1. Exposure Data

1.1 Nomenclature

1.1.1 *Optical radiation*

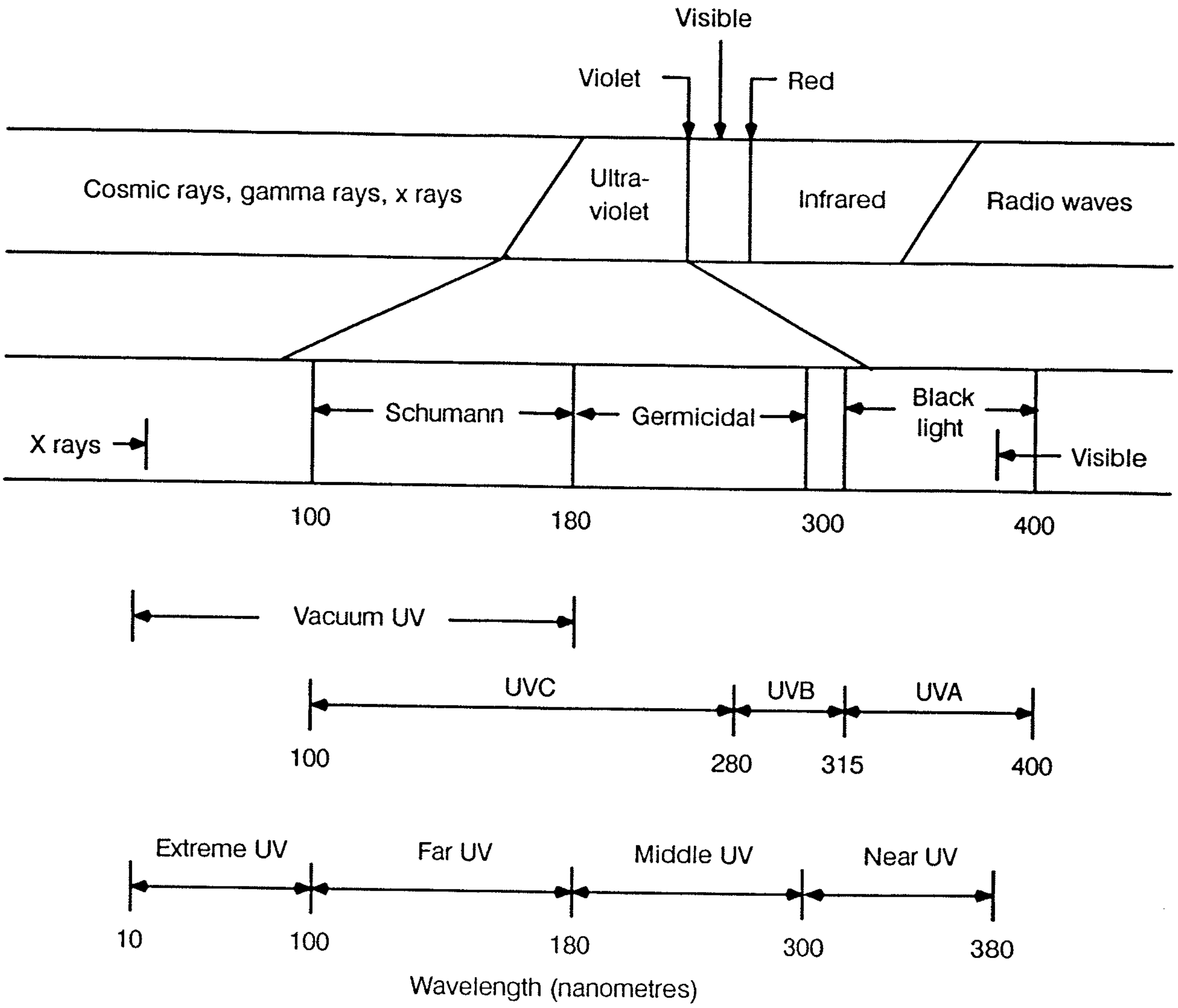
Optical radiation is radiant energy within a broad region of the electromagnetic spectrum that includes ultraviolet (UV), visible (light) and infrared radiation. Ultraviolet radiation (UVR) is characterized by wavelengths between 10 and 400 nm—bordered on the one side by x rays and on the other by visible light (Fig. 1). Solar radiation is largely optical radiation, although ionizing radiation (i.e., cosmic rays, gamma rays and x rays, which have wavelengths less than approximately 10 nm) and radio-frequency radiation (i.e., wavelengths greater than 1 mm: microwaves and longer radio waves) are also present in the spectrum.

The optical radiation spectrum is generally considered to fall between 10 nm and 1 mm, and several different conventions have been developed to describe different bands within this spectrum. It is important to recognize that no single convention is uniquely 'correct' but that each may be useful for a particular branch of science and technology. For example, in optics, it is convenient to separate the spectrum into different bands on the basis of the transmission and absorption properties of optical materials (e.g., glass and quartz). In one optical convention, shown in Figure 1, UVR is divided into vacuum UV, extending from 10 to 180 nm; middle UV, from 180 nm to 300 nm; and near UV, from 300 nm to 380 or 400 nm. Meteorological scientists typically define optical spectral regions on the basis of atmospheric windows. Some spectral designations are based on uses, e.g., 'germicidal' and 'black-light' regions.

For the purposes of this monograph, the photobiological designations of the Commission Internationale de l'Eclairage (CIE, International Commission on Illumination) are the most relevant and are used throughout to define the approximate spectral regions in which certain biological absorption properties and biological interaction mechanisms may dominate (Commission Internationale de l'Eclairage, 1987). The CIE bands are: UVC (100–280 nm), UVB (280–315 nm) and UVA (315–400 nm). Visible light is the region between 400 nm and 780 nm.

It is important to recognize that these spectral band designations are merely short-hand notations and cannot be considered to designate fine dividing lines below which an effect is present and above which it does not occur. The reader should also be alerted to the fact that the CIE nomenclature is not always followed rigorously and that some authors introduce slight variations; for example, distinguishing between UVB and UVA at 320 rather than 315 nm (frequently used in the USA) and defining UVC as 200–280 nm (Moseley, 1988). The German Industrial Standard (DIN 5031) defines UVA as radiation between 315 and 380 nm (Mutzhas, 1986).

Figure 1. Electromagnetic spectrum with enlargement of ultraviolet (UV) region



Adapted from WHO (1979), Morison (1983a), Sylvania (undated)

From the viewpoint of photochemistry and photobiology, interactions of optical radiation with matter are considered to occur when one photon interacts with one molecule to produce a photochemically altered molecule or two dissociated molecules (Phillips, 1983; Smith, 1989). In any photochemical interaction, the energy of the individual photon is important, since this must be sufficient to alter a molecular bond. The photon energy is generally expressed in terms of electron volts (eV). A wavelength of 10 nm corresponds to a photon energy of 124 eV, and 400 nm to an energy of 3.1 eV (WHO, 1979). The number of altered molecules produced relative to the number of absorbed photons is referred to as the 'quantum yield' (Phillips, 1983). The efficacy of photochemical interaction per incident quantum and the photobiological effects per unit radiant exposure typically vary widely with wavelength. A quantitative plot of such spectral variation, usually normalized to unity at the most effective wavelength, is referred to as an 'action spectrum' (Jagger, 1985).

1.1.2 *Quantities and units*

Two systems of quantities and units are used to describe the characteristics of light and light sources: the radiometric and the photometric systems. Radiometry can be applied to all optical sources and to all exposures to optical radiation (including solar radiation and UVR). Photometry can be used only to describe visible light sources, and photometric quantities are used in illumination engineering. The basic photometric unit is the lumen, which is defined in terms of the spectral response of the human eye (specifically, the spectral response of the CIE 'standard observer'), i.e., the action spectrum of vision, which is initially a photochemical process. It is important to recognize that radiometric quantities and units are absolute, while photometric quantities and units are related to standardized human perception; the relationship between the two sets of units varies significantly with the spectrum of radiation. The effects of optical radiation (including light), other than vision, must therefore be measured and quantified in terms of radiometric units and spectral characteristics rather than photometric units. This is particularly important in relation to the photobiological effects of UVR. Most lamps used for illumination are rated by manufacturers only in photometric terms (e.g., lumen output) and not in terms of UVR emission (Phillips, 1983).

The most important radiometric quantities and units commonly used to describe optical radiation are given in Table 1. Certain terms are used primarily to describe source characteristics, e.g., radiance, radiant intensity; whereas other terms are generally used to describe exposure (irradiance, radiant exposure). The term 'spectral' placed before any of the quantities implies restriction to a unit wavelength band, e.g., spectral irradiance (watts per square metre per nanometre) (Moseley, 1988). For a more detailed discussion of these parameters, see various standard textbooks on radiometry, such as Boyd (1983).

The quantities of radiometry are expressed in terms of absolute energy (Jagger, 1985). Radiant intensity is the power emitted per unit solid angle of a source. Radiance is the radiant intensity per unit area of source. Thus, a fluorescent lamp does not have very high radiance in comparison to the filament of a flashlight bulb, even though it has a high radiant power output. The radiometric term expressed in units of watts per square metre (dose rate) is irradiance, which is also the power striking a unit area of surface.

The energy of UVR falling on a unit surface area of an object was defined in 1954 by the First International Congress of Photobiology as the 'dose'; it has also been referred to as 'exposure dose'. The equivalent radiometric quantity is radiant exposure, expressed in joules per square centimetre or per square metre. Radiant exposure has been referred to as 'energy fluence' in some texts; however, fluence is a radiometric quantity, with the same units as radiant exposure, but referring to energy arriving at a plane of unit area from all directions, including backscatter. Thus, fluence is quite correctly of value in describing an exposure dose at a depth inside tissue; it has, however, seldom been calculated in photobiological studies of the effects of UVR, in which the radiant exposure incident upon the skin is normally measured. Radiant exposure is the amount of energy crossing a unit area of space normal to the direction of propagation of a beam of UVR. If the radiant energy arrives from many directions, as from the sky, then the fluence at one point is the sum of all the component fluences entering a unit sphere of space. The energy fluence rate is the power that crosses a unit area normal to the direction of propagation, or the energy per unit area per unit time

Table 1. Some basic terminology used to quantify optical radiation

Term	International symbol	Definition	SI unit	Synonyms and comments
Wavelength	λ		nm	Nanometre = 10^{-9} m (also called millimicron, mμ)
Radiant energy	Q_e	$\Sigma (P_e \times dt)$	J	Joule; 1 joule = 1 watt $\times$ second; total energy contained in a radiation field or total energy delivered to a given receiver by such a radiation field
Radiant flux	P_e	dQ_e/dt	W	Watt; rate of delivery of radiant energy ('radiant power'); also expressed as ϕ
Irradiance	E_e	dP_e/dA	W/m^2	Radiant flux arriving over a given area ('fluence rate', 'dose rate', 'intensity', 'radiant incidence'). In photobiology, has also been expressed in W/cm^2, mW/cm^2 and μW/cm^2
Radiant intensity	I_e	$dP_e/d\Omega$	W/sr	Watt/steradian; radiant flux emitted by source into a given solid angle (solid angle expressed in steradians)
Radiance	L_e	$dP_e/dA \times d\Omega$	W/m^2 $\times$ sr	Watt/m^2 $\times$ steradian; radiant flux per unit solid angle per unit area emitted by an extended source
Radiant exposure	H_e	$E_e \times t$	J/m^2	Radiant energy delivered to a given area ('fluence', 'exposure dose', 'dose'); t = time in seconds. Has also been expressed as J/cm^2, mJ/cm^2 and μJ/cm^2

Adapted from WHO (1979), Boyd (1983), Jagger (1985), Hoffman (1987) and Weast (1989)

(J/m^2/s or W/m^2). The terms dose (J/m^2) and dose rate (W/m^2) pertain to the energy and power, respectively, striking a unit surface area of an irradiated object (Jagger, 1985).

In terms of visible light perceived by humans, the photometric analogue of the radiance of a source is luminance (brightness), and irradiance is illuminance (measured in 'lux' or lumen per square metre). In photometry, the lumen is the unit of luminous power (Jagger, 1985).

1.1.3 *Units of biologically effective ultraviolet radiation*

In addition to general radiometric quantities, specialized quantities of effective irradiance relative to a specified photochemical action spectrum are used in photochemistry and photobiology. Effective radiant exposures to produce erythema (Jagger, 1985) or photokeratitis are examples. Effective irradiance or radiant exposure is not limited to photobiology, and a similar approach has been used to quantify the photocuring of inks, in photopolymerization (Phillips, 1983) and in assessing the hazards of UVR. In order to weight a source spectrally, the general formula involves an action spectrum and a spectral radiometric quantity. The effective irradiance of a given photobiological process is defined as:

$$\sum_{\lambda_1}^{\lambda_2} E_\lambda \times S_\lambda \times \Delta_\lambda$$

expressed in W/m^2, where E_λ is the spectral irradiance (W/m^2 × nm) at wavelength λ (nm) and Δ_λ is the wavelength interval ($\lambda_1 \rightarrow \lambda_2$) used in the summation (in nm). S_λ is a measure of the effectiveness of radiation of wavelength λ (nm), relative to some reference wavelength, in producing a particular biological end-point. As it is a ratio, S_λ has no units (American Conference of Governmental Industrial Hygienists, 1991).

Effective irradiance is equivalent to a hypothetical irradiance of monochromatic radiation with a wavelength at which S_λ is equal to unity. The time integral of effective irradiance is the effective radiant exposure (also called the 'effective dose').

A unit of effective dose commonly used in cutaneous photobiology is the 'minimal erythema dose' (MED). One MED has been defined as the lowest radiant exposure to UVR that is sufficient to produce erythema with sharp margins 24 h after exposure (Morison, 1983a). Another end-point often used in cutaneous photobiology is a just-perceptible reddening of exposed skin; the dose of UVR necessary to produce this 'minimal perceptible erythema' is sometimes also referred to as an MED. In unacclimatized, white-skinned populations, there is an approximately four-fold range in the MED of exposure to UVB radiation (Diffey & Farr, 1989). When the term MED is used as a unit of exposure dose, however, a representative value is chosen for sun-sensitive individuals. If, in the above expression for effective irradiance, S_λ is chosen as the reference action spectrum for erythema (McKinlay & Diffey, 1987) and a value of 200 J/m^2 at wavelengths for which S_λ is equal to unity is assumed for the MED, the dose (expressed in MED) received after an exposure period of t seconds is

$$t \times \Sigma\, E_\lambda \times S_\lambda \times \Delta_\lambda/200.$$

Notwithstanding the difficulties of interpreting accurately the magnitude of such an imprecise unit as the MED, it has the advantage over radiometric units of being related to the biological consequences of the exposure.

1.2 Methods for measuring ultraviolet radiation

UVR can be measured by chemical or physical detectors, often in conjunction with a monochromator or band-pass filter for wavelength selection. Physical detectors include radiometric devices, which depend for their response on the heating effect of the radiation, and photoelectric devices, in which incident photons are detected by a quantum effect such as the production of electrons. Chemical detectors include photographic emulsions, actinometric solutions and UV-sensitive plastic films.

1.2.1 *Spectroradiometry*

The fundamental way of characterizing a source of UVR is on the basis of its spectral power distribution in a graph (or table) which indicates the radiated power as a function of wavelength. The data are obtained by a technique known as spectroradiometry. Spectral measurements are often not required as ends in themselves but are used to calculate biologically weighted radiometric quantities. A spectroradiometer comprises three essential components (Gibson & Diffey, 1989):

(i) input optics, such as an integrating sphere or Teflon diffuser, which collects the incident radiation and conducts it to

(ii) the entrance slit of a monochromator, which disperses the radiation by means of one or two wavelength dispersive devices (either diffraction grating or prism). The monochromator also incorporates mirrors to guide the radiation from the entrance slit to the dispersion device and on to the exit slit, where it is incident on

(iii) a radiation detector, normally a photodiode or, for higher sensitivity, a photomultiplier tube.

Spectroradiometry is generally considered to be the best way of specifying UV sources, although the accuracy of spectroradiometry, particularly with respect to the UVB waveband of terrestrial radiation, is affected by a number of parameters including wavelength calibration, band width, stray radiation, polarization, angular dependence, linearity and calibration sources. It is therefore essential to employ a double monochromator for accurate characterization of terrestrial UVR and particularly UVB (Garrison *et al.*, 1978; Kostkowski *et al.*, 1982; Gardiner & Kirsch, 1991).

1.2.2 *Wavelength-independent (thermal) detectors*

General-purpose radiometers incorporate detectors that have a flat response over a wide range of wavelengths. Such thermal detectors operate on the principle that incident radiation is absorbed by a receiving element, and the temperature rise of the element is measured, usually by a thermopile or a pyroelectric detector. A thermopile, which comprises several thermocouples connected in series for improved sensitivity, must have a window made of fused silica for measuring UVR at wavelengths down to at least 250 nm. Pyroelectric detectors rely on a voltage generated by temperature changes in a lithium tantalate crystal. Thermal detectors are normally used to measure the total radiant power of a source rather than just the UV component (Moseley, 1988).

Instruments for measuring broad-band solar radiation fall into three categories: pyroheliometers, pyranometers and pyranometers with a shading device (Iqbal, 1983). These types of instrument find their applications in meteorology rather than in UV photobiology.

1.2.3 *Wavelength-dependent detectors*

Detectors of this type have a spectral response that varies widely depending on the types of detector and filters that may be incorporated. Detectors can be designed to have a spectral response that matches a particular action spectrum for a photobiological end-point. The success with which this is achieved is variable. The most widely used device, particularly for measuring solar UVR, has been the Robertson–Berger meter (Robertson, 1972; Berger, 1976), which incorporates optical filters, a phosphor and a vacuum phototube or photovoltaic cell. This device measures wavelengths of less than 330 nm in the global spectrum with a spectral response that rises sharply with decreasing wavelength. It has been used to monitor natural UVR continuously at several sites throughout the world (Berger & Urbach, 1982; Diffey, 1987a).

Detectors incorporating a photodiode or vacuum photocell in conjunction with optical filter(s) and suitable input optics (e.g., a quartz hemispherical detector) have been produced to match a number of different action spectra. One such detector is the International Light Model 730 UV Radiometer, which has a spectral response close to the action spectrum designated by the American Conference of Governmental Industrial Hygienists for evaluating the hazard to health of exposure to UVR, and has been used to measure irradiance over different terrains (Sliney, 1986).

Wavelength-dependent detectors with spectral responses largely in the UVA waveband are used, for example, in measuring the output of irradiation units for the treatment of psoriasis by psoralen photochemotherapy (Morison, 1983a).

A different yet complementary approach is the use of various photosensitive films as UV dosimeters. The principle is to relate the degree of deterioration of the films, usually in terms of changes in their optical properties, to the dose of incident UVR. The principal advantages of the film dosimeter are that it provides a simple means of integrating exposure continuously and allows simultaneous comparison of numerous sites that are inaccessible to bulky, expensive instruments (Diffey, 1987a). The most widely used photosensitive film is polymer polysulfone (Diffey, 1989a). Personal dosimeters of polysulfone film have been developed and used in a number of dosimetric studies (Challoner *et al.*, 1976, 1978; Leach *et al.*, 1978; Holman *et al.*, 1983a; Larkö & Diffey, 1983; Diffey, 1987a; Schothorst *et al.*, 1987a; Slaper, 1987; Rosenthal *et al.*, 1990).

It is difficult to achieve a prescribed UVR spectral response with wavelength-dependent detectors. Accurate results can be achieved only if the detectors are calibrated against the appropriate source spectrum using a spectroradiometer (Gibson & Diffey, 1989). Unless this is done, severe dosimetric errors can arise, particularly with measurements of solar UVR (Diffey, 1987a; Sayre & Kligman, 1992).

Accurate measurement of UVB radiation is far more difficult than would appear initially. The primary problem is that the UVB produced by most optical sources—the sun as well as incandescent and fluorescent lamps used for illumination—is only a very small fraction (i.e., less than 0.3%) of the total radiant energy emitted. Additionally, biological action spectra (e.g., for erythema and photokeratitis) typically decrease dramatically within the same waveband in which the source spectrum increases (Diffey & Farr, 1991a). This means that either a spectroradiometer or a direct-reading filtered 'erythemal' or 'hazard' meter must reject out-of-band radiant energy to better than one part in 10^4 or even 10^5. The spectral band-width of a monochromator can also greatly affect measurement error: too large a band-width can reduce the steepness of reported action spectra.

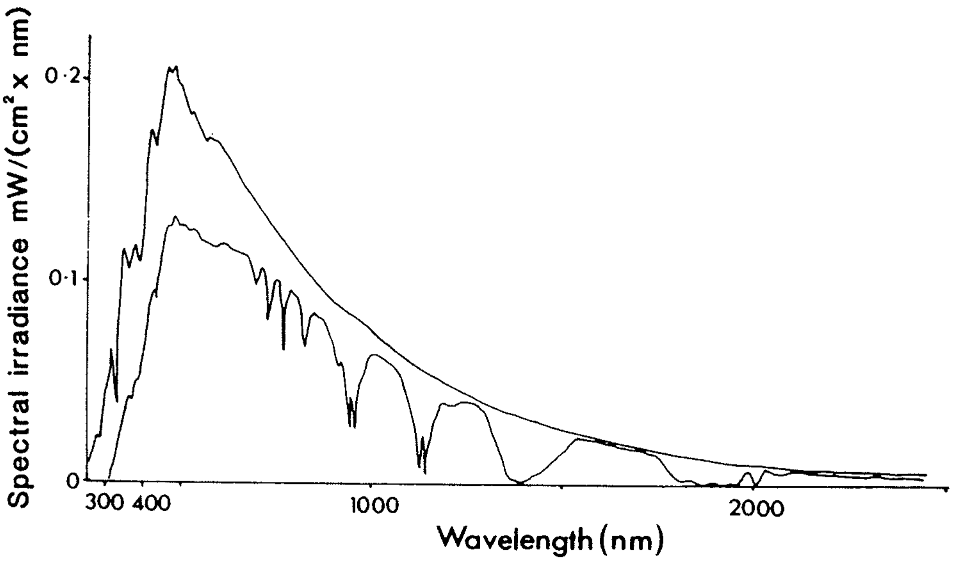
1.3 Sources and exposures

In the broadest sense, UVR may be produced when a body is heated (incandescence) or when electrons that have been raised to an excited state return to a lower energy level, as occurs in fluorescence, in an electric discharge in a gas and in electric arcs (optical plasma) (Sliney & Wolbarsht, 1980; Phillips, 1983; Moseley, 1988). The characteristics of exposures to both terrestrial solar radiation (an incandescent source) and artificial light sources are discussed in the following sections.

1.3.1 *Solar ultraviolet radiation*

Optical radiation from the sun is modified significantly as it passes through the Earth's atmosphere (Fig. 2), although about two-thirds of the energy from the sun that impinges on the atmosphere penetrates to ground level. The annual variation in extra-terrestrial radiation is less than 10%, but the variation in the modifying effect of the atmosphere is far greater (Moseley, 1988). Measurements corrected for atmospheric absorption show that the visible portion comprises approximately 40% of the total radiation received at the surface of the Earth. While UVR comprises only a small proportion of the total radiation (approximately 5%), this component is extremely important in various biological processes. The principal effect of infrared radiation is to warm the earth; approximately 55% of the solar radiation received at the surface of the earth is infrared (Foukal, 1990).

Fig. 2. Spectral irradiance from the sun outside the Earth's atmosphere (upper curve) and at sea level (lower curve)



From Moseley (1988)

On its path through the atmosphere, solar radiation is absorbed and scattered by various constituents of the atmosphere. It is scattered by air molecules, particularly oxygen and nitrogen (Rayleigh scattering), which produce the blue colour of the sky. It is also scattered by aerosol and dust particles (Mie scattering) and is scattered and absorbed by atmospheric pollution. Total solar irradiance and the relative contributions of different wavelengths vary with altitude. Clouds attenuate solar radiation, although their effect on infrared radiation is greater than on UVR. Reflection of sunlight from certain ground surfaces may contribute significantly to the total amount of scattered UVR. An effective absorber of solar UVR is ozone in the stratosphere (Moseley, 1988). An equally important absorber in the longer wavelengths (infrared) is water vapour (Diffey, 1991); a secondary absorber in this range is carbon dioxide. These two filter out much of the solar energy with wavelengths longer than 1000 nm (Sliney & Wolbarsht, 1980).

The quality (spectral distribution) and quantity (total UV irradiance) of UVR reaching the Earth's surface depend on the radiated power from the sun and the transmitting properties of the atmosphere. Although UVC exists in the extra-terrestrial solar spectrum, it is filtered out completely by the ozone layer in the atmosphere. UVB radiation, which represents about 5% of the total solar UVR that reaches the Earth (Sliney & Wolbarsht, 1980), has been considered to be the most biologically significant part of the terrestrial UV spectrum. The levels of UVB radiation reaching the surface of the Earth, although heavily attenuated, are also largely controlled by the ozone layer.

Ozone (O_3) is a gas which comprises approximately one molecule out of every two million in the atmosphere. It is created by the reaction of molecular oxygen (O_2) with atomic oxygen (O), formed by the dissociation of O_2 by short-wavelength UVR (< 242 nm) in the stratosphere at altitudes between about 25 and 100 km. Absorption of UVR at wavelengths up to about 320 nm converts the ozone back to O_2 and O, and it is this dissociation of ozone that is responsible for preventing radiation at wavelengths less than about 290 nm from reaching the Earth's surface (Moseley, 1988; Diffey, 1991). Molina and Rowland (1974) first proposed that chlorofluorocarbons and other gases released by human activity could alter the natural balance of creative and destructive processes and lead to depletion of the stratospheric ozone layer. Substantial reductions, of up to 50%, in the ozone column observed in the austral spring over Antarctica were first reported in 1985 and may continue. There are, however, serious limitations in our current understanding of and ability to quantify ozone depletion at the present levels of contaminant release and in our ability to predict the effects on stratospheric ozone of any further increases (United Nations Environment Programme, 1989; United Kingdom Stratospheric Ozone Review Group, 1991).

A number of factors influence terrestrial UVR levels:

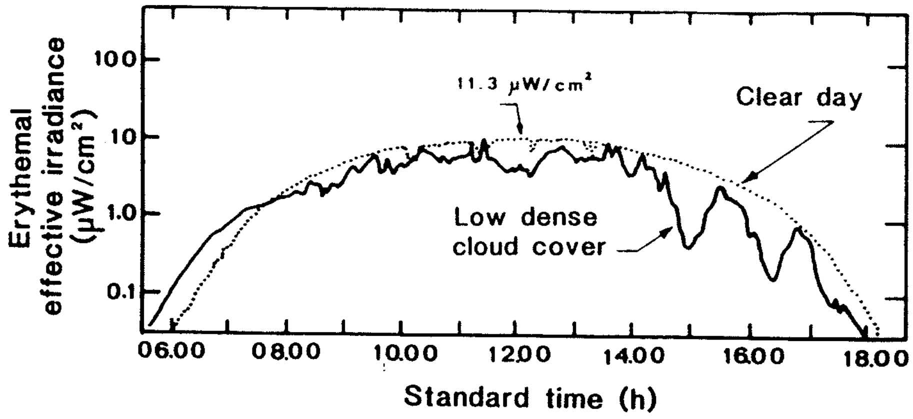
- *Variations in stratospheric ozone with latitude and season* (United Nations Environment Programme, 1989)
- *Time of day*: In summer, about 20–30% of the total daily amount of UVR is received between 11:00 and 13:00 h and 75% between 9:00 and 15:00 h (Diffey, 1991; Table 2 and Fig. 3). Although the amount of visible light falling on the ground in the summer may vary by only 30% between 12:00 and 15:00 h (local solar time), the short-wavelength component of the UVB spectrum undergoes a dramatic change during

Table 2. Percentage of daily UVB and UVA radiation received during different periods of a clear summer's day. Solar noon is assumed to be at 12:00 h, i.e., no allowance is made for daylight saving time

Latitude (°N)	UVB		UVA	
	11:00–13:00 h	9:00–15:00 h	11:00–13:00 h	9:00–15:00 h
20	30	78	27	73
40	28	75	25	68
60	26	69	21	60

From Diffey (1991)

Fig. 3. Daily variation in ultraviolet radiation: erythemal effective irradiance falling on a horizontal earth surface at Denver, CO, USA, on one summer's day



From Machta *et al.* (1975)

this period. At a wavelength of 300 nm, the spectral irradiance decreases by 10 fold, from approximately 1.0 to 0.1 μW/(cm^2 × nm) (Sliney, 1986).

- *Season*: Seasonal variation in terrestrial UV irradiance, especially UVB, at the Earth's surface is significant in temperate regions but much less nearer the equator (Table 3).

Table 3. Typical values for ambient daily and annual UVB radiation expressed in minimal erythema dose (MED)

Latitude (°N)	Diurnal UVB (MED)			
	Winter	Spring/Autumn	Summer	Annual
20 (Hawaii, USA)	14	20	25	6000
30 (Florida, USA)	5	12	15	4000
40 (Spain)	2	7	12	2500
50 (Belgium)	0.4	3	10	1500

From Diffey (1991)

- *Geographical latitude*: Annual UVR exposure dose decreases with increasing distance from the equator (Table 3).
- *Clouds*: Clouds reduce UV ground irradiance; changes in UVR are smaller than those of total irradiance because water in clouds attenuates solar infrared radiation much more than UVR. Even with heavy cloud cover, the scattered UVB component of sunlight (often called skylight) is seldom less than 10% of that under clear sky; however, very heavy cloud cover can virtually eliminate UVB even in summer. Light clouds scattered over a blue sky make little difference in sunburning effectiveness unless they directly cover the sun. Complete light cloud cover prevents about 50% of UVB energy, relative to that from a clear sky, from reaching the surface of the Earth (Diffey, 1991).

- *Surface reflection*: The contribution of reflected UVR to a person's total UVR exposure varies in importance with a number of factors (Table 4). A grass lawn scatters about 3% of incident UVB radiation. Sand reflects about 10–15%, so that sitting under an umbrella on the beach can lead to sunburn both from scattered UVB from the sky and reflected UVB from the sand. Fresh snow has been reported to reflect up to 85–90% of incident UVB radiation, although reflectance of about 30–50% is probably more typical. Ground reflectance is important, because parts of the body that are normally shaded are exposed to reflected radiation (Diffey, 1990a).

Table 4. Representative terrain reflectance factors for horizontal surfaces measured with a UVB radiometer at 12:00 h (290–315 nm) in the USA

Material	Reflectance (%)
Lawn grass, summer, Maryland, California and Utah	2.0–3.7
Lawn grass, winter, Maryland	3.0–5.0
Wild grasslands, Vail Mountain, Colorado	0.8–1.6
Lawn grass, Vail, Colorado	1.0–1.6
Flower garden, pansies	1.6
Soil, clay/humus	4.0–6.0
Sidewalk, light concrete	10–12
Sidewalk, aged concrete	7.0–8.2
Asphalt roadway, freshly laid (black)	4.1–5.0
Asphalt roadway, two years old (grey)	5.0–8.9
House paint, white, metal oxide	22
Boat dock, weathered wood	6.4
Aluminium, dull, weathered	13
Boat deck, wood, urethane coating	6.6
Boat deck, white fibreglass	9.1
Boat canvas, weathered, plasticized	6.1
Chesapeake Bay, Maryland, open water	3.3
Chesapeake Bay, Maryland, specular component of reflection at Z = 45 °N	13
Atlantic Ocean, New Jersey coastline	8.0
Sea surf, white foam	25–30
Atlantic beach sand, wet, barely submerged	7.1
Atlantic beach sand, dry, light	15–18
Snow, fresh	88
Snow, two days old	50

From Sliney (1986)

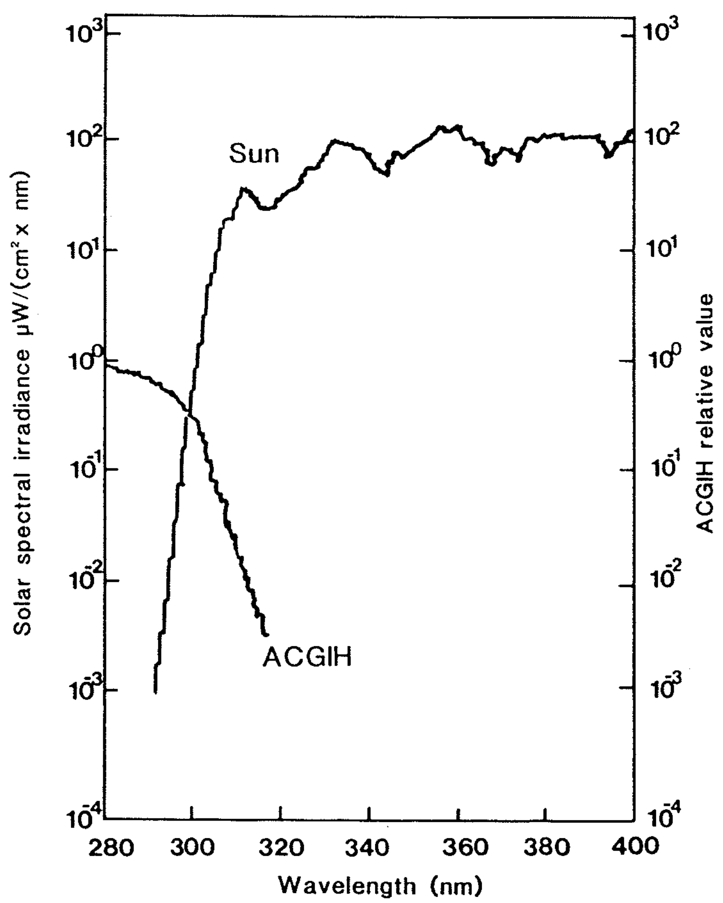
- *Altitude*: In general, each 300-m increase in altitude increases the sunburning effectiveness of sunlight by about 4%. Conversely, places on the Earth's surface below sea level have lower UVB exposures than nearby sites at sea level (Diffey, 1990a).

- *Air pollution*: Tropospheric ozone and other pollutants can decrease UVR, particularly in urban areas (Frederick, 1990).

(*a*) *Measurements of terrestrial solar radiation*

Since UVR wavelengths between about 295 and 320 nm (UVB radiation) in the terrestrial solar spectrum are thought to be those mainly responsible for adverse health effects, a number of studies have concentrated on measuring this spectral region (Sliney, 1986). Accurate measurements of UVR in this spectral band are difficult to obtain, however, because the spectral curve of terrestrial solar irradiance increases by a factor of more than five between 290 and 320 nm (Fig. 4). Nevertheless, extensive measurements of ambient

Fig. 4. Action spectrum designated by the American Conference of Governmental Industrial Hygienists (ACGIH) for assessing the hazard of ultraviolet radiation (very similar to erythemal action spectrum from 300–230 nm) and the solar spectrum. The ACGIH action spectrum, which is unitless, is closely fit by some radiometers; however, because of the small overlap of the terrestrial solar spectrum with the action spectrum, problems of stray light must be dealt with by constant checks with a filter that blocks wavelengths of less than 320 nm

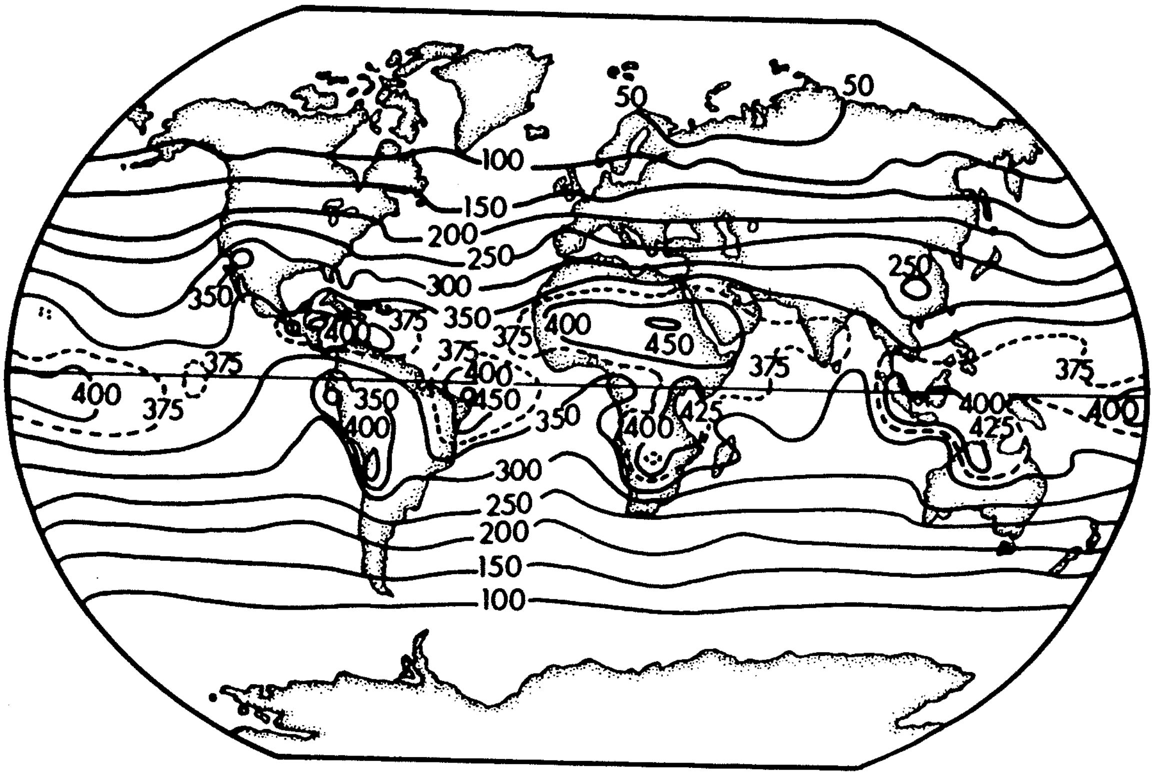


Adapted from Sliney *et al.* (1990)

UVR in this spectral band have been performed worldwide (Schulze, 1962; Schulze & Gräfe, 1969; Henderson, 1970; Sundararaman *et al.*, 1975; Garrison *et al.*, 1978; Doda & Green, 1980; Mecherikunnel & Richmond, 1980; Kostkowski *et al.*, 1982; Ambach & Rehwald, 1983; Blumthaler *et al.*, 1983; Livingston, 1983; Blumthaler *et al.*, 1985a,b; Kolari *et al.*, 1986; Hietanen, 1990; Sliney *et al.*, 1990). Longer-wavelength UVR (UVA) was measured at the same time in many of these studies. Measurements of terrestrial solar UVA radiation are less subject to error than measurements of UVB, since the spectrum does not vary widely with zenith angle and the spectral irradiance curve is relatively flat.

Maps of annual UVR exposure, such as that shown in Figure 5, have been compiled for epidemiological studies of skin cancer and other diseases (Schulze, 1962, 1970; Scotto *et al.*, 1976). Despite the large numbers of measurements, their interpretation in relation to human exposure has been complicated by three factors: (i) the considerable variation in UVB spectral irradiance with solar position throughout the day and with season; (ii) the effect of the geometry of exposure of individuals; and (iii) variation between humans in outdoor exposure and the parts of their bodies that are exposed.

Fig. 5. Global distribution of ultraviolet radiation

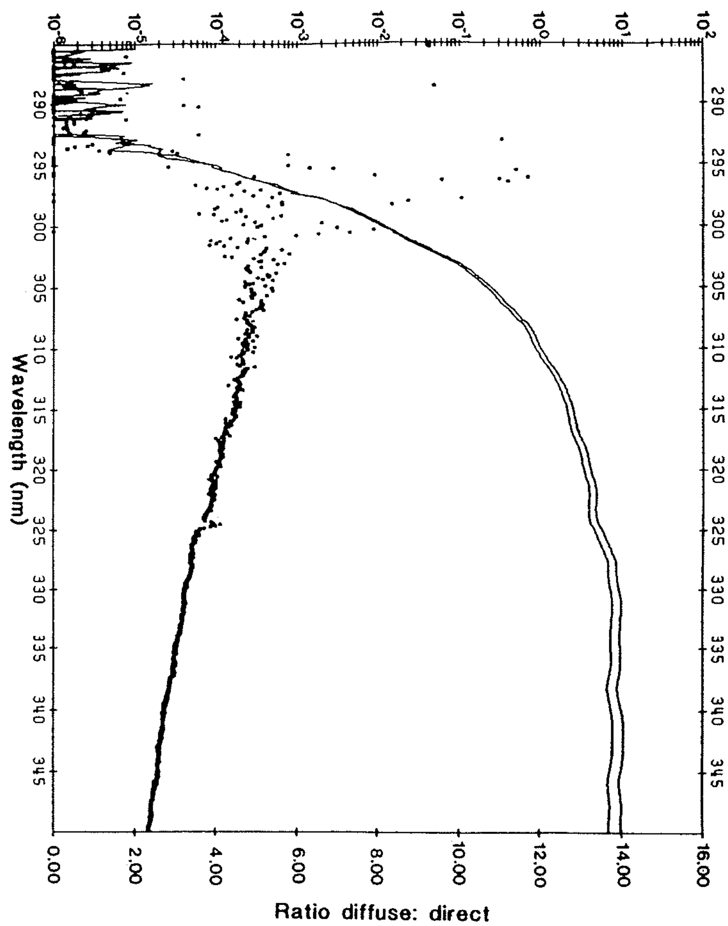


From Schulze (1970); WHO (1979)

The total solar radiation that arrives at the Earth's surface is termed 'global radiation', and measurements of terrestrial UVR most frequently pertain to this quantity, i.e., the radiant energy falling upon a horizontal surface from all directions (both direct and scattered radiation). Global radiation comprises two components, referred to as 'direct' and 'diffuse'.

Approximately 70% of the UVR at 300 nm is in the diffuse component rather than in the direct rays of the sun (Fig. 6). The ratio of diffuse to direct radiation increases steadily from less than 1.0 at 340 nm to at least 2.0 at 300 nm (Garrison *et al.*, 1978).

Fig. 6. Diffuse and direct solar spectral irradiance (solar zenith angle, 45°)

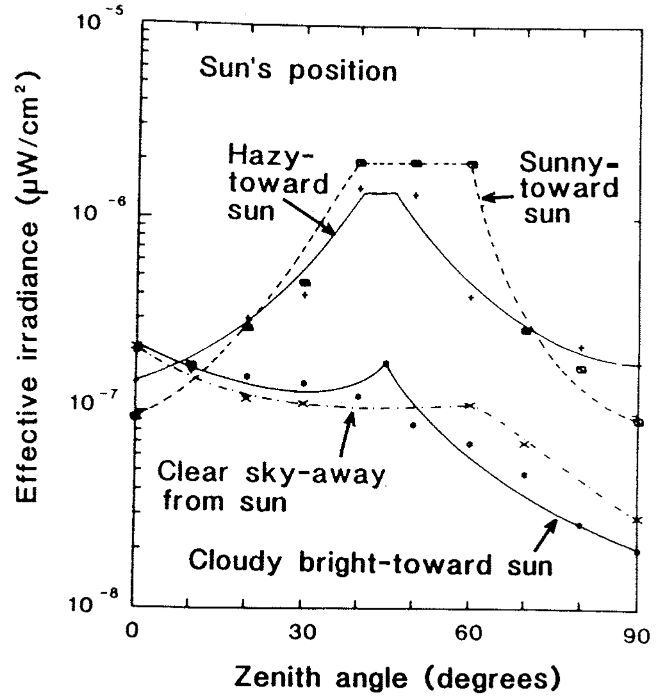


From Garrison *et al.* (1978)

UVR reflected from the terrain (the albedo) may also be important; however, essentially all measurement programmes have been limited to the direct and total diffuse components of sunlight. While such measurements are of interest in calculating the exposure dose of UVR of a prone individual, they are of very limited value in estimating exposure of the eye and shaded skin surfaces (e.g., under the chin), where the UVB radiation incident upon the body from terrain reflectance and horizon sky is of far greater importance. Sliney (1986) and Rosenthal *et al.* (1988) reported measurements of outdoor ambient UVR that included the reflected component to the eye. Exposure data for different anatomical sites is of value in developing biological dose–response relationships (Diffey *et al.*, 1979). The fact that ocular exposure differs significantly from cutaneous exposure is emphasized by the finding that photokeratitis is seldom experienced during sunbathing yet the threshold for UV photokeratitis is less than that for erythema of the skin (Sliney, 1986).

Measurements of the angular distribution of UVR relative to solar position and cloud distribution have been reported (Sliney, 1986; Fig. 7). A cloud obscuring the sun had no effect upon the UV radiance of open blue sky or the horizon sky; however, when the sun was 'out' (i.e., in an open sky), clouds near the horizon opposite the sun apparently reflected more UVR than would otherwise be present from the blue sky. This confirms the findings of studies of photographs of the sky taken through a narrow-band filter at 320 nm (Livingston, 1983), which revealed that the sky looks almost uniformly bright even when clouds are present and the clouds disappear into a uniformly hazy sky. Only the sun stands out, as would be expected from the plots on Figure 7. When the sun is near the horizon and can be looked at without great discomfort (i.e., at Z = 75–90 °), the effective UV irradiance is again of the order of 0.3 μW/cm2, e.g., about 0.08–1.1 μW/cm^2 at an elevation angle of 12–15 ° (Sliney, 1986).

Fig. 7. Semilogarithmic plots of the angular dependence of skylight for 290–315 nm ultraviolet radiation (UVR) with the sun at zenith angle of about 45 °. A narrow field-of-view detector was scanned from zenith to the horizon. Uppermost curves show that direct UVR from the sun is more than 10 times greater than scattered UVR normally incident upon the eye at near-horizon angles where the zenith angle Z = 70–90 °. Most surprising is the similarity of blue sky and cloudy sky UV irradiances at zenith or near the horizon.



Adapted from Sliney (1986)

(*b*) *Personal exposures*

The exposure of different anatomical sites to solar UVR depends not only on ambient UVR and orientation of sites with respect to the sun but also on cultural and social behaviour, type of clothing and whether spectacles are worn.

Measurements of ambient UVR are useful in that they provide upper limits on human exposure (Scotto *et al.*, 1976). They are of lesser value for assessing exposure doses received by groups of individuals. Polysulfone film has been used to monitor personal exposure to solar UVR (see p. 49). The wide variations in recorded exposure doses reflect diversity of behaviour and, in most cases, the small numbers (< 30) of subjects monitored. Nevertheless, it can be estimated that recreational (excluding vacations) exposure to the sun of people in northern Europe (where most of these studies were carried out) results in an annual solar exposure dose to the face of 20–100 MED, depending on the propensity for outdoor pursuits. The annual weekday UV exposure dose of indoor workers is around 30 MED; as a two-week outdoor vacation can result in a further 30–60 MED, the total annual exposure dose to the face of most indoor workers is probably in the range 40–160 MED. Outdoor workers at the same latitudes receive about two to three times these exposure doses, typically around 250 MED (Diffey, 1987b; Slaper, 1987).

An alternative approach to estimating personal exposure is to combine measured data on ambient UVR with a behavioural model of exposure. This approach was applied to a group of more than 800 outdoor workers in the USA (40 °N) by Rosenthal *et al.* (1991). These investigators estimated annual facial exposure doses of 30–200 MED, which are considerably lower than those estimated for outdoor workers in northern Europe, perhaps because Rosenthal *et al.* assumed facial exposure to be about 5–10% of ambient. A number of researchers have used polysulfone film badges on both human subjects (Holman *et al.*, 1983a; Rosenthal *et al.*, 1990) and mannequins (Diffey *et al.*, 1977, 1979; Gies *et al.*, 1988) to measure solar UVR exposure on the face relative to ambient exposure. The results vary considerably, reflecting factors such as positioning of film badges, behaviour of individuals, solar altitude and the influence of shade. Examination of the data suggests, however, that the exposure of an unprotected face is probably close to 20% of the ambient. Using this estimate, the annual facial exposure doses in the outdoor worker group studied by Rosenthal *et al.* (1991) would be about 80–500 MED. These data demonstrate clearly the current uncertainties associated with estimates of population exposure doses.

1.3.2 *Exposure to artificial sources of ultraviolet radiation*

(*a*) *Sources*

Six artificial sources that often produce UVR incidental to the production of visible light (Sliney & Wolbarsht, 1980; Phillips, 1983; Moseley, 1988) are described below.

(i) *Incandescent sources*

Optical radiation from an incandescent source appears as a continuous spectrum. Incandescent sources are usually ascribed a certain 'colour temperature', defined as the temperature of a black body that emits the same relative spectral distribution as the source. UVR is emitted in significant quantity when the colour temperature exceeds 2500 °K (2227 °C). Tungsten–halogen lamps in a quartz envelope (colour temperature, 3000 °K [2727 °C]) may emit significant UVR, whereas the UVR emission of an ordinary tungsten light bulb is negligible.

(ii) *Gas discharge lamps*

Another method of producing optical radiation is to pass an electric current through a gas. The emission wavelengths are determined by the type of gas present in the lamp and appear as spectral lines. The width of the lines and the amount of radiation in the interval between them (the continuum) depend on the pressure in the lamp. At low pressures, fine lines with little or no continuum are produced; as pressure is increased, the lines broaden and their relative amounts alter. Low-pressure discharge lamps, commonly containing mercury, argon, xenon, krypton or neon, are useful for spectral calibration. Medium-pressure mercury lamps operate at an envelope temperature in the region of 600–800 °C.

(iii) *Arc lamps*

Arc lamps operate at high pressures (20–100 atm [2020–10133 kPa]) and are very intense sources of UVR. Commonly available lamps contain xenon, mercury or a mixture of the two elements, which are effective sources of UVR. Xenon arc lamps operate at a colour temperature of 6000 °K (5727 °C); they are often used as the light source in solar simulation or are combined with a monochromator in spectral illumination systems. Deuterium arc lamps provide a useful source of UVC radiation and find their main use in spectrophotometers and as a calibration source for spectroradiometers.

(iv) *Fluorescent lamps*

The primary source of radiation in a fluorescent lamp arises from a low-pressure mercury discharge, which produces a strong emission at 254 nm, which in turn excites a phosphor-coated lamp to produce fluorescence. By altering the composition and thickness of the phosphor and the glass envelope, a wide variety of emission spectral characteristics can be obtained. The output is thus chiefly the fluorescent emission spectrum from the coating, with a certain amount of breakthrough of UVB mercury lines at 297, 303 and 313 nm, as well as those in the UVA and visible regions (WHO, 1979).

(v) *Metal halide lamps*

The addition of other metals (as halide salts) to a mercury discharge lamp allows for the addition of extra lines to the mercury emission spectrum. Most such tubes are basically medium-pressure discharge lamps with one or more metal halide additives, usually iodide. Advantage has been taken of the strong lead emission lines at 364, 368 and 406 nm in the lead iodide lamp, in which there is a 50% increase in output in the region between 355 and 380 nm compared to a conventional mercury lamp. Antimony and magnesium halide lamps provide spectral lines in the UVB and UVC regions.

(vi) *Electrodeless lamps*

A type of lamp recently introduced on a large scale is the electrodeless lamp. In this design, the discharge tube absorbs microwave energy fed, via waveguides, into a microwave chamber containing the tube. Two 1500-W magnetrons generate microwave energy at 2450 MHz. The life of such lamps is longer than that of electrode lamps, and a greater range of metal halides is available. Electrodeless lamps are used extensively for UV curing of inks and coatings, particularly when a short lamp length is adequate for the area to be irradiated. They have often been the first choice for curing prints on containers such as two-piece cans, plastic pots and bottles, and tubes.

(*b*) *Human exposure*

Although the sun remains the main source of UVR exposure for humans, the advent of artificial UVR sources has increased the opportunity for both intentional and unintentional exposure.

Intentional exposure is most often to acquire a tanned skin, frequently using sunbeds and solaria emitting principally UVA (315–400 nm) radiation (Diffey, 1987c). Another reason for intentional exposure to artificial UVR is the treatment of skin diseases, notably psoriasis.

Unintentional exposure is most often the result of occupation, and workers in many industries (see p. 66) may be exposed to UVR from artificial sources. The general public is exposed to low levels of UVR from sources such as fluorescent lamps used for indoor lighting and may be exposed in shops and restaurants where UVA lamps are employed in traps to attract flying insects.

(i) *Cosmetic use*

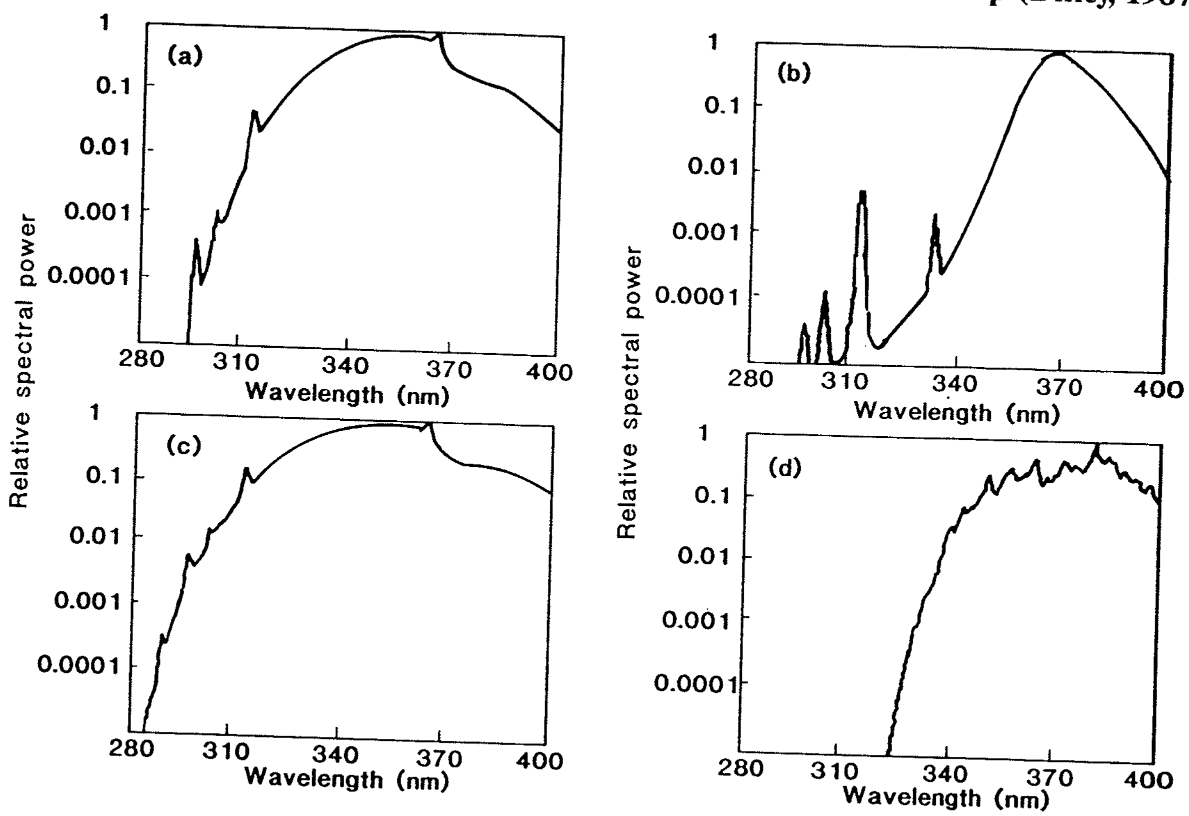
To some individuals, a tanned skin is socially desirable. A 'suntanning industry' has grown up, particularly in northern Europe and North America, in which artificial sources of UVR supplement exposure to sunlight.

Description of UVR sources used for tanning: Prior to the mid-1970s, the source of UVR was usually an unfiltered, medium- or high-pressure mercury arc lamp which emitted a broad spectrum of radiation, from UVC through to visible and infrared radiation (Diffey & Farr, 1991b). The units often incorporated one or more infrared heaters and were commonly called 'sunlamps' or 'health lamps' (Anon., 1979). One disadvantage of this type of unit was that the area of irradiation was limited to a region such as the face and so whole-body tanning was tedious. By incorporating several mercury arc lamps into a 'solarium', whole body exposure was achieved. Tanning devices based on mercury arc lamps emit relatively large quantities of UVB and UVC radiation, resulting in a significant risk of burning and acute eye damage. Solaria that incorporate unfiltered mercury arc lamps are therefore now less popular (Diffey, 1990a).

So-called UVB fluorescent lamps (e.g., Westinghouse FS Sunlamp, Philips TL12) emit approximately 55% of their UV energy in the UVB and approximately 45% in the UVA regions (Diffey & Langley, 1986). They were often used in tanning booths, more commonly in the USA than in Europe.

Sunbeds, incorporating high-intensity UVA fluorescent lamps, were developed in the 1970s. These devices consist of a bed and/or canopy incorporating 6–30 fluorescent lamps 150–180 cm in length. The earliest type of UVA lamp used in sunbeds is typified by the Philips TL09, Wotan L100/79 and Wolff Solarium lamps (Diffey, 1987c). The spectral power distribution from this type of lamp is shown in Figure 8a. The emission spectrum comprises the fluorescence continuum, extending from about 315 to 400 nm and peaking at 350–355 nm, together with the characteristic lines from the mercury spectrum down to 297 nm (UVB) (Diffey & McKinlay, 1983). The UVA irradiance at the skin surface from a typical sunbed or suncanopy containing these lamps is between 50 and 150 W/m^2 (Bowker & Longford, 1987; Bruyneel-Rapp *et al.*, 1988).

Fig. 8. Spectral emissions of different lamps used for cosmetic tanning: (a) Philips TL09 (Diffey, 1987c); (b) Philips TL10R (Diffey, 1987c); (c) Wolff Bellarium S (B.L. Diffey, unpublished data); (d) optically filtered high-pressure metal halide lamp (Diffey, 1987c)



In the mid-1980s, another type of UVA fluorescent lamp (Philips TL10R) was introduced especially for cosmetic tanning. The principal features of this type of lamp were a reflector intrinsic to the lamp envelope and a fluorescence spectrum extending from about 340 to 400 nm, peaking at 370 nm (Fig. 8b); note also the presence of characteristic mercury lines in the UVB region. The skin surface irradiance from a sunbed or suncanopy incorporating Philips TL10R lamps is typically around 250 W/m2 (Diffey, 1987c).

Another type of UV fluorescent lamp that has been used in sunbeds is the so-called 'fast tan' tube. This type of lamp is typified by the Wolff Bellarium S, the spectral power distribution of which is shown in Figure 8(c). The spectrum extends from about 290 to 400 nm and peaks at around 350 nm (Diffey & Farr, 1987).

Optically filtered, high-pressure mercury lamps doped with metal halide additives are also used in cosmetic tanning. The spectral emission lies entirely within the UVA waveband (Fig. 8d), and irradiances at the skin surface of more than 1000 W/m^2 can be achieved. The best known of this type of unit is probably the UVASUN (Mutzhas, 1986).

A summary of the physical and photobiological emissions from these different types of lamps is given in Table 5 (Diffey & Farr, 1991a).

Table 5. Characteristics of different ultraviolet (UV) lamps used for tanning

Lamp	Radiation emission (%)			Contribution to tanning (%)		
	UVA	UVB	UVC	UVA	UVB	UVC
Mercury arc sunlamp	40	40	20	0	35	65
Simulated sunlight lamp	95	5	0	20	80	0
Type I UVA lamp	99	1	0	60	40	0
Type II UVA lamp	> 99.9	< 0.1	0	> 90	< 10	0
Optically filtered high-pressure lamp[a]	100	0	0	100	0	0
Summer UV sunlight[b]	95	5	0	20	80	0

From Diffey & Farr (1991b) unless otherwise specified
[a]From Mutzhas (1986)
[b]From Sliney & Wolbarsht (1980)

Exposure to UVR sources used for tanning: Telephone surveys carried out in the Netherlands (Bruggers *et al.*, 1987) and in the United Kingdom (Anon., 1987) in the mid-1980s showed that 7–9% of the adult population in each country had used sunbeds in the previous one to two years. A more recent market survey in the United Kingdom (R. McLauchlan, personal communication), with a sample size of 5800, gave a slightly higher figure, with 10% of the population having used a sunbed during the previous year (1988) and 19% of the sample admitting to having used a sunbed at some time in the past. In these and other surveys in the United Kingdom (Diffey, 1986) and the USA (Dougherty *et al.*, 1988), women accounted for 60–85% of users, about half of the subjects being young women aged between 16 and 30. The commonest reason given for using tanning equipment was to acquire a pre-holiday tan (Anon., 1987; R. McLauchlan, personal communication); other reasons included perceived health benefits, reduction of stress and improved relaxation, protection of the skin before going on holiday, sustaining a holiday tan and treatment of skin diseases such as psoriasis and acne (Diffey, 1986; Dougherty *et al.*, 1988).

In the Dutch survey (Bruggers *et al.*, 1987), about half of the users interviewed used tanning equipment at home and the other half used facilities at commercial premises, such as tanning salons, hairdressers, sports clubs and swimming pools. Most people had used UVA equipment; 24% had used either UVB mercury arc sunlamps or solaria incorporating these lamps. A more recent survey in the United Kingdom (McLauchlan, 1989) confirmed the Dutch finding that the amount of use at home and at commercial premises was approximately the same. A survey carried out at commercial establishments in the United Kingdom indicated that all the equipment used emitted primarily UVA radiation, mostly from fluorescent UVA lamps and 10% from optically filtered high-pressure metal halide lamps (Diffey, 1986). Sales of tanning appliances in the United Kingdom increased rapidly during the 1980s, but by the end of the decade there appeared to be a steady, or possibly reduced, level of sales (Diffey, 1990a).

The mean number of tanning sessions per year in the Dutch study was 23 (Bruggers *et al.*, 1987). In the United Kingdom, half-hour sessions were the most popular (Diffey, 1986). Each tanning session with UVA equipment normally results in an erythemally-weighted exposure of about 0.8 MED (150 J/m^2), whereas exposure to mercury arc lamps results in about 2 MED per session (400 J/m^2). In the Dutch survey, it was estimated that the median annual exposure was 24 MED (4.8 kJ/m^2) (Bruggers *et al.*, 1987).

(ii) *Medical and dental applications*

UVR has both diagnostic and therapeutic applications in medicine and dentistry. The diagnostic uses are confined largely to fluorescing of skin and teeth, and the UVR source is normally an optically filtered medium-pressure mercury arc lamp producing radiation mainly at 365 nm (so-called 'Wood's lamps') (Caplan, 1967). Radiation exposure is limited to small areas (< 15 cm in diameter), and the UVA radiation dose per examination is probably no more than 5 J/cm^2. The therapeutic uses of UVR, which result in considerably higher doses, are mainly in the treatment of skin diseases and occasionally the symptomatic relief of pruritus.

Phototherapy: The skin diseases that are most frequently treated with UVR are psoriasis and eczema. Phototherapy of psoriasis at hospital may include the use of tar and related derivatives and other substances, such as anthralin, on the skin (Morison, 1983a; see also IARC, 1987a).

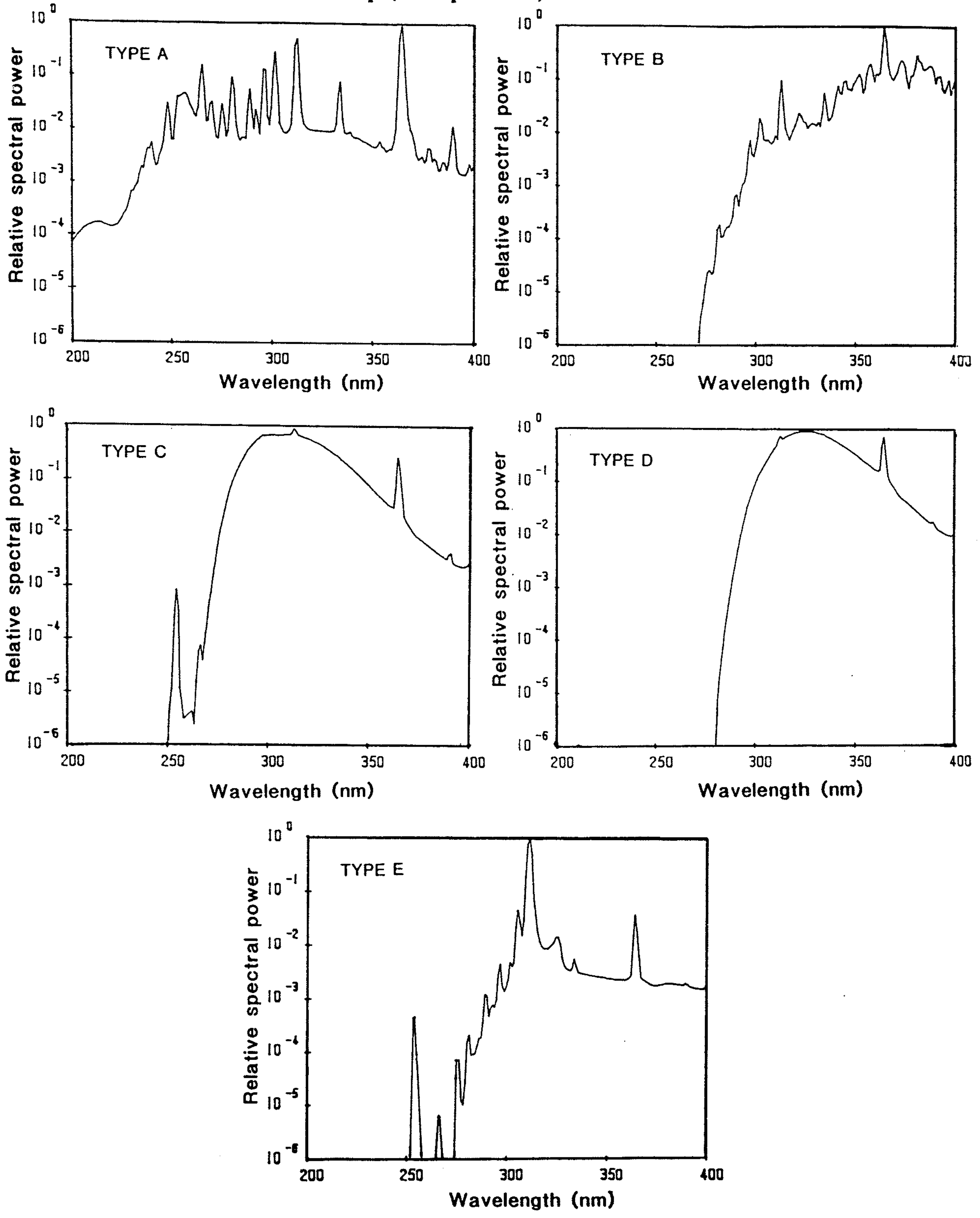
The first treatment of psoriasis with an artificial source of UVR is credited to Sardemann, who used a carbon arc lamp of the type developed by Finsen at around the turn of the century. These lamps were unpopular in clinical practice because they emitted noise, odour and sparks, and they were superseded by the development of the medium-pressure mercury arc lamp. In the 1960s, a variety of metal halides were added to mercury lamps to improve emissions in certain regions of the UV and visible spectra. Fluorescent lamps were developed in the late 1940s; since then, a variety of phosphor and envelope materials have been used to produce lamps with emissions in different regions of the UV spectrum, such that, today, there exists a wide range of lamps for the phototherapy of skin diseases (Diffey & Farr, 1987).

Lamp systems can be classified into one of five categories in terms of suitability for phototherapy (Diffey, 1990b):

Type A: a single, medium-pressure mercury arc or metal halide lamp;
Type B: one or more vertical columns containing five or six optically filtered high-pressure metal halide lamps;
Type C: a canopy or cubicle containing fluorescent sunlamps which emit predominantly UVB but also significant amounts of radiation at wavelengths below 290 nm (e.g., Westinghouse FS sunlamp, Philips TL12 and Sylvania UV21 lamps);
Type D: a canopy, sunbed or cubicle incorporating fluorescent lamps which emit predominantly UVB radiation and negligible amounts of radiation at wavelengths below 290 nm (e.g., the Wolff Helarium);
Type E: a newly developed fluorescent lamp that emits a narrow band of radiation around 311–312 nm (Philips TL01).

The spectral power distributions characteristic of each of these five types of lamp are shown in Figure 9. The therapeutic radiation for psoriasis lies principally within the UVB waveband (Parrish & Jaenicke, 1981), and the cumulative UVB dose required for clearing

Fig. 9. Spectral power distributions of different types of phototherapy lamp (Diffey, 1990b). Type A: unfiltered medium-pressure mercury arc lamp; type B: optically filtered iron iodide lamp; type C: fluorescent sunlamp (Philips TL12); type D: Wolff Helarium lamp; type E: narrow-band UVB fluorescent lamp (Philips TL01)



psoriasis is typically 100–200 MED (Diffey, 1990a), usually delivered over a course consisting of 10–30 exposures over 3–10 weeks (van der Leun & van Weelden, 1986).

Annual doses received by 90% of patients given UVB phototherapy for psoriasis range from about 60 to 670 MED, with a typical dose in a single course being between 200 and 300 MED (Slaper, 1987).

Psoralen photochemotherapy (see also IARC, 1980, 1986a, 1987b): This form of treatment, known colloquially as PUVA, involves the combination of photoactive drugs, psoralens (P), with long-wave UVR (UVA) to produce a beneficial effect. Psoralen photochemotherapy has been used to treat many skin disease in the past decade, although its principal success has been in the management of psoriasis (Parrish *et al.*, 1974), a disorder characterized by an accelerated cell cycle and rate of DNA synthesis. Psoralens may be applied to the skin either topically or systemically; the latter route is generally preferred, and the psoralen most commonly administered is 8-methoxypsoralen. The patient is usually exposed to UVA radiation from banks of fluorescent lamps with the spectral power distribution shown in Figure 8a. Values for UVA irradiance in clinical treatment cubicles have been found to range from 16 to 140 W/m^2 (Diffey *et al.*, 1980; Diffey, 1990b), although an irradiance of 80 W/m^2 is probably typical. The UVA dose per treatment session is usually in the range 1–10 J/cm^2 (Diffey *et al.*, 1980).

Generally, approximately 25 treatments over a period of 6–12 weeks, with a cumulative UVA dose of 100–250 J/cm^2, are required to clear psoriatic lesions (Melski *et al.*, 1977; Henseler *et al.*, 1981). PUVA therapy is not a cure for psoriasis, and maintenance therapy is often needed at intervals of between once a week to once a month to prevent relapse (Gupta & Anderson, 1987).

Neonatal phototherapy for hyperbilirubinaemia: Phototherapy is sometimes used in the treatment of neonatal jaundice or hyperbilirubinaemia. The preferred method of treatment is to irradiate the baby for several hours a day for up to one week with visible light, particularly blue light (Sisson & Vogl, 1982). The lamps used for phototherapy, although intended to emit only visible light, may also have a UV component: One commercial neonatal phototherapy unit was found to emit not only visible light and UVA but also radiation at wavelengths down to 265 nm (Diffey & Langley, 1986).

Fluorescence in cutaneous and oral diagnosis: Wood's light—a source of UVA obtained by filtering optically a mercury arc lamp with 'blackglass'—is used by dermatologists as a diagnostic aid in skin conditions that produce fluorescence (Caplan, 1967; Diffey, 1990a). As irradiation of the oral cavity with a Wood's lamp can produce fluorescence under certain conditions, this has been used in the diagnosis of various dental disorders, such as early dental caries, the incorporation of tetracycline into bone and teeth, dental plaque and calculus (Hefferren *et al.*, 1971).

Polymerization of dental resins: Pits and fissures in teeth have been treated using an adhesive resin polymerized with UVA. The resin is applied with a fine brush to the surfaces to be treated and is hardened by exposure to UVA radiation at a minimal irradiance of 100 W/m^2 for 30 s or so (Eriksen *et al.*, 1987; Diffey, 1990a).

(iii) *Occupational exposures*

Artificial sources of UVR are used in many different ways in the working environment. In some cases, the UV source is well contained within an enclosure and, under normal circumstances, presents no risk of exposure to personnel. In other applications of UVR, it is inevitable that workers are exposed to some radiation, normally by reflection or scattering from adjacent surfaces. Occupational exposure to UVR is also a consequence of exposure to general lighting in the workplace.

Industrial photoprocesses: Many industrial processes involve a photochemical component. The large-scale nature of these processes often necessitates the use of high-power (several kilowatts) lamps such as high-pressure metal halide lamps (Diffey, 1990a).

The principal industrial applications of photopolymerization include the curing of protective coatings and inks and photoresists for printed circuit boards. The curing of printing inks by exposure to UVR is now widespread; as the cure takes only a fraction of a second, UV drying units can be installed between printing stations on a multicolour line, so that each colour is dried before the next is applied. Another major use of UV curing has been for metal decorating in the packaging industry (Phillips, 1983). UVA is also used to inspect printed circuit boards and integrated circuits in the electronics industry (Pauw & Meulemans, 1987).

Artificial sources of UVR are used to test the weathering capability of materials such as polymers. Xenon-arc lamps are often the light source because their emission spectra is similar to the spectrum of terrestrial sunlight, although some commercial weathering chambers incorporate carbon-arc lamps, high-pressure metal halide lamps or fluorescent sunlamps (Davis & Sims, 1983).

Sterilization and disinfection: Radiation with wavelengths in the range 260–265 nm is the most effective for this use, since it corresponds to a maximum in the DNA absorption spectrum. Low-pressure mercury discharge tubes are thus often used as the radiation source, as more than 90% of the radiated energy lies in the 254 nm line. These lamps are often referred to as 'germicidal lamps', 'bactericidal lamps' or simply 'UVC lamps' (Diffey, 1990a).

UVC radiation has been used to disinfect sewage effluents, drinking-water, water for the cosmetics industry and swimming pools. Germicidal lamps are sometimes used inside microbiological safety cabinets to inactivate airborne and surface microorganisms (Diffey, 1990a). The combination of UVR and ozone has a very powerful oxidizing action and can reduce the organic content of water to extremely low levels (Phillips, 1983).

Welding (see also IARC, 1990): Welding equipment falls into two broad categories: gas welding and electric arc welding. Only the latter process produces significant levels of UVR, the quality and quantity of which depend primarily on the arc current, shielding gas and metals being welded (Sliney & Wolbarsht, 1980).

Welders are almost certainly the largest occupational group with exposure to artificial sources of UVR. It has been estimated (Emmett & Horstman, 1976) that there may be as many as half a million welders in the USA alone. The levels of UV irradiance around electric arc welding equipment are high; effective irradiance (relative to the action spectrum of the American Conference of Governmental Industrial Hygienists) at 1 m at an arc current of 400 A ranged from 1 to 50 W/m^2 (Table 6), and the unweighted UVA irradiance ranged from 3 to

70 W/m², depending on the type of welding and the metal being welded (Cox, 1987; Mariutti & Matzeu, 1987). It is not surprising therefore that most welders at some time or another experience 'arc eye' or 'welder's flash' (photokeratitis) and skin erythema. The effective irradiance at 0.3 m from many types of electric welding arcs operating at 150 A is such that the maximum permissible exposure time for an 8-h working period on unprotected eyes and skin varies from a few tenths of a second to about 10 s, depending on the type of welding process and the material used (Cox, 1987).

Table 6. Limits of exposure to ultraviolet radiation and radiation effectiveness

Wavelength (nm)	Exposure limit (J/m²)	Relative spectral effectiveness (S_λ)[a]
180	2500	0.012
190	1600	0.019
200	1000	0.030
205	590	0.051
210	400	0.075
215	320	0.095
220	250	0.120
225	200	0.150
230	160	0.190
235	130	0.240
240	100	0.300
245	83	0.360
250	70	0.430
254[b]	60	0.500
255	58	0.520
260	46	0.650
265	37	0.810
270	30	1.000
275	31	0.960
280[b]	34	0.880
285	39	0.770
290	47	0.640
295	56	0.540
297[b]	65	0.460
300	100	0.300
303[b]	250	0.120
305	500	0.060
308	1200	0.026
310	2000	0.015
313[b]	5000	0.006
315	1.0×10^4	0.003
316	1.3×10^4	0.0024
317	1.5×10^4	0.0020
318	1.9×10^4	0.0016
319	2.5×10^4	0.0012

Table 6 (contd)

Wavelength (nm)	Exposure limit (J/m^2)	Relative spectral effectiveness (S_λ)[a]
320	2.9×10^4	0.0010
322	4.5×10^4	0.00067
323	5.6×10^4	0.00054
325	6.0×10^4	0.00050
328	6.8×10^4	0.00044
330	7.3×10^4	0.00041
333	8.1×10^4	0.00037
335	8.8×10^4	0.00034
340	1.1×10^5	0.00028
345	1.3×10^5	0.00024
350	1.5×10^5	0.00020
355	1.9×10^5	0.00016
360	2.3×10^5	0.00013
365[b]	2.7×10^5	0.00011
370	3.2×10^5	0.000093
375	3.9×10^5	0.000077
380	4.7×10^5	0.000064
385	5.7×10^5	0.000053
390	6.8×10^5	0.000044
395	8.3×10^5	0.000036
400	1.5×10^6	0.000030

From American Conference of Governmental Industrial Hygienists (1991); wavelengths chosen are representative, and other values should be interpolated at intermediate wavelengths.

[a]For explanation, see pp. 46–47

[b]Emission lines of a mercury discharge spectrum

In a survey of electric arc welders in Denmark, 65% of those questioned had experienced erythema; however, as no indication of the frequency of skin reactions was reported, it is not possible to estimate annual exposure (Eriksen, 1987). Monitoring of the exposure to UVR of non-welders working in the vicinity of electric arc welding apparatuses showed that their daily exposure dose exceeded the maximum permissible exposure limits by almost an order of magnitude (Barth *et al.*, 1990).

Phototherapy: Although there is a trend to the use of enclosed treatment cubicles, some of the lamps used to treat skin disease (see the section on medical and dental applications) are unenclosed, emit high levels of UVR and can present a marked hazard to staff; at 1 m from these lamps, the recommended 8-h occupational exposure limits can be exceeded in less than 2 min (Diffey & Langley, 1986).

In a study of the exposure of staff in hospital phototherapy departments (Larkö & Diffey, 1986), annual exposure to UVR could be estimated from the number of occasions per year on which staff had experienced at least minimal erythema (Diffey, 1989b). Estimated annual occupational exposures to UVR were 15, 92 and 200 MED, corresponding to a frequency of erythema of once per year, once per month and once per week, respectively.

Operating theatres: UVC lamps have been used since the 1930s to decrease the levels of airborne bacteria in operating theatres (Berg, 1987). The technique requires complete protection of the eyes and skin of staff and patients; for this and other reasons, filtered air units are often preferred.

Research laboratories: Sources of UVR are used by most experimental scientists engaged in aspects of photobiology and photochemistry and in molecular biology. These applications, in which the effect of UV irradiation on biological and chemical species is of primary interest to the researcher, can be differentiated from UV fluorescence by absorption techniques where the effect is of secondary importance (Diffey, 1990a).

UV photography: There are two distinct forms of UV photography: reflected or transmitted UV photography and UV fluorescence photography. In both applications, the effective radiation lies within the UVA waveband (Lunnon, 1984).

UV lasers: High-power lasers which emit in the UV region, used in nuclear and other research laboratories, are far less common than those that emit in the visible or infrared regions of the electromagnetic spectrum.

Nitrogen lasers emit at a wavelength of 337 nm (Phillips, 1983), and instruments with a peak power output of up to 2.3 MW per pulse are available. Nitrogen lasers can be used in conjunction with fluorescent dyes to produce spectral emissions of 360–900 nm, with a power pulse of 200–480 kW. If frequency doubling crystals are used in conjunction with a nitrogen laser, UV emissions down to 260 nm are possible.

An alternative laser source of UVR is the excimer laser. (The term 'excimer' denotes a homonuclear molecule which is bound in an electronically excited state but is dissociative in the ground state [Phillips, 1983].) The wavelength of the pulsed UVR from this type of laser depends on the excimer molecules, such as ArF, F_2, XeCl and KrF, which emit at 193, 157, 308 and 248 nm, respectively (Phillips, 1983; Bos & de Haas, 1987). On the basis of worst-case assumptions, the estimated annual risk for skin cancer for workers exposed to UV lasers in medical applications is equivalent to about one additional day of sunbathing, and that for workers exposed to UV lasers in laboratories is comparable to the risk for outdoor workers (Sterenborg *et al.*, 1991).

Quality assurance in the food industry: Many contaminants of food products can be detected by UV fluorescence techniques. For example, the bacterium *Pseudomonas aeruginosa*, which causes rot in eggs, meat and fish, can be detected by its yellow-green fluorescence under UVA irradiation. One of the longest established uses of UVA fluorescence in public health is to demonstrate contamination with rodent urine, which is highly fluorescent (Ultra-Violet Products, Inc., 1977).

Insect traps: Many flying insects are attracted by UVA radiation, particularly in the region around 350 nm. This phenomenon is the principle of electronic insect traps, in which a UVA fluorescent lamp is mounted in a unit containing a high-voltage grid. The insect, attracted by the UVA lamp, flies into the unit and is electrocuted in the air gap between the high-voltage grid and a grounded metal screen. Such units are commonly found in areas where food is prepared and sold to the public (Diffey, 1990a).

Sunbed salons and shops: The continuing popularity of UVA sunbeds and suncanopies for cosmetic tanning has resulted in the establishment of a large number of salons and shops selling sunbeds for use at home. Some shops may have 20 or more UVA tanning appliances, all switched on, thus exposing members of the public and staff to high levels (> 20 W/m^2) of UVA radiation (Diffey, 1990a).

Discotheques: UVA 'blacklight' lamps are sometimes used in discotheques to induce fluorescence in the skin and clothing of dancers. The levels of UVA emitted are usually low (< 10 W/m^2) (Diffey, 1990a).

Offices: Signatures can be verified by exposing a signature obtained with colourless ink to UVA radiation, under which it fluoresces. UVA exposure of office staff is normally to hands, and irradiance is low (< 10 W/m^2) (Diffey, 1990a).

(iv) *General lighting*

Fluorescent lamps used for general lighting in offices and factories emit small quantities of both UVA and UVB. A UVA irradiance of 30 mW/m^2 (Diffey, 1990a) and a UVB irradiance of 3 mW/m^2 (McKinley & Whillock, 1987) were found for bare fluorescent lamps with a typical illuminance of 500 lux. These UV levels give rise to an annual exposure of indoor workers to no more than 5 MED, and this dose can be reduced appreciably by the use of plastic diffusers (McKinlay & Whillock, 1987). A study of the personal doses of UVR received by workers in the car manufacturing industry who were engaged in inspecting paintwork of new cars under bright fluorescent lamps indicated a similar annual exposure (Diffey *et al.*, 1986). Most plastic diffusers reduce erythemally effective irradiance to 0.2% or less of that of the bare lamp. An exception is clear acrylic diffusers, which absorb only about 20% of the erythemally effective radiation. The absorption of UVA radiation by diffusers is less effective, transmission ranging from 1% for opal polycarbonate to 74% for clear acrylic (McKinlay & Whillock, 1987). Spectroradiometric measurements of the UV levels from indoor fluorescent lamps carried out in the USA, however, indicated much higher annual doses for people exposed occupationally for 2000 h per year: The annual estimated exposure dose ranged from 8 to 30 MED for an illuminance level of 500 lux from bare lamps (Cole *et al.*, 1985).

Desk-top lights which incorporate tungsten–halogen (quartz) lamps may result in exposure to UVR of the hands and arms, if the lamps are used in excess of recommended occupational exposure levels (McKinlay *et al.*, 1989). Experimental studies have shown that erythema can be induced in susceptible individuals after a 15-min exposure at 10 cm from a 100-W tungsten–halogen source, principally by the UVB component of the emission (Cesarini & Muel, 1989). Tungsten–halogen lamps are also used for general lighting (e.g., spotlights, indirect lighting, floor lamps) in some countries.

(c) *Regulations and guidelines*

(i) *Cosmetic use*

The most comprehensive guidelines for the use of sunlamps and sunbeds in cosmetic tanning are those published by the International Electrotechnical Commission (1987, 1989). The guidelines classify tanning appliances into one of four types according to the effective irradiance at short ($\lambda \leq 320$ nm) and long ($320 < \lambda \leq 400$ nm) UV wavelengths (Table 7).

Table 7. Classification of tanning appliances

Type	Effective irradiance (W/m²)	
	$\lambda \leq 320$ nm	320 nm $< \lambda \leq 400$ nm
1	< 0.0005	≥ 0.15
2	0.0005–0.15	≥ 0.15
3	< 0.15	< 0.15
4	≥ 0.1	< 0.15

From International Electrotechnical Commission (1989)

Effective radiance is defined as:

$$\sum_{250}^{400} E_\lambda \times S_\lambda \times \Delta_\lambda,$$

where E_λ is the spectral irradiance (W/m^2 × nm) at wavelength λ (nm) at the shortest recommended exposure distance; Δ_λ is the wavelength interval used in the summation; and S_λ is the relative erythemal effectiveness recently adopted by the Commission Internationale de l'Eclairage (McKinlay & Diffey, 1987), specified as shown in Table 8. The guidelines recommend that the exposure time for the first session on untanned skin should correspond to an effective dose not exceeding 100 J/m^2; this is approximately equivalent to 1 MED for subjects with sun-reactive skin type I. The annual exposure should not exceed an effective dose of 25 kJ/m^2 (International Electrotechnical Commission, 1989).

Table 8. Specifications of relative erythemal effectiveness

Wavelength (λ; nm)	Relative erythemal effectiveness (S_λ) (weighting factor)
$\lambda < 298$	1
$298 < \lambda < 328$	$10^{0.094(298-\lambda)}$
$328 < \lambda \leq 400$	$10^{0.015(139-\lambda)}$

From McKinlay & Diffey (1987); International Electrotechnical Commission (1989)

Although these guidelines form the basis of several national standards on sunlamp and sunbed use, it should be noted that variations exist; for example, in the Netherlands, Norway and Sweden, certain UV appliances are not permitted. Regulations concerning the use of tanning appliances are in force in only a few countries, but many others have published advice on sunbed use, including information on adverse effects, as well as guidelines on manufacturing standards.

(ii) *Occupational exposure*

Guidance on the maximal limits of exposure to UVR as a consequence of occupation is given by the International Non-ionizing Radiation Committee of the International Radiation

Protection Association. These exposure limits, which apply only to incoherent (i.e., non-laser) sources, represent conditions under which it is expected that nearly all individuals may be repeatedly exposed without adverse effects and are below levels which would be used for medical or cosmetic exposure to UVR. The limits for occupational exposure to UVR incident upon the skin or eye were considered separately for the UVA spectral region (315–400 nm) and the actinic UV spectral region (UVC and UVB, 180–315 nm). In 1984, the limit provided an equal spectral weighting between 315 and 400 nm, a maximal 1000-s radiant exposure of 10 KJ/m^2 and a maximal irradiance of 10 W/m^2 for longer periods (International Non-ionizing Radiation Committee of the International Radiation Protection Association, 1985). Studies of skin and ocular injury resulting from exposure to UVA led the Committee to issue revised exposure limits in 1988: For the UVA spectral region (315–400 nm), the total radiant exposure incident upon the unprotected eye should not exceed 1.0 J/cm^2 (10 kJ/m^2) within an 8-h period, and the total 8-h radiant exposure incident upon the unprotected skin should not exceed the values given in Table 6. Values for the relative spectral effectiveness S_λ are given up to 400 nm to expand the action spectrum into the UVA region for determining the exposure limit for skin exposure. For the actinic UV spectral region (UVC and UVB, 180–315 nm), the radiant exposure incident upon the unprotected skin or eye within an 8-h period should not exceed the values given in Table 6 (International Non-ionizing Radiation Committee of the International Radiation Protection Association, 1989).

The effective irradiance (E_{eff}) in W/m^2 of a broad-band source weighted against the peak of the spectral effectiveness curve (270 nm) is determined according to the formula:

$$E_{eff} = \Sigma\ E_\lambda \times S_\lambda \times \Delta_\lambda,$$

where E_λ is the spectral irradiance (W/m^2 $\times$ nm) from measurements, S_λ is the relative spectral effectiveness (Table 6) and Δ_λ is the band-width (nm) of the calculation or measurement interval (International Non-ionizing Radiation Committee of the International Radiation Protection Association, 1985).

The maximal permissible exposure time in seconds for exposure to UVR incident on the unprotected skin or eye within an 8-h period is computed by dividing 30 J/m^2 by the value of E_{eff} in W/m^2 (American Conference of Governmental Industrial Hygienists, 1991). A worker receiving the maximal permissible exposure of 30 J/m^2 per 8-h day will, in the course of a working year, have a cumulative dose of 60–70 MED (Diffey, 1988), a value comparable with the natural exposure of non-occupationally exposed indoor workers (Diffey, 1990a).

Occupational exposure limits to lasers were also defined by the International Non-Ionizing Radiation Committee of the International Radiation Protection Association in 1989, at 3 mJ/cm^2 and 40 mJ/cm^2 over 8 h for argon–fluoride and xenon–chloride lasers, respectively (Sliney, 1990).