Disclaimer

These notes have been prepared based on my understanding of the ICNIRP Guidelines "Guidelines on limits of exposure to Broadband incoherent optical radiation (0.38 to 3 uM)" and are presented to assist amateur astronomers assess the safety or otherwise of various solar filters. Focus has been given obviously to the dangers to the human eye; there may be other factors which affect you choice of filter i.e. camera and CCD sensitivities and response.

Filters must always be securely fixed in place and double checked for safety before use.

The use of optical equipment to view the Sun is inherently dangerous, and the final choice of filter/ protection is your responsibility – not mine.

Summary:

Sunlight and the eye

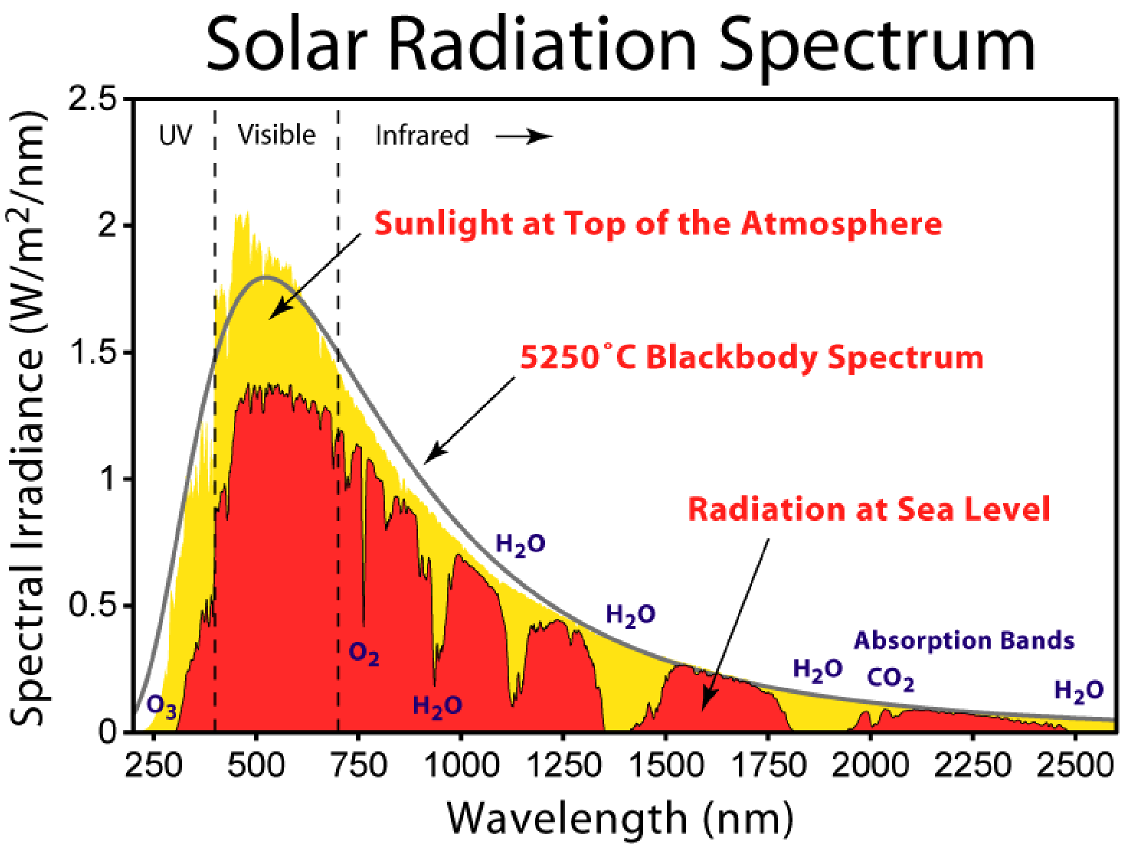
The human eye is sensitive to solar radiation from 380nm through to about 780nm. The maximum daylight sensitivity (photopic vision) occurs at 555nm (in the green part of the sun's spectrum). As we age, our sensitivity to shorter wavelengths decreases, and in the adult population less than 1% of radiation below 340 nm and 2% of radiation between 340 and 360 nm reaches the retina.

The light from the Sun contains radiation energy across the whole spectrum. It generally radiates as a Black Body with energy peaking around 500nm. Due to the absorption/ reflection by the Earth's atmosphere the energy levels vary across the whole spectrum. (See Diagram: Solar Radiation Spectrum, below)

Visible light extends from approximately 380nm to 780nm. The light between 100nm and 400nm is commonly called Ultraviolet (UV), [UV-C, 100-289nm; UV-B, 280-315nm; UV-A, 315-380nm), red light beyond 780nm is called Infrared (IR). [IR-A, 780-1400nm; IR-B, 1400-3000nm; IR-C, 3000nm – 1mm]

Energy in the UV-A, can cause damage to the eye (as well as the skin), likewise IR-A radiation can cause thermal injury to the eye. Normal visible light, if bright enough, can cause partial loss of sensitivity and temporary blindness ("snow blindness", coloured after-images)

Damage to the eye is more likely to occur due to exposure to UV-A, and bright visual light, rather than IR. There is a human "self defense" reaction which generally makes involuntary eye movement when the eye is exposed to extremely bright light (eye movement, squinting, closing the eye) which reduces the effect of the energy, and gives some protection.



Solar Radiation

The diagram above shows the energy level distribution, Spectral Irradiance ($W/m^2/nm$), across the solar spectrum. Of interest, is the quick drop in energy levels in the UV. Unfortunately, not withstanding this reduced energy, the shorter wavelengths have more penetrating power (Think in terms of X-rays) and as a result are more dangerous. The dips in the IR regions are caused by water absorption in the atmosphere. Considering the radiation from 380nm through to 1200nm, you can see that almost 90% is in the visual and IR. To calculate the total energy in any specific bandwidth, we need to add all the wavelength Irradiance levels across the band width.

On the surface of the Earth, the average solar irradiance is 342 W/m^2

The Sun appears as a circular disk approx 31 minutes of arc diameter (½ Degree).(Expressed in radians this is 0.009 radian, or 0.9mrad)

ND filters

The Neutral Density (ND) rating of a filter is the measure of the attenuation of the energy through the filter. ND is measured in multiples of the power of ten. i.e. A ND1 filter would reduce the energy by 1/10, a ND2 by 1/100, a ND3 by 1/1000 etc.

WHO / Dr Chou recommendations

The World Health Organisation (WHO) accept the American National Standards Institute's recommendation that at least 60 to 92% of the normal solar UV-A and visible light be filtered out. This would mean at least a naked eye filter (i.e. sunglasses) with an equivalent ND2 across all wavelengths. Bear in mind this recommendation is for general outdoors activities, not for staring at the Sun.

Dr Chou, Associate Professor; School of Optometry University of Waterloo; Waterloo, Ontario, Canada prepared a comprehensive guide to Solar Filters in the late 90's. This was published in Sky & Telescope, Feb 1998.

See http://www.mreclipse.com/Special/filters.html#pfilter

To quote Dr Chou:

Filter Transmittance

The luminous transmittance of the filter, when determined as described in clause 6 of EN167, shall not exceed 0.0032%(Ed: ND2.5). Filter transmittance in the waveband 280 to 380 nm (ultraviolet radiation) shall not exceed 0.003% (Ed: ND2.5) at any wavelength. Transmittance in the near infrared waveband (780 to 1400 nm) shall not exceed 0.027% (Ed: ND2) at any wavelength. Filters with luminous transmittance (in the waveband 380 to 780 nm) equivalent to scale number 12 to 16 (Ed: ND3 to ND5) as specified in Table 1 of EN169:1992 are considered suitable for direct observation of the sun. It should be noted that many observers will find the solar image uncomfortably bright when filters with scale numbers of 12 or 13 are used.

Summarising this recommendation:

ND2 or ND 2.5 for UV and IR protection

ND3 to ND5 for visual wavelengths

Effect of Optical Equipment

The size of the solar disk as projected on the inside of the naked eye is 0.15mm diameter, so all the solar radiation is concentrated on this area of the eye (retina).

Any optical equipment used to observe the Sun has the effect of concentrating the heat and light energy into the eyepiece and on to the eye. When exposed to reasonably bright light, our iris will naturally contract to reduce the amount of light entering the eye. An eye at night (dark adapted) can have an aperture of 7mm, whereas during the day this will reduce to about 3mm.

NB. It is assumed that the image of the Sun in the eyepiece is the same as the aperture of the eye. i.e. the exit pupil is 3mm diameter. This would be achieved with an 80mm refractor at x26 magnification. Higher magnifications would obviously result in larger solar images, only a portion of which would be visible to the eye at any one time. This would significantly reduce the irradiance of the eye. I've not taken this into account. An additional safety margin!

Taking 3mm as a good average, we can easily calculate the impact of larger objectives:

Naked eye, aperture 3mm	Effective area: 14.13 sq mm (0.1413 cm^2)
40mm Objective	Effective area: 2513.26 sq mm (x 178 naked eye)
60mm Objective	x 400 naked eye
80mm Objective	x 711 naked eye
100mm Objective	x 1111 naked eye

When considering solar filters the above factors must be considered. Think about Boy Scouts starting a fire with a magnifying glass!! 342W/m2 from the Sun, focused with a 100mm magnifying glass will generate 2.7W on the grass, that's enough to start a fire at above 200^0 C if focused on a small enough area!!!

ICNIRP safe exposure limits

ICNIRP has prepared a series of recommendations which determine the "safe exposure limits" for various bandwidths. The safe exposure limit is very conservative and is based on research carried out over the last 20 years and takes into account:

- Short high intensity exposures
- Long cumulative exposure
- Photochemical and thermal injury

They define 5 types of risk, the main three for solar observers are:

1. thermal injury of the retina (380- 1400nm)
2. “blue-light” photochemical injury of the retina (380-550nm)
3. near-infrared thermal injury of the crystalline lens in the eye (800nm upwards)

“blue-light” injury is the partial loss of sensitivity and temporary blindness (“snow blindness”, weld flash, coloured after-images) mentioned before. The impact of exposures over 10 seconds is minimized by the natural eye movements “spreading” the image over a larger area of the retina. The size and brightness of the object being observed also affect the risk.

Thermal injury is strongly dependent upon heat conduction from the tissues. It requires an “intense exposure within seconds to cause tissue coagulation” Normally it requires a temperature of “at least 45 degrees to produce a thermal burn”. Therefore the effect is dependent upon the tissue temperature and the exposure spot size.

If you consider, observing in bright sunlight your body temp will be 37 degrees, it would require a localized temperature increase of only 8 degrees.

ICNIRP calculates the “safe exposure limits” based on radiometric and photometric exposure. Unfortunately this means if we want to do the calculations ourselves, we need an understanding of the various quantities and units.

Radiance: (W/m^2/ sr) is the brightness of the object. Where “sr” is the solid angle (steradian), subtended by the source.

Irradiance: (W/m^2) is the radiation spread over an area

Luminance: (cd/m^2) is another measure of brightness

Illuminance (lm/m^2 or Lux) is the brightness spread over an area

(For the Sun, the conversion from energy to brightness is approx 100 lm/W.)

ICNIRP also use various weighting factors to help determine the safe exposures, and these are listed, by wavelength in the Table on page 554 of the *Guidelines.*

Blue-light photochemical retinal hazard (300-700m)

Safe exposure limits in the ICNIRP for UV (Blue-light) are <100J/cm^2/sr (effective)

The effective radiance, sum (300-700)[L(lamda) x B(lamda) x exposure time x delta wavelength) must not exceed the above. The factor B (lamda) is given on page 554 of the ICNIRP guidelines, for delta of 5nm.

The SI steradian (abbreviated "sr")- The solid angle is proportional to the surface area, *S*, of a projection of that object onto a sphere centered at that point, divided by the square of the sphere's radius, *R*. (Symbolically, $\Omega = S/R^2$).

Or for small sources (<0.011 rad), <10mJ cm^2 (0.01J/cm^2)

(J=Joule =The work done to produce power of one watt continuously for one second)

Retinal thermal hazards (380-1400nm)

Safe exposure limits in the ICNIRP for thermal hazards are <5/(alpha x $T^{0.25}$) W/cm^2/sr (effective), where alpha is the angular image size on the retina (in radians) and T the exposure time, limited to a maximum of 10 seconds.

The effective radiance, sum (380-1400)[L(lamda) x R(lamda) x delta wavelength must not exceed the above. The factor R (lamda) is given on page 554 of the ICNIRP guidelines, for delta of 5nm.

For wavelengths above 780nm the maximum radiation should be <100 W/m^2 (0.01W/cm^2) for very long exposures or 1.8 x $T^{-3/4}$ W/cm^2 For T< 1,000 seconds

i.e. for a 10second exposure, the limit would be 0.32W/cm^2

Naked eye solar observing

To comply with Dr Chou's recommendations, a filter with an attenuation of ND3 would be a minimum choice. How does this compare with the ICNIRP recommendations??

The solar irradiance is 342 W/m2, or 0.0342 W/cm2; based on an observation time of 10 second, this is 0.342 J/cm2.

The ICNIRP gives a "Blue light" safe limit of 0.01J/cm2. To comply we would need a minimum of a ND2 filter.

What about the thermal effects?

The hazard limit is <5/(alpha x $T^{0.25}$) ; alpha = 0.009 radians (The angular size of the solar disk on the retina) and T=10 seconds, gives 312 W/cm^2/sr

Based on the Solar radiation of 0.0342 W/cm^2 , a R(lamda) total of 152.78 (from 380nm to 1400nm, at 5nm delta) gives 25.88 W/cm^2 /sr. This would be more than adequately covered by the ND2 minimum for UV protection.

Application of safe exposure limits to solar observing

1. White light observing

Amateurs have a variety of white light solar filters available. These range from full aperture solar aluminized mylar film, Herschel wedge prisms to "Sun filters" which screw into a standard eyepiece. I'll consider, by way of example, all three types.

Full Aperture Filter

A full aperture filter if used correctly, in my opinion is the safest option. It effectively prevents any harmful radiation entering the telescope, prevents heat build up inside the scope and any thermal damage to the optics. Depending on the design of the filter there can be a colour shift; the image of the Sun appearing pink, yellow or green. The outcome is purely aesthetic.

To be safe and effective the filter must attenuate all wavelengths from 380nm through to 1200nm, and drop the irradiation to below the ICNIRP limits. All of the commercially available filters (i.e. AstroZap, Baader, 1000 Oaks, JMB) offer at least ND3.8 (up to ND5) and although there is a rise in transmission above 700nm are to be recommended.

Herschel Wedge

This diagonal reflects a little light into the eyepiece and the rest is deflected away. It can be used in conjunction with a full aperture filter or on its own.

The Baader unit, reflects 4.6% of the incident light and is fitted with a ND3 filter. So the equivalent attenuation is about ND 4.5 Note: The ND filter MUST be fitted at all times to make this a safe system.

“Solar” eyepiece filters

These are generally sold with cheaper “supermarket” telescopes and are designed to screw into the eyepiece. From what I’ve seen these are similar to ND3 filters. THESE SHOULD BE BANNED! If you ever see one, grab it and throw it away!

The problem is the amount of heat generated so close to the focus of the telescope is enough to crack the filter, when this happens the full blast of the sun’s energy is allowed through to the eye. VERY DANGEROUS.

2. ERF’s and solar Ha telescopes

The Cornado PST, Solar Max, SolarView, Lunt, Modified PST systems etc are basically designed along similar lines. Most are fitted with a full aperture energy rejection filter (ERF) which prevents most of the heat and light from entering the telescope. An etalon filter “cuts” the solar spectrum into narrow light and dark bands which only passes light in a band approximately 0.07nm wide (one of which is centred on Ha line 636.5nm) and finally a Blocking Filter, a very narrow bandwidth filter (usually about 0.4nm) centered on and separating the Ha line from the background. This then provides detailed images of the solar disk in the Ha wavelength. For maximum contrast the narrower the bandwidth the better the result and some systems (double stacking of etalons) can achieve 0.05nm bandwidth.

Cornado PST

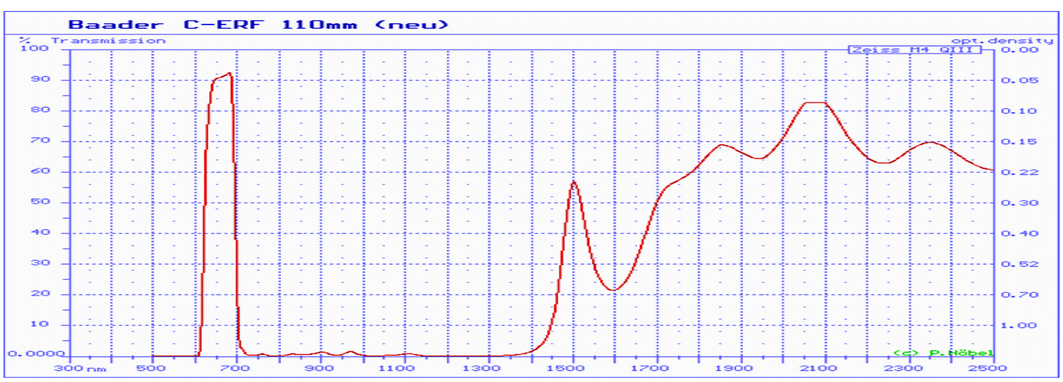
This is a 40mm aperture unit with an effective focal ratio of 10, focal length 400mm. Originally the front objective we assume, acted as an ERF, and had a gold coloured coating, reflecting UV-IR and most of the visible light. There are no additional filters in the etalon assembly, the blocking filter (BF5) being mounted at the rear of the eyepiece holder. The early units suffered from deterioration of the front objective (“rust”) and were replaced with an AR (Anti-reflection) coated objective. At the same time Meade/ Coronado added an “ERF” type filter element at the front of the eyepiece holder. This appears to be a broadband red filter, suppressing the UV –IR though-put.

As I’m not aware of any safely related concerns with the PST, I’d have to say the Meade/ Coronado engineers appear to have designed a satisfactory filter solution.

Issues can arise when the PST etalon is used in a modified solar telescope. The usual configuration for this mod, is to mount an ERF on the objective, remove the PST etalon from the PST body and fit it into the telescope tube followed by either the blocking filter from the PST, or one of the larger Coronado blocking filters (BF10 or BF15). Obviously after the etalon, the filtering is equivalent to the original PST.

Questions arise as to the safety of the ERF. This filter should reject UV-A, visible light (other than the Ha or Cak) and IR-A.

Baader C-ERF



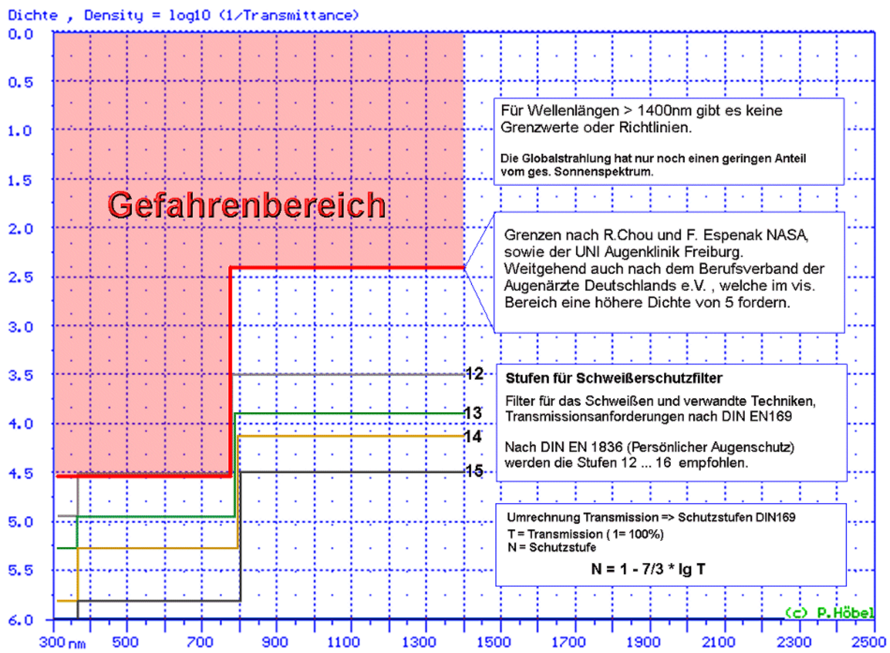
This ERF is designed for Ha observing, and provides an effective cut-off around the Ha (600nm-700nm) and above 1400nm.

It provides ND5 attenuation to the UV-A, visible, and IR-A regions, so is a very good option.

On Peter Hobel’s excellent webpage:

http://translate.google.com/translate?u=www.sonnen-filter.de%2F&hl=en&ie=UTF8&sl=de&tl=en

He presents a graph of the various attenuation limits/ wavelength based on EU recommendations (Basically ND 4.5 being a "safe" limit up to 700nm and ND 2.5 beyond; this matches well with the ICNIRP/ WHO/ Dr Chou recommendations)



3. Spectroscopes and narrow bandwidth observing

A slit spectroscope only allow a very small percentage of the light to enter the instrument, typical slit widths being 20 to 30 micron and by their nature they then spread all the energy over a large image of the spectrum. The resulting image hazard is minimal. The main issue in observing the Sun will be the build-up of heat on the slit and the front of the spectroscope. Providing there is no damage to this area, the resulting spectrum will be safe to view. For these practical reasons, I usually limit the aperture to 50mm or less. This gives more than enough light even for a high resolution (R=20000) spectroscope.

Similarly for narrow band viewing of the Sun; i.e. using a suitable filter say, a 2" or 1 ¼" Calcium line filter (Cak – 396nm) of 0.02nm (i.e. The CaK PST filter) or 10 to 20nm "narrow bandwidth filters". The heat and solar radiation will certainly pose a safety issue to the filter material and if not given some protection could be subject to thermal failure and crack causing possible risk to the eye and/ or camera.

As the eye is only marginal sensitive to these short wavelengths, filtering to say, 10nm bandwidth further reduces the hazards. For a 10 second exposure, ICNIRP "Blue Light" recommendations for such a set-up would give:

(0.5 x 0.05 x 10 x 10)= 2.5 $W/m^2/sr$, which is about 1/40th the limit.

This is based again on "naked eye" hazards, so needs to be multiplied by the concentration of the telescope.

I.e. 40mm would take this exposure to x178 = 445, more than 4 times the recommendation! Need a ND1 filter

60mm, (1000 v's 100) need a ND1 filter

80mm, (1777.5 v's 100)need a ND1.5

100mm, (2775 v's 100) need a ND1.5-2.0 filter.

SUMMARY

Naked eye – ND3 absolute minimum, suggest up to ND4.5

Based on a filter system/ location which does NOT allow excessive heat build-up (ie risk of thermal cracking) to occur in the telescope:

White light, telescope – ND 3.8 (Photography/ CCD), visual ND5

Narrowband filters – ND1 to ND 2, depending on aperture

Ken Harrison (Merlin66), Cobham 9th June 2008

Addition Information

Some other information on UV and solar radiation risks.

World Health Organisation Statements

Just as with the skin, UV exposure to the eye is cumulative over a lifetime and may cause irreversible damage. Sunglasses help your vision and protect your eyes. They make you feel more comfortable under bright light conditions as they reduce glare and improve contrast. Most importantly, good sunglasses filter UVA and UVB radiation and can prevent damage to the eye.

You cannot tell how much UV radiation a pair of sunglasses block based on the colour of the lenses, their darkness or their price. UV transmission through sunglasses varies considerably. However, most sunglasses on sale filter a large percentage of UV radiation. According to the American National Standards Institute, general purpose sunglasses must block between 60 and 92 per cent of visible light and UVA, and between 95 and 99 per cent of UVB. For sunglasses to be fully protective against UV radiation, the lenses must absorb all UV radiation and side protection should be provided. This is especially important in extreme UV environments, for example during hiking or climbing at altitude or skiing.

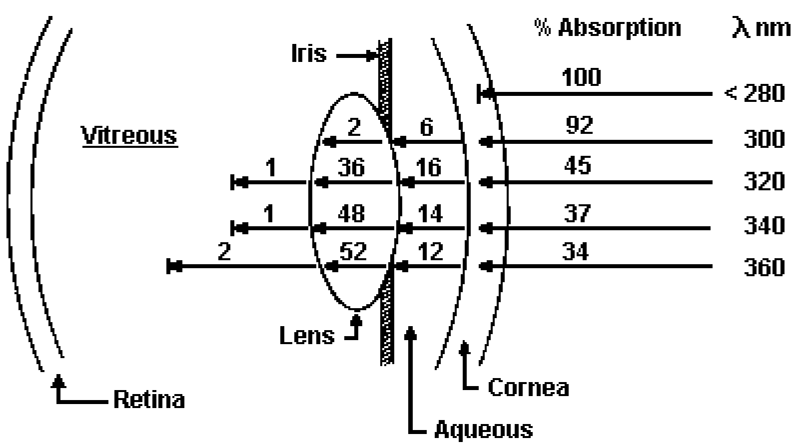
INTERNATIONAL PROGRAMME ON CHEMICAL SAFETY

ENVIRONMENTAL HEALTH CRITERIA 160

ULTRAVIOLET RADIATION

This report contains the collective views of an international group of experts and does not necessarily represent the decisions or the stated policy of the United Nations Environment Programme, the International Labour Organisation, or the World Health Organization.

Figure 10.2 Schematic of absorption of UV in the ocular media. Values represent the percent of UV incident upon the corneal surface that are absorbed by various layers. From Sliney & Wolbarscht (1980), based on data from Boettner & Wolter (1962)



10.6 Diseases of the Choroid and Retina

Among adults, only extremely small amounts of UVA and UVB at wavelengths below 380 nm reach the retina, because of the very strong absorption by the cornea and lens. Less than 1% of radiation below 340 nm and 2% of radiation between 340 and 360 nm reaches the retina (Barker and Brainard, 1993). Even in early childhood the highest spectral transmittance reaches about 4% in the UVB and is generally of the order of 1%. However, because of the biological activity of the shorter wavelengths of UVB, the biological importance of the small amount of this radiation that does reach the retina cannot be completely neglected. As children age, UV is increasingly absorbed by the cornea and lens, and the proportion reaching the retina decreases. This suggests firstly, that exposure to UV during childhood may be of more importance than exposure to UV during adult life, and secondly, that exposure to longer wavelength radiation (e.g. visible light) may be of more importance in adulthood.

10.4.1 Photokeratitis and photoconjunctivitis

Pitts (1974, 1978) in a series of laboratory studies on humans estimated the mean threshold of UVB (290-315 nm) for photokeratitis at 3500 J m^{-2}. These laboratory data are supported by Blumthaler *et al.* (1987), who estimated that the radiant exposures in clinically observed cases of photokeratitis ranged from 1200 to 5600 J m^{-2}. It is estimated that 100 to 200 seconds of direct, unattenuated exposure to 295-315 nm solar radiation will result in photokeratitis (Sliney, 1987; Wittenberg, 1986).

There is inadequate evidence of an association between ocular UV exposure and acute solar retinitis, age-related macular degeneration, acceleration of pigmentary retinopathies and exfoliation syndrome

12. HEALTH HAZARD ASSESSMENT

12.1 Introduction

International guidelines on protection against UV given in chapter 13 are based on available scientific data (IRPA/INIRC, 1991). The guidelines define occupational exposure limits (ELs) below which it is expected that nearly all people may be repeatedly exposed without adverse effects. The Els are intended to be used to evaluate potentially hazardous exposures from, for example, solar radiation, arcs, gas and vapour discharges, fluorescent lamps and incandescent sources. The Els are generally below levels which are often used for the UV exposure of patients required as part of medical treatment and below levels associated with sunbed exposure. IRPA/INIRC recommend that, where they are to be incorporated in regulations, the ELs should be considered as absolute limits for the eye.

13. INTERNATIONAL GUIDELINES ON EXPOSURE TO ULTRAVIOLET RADIATION

A number of national and international organizations have promulgated guidelines or standards on exposure to UV. Most are based upon the same basic criteria of ACGIH (1993) and IRPA/INIRC (1991).

The basic exposure limit (EL) for UV incident on the eye is 30 J m^{-2} effective), when the spectral irradiance E_{lambda} at the eye surface is mathematically weighted with the hazard relative spectral effectiveness factor S_{lambda} from 180 nm to 400 nm. This is given as follows:

E_{eff} = Sigma E_{lambda} S_{lambda} $Delta_{lambda}$

where:

E_{eff} = effective irradiance W m^{-2}

E_{lambda} = spectral irradiance from measurements in W m^{-2} nm^{-1}

S_{lambda} = relative spectral effectiveness factor (unit-less)

$Delta_{lambda}$ = bandwidth of the calculation or measurement in nm

At 270 nm in the UVC range, S_{lambda} is 1.0, but at 360 nm in the centre of the UVA range, its value falls to 0.00013, and continues to fall for longer wavelengths.

For the UVA, the total radiant exposure incident on the unprotected eye should not exceed 10^4 J m^{-2} (1 J cm^{-2}) within an 8 h period.

The radiant UV exposure incident upon the unprotected eye within an 8-hour period should not exceed the values given in table 13.1.

Table 13.1 International UV exposure limits and spectral weighting factor (IRPA/INIRC, 1991)

Wavelength[a] (nm)	EL ($J\ m^{-2}$)	EL ($mJ\ cm^{-2}$)	Relative Spectral Effectiveness S_{lamda}
180	2,500	250	0.012
190	1,600	160	0.019
200	1,000	100	0.030
205	590	59	0.051
210	400	40	0.075
215	320	32	0.095
220	250	25	0.120
225	200	20	0.150
230	160	16	0.190
235	130	13	0.240
240	100	20	0.300
245	83	8.3	0.360
250	70	7.0	0.430
254[b]	60	6.0	0.500
255	58	5.8	0.520
260	46	4.6	0.650
265	37	3.7	0.810
270	30	3.0	1.000
275	31	3.1	0.960
280[b]	34	3.4	0.880
285	39	3.9	0.770
290	47	4.7	0.640
295	56	5.6	0.540
297[b]	65	6.5	0.460
300	100	10	0.300
303[b]	250	25	0.190

305	500	50	0.060
308	1,200	120	0.026
310	2,000	200	0.015
313[b]	5,000	500	0.006
315	1.0×10^4	1.0×10^3	0.003
316	1.3×10^4	1.3×10^3	0.0024
317	1.5×10^4	1.5×10^3	0.0020
318	1.9×10^4	1.9×10^3	0.0016
319	2.5×10^4	2.5×10^3	0.0012
320	2.9×10^4	2.9×10^3	0.0010
322	4.5×10^4	4.5×10^3	0.00067
323	5.6×10^4	5.6×10^3	0.00054
325	6.0×10^4	6.0×10^3	0.00050
328	6.8×10^4	6.8×10^3	0.00044
330	7.3×10^4	7.3×10^3	0.00041
333	8.1×10^4	8.1×10^3	0.00037
335	8.8×10^4	8.8×10^3	0.00034
340	1.1×10^5	1.1×10^4	0.00028
345	1.3×10^5	1.3×10^4	0.00024
350	1.5×10^5	1.5×10^4	0.00020
355	1.9×10^5	1.9×10^4	0.00016
360	2.3×10^5	2.3×10^4	0.00013
365[b]	2.7×10^5	2.7×10^4	0.00011
370	3.2×10^5	3.2×10^4	0.000093
375	3.9×10^5	3.9×10^4	0.000077
380	4.7×10^5	4.7×10^4	0.000064
385	5.7×10^5	5.7×10^4	0.000053
390	6.8×10^5	6.8×10^4	0.000044
395	8.3×10^5	8.3×10^4	0.000036
400	1.0×10^6	1.0×10^5	0.000030

[a] Wavelengths chosen are representative; other values should be interpolated at intermediate wavelengths.
[b] Emission lines of a mercury discharge spectrum.

The permissible exposure duration, t_{max}, for exposure (in seconds) to UV is calculated by:

$$t_{max} = 30/\ E_{eff}\ (W\ m^{-2})$$

Examples are provided in table 13.2.

Table 13.2 Limiting UV exposure durations based on exposure limits (IRPA/INIRC, 1991)

Duration of exposure per day	Effective irradiance	
	E_{eff} (W m^{-2})	E_{eff} (μW cm^{-2})
8 hours	0.001	0.1
4 hours	0.002	0.2
2 hours	0.004	0.4
1 hour	0.008	0.8
30 minutes	0.017	1.7
15 minutes	0.033	3.3
10 minutes	0.05	5

14.3 Protection Factors

The concept of a protection factor is useful when attempting to quantify the UV protection that items such as sunscreens, clothing and eyewear can provide (Gies *et al.,* 1992). To determine the protection factor, the following procedure is conducted. An effective dose (ED) of UV to the eye is calculated by summing the incident solar spectral power over the wavelength range 280 to 400 nm. In order to determine the effective dose (ED_m) for the eye when it is protected, the calculation is repeated with the spectral transmission of the protection item as an additional weighting. The protection factor (PF) is then defined as the ratio of ED to ED_m and is given by the following equation:

$$PF = \frac{ED}{ED_m} = \frac{\text{Sigma}E_{lambda}.S_{lambda}.\text{Delta lambda}}{\text{Sigma}E_{lambda}.S_{lambda}.T_{lambda}.\text{Delta lambda}}$$

where:

E_{lambda} = spectral irradiance (W m^{-2} nm^{-1}) at wavelength lambda

S_{lambda} = relative spectral effectiveness

T_{lambda} = spectral transmission of protective item at wavelength lambda

Delta lambda = wavelength interval or bandwidth (nm)

lambda = wavelength (nm)

IR Research (ICNIRP)

Effects on the eye

Any calculation of potential thermal hazards from intense incoherent optical sources normally includes a consideration of the contributions of IR-A and IR-B, but IR-C is seldom considered for most light sources, including the sun or molten metals, since the contribution of IR-C is marginal. Different ocular structures are affected by different infrared spectral bands: for wavelengths up to 1,350 –1,400 nm, the ocular media transmit energy to the retina. At longer wavelengths, the anterior segment of the eye absorbs incident energy. The infrared radiation that is absorbed by the anterior segment (the cornea, aqueous, and lens) can produce clouding of the cornea and lens when the corresponding thresholds are exceeded. Exposure limits are set to protect both against acute as well as chronic exposure. Data on which to base exposure limits for chronic exposure of the anterior portion of the eye to infrared radiation are very limited. Sliney and Freasier (1973) stated that the average corneal exposure from infrared radiation in sunlight was of the order of 1 mW cm 2, considering that the eyes are seldom directed toward the sun except at sunrise and sunset. Glass and steel workers exposed in hot environments to infrared irradiances of the order of 80–400 mW cm 2 daily for 10–15 y have reportedly developed lenticular opacities (Sliney and Wolbarsht 1980; Lydahl 1984). The corneal and lenticular exposures are affected by the relative position of the source and the degree of lid closure. Pitts and Cullen (1981) showed that the threshold exposures for acute lenticular changes caused by IR-A were of the order of 50 MJ m_2 (5 kJ cm_2) for exposure durations of the order of an hour or longer. Threshold irradiances for damage were at least 40 kW m_2 (4 W cm_2). Although Vos and van Norren (1994) argued that an irradiance of 1 kW m_2 would not increase the temperature of the anterior segment of the eye by more than 1°C, and that this level would be acceptable. The Commission herefore recommended that, for very warm environments (>35°C), the ocular irradiance should not exceed 100 W m_2 for lengthy exposures. However, higher irradiances could be safely sustained for shorter periods. Radiant energy absorbed in the cornea, aqueous humour, and lens is transported by conduction, and some heating will occur in the lens regardless of the optical penetration depth.

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Penetration depth strongly varies in the IR-A and IR-B spectral bands, but these variations— between 1.2 and 3 _m— have only a minor effect on the final temperature rise resulting from exposure to a continuous source once thermal equilibrium is achieved.
As previously noted, rapidly changing photochemical action spectra are characteristic of ultraviolet and short-wavelength light exposure. Spectral data are therefore particularly important in that wavelength range. Because the infrared effects are thought to be largely thermal, chronic infrared exposures of the cornea and lens are not believed to involve rapid changes in spectral sensitivity (Barthelmess and Borneff 1959; Sliney 1986, 2002). There have been several efforts to mathematically model heat transport within the eye and to calculate temperature rises in an IR-exposed eye. Calculations for the human eye (Scott 1988a, b; Okuno 1991, 1994) show that ocular temperatures generally rise rapidly with exposure time for the first two minutes, then gradually level off and reach the maximum within approximately 5 min. Scott (1988a, b) also showed that it takes several minutes for the eye to cool down after an exposure ceases. The cornea is extremely sensitive to thermal stimulus and this will tend to limit hazardous infrared exposure (Dawson 1963; Beuerman and Tanelian 1979). In addition to the criteria to protect the cornea and lens against thermal damage from infrared exposure, a second criterion is required to protect the retina against thermal injury. Synergism between thermal and photochemical effects in the lens and retina has been studied in a number of experiments. Thermal enhancement of photochemical reaction has been experimentally demonstrated (Pitts and Cullen 1981; Ham and Mueller 1989), although the effect is less than a factor of two; this has been taken into account in deriving the exposure limits by introducing a greater margin of safety.

The current ICNIRP (1997) guidelines for infrared radiation and recommendations for their application to IR-C wavelength ranges are as follows.

CORNEA AND LENS

To avoid thermal injury of the cornea and possible delayed effects on the lens of the eye (cataractogenesis), infrared radiation (770 nm _ _ _ 3 _m) should be limited to 100 W m_2 (10 mW cm_2) for lengthy exposures (1,000 s), and to 1.8 *t*_3/4Wcm_2 for shorter exposure durations:
or
*E*IR _ 18*t*_3/4 kW m_2 for *t* 1,000 s
(4a)

*E*IR _ 1.8*t*_3/4 W cm_2 for *t* 1,000 s
or
*E*IR _ 100 W m_2 for *t* 1,000 s
(4b)
*E*IR _ 10 mW cm_2 for *t* 1,000 s.

Retina (IR-A only)
Higher temperature sources may produce significant levels of IR-A radiation. For an infrared heat lamp or any near-IR source that provides no strong visual stimulus, the near-IR, or IR-A (770 –1,400 nm), should be limited to:
*L*_ _ R___ _ __ _ _6,000 W_ m_2
_ sr_1_/_ _for *t* 10 s_ (5a)
or
*L*_ _ *R*___ _ __ _ _0.6 W_ cm_2
_ sr_1_/_ _for *t* 10 s_, (5b)
where *L*_ is the spectral radiance, which is not to be averaged over angles of acceptance less than 11 mrad.
R(_) is the retinal thermal weighting function defined in ICNIRP (1997) and _ is the angular subtense of the source specified in units of milliradians. For very large sources _ is limited to 100 mrad and the spectrally weighted radiance reduces to 60 kW cm_2 sr_1, or 6 W cm_2 sr_1.
For exposure durations less than 10 s, eqn (4) of the ICNIRP (1997) guidelines applies.
Since wavelengths greater than 1,400 nm do not contribute to the retinal hazard, this limit does not relate to IR-C exposure.