since there may be more than one erythematous mechanism and, therefore, more than one erythematous action spectrum, the effect of radiation of two widely differing

wavelengths in the 200 nm to 315 nm range may not be simply additive. The EL should be used with caution in evaluating sources such as the sun having a rapidly increasing spectral irradiance in the 290-310 nm range. Large errors can arise because of the difficulty in making accurate spectral measurements of such sources in this region.

The EL may not provide adequate protection for photosensitive individuals or for normal individuals exposed concomitantly to chemical, pharmaceutical, or phyto-photosensitizers, and special precautions must be taken for such cases.

The EL should reduce the risk of occurrence of chronic skin effects by preventing acute effects and limiting life-long UVR exposure. An action spectrum for UVR skin carcinogenesis is not known for man, although the erythemic action spectrum has been used for global estimates of UV exposure. It should be remembered that occupational exposure to UV-B adds to an individual's nonoccupational exposure to solar UV-B.

In the UV-A region there is only limited data available on which an EL may be established. However, few industrial sources emit sufficient intensity in this spectral region to cause adverse biologic effects. Skin damage is principally thermal in nature requiring very high irradiances except in photosensitive individuals. Photokeratitis and lenticular opacities have been produced in experimental animals with acute exposure at high radiant exposures. There are no indications that the low levels of UV-A found in most indoor work environments present a hazard although it has been hypothesized as one causative agent for cataract in the past. Thus, the EL for UV-A should be below most conceivable thermal or photochemical injury mechanisms.

#### Ultraviolet Radiation Sources and Hazard Evaluations

A number of different sources of UVR will be investigated including various lamps, welding arcs and solar radiation. Table 1 (p 76) is a Summary of results, measured and calculated, for all sources.

##### A. Lamps

The general characteristics of lamps and pertinent technical characteristics will be briefly reviewed. There are several methods for cataloging lamps from the standpoint of potential hazards it is convenient to use the following categories:

- a. incandescent filament lamps
- b. low pressure discharge lamps

- c. fluorescent lamps
- d. high intensity discharge lamps
- e. short arc lamps
- f. carbon arcs

(a) Incandescent lamps

Solid-body incandescent materials such as iron and tungsten used in filament lamps seldom exceed black-body temperatures of 3000K. From Figure 3 it can be seen that their spectral distributions peak in the red end of the spectrum with a relatively small fraction of visible (blue) and UV radiation. Such light sources present no problems from a safety standpoint and will not be considered in detail.

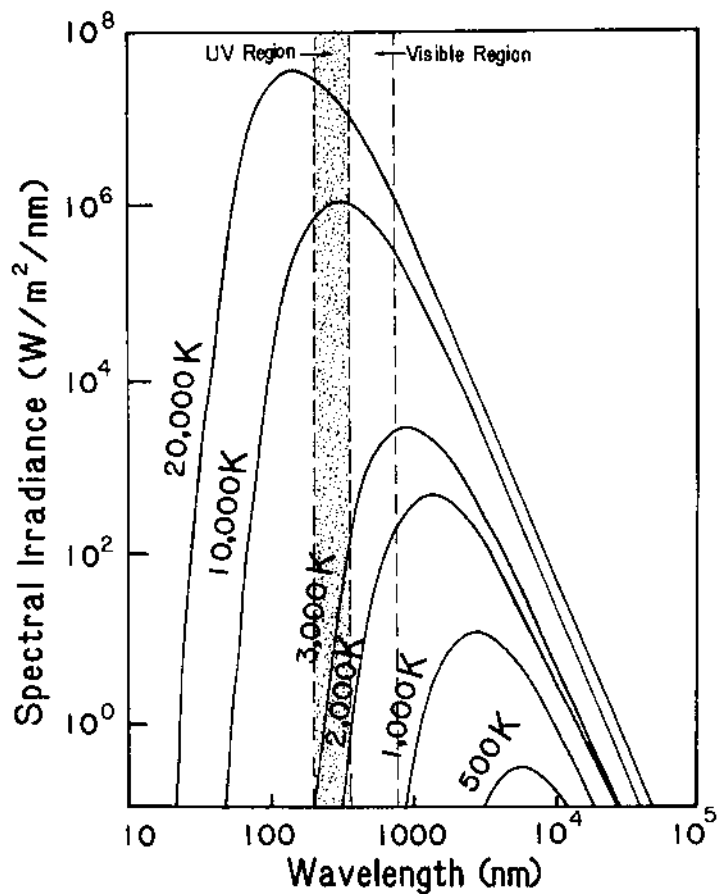


Figure 3: Blackbody emission as a function of temperature.

(b) The low pressure discharge (mercury) lamp

The mercury lamp in the various forms is one of the most important and widely utilised light and UVR sources. It is also potentially hazardous. The lamp consists of a UV transmitting tube with an electrode at each end. The

filling is not mercury alone, but a mixture of a single drop of mercury and an inert gas, usually argon, at a pressure of a few torr. The pressure of mercury is just its vapour pressure (7mT) at the operating temperature, which is approximately 40°C. The inert gas is therefore at a much higher pressure than the mercury, but contributes almost nothing to the spectral output. However it plays a vital part in both the establishment and the maintenance of the discharge. When a lamp is first switched on, electrons are accelerated in the electric field. Because the vapour pressure of mercury is so low, most of the collisions which take place are between electrons and argon atoms. The lowest argon excited state is metastable, i.e. non-radiative but on collision can cause ionisation of a mercury atom.

Mercury emission occurs at a number of specific wavelengths including the UV wavelengths of 189, 254, 297, 303, 313 and 365 nm. However almost 90% of energy is emitted at 254 nm. The 254 nm radiation is a highly reactive wavelength to the eyes and skin and extreme care must be taken in its use.

Germicidal or UV-C lamps are effective in destroying bacteria and moulds and are used extensively in hospitals, cold-storage facilities, and food handling and processing rooms. A typical spectrum is shown in Figure 4. The spectral irradiance, weighted as indicated in the Appendix, is also shown. The weighted spectral irradiance is  $34 \text{ mW/cm}^2$  and a total exposure time of only approximately 15 minutes (see Appendix, Table 2) is permitted. These lamps are normally in either enclosed cabinets or mounted in a room in such a manner as to reduce the irradiances to an acceptable level.

Portable domestic sunlamps have similar emission spectra as shown in Figure 5. Although these units are used predominantly in non-occupational situations they are potentially hazardous with an effective irradiance of  $63 \text{ mW/cm}^2$  at 1.6m. An Australian standard dealing with safe use of sunlamps is presently in preparation.

### (c) Fluorescent lamps

Most low pressure mercury lamps are used for lighting, with a fluorescent powder coating on the inside wall which converts the 185 and 254 nm radiation from the arc into visible radiation suitable for illumination. Fluorescent tubes are also used for purposes other than illumination with fluorescent coatings chosen to emit bands of radiation centering on wavelengths between about 300 and 450 nm. The most common emits a broad band of UV-A, with peak emission at 360-370 nm. There are two versions of this lamp. One has a tube

made from normal soda glass and the other a tube made from "Wood's" glass. Wood's glass contains oxides of nickel and cobalt, and is opaque to visible radiation but transmits UV-A. Lamps having such phosphors or filters are called "blacklight" units.

There is always an energy loss when a fluorescent wavelength converter is used because even if the quantum yield is unity, each energetic 254 nm photon is converted into a less energetic photon of a longer wavelength.

In the study of solarium (artificial suntanning establishments) two different types of UV fluorescent tubes were encountered (Gies et. al., 1985). UV-B tubes (Figure 6) found in 'stand-up' tanning booths and UV-A tubes (Figure 7) which are used in sunbeds. An Australian Standard (SAA, 1983) now covers the artificial suntanning industry and only UV-A lamps would meet the emission requirements. The main use of these lamps are in the medical (phototherapy) and recreational areas and would rarely be encountered in occupational situations.

Blacklights are often used with fluorescent powders in many nondestructive testing applications as well as for special effects in entertainment. Figure 8 shows a typical emission spectrum. The measured UV-A irradiance at a distance of 0.8 m was  $10.5 \text{ W/m}^2$  slightly greater than that permitted by the IRPA standard. This unit contains a mercury lamp with a "Wood's" filter physically held in front. Problems would arise if leakage around the filter occurs or if the filter was cracked.

#### (d) High intensity discharge (HID) lamps

The most common HID lamps are mercury, high-pressure sodium and metal-halide lamps. Gas pressures are typically 2-4 atmospheres. These lamps often present potential hazards and require evaluation. Most employ two envelopes - the inner envelope or arc tube is generally of quartz while the outer envelope is typically of hard borosilicate glass. The outer envelope is to minimise ambient temperature and draft changes but it also plays an important role in filtering out UV-B and UV-C radiation. The lamps are sometimes operated with fluorescent phosphors in the outer envelope. In high pressure mercury discharge lamps the emission is no longer exclusively the atomic spectral lines of the low pressure lamp but is a continuum with the five principal visible emission lines (405, 436, 546, 557 and 559 nm) having much of the output energy.

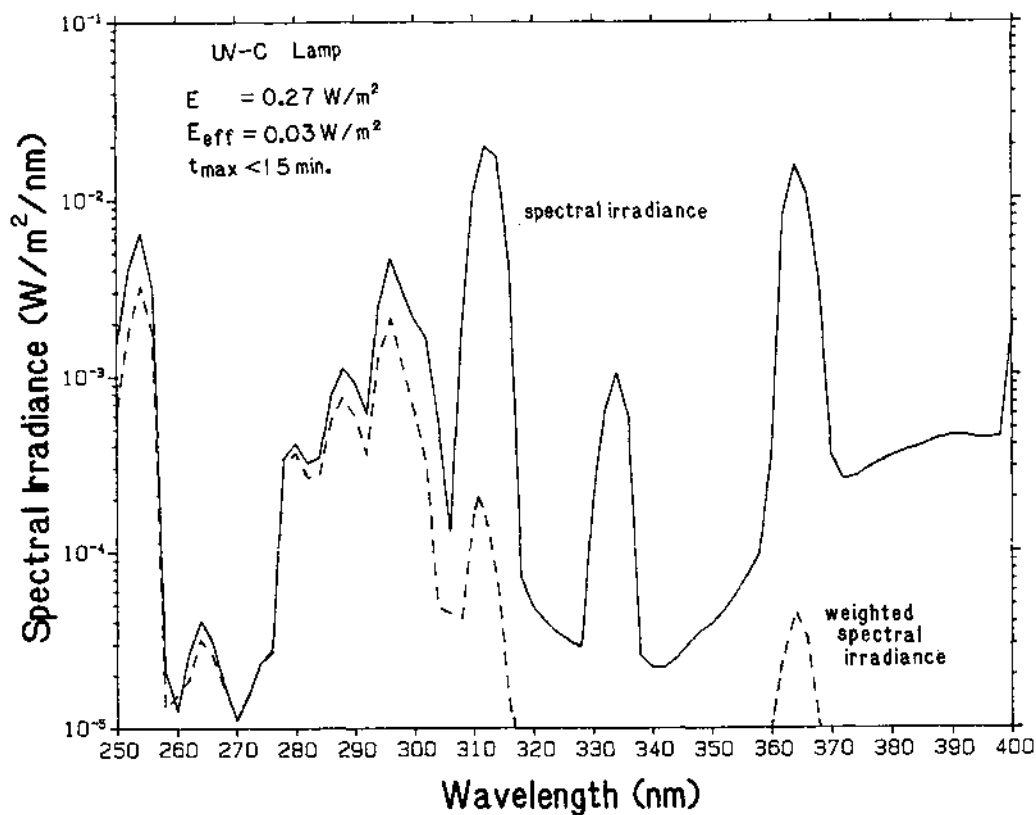


Figure 4: Spectral irradiance of a UV-C or germicidal lamp. Dashed curve represents the weighted distribution.

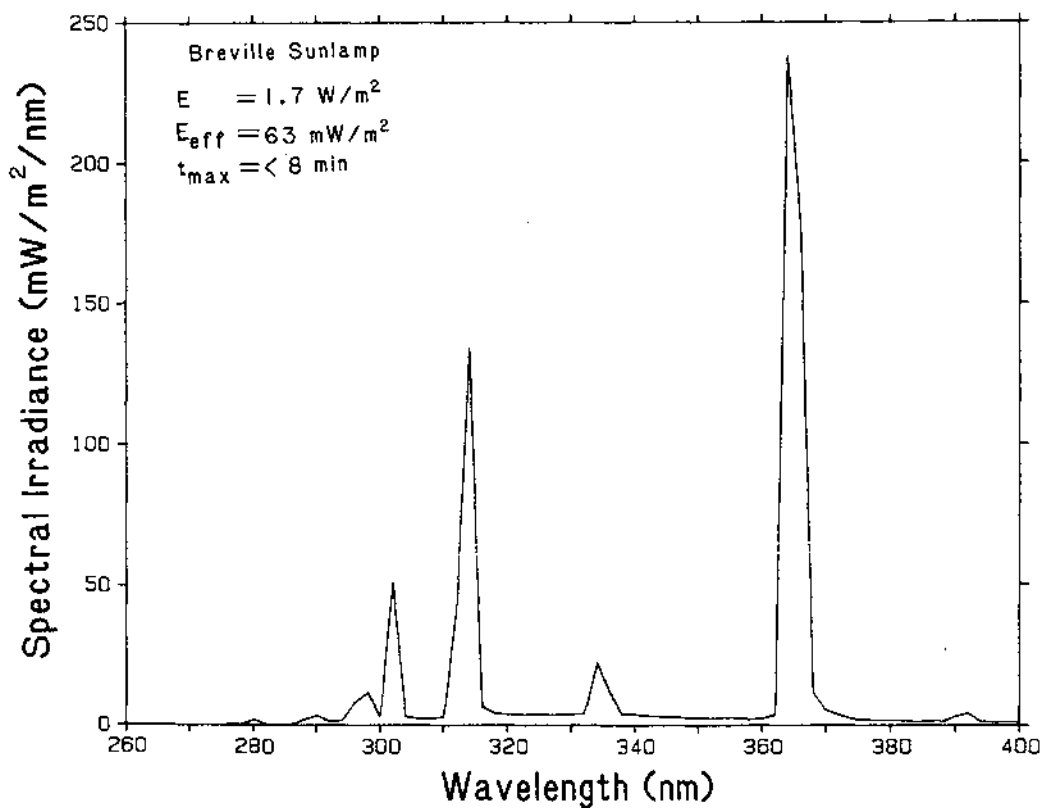


Figure 5: Spectral irradiance of a Breville Sunlamp.

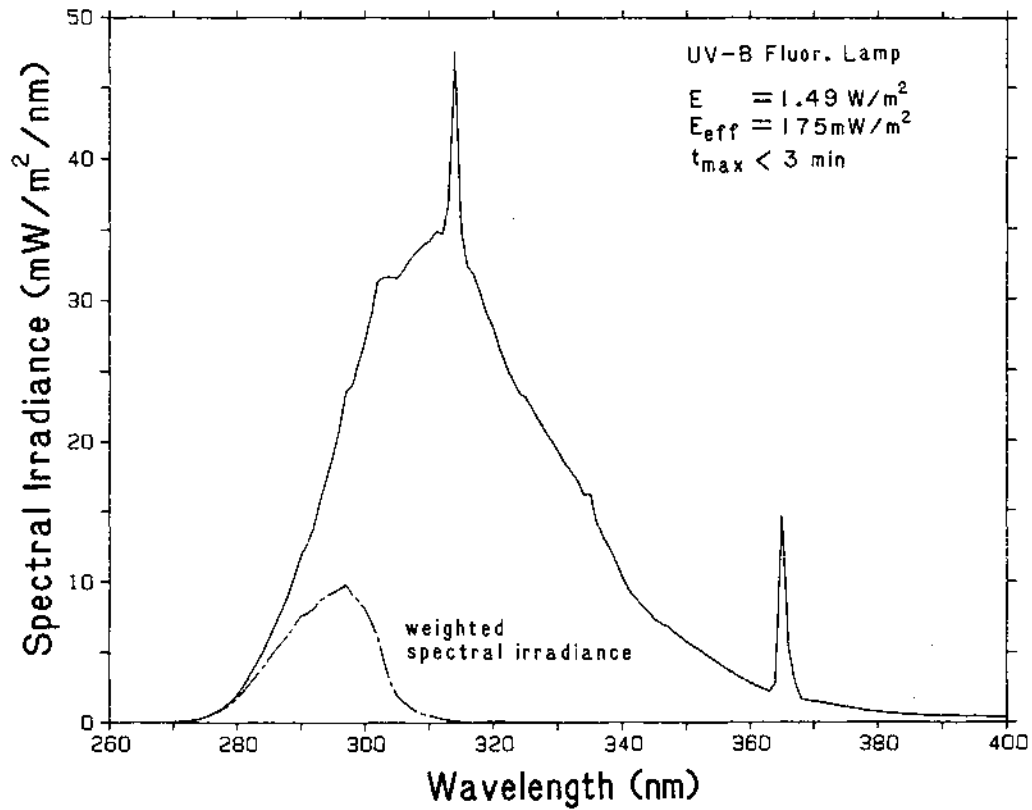


Figure 6: Weighted and unweighted spectral irradiance of a UV-B fluorescent lamp.

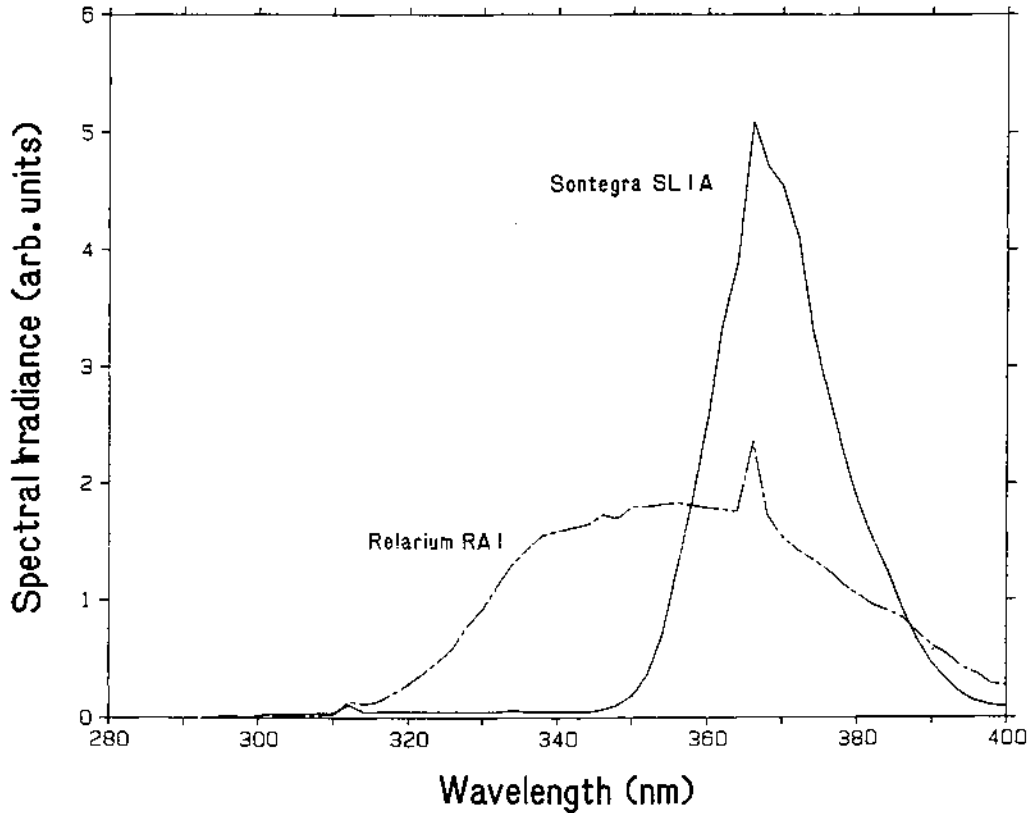


Figure 7: Spectral irradiance of two different UV-A fluorescent lamps.

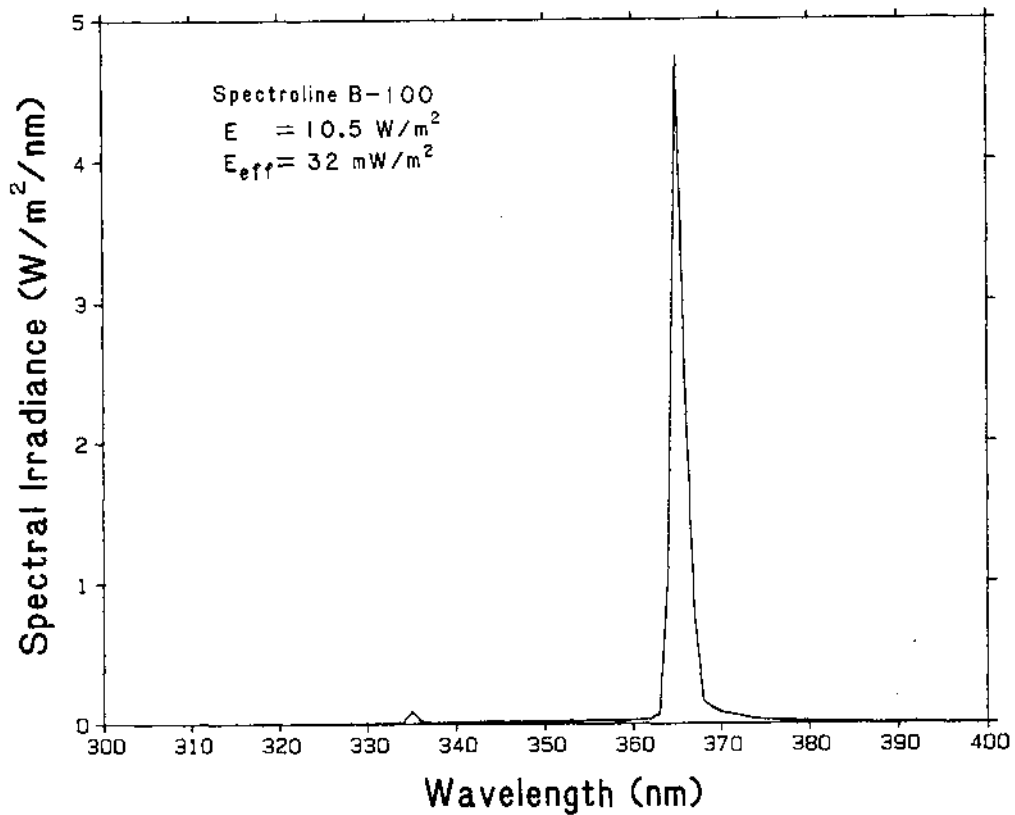


Figure 8: Spectral distribution of a Spectroline B-100 blacklight.

The high pressure sodium lamps are being used increasingly for outdoor and more recently indoor lighting. The lamp is constructed with two envelopes the inner of polycrystalline alumina which has a low transmittance for UV-B and UV-C. These lamps are not considered hazardous.

The metal halides lamps are very much like mercury lamps with a phosphor coating. These lamps contain mercury as well as mixtures of various metal halides (sodium, thalium, indium etc).

(e) Short-arc lamps

Short, compact-arc (0.3 to 10 mm gap) lamps are the brightest continuous lamp sources available, and are typically used for searchlights and solar simulators. The short-arc lamps are generally direct current (dc) and specialized starting circuits and high-current, low-voltage power supplies are required. Xenon, mercury-xenon, and mercury are the most common. All of the short-arc lamp types employ quartz envelopes and therefore emit sufficient UV-B and UV-C radiation to present serious eye and skin hazards for direct exposure. The quartz envelopes are exceedingly hot and would cause burns of the skin if touched momentarily. In addition, the high-pressure lamps present an explosion hazard if not handled carefully.

(f) Carbon arcs

Carbon-arc sources were once widely used, but they have generally been replaced in projectors, spotlights and searchlights by short-arc lamps. The arc is open, as in a welding arc and produces an emission rich in UV-B and UV-C as well as visible.

B. Welding arcs

The largest number of personnel exposed to intense sources of optical radiation would be welders and their assistants.

There are two broad categories of welding equipment - gas (acetylene) welding and electric-arc welding. The ultraviolet emission from a gas welding torch is quite small and is not considered a hazard.

There are a variety of different arc welding and cutting processes and all vary in their UV emission. Examples of welding processes include carbon arc welding (CAW), shielded metal arc welding (SMAW) gas tungsten arc welding (GTAW), gas metal arc welding (GMAW) and plasma arc welding (PAW). The most common shielding gases are argon, helium and carbon dioxide. The irradiance depends on the type of process and the arc current. The structure in the spectrum is due to the metals involved and to the shielding gases. It has been found that the average spectral irradiance does not vary greatly from the UV to the near infrared and is typically of the order of  $10 \text{ mW/m}^2/\text{nm}$  at a distance of 1 m.

The emission spectra from three different arc welding processes are shown in Figure 9 and additional information is given in Table 1. Extremely high effective irradiances are calculated and it is obvious why full protection (approximately  $100\text{-}1000 \text{ mW/m}^2$ ) is required for the operators and nearby workers.

C. Video Display Terminals (VDTs)

In recent years concern has been expressed that radiation emissions from VDTs could be a health hazard for operators. The results of a comprehensive measurement programme have been published by ARL (Joyner et. al. 1984).

The UV emission is simply the tail of the visible peak. Typical results are given in Figure 10 for different colours generated on a Wang colour VDT. The measured irradiances are between three and six orders of magnitude below the UV-A recommended limit. Hence UVR emissions from VDTs are of no concern.

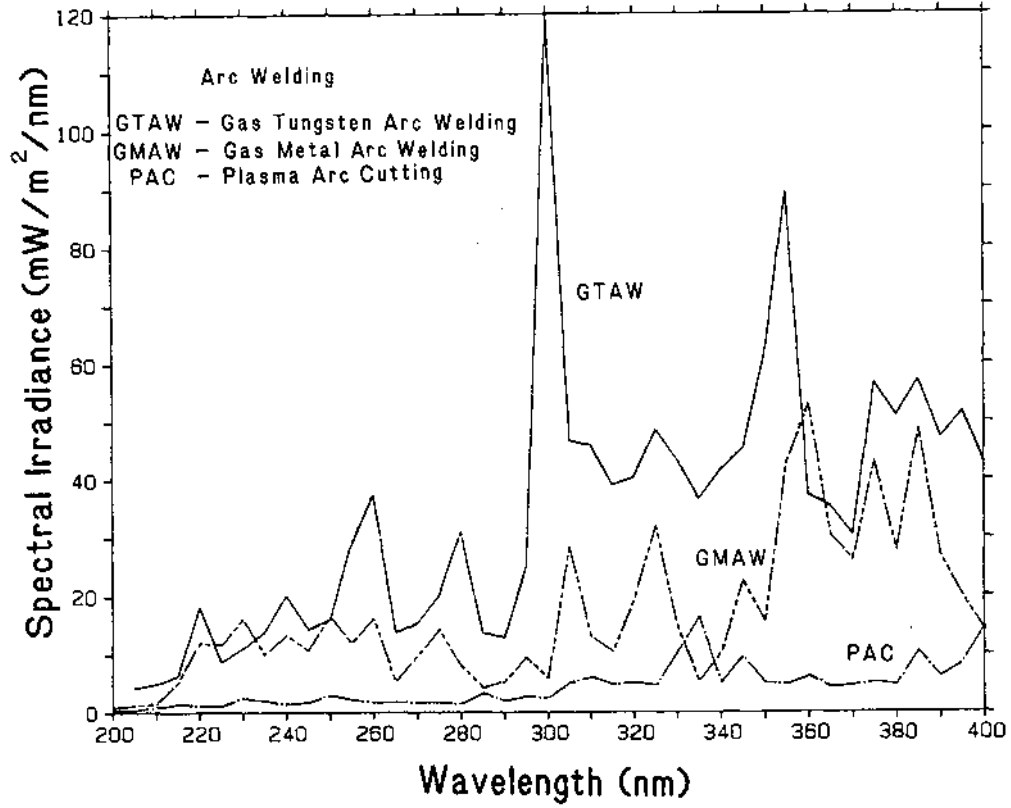


Figure 9: Spectral irradiance of three welding processes. Original data from Lyon et al (1976).

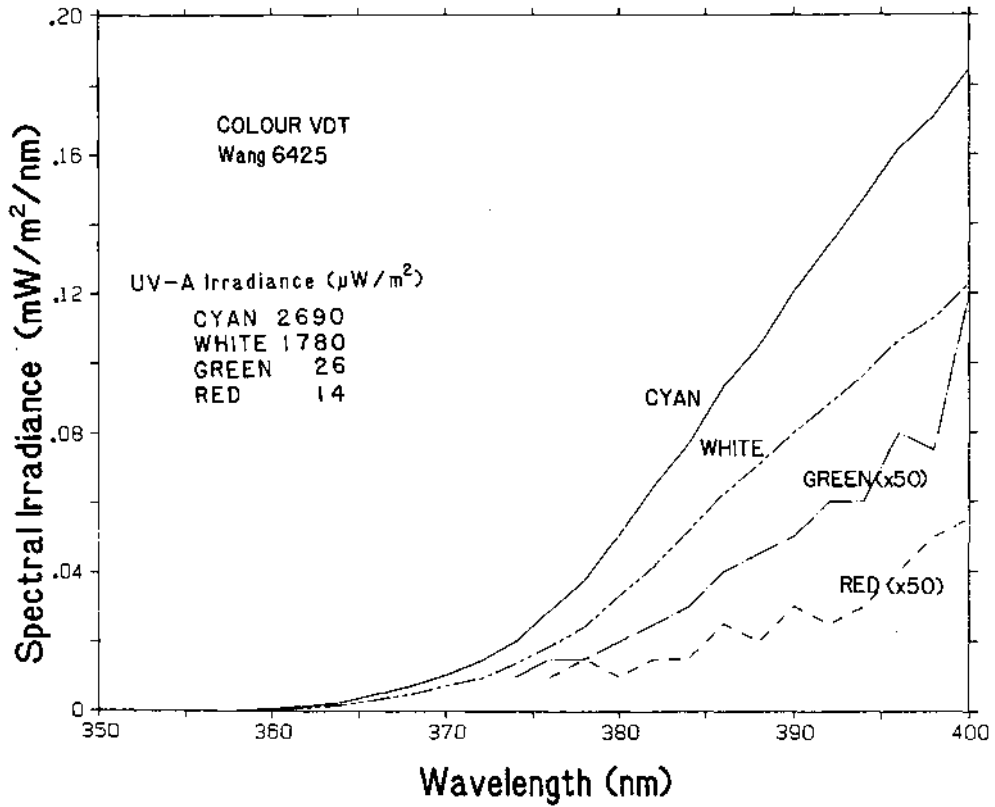


Figure 10: Ultraviolet spectral irradiances of a colour video display terminal.

#### D. Solar Radiation

If it is assumed that the sun radiates as a blackbody it can be calculated that the effective temperature of its surface is approximately 6000K. From Figure 1 it can be seen that as the temperature of the blackbody increases the peak wavelength shifts to shorter wavelengths (Wiens Displacement Law) and appreciable UVR is emitted.

The extra terrestrial solar radiation (solar constant) is approximately  $1351 \text{ W/m}^2$  of which a  $900 \text{ W/m}^2$  reaches the earlier surface. About  $45 \text{ W/m}^2$  is UV-A and  $2 \text{ W/m}^2$  UV-B.

A typical noontime summer solar spectrum is given in Figure 11. Also shown is the weighted spectral distribution. Less than 4% of the solar UVR is UV-B however on weighting this figure rises to 37% (IRPA, ACGIH weighting) or 72% (modified IRPA weighting).

The solar exposure permitted to an unprotected outdoor worker would be limited to only a few minutes if the exposure took place at noon. Permitted times increase rapidly prior to 1000 hours or after 1400 hours. In any case workers or non-workers should be completely protected outdoors.

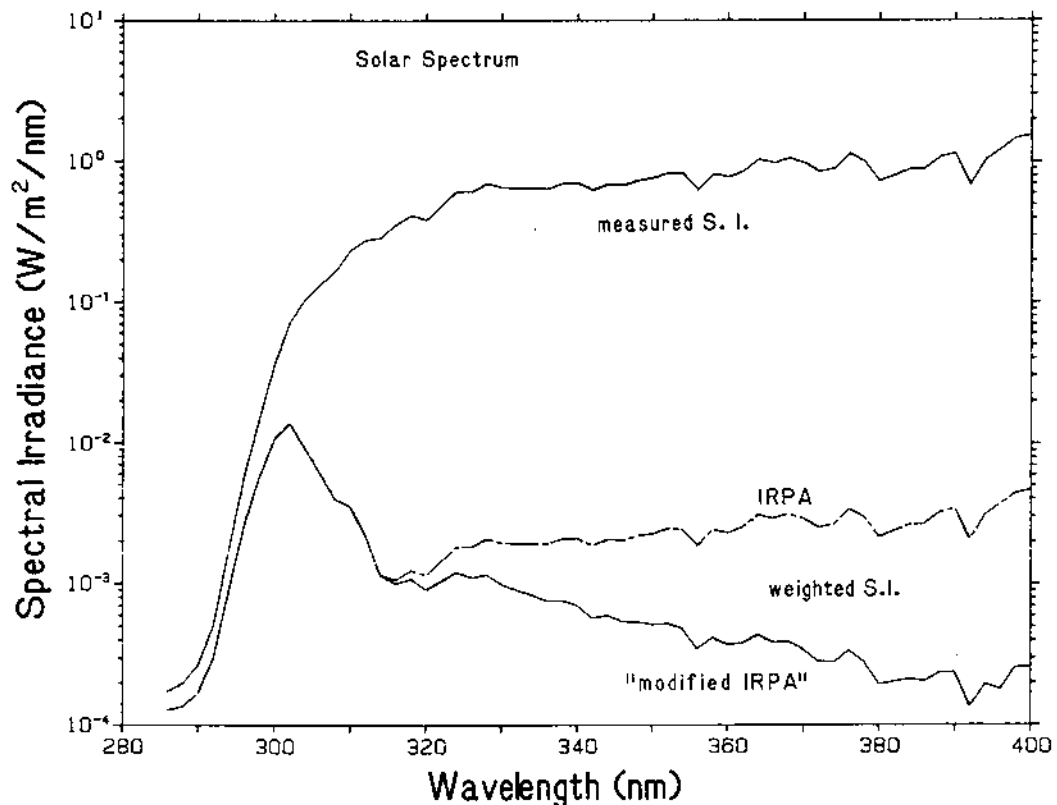


Figure 11: Weighted and unweighted solar spectral irradiances.

### PROTECTION AGAINST OVEREXPOSURE TO UVR

Although many sources of ultraviolet radiation also emit copious quantities of visible light, some do not. For example, germicidal lamps which generate large amounts of ultraviolet radiation give off only a faint visible glow. It is unsafe, therefore, to judge hazard potential solely by brightness.

Where sources are powerful enough to be a hazard, protection against overexposure may be achieved by a combination of:

- (a) administrative control measures,
- (b) engineering control measures,
- (c) personal protection.

Emphasis should be placed on administrative and engineering control measures to minimise the need for personal protection.

#### Administrative Control Measures

##### Limitation of access

Access to an area where equipment emits ultraviolet radiation should be limited to those persons directly concerned with its use.

##### Hazard awareness

All persons concerned with the use of equipment which emits ultraviolet radiation should be made aware of this and should be informed of the hazards.

##### Hazard warning signs and lights

Hazard warning signs should be used to indicate the presence of a potential ultraviolet radiation hazard. Warning lights may be used to show that the equipment is energised.

##### Distance as a safety factor

The user should keep as far away from the source of ultraviolet radiation as is practicable. As a rule of thumb, at large distances (greater than twice the greatest dimension of the source) the intensity of the radiation falls off as the square of the distance from the source. At shorter distances, the intensity falls off approximately linearly with distance.

#### Limitation of exposure time

The exposure time should be kept to the minimum, and the maximum exposure limits given in the Appendix should not be exceeded.

#### Maintenance work on equipment emitting ultraviolet radiation

Maintenance work often requires an engineer to be very close to the source. The power supply must be disconnected before any work is carried out; to ensure this the equipment should be interlocked.

### Engineering Control Measures

#### Containment

Indiscriminate emission of ultraviolet radiation into the workplace must not be allowed. This can be prevented either by carrying out the process within a sealed housing or by providing a screened area.

#### Sealed housings

Wherever possible, the radiation should be contained within a sealed housing. If observation ports are required they should be made of suitably absorbent materials such as certain grades of acrylics, PVC and window glass.

#### Screened areas

Where the exposure process takes place external to the source housing, a screened area should be provided where it may be carried out. Such an area would be subject to the administrative control measures outlined above. Persons entering the area should be adequately protected from the ultraviolet radiation, as described below.

#### Use of interlocks

Interlocks should be fitted to the source housing to prevent excessive and unnecessary exposure. Interlocks are necessary where the removal of a cover from the housing could result in a high exposure.

#### Elimination of reflected ultraviolet radiation

Many surfaces, especially those of shiny metal or glossy light-coloured paints, are good reflectors of ultraviolet radiation. To reduce the intensity of reflected radiation, surfaces should be painted in a dark, matt colour.

## Personal Protection

### Protection of the skin

The most effective way to protect the skin from ultraviolet radiation is to cover it. The areas of skin usually at risk are the backs of the hands, the forearms and the face and neck. The hands can be protected by wearing gloves. The arms should be covered by long sleeves of material with low UV-B transmission. In general, materials which are visibly opaque are suitable. The face can be protected by a face shield and this will also provide eye protection.

Further information can be found in Australian Standard 1558-1973 (amended 1978) Protective clothing for welders.

### Protection of the eyes

Goggles, spectacles or face shields which absorb ultraviolet should be worn where there is a potential eye hazard. In welding operations, there is also the possibility of retinal damage from the intense visible radiation emitted. Welders should be protected by a welding helmet or mask fitted with the appropriate absorption filters. Information about such protection is contained in the Australian Standards 1338 (SAA, 1981) and 1336 (SAA, 1982).

Some high pressure lamps are potential explosive hazards and the eyes should be protected against flying fragments of glass. Particular care should be taken to protect the eyes and hands when such lamps are being removed or replaced.

### Hazards from ozone

The photochemical interaction of short wavelength ultraviolet radiation and oxygen in the air forms the colourless toxic gas, ozone. Ozone is a powerful oxidising agent and cells on the body surfaces may be damaged when they are exposed to it. A concentration higher than 0.1 parts per million, the threshold limit value, may cause smarting of the eyes and a feeling of discomfort in the nose and throat. However, this concentration should be detectable by smell, the gas having a characteristic, penetrating odour. Exposure above this concentration can damage the cells lining the airways of the lung and produce a form of bronchitis. Exposure to concentrations in excess of 1 part per million can cause acute and serious interference with the normal function of the lung and may lead to convulsions and loss of consciousness.

The hazards from ozone may be avoided by ensuring adequate ventilation in the area around a source. Very intense short wavelength sources may require an extraction system to remove ozone.

### CONCLUSIONS

The acute effects of overexposure to ultraviolet radiation are generally painful and should act as a deterrent against further exposure. The effects of repeated exposures may be much more serious but may not become apparent for several years.

It is therefore important to protect against unnecessary exposure. Protection may be achieved by a combination of administrative and engineering controls, and personal protection. In many cases it will be easy to decide on the control procedures to adopt.

TABLE 1. WEIGHTED AND UNWEIGHTED IRRADIANCE  
AND SPECTRAL DISTRIBUTION OF SOME UVR SOURCES

Source	Distance	Irrad. W/m <sup>2</sup>	Weighted Irrad. mW/m <sup>2</sup>	Distribution of unweighted (weighted) UVR			tmax sec.
				%UV-C	%UV-B	%UV-A	
UV-C germicidal lamp	180 mm	0.27	34	11.2(46.2)	50.5(52.9)	38.3( 0.9)	880
UV-B fluorescent lamp	460 mm	1.49	175	0.4( 3.5)	51.3(95.3)	48.2( 1.2)	170
Sontegra UV-A fluor.lamp	~50 mm	8.2	30	- ( - )	0.8(18.6)	99.2(81.4)	1000
Relarium UV-A fluor.lamp	~50 mm	22.0	68	- ( - )	0.7( 3.1)	99.3(96.9)	440
Breville Sunlamp	1.6 m	1.7	63	0.2( 6.0)	32.0(88.6)	67.7( 5.5)	480
B-100 blacklight	0.8 m	10.5	32	<0.1( 0.9)	<0.1( 1.6)	99.9(97.5)	-
GTAW welding arc	1.0 m	6.81	1070	18.2(59.7)	22.0(39.2)	59.8( 1.1)	285
GMAW welding arc	1.0 m	3.44	465	23.5(78.7)	11.0(19.9)	65.5( 1.5)	65
PAC welding arc	1.0 m	0.86	96	15.6(61.9)	14.5(36.2)	69.9( 1.9)	320
Solar radiation	-	70.8	326	- ( - )	3.7(37.0)	96.2(63.0)	95

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APPENDIX: Summary of the IRPA exposure standard.OCCUPATIONAL STANDARD FOR  
EXPOSURE TO ULTRAVIOLET RADIATION

These exposure limit (EL) values refer to ultraviolet radiation (UVR) in the spectral region between 180 and 400 nm and represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect. These EL values for exposure of the eye or the skin may be used to evaluate potentially hazardous exposure from UVR. The limits do not apply to ultraviolet lasers. These values should be used as guides in the control of exposure to both pulsed and continuous sources where the exposure duration is not less than 0.1  $\mu$ sec. These EL's are below levels which would be used for UV exposures of patients required as a part of medical treatment or for elective cosmetic purposes.

These values should be used as guides in the control of exposure to UVR sources and as such are intended as upper limits for nontherapeutic and noncosmetic exposure.

## Exposure Limits:

The EL for occupational exposure to UVR incident upon skin or eye where irradiance values are known and exposure time is controlled are as follows:

1. For the near ultraviolet UV-A spectral region (315 to 400 nm) the total irradiance incident upon the unprotected skin or eye should not exceed  $10\text{W/m}^2$  ( $1\text{mW/cm}^2$ ) for periods greater than  $10^3$  seconds (approximately 16 minutes) and for exposure times less than  $10^3$  seconds should not exceed  $10\text{kJ/m}^2$  ( $1.0\text{J/cm}^2$ ).
2. For the actinic UV spectral region (UV-C and UV-B from 180 to 315 nm), the radiant exposure incident upon the unprotected skin or eye within an 8-hour period should not exceed the values given in Table 1. Values are given to 318 nm to aid in spectroradiometric measurements.
3. To determine the effective irradiance of a broadband source weighted against the peak of the spectral effectiveness curve (270 nm), the following weighting formula should be used:

$$E_{\text{eff}} = \sum E_{\lambda} \cdot S_{\lambda} \cdot \Delta\lambda$$

where:

$E_{\text{eff}}$  = effective irradiance in  $\text{W/m}^2$  ( $\text{J/s.m}^2$ ) normalized to a monochromatic source at 270 nm

$E_{\lambda}$  = spectral irradiance in  $\text{W/m}^2/\text{nm}$

$S_{\lambda}$  = relative spectral effectiveness (unitless)

$\Delta\lambda$  = bandwidth in nanometers of the calculated or measurement intervals

4. Permissible exposure time in seconds for exposure to actinic UVR incident upon the unprotected skin or eye may be computed by dividing  $30\text{J/m}^2$  by  $E_{\text{eff}}$  in  $\text{W/m}^2$ . The maximum exposure duration may also be determined using Table 2 which provides representative exposure durations corresponding to effective irradiances in  $\text{W/m}^2$ .

TABLE 1

## VALUES FOR UVR EL AT REPRESENTATIVE WAVELENGTHS

Wavelength (nm)	EL (J/m <sup>2</sup> )	EL (mJ/cm <sup>2</sup> )	Relative Spectral Effectiveness S <sub>λ</sub>
180+	1000	100	0.03
190+	1000	100	0.03
200	1000	100	0.03
205	590	59	0.051
210	400	40	0.075
215	320	32	0.095
220	250	25	0.12
225	200	20	0.15
230	160	16	0.19
235	130	13	0.24
240	100	10	0.30
245	83	8.3	0.36
250	70	7.0	0.43
* 254	60	6.0	0.50
255	58	5.8	0.52
260	46	4.6	0.65
265	37	3.7	0.81
270	30	3.0	1.0
275	31	3.1	0.96
280	34	3.4	0.88
285	39	3.9	0.77
290	47	4.7	0.64
295	56	5.6	0.54
297	65	6.5	0.46
300	100	10	0.30
303	250	25	0.19
305	500	50	0.06
308	1200	120	0.026
310	2000	200	0.015
313	5000	500	0.006
315	10000	1000	0.003
316 <sub>α</sub>	15000	1500	0.002
317 <sub>α</sub>	20000	2000	0.0015
318 <sub>α</sub>	30000	3000	0.001

- \* Principal emission line of low-pressure quartz-mercury lamps.  
+ Tentative values given for use only when sources emit substantial amounts of UVR in this band.  
<sub>α</sub> Values provided for guidance in spectroradiometer measurements.

TABLE 2

## LIMITING UVR EXPOSURE DURATIONS BASED ON EL

Duration of Exposure Per Day	Effective Irradiance	
	$E_{\text{eff}}$ ( $\text{W}/\text{m}^2$ )	$E_{\text{eff}}$ ( $\mu\text{W}/\text{cm}^2$ )
8 hrs	0.001	0.1
4 hrs	0.002	0.2
2 hrs	0.004	0.4
1 hr	0.008	0.8
30 min	0.017	1.7
15 min	0.033	3.3
10 min	0.05	5
5 min	0.1	10
1 min	0.5	50
30 sec	1.0	100
10 sec	3.0	300
1 sec	30	3,000
0.5 sec	60	6,000
0.1 sec	300	30,000