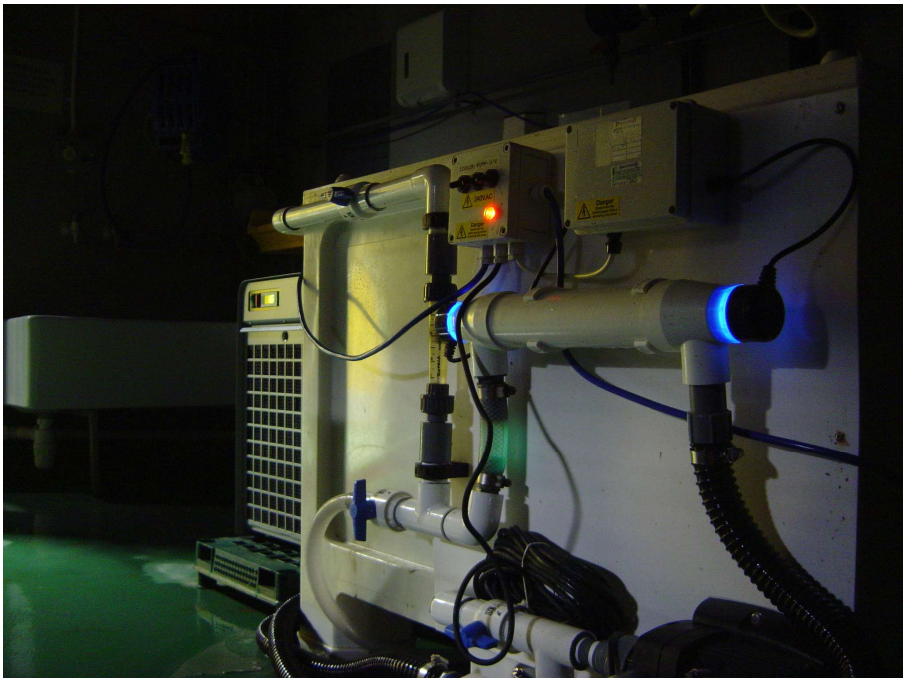
UV Disinfection in Depuration Theory and Practice



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Ultraviolet Disinfection Technology

1.0 Introduction

Light has both particle and wave properties. It is transmitted in discrete packets of energy (Photons) and yet has a frequency and wavelength.

Range Name	Wave length Range (nm)
Near Infrared	**700 – 1000**
Visible	**400 – 700**
Ultraviolet UVA UVB UVC	 **315 – 400** **280 – 315** **200 – 280**
Vacuum Ultraviolet VUV	**100 - 200**

Table 1: Spectral Ranges of interest in Photochemistry

1.1 Ultraviolet Light

UV light is shorter in wavelength (higher in energy) than visible light. It is called ultraviolet because it is just beyond violet light. Technically, ultraviolet light is defined to be any wavelength of light - also called electromagnetic radiation - shorter than 400 nanometers.

The sun emits ultraviolet light with UVA and UVB (280-400nm) being responsible for sun tanning and sun burning. UVC, which is almost entirely filtered out through the ozone layer in the high atmosphere, can penetrate cells and cause damage to the DNA. This damage leads to the inactivation of micro-organisms in drinking water.

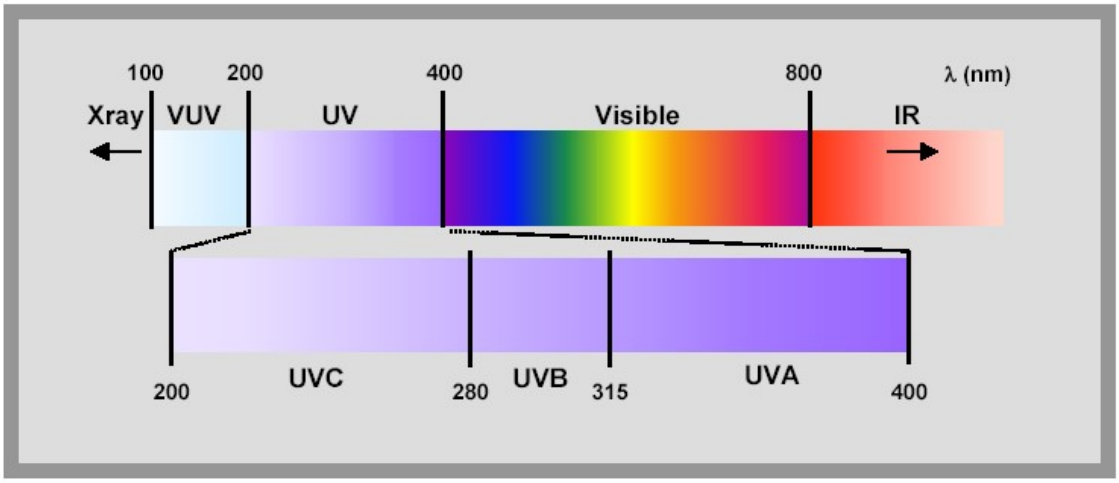


Figure 1. Electromagnetic spectrum

NB: For the same reason that UVC is harmful to micro-organisms, it can be harmful to humans as well. UVC can cause skin irritation and severe eye damage. For this reason, it is important to never look at the bulb when it is switched on. Direct exposure can be avoided by never opening the UV-Tube when it is plugged in to the power source, whether or not the light is on. The UV-Tube design uses a Plexiglas or glass window that completely filters out all UVC, leaving only harmless blue light.

1.2 Biological Effects

UVC light inactivates micro-organisms by damaging their genetic material and rendering them unable to replicate. Ultraviolet light is absorbed by proteins, RNA and DNA. Absorption of UV by proteins in the membranes at high Fluences (UV Doses), ultimately leads to the disruption of the cell membrane and hence death of the cell. However at much lower fluences (UV Dose), absorption of UV by DNA (or RNA in some viruses) can disrupt the ability of the micro-organism to replicate and thus interfere with their ability to cause disease.

Ultraviolet light in the UVC region creates photoproducts, such as connecting adjacent base pairs, which then obstruct the replication process. With enough of these altered base pairs, replication is prevented. The maximum absorption of DNA - and maximum formation of photoproducts - occurs between 260-265 nm. The microbiocidal effect of UV radiation is achieved in the spectral range of 240-290 nm, peaking at 265nm (Hoyer 1998).

Photoproducts are formed by pyrimidine bases (thymine, cytosine and uracil) at a much higher rate than by purine bases (adenine, guanine). The most common photoproducts are cyclobutyl dimers, which are formed when two adjacent pyrimidine bases join to form a four carbon ring. Although pyrimidine dimers are often composed of two thymines, they may also be composed of two cytosines, or a thymine and a cytosine. Other, less common photoproducts include pyrimidine adducts, spore photoproducts, pyrimidine hydrates and DNA-protein crosslinks (Harm, 1980). This is the fundamental mechanism of UV disinfection.

Some micro-organisms (particularly bacteria) have repair mechanisms that dissociate the pyrimidine dimers. This process is triggered by the absorption of

UVA light and is called *photoreactivation*. The repair mechanism can be overcome, but this requires a high fluence (UV dose).

1.3 Disinfection By-Products

UV treatment, unlike chlorination produces no known disinfection by-products (Wolfe, 1990; National Drinking Water Clearinghouse, 2000; de Veer, 1994).

2.0 Terminology – light emission

(From Bolton, 2001)

2.1 Radiant Energy

Radiant energy (*Q*) is the total amount of radiant energy (J) emitted from a source over a given period of time.

2.2 Radiant Power

The *Radiant Power* (P_Φ) of a source is the rate of radiant energy emission or the total radiant power (W) emitted in all directions by a light source.

E.g. the radiant power of the sun is 3.843×10^{26} W. In theory, P_Φ should include all wavelengths emitted by the source; however, P_Φ is usually restricted to the wavelength range of interest for photochemistry. So if a light source is being used for ultraviolet photochemistry, P_Φ would be specified for emission in the 200 – 400 nm ultraviolet range.

2.3 Radiant power efficiency

The radiant power efficiency (ŋ) of a lamp is defined as

$$ŋ = P_\Phi / P_E$$

Where P_E is the input electrical power (W) required to run the lamp and its power supply.

Radiant emittance or excitance

The *Radiant emittance or excitance* (*M*) (W m^{-2}) of a source is the radiant power emitted in all outward-bound directions from an infinitesimal area on the surface of the source.

2.4 Radiant Intensity

The *radiant intensity* (*I*) (W sr^{-1}) is the total radiant power *P* emitted from the source in a given direction about an infinitesimal solid angle dΩ. In a non absorbing medium the radiant power does not fall off with distance.

3.0 Terminology – light receipt

(From Bolton, 2001)

Emitted light from a source irradiates outward at the speed of light (c = 2.99792458 x 10^8 m s^{-1}). When light impinges on an object it may be reflected, transmitted or absorbed. There are several terms that relate to the receipt of light.

3.1 Irradiance

Irradiance (symbol *E*; units W m^{-2}) is the total radiant power *incident* from all upward directions *on* an infinitesimally small element or *surface* area dS containing the point under consideration divided by dS.

3.2 Radiant exposure

Radiant exposure (symbol *H*; units J m^{-2}) is the total radiant energy *incident* from all upward directions *on* an infinitesimally small element or *surface* area dS containing the point under consideration divided by dS.

3.3 Fluence Rate

Fluence Rate (symbol *E'*; units W m^{-2}) is defined as the total radiant power *incident* from all upward directions *on* an infinitesimally small sphere of cross-section area d*A*, divided by d*A*.

The following are important characteristics of irradiance and fluence rates:

- For a parallel and perpendicularly incident beam not scattered or reflected, irradiance and fluence rate become identical
- For any UV source within a three-dimensional volume, the integration of the irradiance over the interior surface of the volume yields the UV power of the lamp. This is not true for the fluence rate.
- The appropriate term for UV disinfection is 'fluence rate' because a micro-organism can receive UV power from any direction especially if there is more than one UV lamp in the vicinity.
- The appropriate term for UV curing is 'irradiance' because the surface to be cured is exposed to UV from only one direction.

For a position at r cm from the point source, the irradiance is given by

$$E = P_\Phi / 4\pi r^2$$

E.g. the average distance of the Earth to Sun distance is 1.4957 x 10^{11}m. The average solar irradiance just outside the Earth's atmosphere is calculated as follows:

$$E_{Earth} = \frac{3.843 \times 10^{26} W}{4\pi (1.4957 \times 10^{11} m)^2} = 1.367\ Wm^{-2}$$

NB part of this irradiance is absorbed or scattered in the Earth's atmosphere so that at the surface of the earth on a cloudless day receives irradiance of about 1,000 Wm^{-2}.*

3.4 Fluence (UV dose)

Fluence (symbol *H*'; units J m^{-2}), also called 'UV dose', is defined as the total radiant energy of all wavelengths passing in *all* directions through an infinitesimally small sphere of cross-sectional area d*A*, divided by d*A*.

If the fluence rate is constant over time, the *fluence* is given by the *fluence rate* times the *exposure time* in seconds. The term UV dose is often used in disinfection literature. It represents the UV exposure of a given micro-organism in the germicidal range. Many authors use mW.s cm^{-2} but the equivalent mJ cm^{-2} (equal to 10 J m^{-2}) is preferred.

The term 'fluence' is preferred to that of UV dose, since the term 'Dose' is used to imply *total absorbed energy* (e.g. UV dose required to induce sunburn on the skin). Fluence represents radiant energy 'incident' on a micro-organism and in most cases only a small fraction (about 1%) of radiant energy is absorbed (Bolton , 2001).

4.0 Fluence Calculation Within the UV-Unit

To inactivate a given micro-organism in water, it must be hit with a certain amount or dose of UV light. Fluence is determined by variables associated with the design and operation of the UV disinfection device, as well as the characteristics of the water that is treated.

Fluence is calculated as the product of light intensity of a given wavelength and exposure time. Intensity at any given point is determined by bulb strength and the geometry of the reactor. The greater the thickness of water that the light travels through, the lower the intensity received. The exposure time is governed by the geometry and the hydrodynamics of the reactor. The UV-Tube/reactor should be designed such that the lowest fluence received by any of the water is sufficient to achieve the desired reduction in micro-organisms. Fluence may be reported in mW-sec/cm^2, which is equivalent to mJ/cm^2 (equivalent in the SI units to 10 J/m^2). Standard doses delivered by a UV drinking water treatment system are between 150 and 500 J/m^2.

Intensity decreases due to attenuation and dissipation. In other words, the further from the source, the lower the strength of the light, because it is spread over a larger area (due to dissipation) and interacts with molecules in the water (attenuation).

While dissipation is predicted simply by the geometry of the UV-Tube, attenuation depends on characteristics of the water. If the water contains a high concentration of materials that absorb UV light, then less UV will be transmitted. The amount of light absorbed per centimetre is expressed as the absorption coefficient (c.a.). As this coefficient increases, transmissivity decreases exponentially; therefore the absorption coefficient of the water plays a very important role in the effectiveness of the UV disinfection device.

4.1 Absorption Coefficient

The absorption coefficient describes how much light is lost as it travels through a medium. It can be determined experimentally and is reported in inverse centimeters. The absorption coefficient of pure distilled water is close to zero. Natural organic matter, iron, nitrate and manganese absorb UVC light and will increase the absorption coefficient of a water sample (Kolch, 1999). Absorption coefficients in drinking water would be expected in the range of 0.01 to 0.2 cm^{-1}.

It is difficult to accurately evaluate the effects of salt water given the dissolved salts and suspended particles contained therein i.e. potential absorbing materials that impact on transmission. If the coefficient of absorption (c.a.) for UV (@ 254nm) is known, the irradiance scales for water can be calculated as follows:

Irr (water) = Irr (air) x e^ (-c.a. x path length)

Typical values of c.a. for tap water are around 0.1cm^{-1} (the path length then needs to be defined in cm). In seawater the influence of seawater on UVT (UV transmission/path length) may be worse. Typically 0.3cm^{-1} is used as worse case for design purposes (A. Albrecht pers. comm.). The typical path length in UV reactors currently employed for depuration systems is 2.5cm.

4.2 Flow Rate

The higher the flow rate, the shorter the retention time in the unit, therefore the smaller the dose received by the water. An appropriate flow rate must be determined based on the other characteristics of the water and on the desired dose.

4.3 Suspended particles, particle-associated micro-organisms and turbidity

Turbidity is often thought to be a limiting feature in ultraviolet disinfection. However, work has shown that particles, as long as they are not UV-absorbers, do not significantly reduce the overall irradiance by either shading or scattering, but only when organisms are embedded within them (Linden, 1998; Emerick, 1999). Particle suspension can increase the apparent absorption coefficient - as measured by a spectrophotometer - by scattering rather than absorbing light (Linden, 1998). This effect can lead to under prediction of design capabilities.

4.3.1 Turbidity and UV Disinfection of Seawater for use in Depuration Systems

Particles in suspension are known to reduce the effectiveness of UV disinfection units. This applies both to primary disinfection of intake waters and in-line units in recirculating systems. As stated above, this is due to a combination of the effect of the particles on the scattering and absorption of the radiation and the protection of adherent micro-organisms. Suspended organic material will also reduce the effectiveness of chemical disinfection systems. It is therefore necessary to limit the concentration of suspended particles in order to ensure that the disinfecting systems achieve their desired effect, i.e. killing of pathogenic organisms.

A significant proportion of the pathogens and indicator organisms present in seawater is normally associated with particulate material and therefore removal of this material will, in itself, improve the microbiological quality.

The amount of material in suspension may be measured as suspended solids *per se* (in mg/l) or by the turbidity of the liquid (in nephelometric or formazin turbidity units [NTU or FTU]). Older US turbidity measurements may be given in Jackson Turbidity Units (JTU): some authorities regard NTU and JTU as approximately equivalent at values around 40 and below. The measurement of suspended solids requires laboratory facilities. Turbidity measurements may be performed on site or in a laboratory and are therefore preferable for routine monitoring purposes. There is not a direct relationship between the suspended solids content and turbidity as the latter depends on the size and nature of the particles that are present.

Relatively small amounts of material in suspension will cause measurable attenuation of UV inactivation of micro-organisms using low-pressure UV lamps. In drinking water applications it is recognized that a measurable effect can take place at turbidities exceeding 1 NTU. However, in other situations, turbidities of <5 NTU have not been shown to have a significant effect[1]. Removal of particulate material will markedly increase UV inactivation[2]. More marked attenuation of the effect of UV has been found at turbidities exceeding 15 NTU[3].

Given that calculations on the UV lamp requirements for depuration systems used in England and Wales have not taken particle-associated attenuation into account, it would be preferable if industry guidance were available to the effect that the turbidity of the intake water should be kept below 5 NTU. Where intake water exceeds 15 NTU, it should be subjected to an approved settlement or filtration procedure prior to the UV disinfection step.

4.4 Lamp characteristics

The maximum UV absorbance of DNA/RNA, 260-265 nm, coincides quite closely with peak output of low-pressure mercury arc lamps at 253.7 nm. Two different types of lamps are typically used in water disinfection, medium pressure and low pressure mercury vapor arc lamp. Lamps currently used in depuration systems in England and Wales are of the low-pressure design.

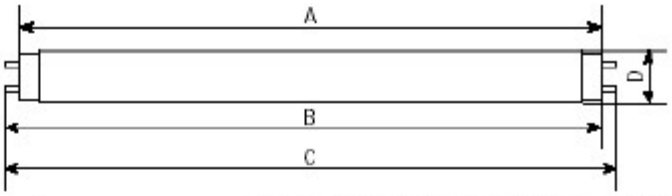
Fluence depends on bulb strength. For example, a 25 Watt low pressure GE 25T8 as supplied by TMC (Tropical Marine Centre) bulb emits approximately 5 Watts at a distance of 1 metre at 254 nm wavelength. As the bulb ages its strength will slowly diminish. Each start is expected to decrease the bulbs lifetime. If the bulb is left on for periods greater than 3 hours, it may last longer. Conversely, if a bulb is turned on and off for periods shorter than 3 hours, its lifetime may be reduced.

4.5 Estimating fluence (UV Dose)

From Bolton, 2001,

The determination of fluence (UV dose), in a UV reactor through which water is flowing at a given flow rate is not straightforward as it varies considerably throughout the reactor, being higher near the quartz sleeve around the UV reactor and lower near the walls of the reactor chamber.

G25T8



Benefits

- **UV output at 254 nm; emits no ozone**
- **Uses standard Bi-pin end caps**
- **Effective in killing most microorganisms**
- **8000 hours Useful Life**

Product Description		G25T8	
Product Code		11082	
Case Quantity		24	
Physical Characteristics			
Bulb Designation		T8	
Bulb Material		Soft Glass	
Dimensions		**Min**	**Max**
Base face to base face (A)	in. (mm)		17.22(437.4) ←
Base face to end of opposite base pin (B)	in. (mm)	17.40(442)	17.50(444.5)
End of base pin to end of opposite pin end (C)	in. (mm)	17.67(448.8)	17.78(451.6)
Bulb Outside Diameter (D)	in. (mm)	0.94(23.9)	1.10(27.9)
Electrical Characteristics			
Nominal Lamp Power at 25° C, 100 hrs	Watts	25	
Nominal Lamp Volts at 25° C, 100 hrs	V rms	46	
Nominal Lamp Current at 25° C, 100 hrs	A rms	0.580	
UV Characteristics			
Peak Emission Wavelength	nm	253.7	
Irradiance @ 1m, 254 nm, 100 hrs	$\mu W/cm^2$	70*	
UV Output @ 254 nm, 100 hrs	Watts	6.9* ←	
Useful Life (80% initial output)	Hours	8000*	
Warning			
Lamp emits UV radiation which may cause eye/skin injury. RG-3 - Avoid exposure of eyes and skin to unshielded lamp			
Risk of electric shock - Turn power off before inspection, installation or removal			
Applicable Regulations			
DoE regulated (yes/no)		no	
Applicable Standards			
ANSI/IESNA		RP-27.4-96	

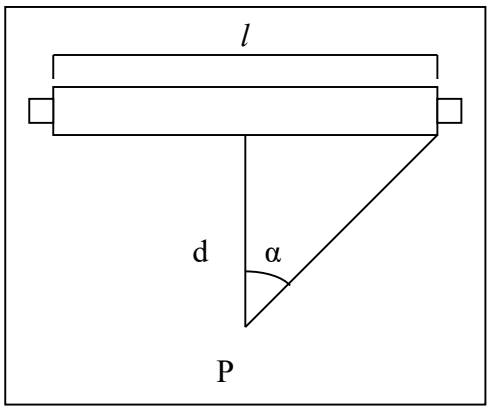
Table 2 : Data sheet for GE Germicidal Lamps G25T8. Critical information for fluence calculation has been highlighted with an arrow.

One can calculate an average fluence rate in a reactor. If one makes the assumption that the flow through the reactor exhibits perfect *plug flow* behaviour and *radial mixing*, then the *fluence* (UV dose) is the average fluence rate X the residence time given by *V/F*, where *V* is the volume (L) of the reactor and *F* is the flow rate (Litres per second).

4.5.1 Irradiance within the UV unit.

Typically the irradiance figure given in the manufacturer's details for the UV characteristics of a given tube (Table 2) detail 254nm irradiance at 1m. The first task is therefore to calculate the irradiance (E) at 2.5 cm (path length within the UV unit) using the following equation (from GE Consumer and Industrial literature):

Irradiance formula



$$E = \frac{\Phi}{2 \times \pi^2 \times l \times d} (2 \times \alpha + \sin(2 \times \alpha))$$

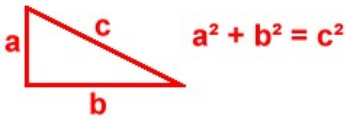
Where E is irradiance (uW/cm^2); Φ is the total flux out of the lamp (generally listed as UVC Watts - expressed in uW); *l* is the arc length of the tube (cm); typically 5cm less than the length (listed as 'max A dimension' minus 5cm in GE literature) of the tube; *d* is the path length (cm) and α is the maximum angle of incidence from 90° at 2.5cm (in radians).

'A' can be first calculated in degrees by using d and half of the value *l* as sides of a right angled triangle. Once all the side lengths are known (using Pythagoras's theorem $a^2 + b^2 = c^2$), the angles can then be calculated.

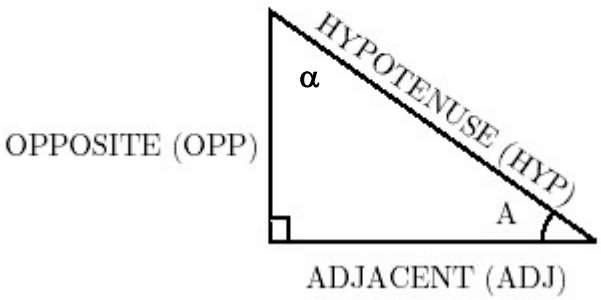
Pythagoras' Theorem

Pythagoras' theorem states that if you square the two shorter sides in a right-angled triangle and add them together, you get the same as when you square the longest side (the hypotenuse).

In the triangle on the right, *a* and *b* are the two shorter sides and *c* is the hypotenuse, so if we square *a* and *b* and add them together ($a^2 + b^2$) we get the same as if we square c (c^2). Therefore, $a^2 + b^2 = c^2$.



$$\text{tangent } A = \tan A = \frac{\text{OPP}}{\text{ADJ}}$$



In this case we want to know the angle in the corner opposite to A (i.e. our angle α) so once angle A is calculated using the equation above angle α can then be calculated as follows:

$$\alpha = 180° - (90 + A)$$

α must then be converted to radians before it can be used in the main formula above (to convert degrees into radians multiply degrees value by π/180).

4.5.3 Theoretical UV dose (fluence)

Before one can obtain a theoretical value for fluence, the exposure time or residency time must be calculated. Typical reaction chamber volumes have been calculated for the two lengths of tubes commonly encountered and are given in Table 3. The following equation is applied.

Exposure or Residency = exposure volume (L) / the flow rate (L/s) = the number of exchanges or residency time in seconds.

Twin jacket 2 x 25W (451.6mm tube), total exposure volume 0.626L Arc length – 387mm
Single Jacket 15-25 (451.6mm tube), total exposure volume 0.313L Arc length – 387mm
Single Jacket 30-55 watt (901mm tube), total exposure volume 1.379L Arc length – 845mm

Table 3: Typical reaction chamber volumes.

The fluence or UV dose is then calculated by multiplying residency time by the irradiance of a given tube at 254nm and distance 2.5cm having taken into consideration the a.c. of seawater.

UV Dose/fluency = Irradiance x Residency time (s)

E.g. For a single 25 watt tube connected to a system employing a flow rate of 20L/minute (0.333L/second):

Residency time = 0.313/0.333 = 0.94sec

α at d value of 2.5 cm = 82.6° or 1.442 radians
arc length (Max A –5cm) = 37.74 cm

This gives an irradiance figure using the irradiance formula above of
11,340 uW/cm^2

Fluence (UV dose) = 11,340 µW/cm^2 x 0.94sec
= 10,660 uWs/cm^2 or 10,660 uJ/cm^2 or **10.6 mJ/cm^2**

4.5.2 Absorption coefficient of seawater.

As previously described, the absorption coefficient of seawater has a profound effect on the irradiance within the reaction vessel and must also be taken into consideration:

Irr (water) = Irr (air) x e^ (-a.c. x path length)

Where e^ is the base of natural logarithms and a.c. =0.3 cm^{-1}.

Using the example above, the irradiance figure of 11,340 uW/cm^2 (effectively the irradiance in air) at path length of 2.5 cm becomes 5351 uW/cm^2 with fluence thus being reduced to 5026 uJ/cm^2 or **5 mJ/cm^2**.

4.5.4 Multiple tube UV systems

Small-scale, medium-scale and large-scale standard design systems often have multiple UV units each containing a UV tube. UV units are typically twinned in parallel, which essentially means that the flow rate is halved through each unit, thus increasing the residency time within each reaction chamber. The reaction vessel volume is effectively doubled for every twinned unit and the flow rate halved (Figure 2).

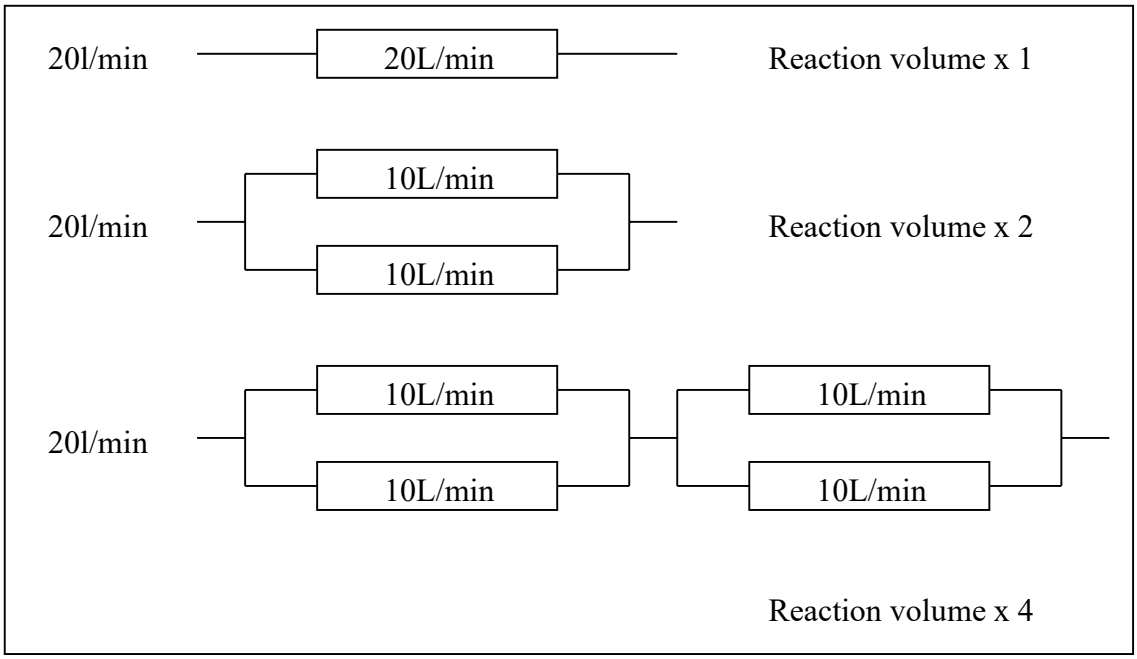


Figure 2: Multiple UV unit effects on Fluence

Equally many systems simply connect up the units in series. To calculate Fluence or UV dose in a number of single tube UV units connected in series the following equation is applied:

Cumulative Residency Time =

(Residency time per tube X number of UV tubes)

Fluence = Cumulative Residency Time X Irradiance

To calculate Fluence or UV dose in multiple tube twinned UV units connected in series the following equation is applied:

Cumulative Residency Time =

(Flow rate (L/s) / 2) X (residency time X number of UV tubes)

Fluence = Cumulative Residency Time X Irradiance

4.6 UV sterilisation in Depuration Systems.

4.6.1 A brief history.

In 1961 Wood described a sterilisation unit consisting of a shallow trough over which UV tubes were suspended. In 1970 Ayres reported on the availability of a totally enclosed cylindrical UV steriliser utilising a 15-30watt UV tube. An early design depuration unit operated with a seawater flow rate of one system capacity volume exchange per hour and the UV lamp requirement was one 30 watt lamp per 2200 litres. The resultant dose would not ensure a total kill but was reported to do so after several cycles.

West in 1986 prescribed a dose of not less than 10mJ/cm^2 (100J/m^2), with the associated text "one 30 watt lamp unit is sufficient to continuously treat 2200 litres of seawater in a re-circulation system". This has been used as the rule of thumb ever since and is the basis of the current approach to depuration system approval in England and Wales.

Design changes over the last 3 decades have led to an increase in stocking densities of shellfish within systems. This has resulted in the need to increase flow rates to provide sufficient dissolved oxygen to the depurating molluscs. This in turn has required an increase in the UV disinfection specifications for these systems.

4.6.2 Current Practices and Implications.

Seafish Standard Design System Type	Seafish UV Recommendation	Minimum Required Flow rate (L/min)	*Theoretical Fluence (Dose) (mJ/cm^2)*	*Fluence taking into account c.a. of seawater (mJ/cm2)*
Small Scale	1 x 25 (451.6mm)	20	*10.6*	*5*
Medium Scale	4 x 30 (901mm)	208.3	*29.7*	*14.0*
Large Scale	6 x 30 (901mm)	158.3	*58.6*	*27.7*
Stack (650 L)	1 x 25 (451.6mm)	15	*14.2*	*6.7*
Bulk Bin	2 x 30W per bin	108.3	*28.5*	*13.4*

Table 4: Fluence values calculated for Seafish standard design systems operated as per Seafish guidance notes.

Current fluence rates employed by standard design depuration systems are given in table 4. All theoretical fluence values (in air) calculated exceed West's' recommendation of 10mJ/cm^2, however, once the coefficient of absorption of seawater is taken into account, the fluence values for the small scale and stack systems both fall below this minimum requirement.

4.6.3 Dose response

The comparison of UV susceptibility of pathogens, facultative pathogens and indicator germs under standardised laboratory conditions (figure 3) effectively illustrates the difference in behaviour with regard to UV sensitivity and photo reactivation. The data shows that inactivation by 4 logs with respect to photo-reactivation requires a UV dose of between 180-340 J/m^2 and exceeds 2-4 times the UV dose without Photo-reactivation.

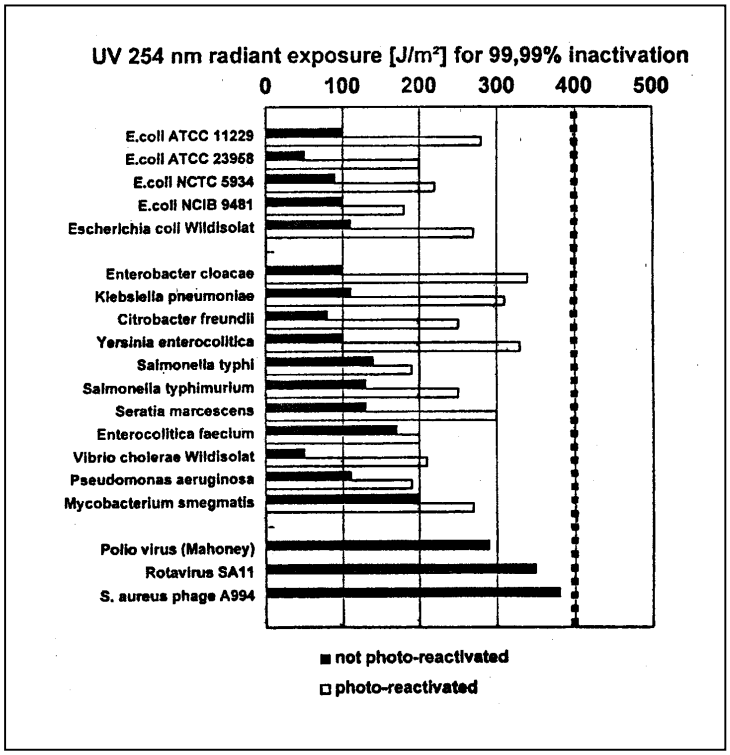


Figure 3 :UV dose required for 4 logs (99.99%) inactivation of bacteria, Spores, viruses and protozoa. The bars represent "in the presence of photo-reactivating light" (open bars) and "in the absence of photo reactivating light" (solid bars). O. Hoyer (1998).

To ensure that viruses and protozoa are inactivated, a dose at least 400 J/m^2 is required (figure 3). This means an inactivation of *E. coli* beyond seven logs at this level of exposure (Hoyer 1998). Given these facts it is clear that on a single pass through the UV systems currently employed by standard design systems, complete inactivation of bacteria and more importantly viruses is not achievable.

The relevant European food safety regulations (EU 853/2004) require the use of clean sea water for depuration "free from microbial contamination". UV systems are used to treat seawater on a single pass, when filling depuration systems. As shown, current doses employed are insufficient to kill the pathogens of interest on a single pass and therefore there is the potential for shellfish to be exposed to contaminated seawater on filling the system.

If we further consider elevated flow rates above those stipulated as minima, then dose received falls below the theoretical values given in table 4. The effect of increasing the flow rate decreases the residency time and concomitantly the UV dose received by circulating water. Thus the efficacy of

the operational UV system is further impaired. Figure 4 illustrates the effect on dose rate when elevating flow rates.

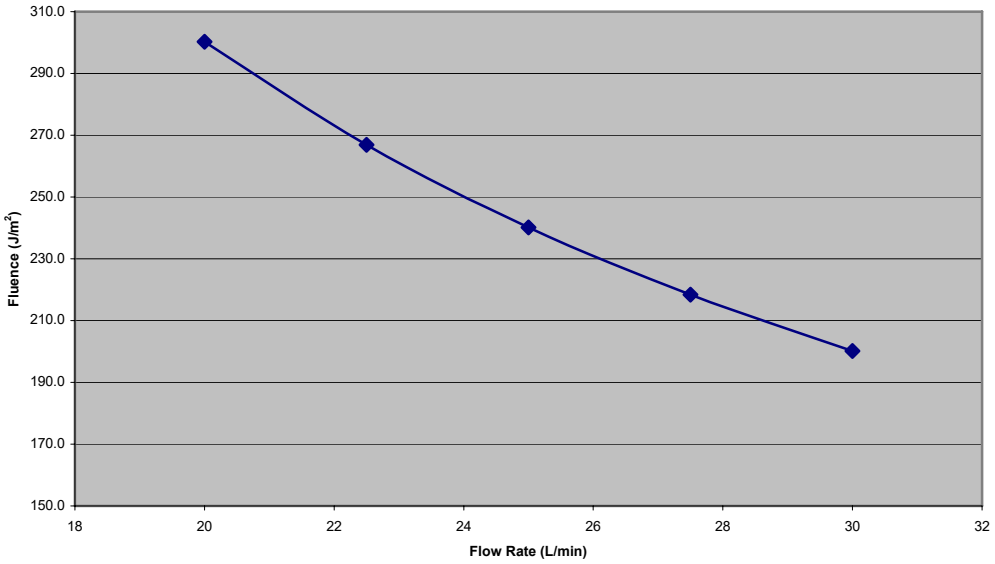


Figure 4: Graph showing the effect of increasing flow rate from the minimum prescribed level to 30 L/min as adopted by some operators for standard design small scale systems.

4.6.4 Conclusion and Recommendations.

Whilst successive passes of seawater through the UV system will inevitably result in a cumulative reduction in the microbial content of the water, as shown by Bolter (1998), persistent contaminants will be accumulated by depurated shellfish.

Given the known relative inefficiency of the depuration process to reduce the viral content of shellfish and the significance of this control step, it could be considered critical that the UV system performance should enable the eradication of all microbiological contaminants on a single pass. In order for this to be achieved, the UV configuration of systems may need to be amended to reflect a minimum dose requirement of 400 J/m2 as described by Hoyer (1998) using current flow rate stipulations. Alternatively, if a high dose on entry into the system is all that is required (rather than also on recirculation) a reduced flow rate could be instead be employed. An example of UV configurations for standard design systems that would meet the 400J/m^2 fluence value are given in table (employing the current prescribed minimum recirculation flow rates). Example flow rates achieving this fluence on fill (only) are given in table given typical current system configurations. N.B. It is not clear whether in all cases these flow rates would be achievable without modification to the existing system/pumps.

Seafish Standard Design System Type	*Example UV configuration*	Flow rate (L/min) Min	*Theoretical Fluence (Dose) (mJ/cm^2) allowing for c.a. of seawater*
Small Scale	*4 x 25 (451.6mm)*	20	40.2
Medium Scale	*8 x 55 (901mm)*	208.3	40.7
Large Scale	*6 x 55 (901mm)*	158.3	40.2
Stack (650 L)	*3 x 25 (451.6mm)*	15	40.2
Bulk bin	*6 x 30 (901mm)*	108.3	40.5

Table 5: Example UV unit configuration meeting 40mJ/cm^2 or 400 J/m^2 for standard design systems using serially connected units.

Seafish Standard Design System Type	Seafish UV Recommendation	*Example flow rate* (L/min)	*Theoretical Fluence (Dose) (mJ/cm^2) allowing for c.a. of seawater*
Small Scale	1 x 25 (451.6mm)	*2.5*	40.2
Medium Scale	4 x 30 (901mm)	*72*	40.6
Large Scale	6 x 30 (901mm)	*108*	40.6
Stack (650 L)	1 x 25 (451.6mm)	*2.5*	40.2
Bulk bin	2 x 30W per bin	*36*	40.6

Table 6: Example flow rates using existing standard UV unit configurations meeting 40mJ/cm^2 or 400 J/m^2 fluence. N.B. It is not clear whether in all cases these flow rates would be achievable without modification to the existing system/pumps.

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