2. Ultraviolet light

General

Ultraviolet (UV) is that part of electromagnetic light bounded by the lower wavelength extreme of the visible spectrum and the X-ray radiation band. The spectral range of UV light is, by definition between 100 and 400 nm (1 nm=10^{-9}m) and is invisible to human eyes. Using the CIE classification the UV spectrum is subdivided into three bands:

UVA (long-wave) from 315 to 400 nm
UVB (medium-wave) from 280 to 315 nm
UVC (short-wave) from 100 to 280 nm

In reality many photobiologists often speak of skin effects from the weighted effect of wavelength above and below 320 nm, hence offering an alternative definition.

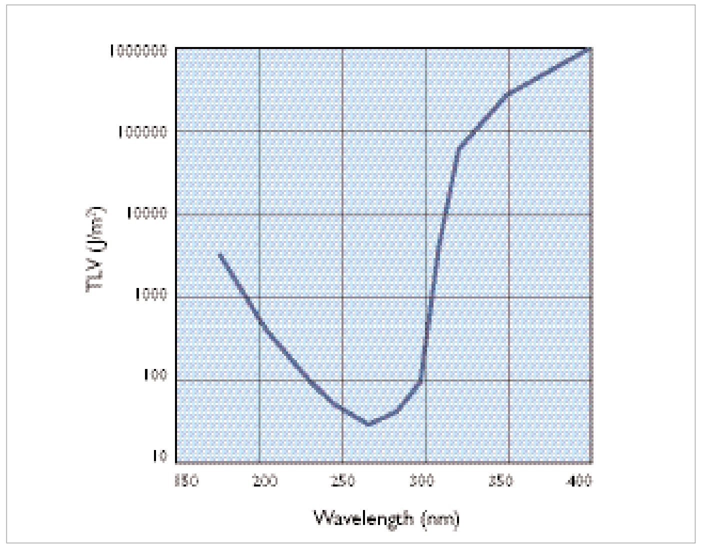

Figure 9. UV Light Threshold Limited Values (TLV) according to ACGIH 1999-2000 (Ref 1).

A strong germicidal effect is provided by the Light in the short-wave UVC band. In addition erythema (reddening of the skin) and conjunctivitis (inflammation of the mucous membranes of the eye) can, also be caused by this form of Light. Because of this, when germicidal UV-Light lamps are used, it is important to design systems to exclude UVC leakage and so avoid these effects.

Self evidently people should avoid exposure to UVC. Fortunately this is relatively simple, because it is absorbed by most products, and even standard flat glass absorbs all UVC. Exceptions are quartz and PTFE. Again fortuitously, UVC is mostly absorbed by dead skin, so erythema can be limited. In addition UVC does not penetrate to the eye's lens; nevertheless, conjunctivitis can occur and though temporary, it is extremely painful; the same is true of erythemal effects.

Permissible UVC Exposures	
Duration of exposure per day	**Irradiance ($\mu W/cm^2$)**
8 hours	0.2
4 hours	0.4
2 hours	0.8
1 hour	1.7
30 minutes	3.3
15 minutes	6.6
10 minutes	10
5 minutes	20
1 minute	100

Table 1. Permissible 254 nm UV exposures, according to ACGIH.

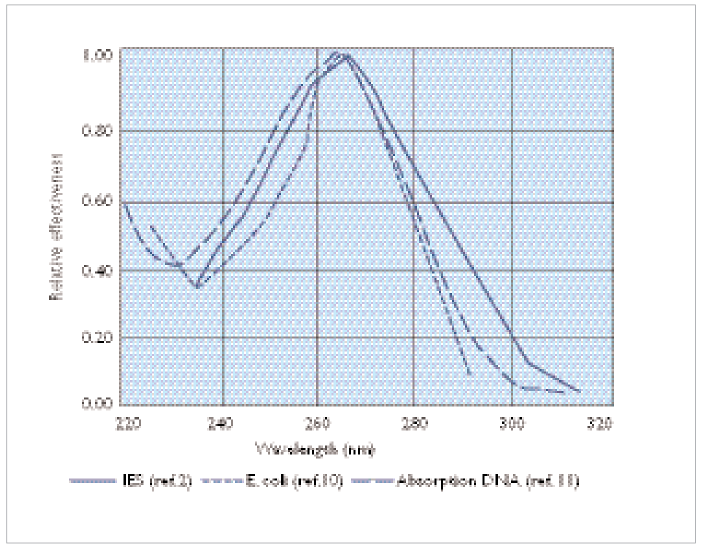

Figure 10. Germicidal action spectrum.

Where exposure to UVC Light occurs, care should be taken not to exceed the threshold level norm. Figure 9 shows these values for most of the CIE UV spectrum. In practical terms, table 1 gives the American Congress of Governmental and Industrial Hygienist's (ACGIH) UV Threshold Limit Effective Irradiance Values for human exposure related to time. At this time it is worth noting that radiation wavelengths below 240 nm forms ozone, O_3 from oxygen in air. Ozone is toxic and highly reactive; hence precautions have to be taken to avoid exposure to humans and certain materials.

2.1 Generation and characteristics of short-wave UV light

The most efficient source for generating UVC is the low-pressure mercury discharge lamp, where on average 35% of input watts is converted to UVC watts. The radiation is generated almost exclusively at 254 nm viz. at 85% of the maximum germicidal effect (figure 10). Philips' low pressure tubular flourescent ultraviolet (TUV) lamps have an envelope of special glass that filters out ozone-forming radiation, in this case the 185 nm mercury line. The spectral transmission of this glass is shown in figure 11 and the spectral power distribution of these TUV lamps is given in figure 12.

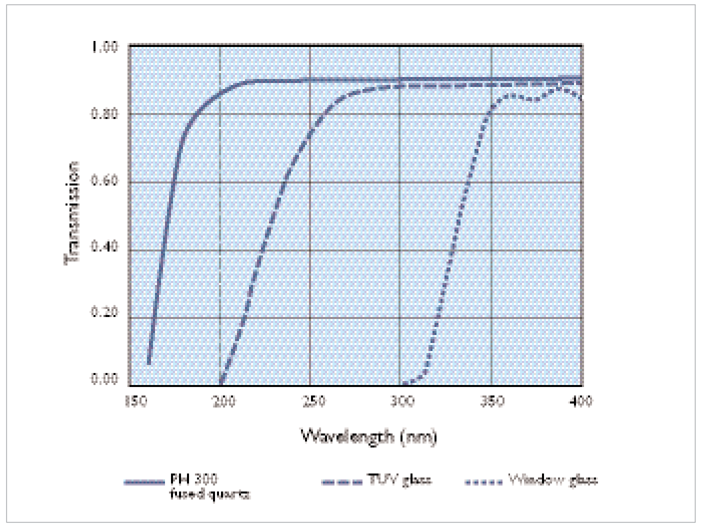

Figure 11. Special transmission of glasses (1mm).

For various Philips germicidal TUV lamps the electrical and mechanical properties are identical to their lighting equivalents.

This allows them to be operated in the same way i.e. using an electronic or magnetic ballast/starter circuit. As with all low pressure lamps, there is a relationship between lamp operating temperature and output. In low pressure lamps the resonance line at 254 nm is strongest at a certain mercury vapour pressure in the discharge tube. This pressure is determined by the operating temperature and optimises at a tube wall temperature of 40°C, corresponding with an ambient temperature of about 25°C. (See page 28, figure 28). It should also be recognised that lamp output is affected by air currents (forced or natural) across the lamp, the so called chill factor. The reader should note that, for some lamps, increasing the air flow and/or decreasing the temperature can increase the germicidal output. This is met in high output (HO) lamps viz. lamps with higher wattage than normal for their linear dimension. (See page 28, figure 29).

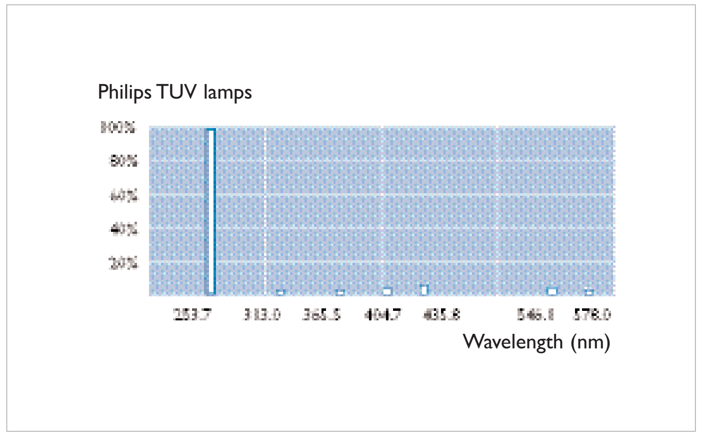

Figure 12. Relative spectral power distribution of Philips TUV lamps.

A second type of UV source is the medium pressure mercury lamp, here the higher pressure excites more energy levels producing more spectral lines and a continuum (recombined radiation) (figure 13). It should be noted that the quartz envelope transmits below 240 nm so ozone can be formed from air.
The advantages of medium pressure sources are:

- High power density
- High power, resulting in fewer lamps than low pressure types being used in the same application
- Less sensitivity to environment temperature. The lamps should be operated so that the wall temperature lies between 600 and 900°C and the pinch does not exceed 350°C. These lamps can be dimmed, as can low pressure lamps

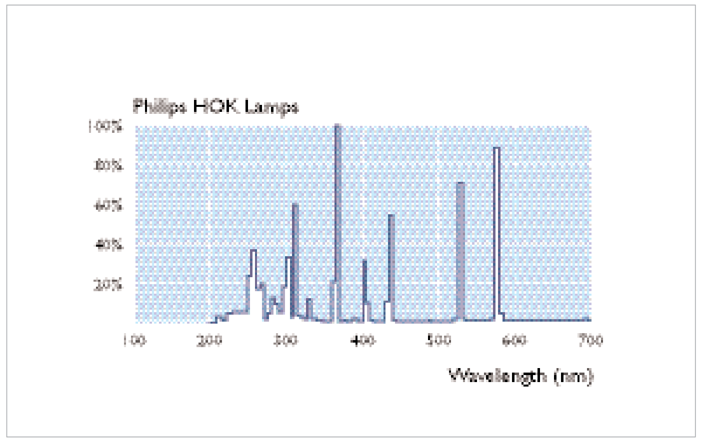

Figure 13. Relative spectral power distribution of Philips HOK and HTK lamps.

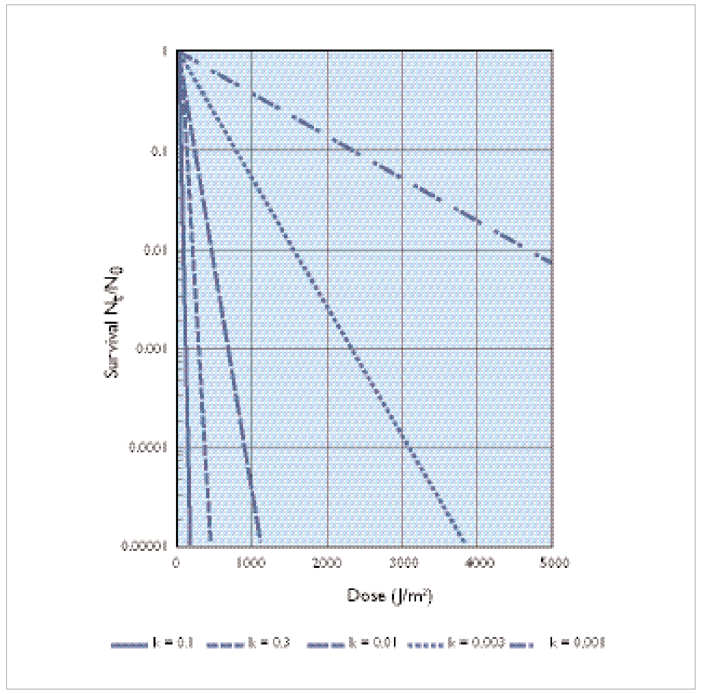

Figure 14. Survival of micro-organisms depending on dose and rate constant k.

2.2 Germicidal action

The UV light emitted by a source is expressed in watts (W) and the irradiation density is expressed in watts per square meter (W/m^2). For germicidal action dose is important. The dose is the irradiation density multiplied by the time (t) in seconds and expressed in joules per square meter (J/m^2). (1 joule is 1W.second).

From figure 10 it can be seen that germicidal action is maximised at 265 nm with reductions on either side. Low pressure lamps have their main emission at 254 nm where the action on DNA is 85% of the peak value and 80% on the IES curve. For wavelengths below 235 nm the germicidal action is not specified, but it is reasonable to assume that it follows the DNA absorption curve.

Micro-organisms effective resistance to UV light varies considerably. Moreover, the environment of the particular micro-organism greatly influences the radiation dose needed for its destruction.
Water, for instance, may absorb a part of the effective radiation depending on the concentration of contaminants in it. Iron salts in solution ware well known inhibitors. Iron ions absorb the UV light.
The survival of micro-organisms when exposed to UV light is given by the approximation:

N_t/N_0 = exp. ($-kE_{eff}t$) 1
Hence ln $N_t/N_0 = -kE_{eff}t$ 2

- N_t is the number of germs at time t
- N_0 is the number of germs before exposure
- k is a rate constant depending on the species
- E_{eff} is the effective irradiance in W/m^2

The product $E_{eff}t$ is called the effective dose H_{eff} and is expressed in $W.s/m^2$ of J/m^2

It follows that for 90% kill equation 2 becomes

$2.303 = kH_{eff}$

Some k value indications are given in table 2, where they can be seen to vary from 0.2 m^2/J viruses and bacteria, to 2.10^{-3} for mould spores and 8.10^{-4} for algae. Using the equations above, figure 14 showing survivals or kill % versus dose, can be generated.

UV dose to obtain 90% killing rate		
Bacteria	**Dose**	**k**
Bacillus anthracis	45.2	0.051
B. megatherium sp. (spores)	27.3	0.084
B. megatherium sp. (veg.)	13.0	0.178
B. parathyphosus	32.0	0.072
B. suptilis	71.0	0.032
B. suptilis spores	120.0	0.019
Campylobacter jejuni	11.0	0.209
Clostridium tetani	120.0	0.019
Corynebacterium diphteriae	33.7	0.069
Dysentery bacilli	22.0	0.105
Eberthella typhosa	21.4	0.108
Escherichia coli	30.0	0.077
Klebsiella terrifani	26.0	0.089
Legionella pneumophila	9.0	0.256
Micrococcus candidus	60.5	0.038
Micrococcus sphaeroides	100.0	0.023
Mycobacterium tuberculosis	60.0	0.038
Neisseria catarrhalis	44.0	0.053
Phytomonas tumefaciens	44.0	0.053
Pseudomonas aeruginosa	55.0	0.042
Pseudomonas fluorescens	35.0	0.065
Proteus vulgaris	26.4	0.086
Salmonella enteritidis	40.0	0.058
Salmonella paratyphi	32.0	0.072
Salmonella typhimurium	80.0	0.029
Sarcina lutea	197.0	0.012
Seratia marcescens	24.2	0.095
Shigella paradysenteriae	16.3	0.141
Shigella sonnei	30.0	0.077
Spirillum rubrum	44.0	0.053
Staphylococcus albus	18.4	0.126
Staphylococcus aureus	26.0	0.086
Streptococcus faecalis	44.0	0.052
Streptococcus hemoluticus	21.6	0.106
Streptococcus lactus	61.5	0.037
Streptococcus viridans	20.0	0.115
Sentertidis	40.0	0.057
Vibrio chlolerae (V.comma)	35.0	0.066
Yersinia enterocolitica	11.0	0.209

Table 2. Doses for 10% survival under 254 nm radiation (J/m^2) and rate constant k (m^2/J), Ref 2, 3, 4, 5, 6 and 7

UV dose to obtain 90% killing rate		
Yeasts	**Dose**	**k**
Bakers' yeast	39	0.060
Brewers' yeast	33	0.070
Common yeast cake	60	0.038
Saccharomyces cerevisiae	60	0.038
Saccharomyces ellipsoideus	60	0.038
Saccharomyces sp.	80	0.029
Mould spores		
Aspergillus flavus	600	0.003
Aspergillus glaucus	440	0.004
Aspergillus niger	1320	0.0014
Mucor racemosus A	170	0.013
Mucor racemosus B	170	0.013
Oospora lactis	50	0.046
Penicillium digitatum	440	0.004
Penicillium expansum	130	0.018
Penicillium roqueforti	130	0.018
Rhizopus nigricans	1110	0.002
Virus		
Hepatitis A	73	0.032
Influenza virus	36	0.064
MS-2 Coliphase	186	0.012
Polio virus	58	0.040
Rotavirus	81	0.028
Protozoa		
Cryptosporidium parvum	25	0.092
Giardia lamblia	11	0.209
Algae		
Blue Green	3000	0.0008
Chlorella vulgaris	120	0.019