UV DISINFECTION & VALIDATION

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Ultraviolet (UV) radiation is being used increasingly to provide an additional barrier to the passage of pathogens in both water and wastewater treatment plants. While chlorine has been the disinfectant of choice since the early 1900s, the recognition of the protozoan pathogens *Cryptosporidium* and *Giardia* as possible contaminants of both water and wastewater has rewritten the rule books. *Cryptosporidium* and *Giardia* are not controlled by chlorine at the doses that are typically able to be used in the water industry. They are, however, killed efficiently by UV; however, UV systems have to be carefully specified to ensure the final barrier is effective. Put simply, there needs to be enough UV energy to kill the "bugs". There is a confusing array of terms and advertising blurb, so this article is about trying to explain them and allow water utilities to be better informed when considering installation of UV systems.

What is UV Disinfection?

UV light is a component of sunlight. It falls in the region between visible light and X-rays in the electromagnetic spectrum between 100nm and 400nm in wavelength (see Figure 1). UV light in itself can be categorised into four separate regions:

- Far UV (or "vacuum") 100nm–200nm;
- UVC 200nm–280nm;
- UVB 280nm–315nm;
- UVA 315nm–400nm.

UVB and UVC are the most important for disinfection, as they have higher germicidal properties. These regions are, however, significantly filtered out by the Earth's atmosphere.

UV light "disinfects" by penetrating inside the cells of microorganisms and damaging their DNA molecules. In doing so, the microorganism is unable to reproduce, thereby rendering it inactive and no longer pathogenic. But what does inactivation reallly mean? Does it mean that every single pathogen that ever passes through the UV system will be inactivated? In reality, this is impossible. Indeed, this is impossible regardless of what disinfection method is used, whether it be UV, chlorine or anything else.

What is possible is that the pathogen of interest is reduced by a predictable amount. This amount is referred to as a "log reduction" (as in "Logarithmic" reduction). A 1-log reduction will see the pathogen of interest reduced by 90% from the influent level. A 2-log reduction will see a 99% reduction, and a 3-log reduction will see 99.9% removed. Scientists have calculated the amount of UV exposure required to inactivate a whole range of different pathogens by various log reductions.

For disinfection of water or wastewater, the UV light is generated by a UV lamp. These lamps contain a small amount of mercury. Because of the mercury, UV lamps should never be disposed of in general waste. They must be disposed of as a hazardous material or, even better, recycled so the mercury can be recovered. Most reputable UV lamp and system suppliers will take the "spent" lamps and dispose of them responsibly after servicing the UV system. It is worth asking the service engineer who services your system how they dispose of the lamps. If a satisfactory response is not gained, consideration might be given to who you engage to perform the service in future.

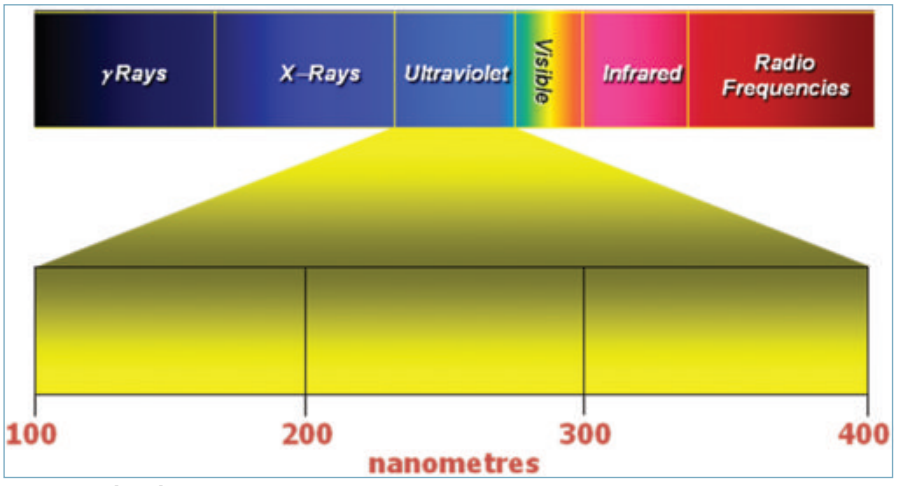

Figure 1. The electromagnetic spectrum.

When electricity is applied to the lamp, the mercury is "excited" and emits UV light. The exact wavelengths emitted depend on the vacuum pressure within the lamp tube itself.

- "Low Pressure" (LP) UV lamps are evacuated to relatively "low" pressures (between 1-10 Pa) and emit germicidal (i.e. UVC) light at a single UVC wavelength of approximately 254nm.
- "Medium Pressure" (MP) lamps are evacuated to what is termed "medium" pressure and emit a broader spectrum of UV light with higher intensities between around 254nm–265nm.

Low-pressure and so called "Amalgam" lamps are about twice as efficient at converting electrical energy into UVC light compared to medium-pressure lamps. However, medium-pressure lamps emit far more UVC energy per lamp than do low-pressure or amalgam lamps. Both low-pressure and medium-pressure lamps are germicidally effective. Table 1 provides a summary of some of the characteristics of the different lamps.

As with normal house lights some lamps are brighter than others. The energy produced by the lamps is measured in mJ/cm^2. This is the amount of UV energy measured in millijoules falling on one square centimetre of surface.

There are a variety of considerations to be taken into account when choosing which of these lamps should be used for a given application.

Selecting a UV System

There are three key parameters that need to be considered when selecting a UV system for disinfection of water or wastewater:

1. Water Quality

The nature and quality of the water to be disinfected is critical, not only in selecting an appropriate UV system, but

Table 1. Comparison of the characteristics of different UV lamps.

Trait	Medium Pressure (MP)	Low Pressure (LP) &/or Amalgam (Low Pressure High Output – LPHO)	Comments
Lamp	Evacuated to medium vacuum pressure	Evacuated to low vacuum pressure	Hence their names – this has nothing to do with the water pressure.
Wavelength range (NB: UVC light has the highest germicidal properties and occurs approximately between 200nm–300nm)	Approximately 200nm–300nm (majority of output is between approximately 240nm–280nm)	Monochromatic at 254nm	While all pathogens' DNA is denatured to some extent at 254nm, their DNA absorbs more broadly across much of the MP UV range. As such, pathogen DNA may be more broadly denatured by MP. This may explain why some studies have shown pathogens are less likely to repair their DNA damage (and therefore survive) after treatment by MP UV.
Input power	Typically 3000W–7000W	LP typically 50W–150W LPHO typically 150W–500W	So, many more LP/LPHO lamps are required to emit the same amount of UVC energy as MP lamps.
Efficiency (conversion of electrical energy to UVC energy)	Approximately 18%	Approximately 35%	So, approximately twice as much electrical energy required by MP lamps to emit the same UV energy as LP/LPHO lamps
Upshot of input power/efficiency	1 lamp	Equals approximately 10 LP lamps Equals approximately 3–4 LPHO lamps	
Lamp life	Typically 8000 hrs	Typically 12000–16000 hrs	
Working temperature of lamp	Many hundreds of degrees C	Less than 100°C	MP systems must constantly have water passing through them to keep the lamps cool. In some circumstances it may be possible for single-lamp LPHO systems (or multi-lamp LP systems) to cope with static water in the chamber for an extended period without over-heating.
Effect of water temperature on UVC output	None. Constant UV output independent of water temperature	LP – bell curve of UVC output (i.e. lower UVC output at lower and higher temperatures, centred around a peak at about 20°C LPHO – some susceptibility to water temperature, but not as dramatic as LP.	
Configuration	Chamber only	Channel or chamber	
Relative lamp price (approximate per lamp)	"100"	"50"	While the price of LP & LPHO lamps is about 50% of MP, the number of extra lamps and labour costs of changing them will usually make MP systems much less expensive to maintain in terms of parts and labour.
Relative running (power) costs – approximate	"100"	"50"	LP & LPHO consume about 50% of power compared to MP systems. This holds, regardless of the number of lamps per system.
Relative cost of ownership summary	– Higher capital costs – Higher cost per lamp – Higher power costs – Lower maintenance/ labour costs	– Lower capital costs – Lower cost per lamp – Lower power costs – Higher maintenance/ labour costs	As a general rule, the larger the system: – Less capital cost difference between LP/LPHO & MP systems. – Lamp and labour costs will increasingly be more expensive for LP/LPHO than MP. – Power costs will increasingly become more expensive for MP than LP/LPHO.

also in deciding if UV disinfection is even possible. Of all water quality parameters, Ultraviolet Transmissivity (UVT) is the most important. This is because the UVT of the water will determine how well the UV light will penetrate the water in order to activate the pathogens. The UVT is measured in a simple laboratory test that determines the amount of UV light at 254nm passing through the sample.

BOD, COD, turbidity, suspended solids (TSS) and dissolved solids (TDS) all affect how UV light can pass through water. Turbidity and TSS are the most limiting factors. TSS above 20mg/L can result in a phenomenon known as "shielding", whereby the pathogens are "shielded" from the UV light and not harmed. Any turbidity in the water also reduces the UVT.

2. Water Flow Rate

A key factor in determining how effective UVC light will be in deactivating a given pathogen is the time that the pathogen is exposed to the UV light (exposure time). The longer the exposure time, the more effective the UV will be at inactivating the pathogen. Therefore, it stands to reason that the slower the flow rate of the water through the UV system, the longer the UV exposure time and vice versa.

Both the instantaneous maximum and minimum flow rates are important because many UV systems have the ability to adjust the power output of the lamps in relation to changes in flow. Daily and hourly flow rates are not suitable as they can mask important "peaks and troughs" in the instantaneous flow rate, thereby resulting in spurious calculations of the true UV exposure time during these peaks and troughs.

3. Pathogen(s) to be inactivated

Different pathogens require different amounts of UV energy to inactivate them. Therefore for any UV system, it must be clear which pathogens are to be inactivated. Table 2, taken from the USEPA *UV Disinfection Guidance Manual* (*UVDGM*), shows the UV dose required to achieve different log removals of pathogens.

For example to achieve 99% removal (log 2) removal of *Cryptosporidium* requires 5.8 mJ/cm^2. To achieve 4-log removal (99.99% removal) requires 22 mJ/cm^2. It is important to note that the relationship between the dose and the log removal, the so called dose response, is not linear. It takes a very much higher dose to achieve log-4 removal compared to log-2 removal.

UV Intensity and UV Dose

UV dose is measured in millijoules seconds per cm^2 (mJ/cm^2) and is calculated using the following parameters:

- UV Intensity (I), measured in milliwatts per cm^2 (mW/cm^2);
- UV Transmittance (UVT) (%);
- Exposure time (t) (seconds).

The relationship between these parameters can be described by the following simplified equation:

UV dose = (I/UVT) x t

The important thing to understand from this relationship is that UV Intensity and UV dose are two different things. UV Intensity measures the "amount" of UV energy actually penetrating through the water being treated. UV dose is the amount of UV energy penetrating the water, multiplied by the amount of time the water is exposed to this energy. It is the UV dose that determines the log reduction of a pathogen.

UV dose is usually quoted as either the "average" dose or Reduction Equivalent Dose (RED). The average dose implies that some of the water being treated will receive the prescribed dose, some will receive more than the prescribed dose, but, importantly, some water will receive less than the prescribed dose. If some water receives less than the prescribed dose, then the prescribed log reduction may not be achieved. This concern has led to the adoption of the RED concept. In essence, RED suggests that all the water passing through the UV system will receive at least the prescribed dose, thereby ensuring the prescribed log reduction targets are achieved. RED is the concept on which UV systems are validated.

Table 2. UV dose requirements in mJ/cm^2 to achieve stated log reductions for some typical water-borne pathogens.

Target Pathogens	Log Inactivation							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	15	22
Giardia	1.5	2.1	3.0	5.2	7.7	11	15	22
Virus	39	58	79	100	121	143	163	186

Table 3. Comparison of key aspects of the USEPA *UVDGM* & German DVGW validation protocols.

	USEPA *UVDGM*	DVGW
Who is permitted to carry out the UV system validation?	Anyone who can prove that the validation protocol outlined in the *UVDGM* has been followed.	Only a DVGW certified facility.
What is the result of the validation procedure?	A detailed report proving the *UVDGM* protocol has been followed.	Certification of the validated UV system.
What UV dose is required to achieve validation?	As much as is required to inactivate a given pathogen by a specified log reduction. (See Table 1.)	40mj/cm^2 RED. This is based on the principal that almost all common water-borne pathogens will experience at least a 4-log reduction at this dose. DVGW don't care about the pathogen or the log reduction, they believe a UV dose of 40 mj/cm^2 is enough to inactivate most "bugs" by 4 log, and so they only require the UV system to deliver this dose.

How are UV Systems Validated?

Clearly it is important to be sure that a particular UV disinfection system actually achieves the log removal it is supposed to. Validating the performance of each and every UV system *in situ* is impractical, therefore another system is necessary. Over the years, there have been many systems developed. The one that has come to be accepted by the international community as the most appropriate is that which verifies system performance by "first principles" – the so called "biodosimetric" approach. This validation system uses actual pathogens to test the log reduction achieved by a given UV system in the following steps.

1. The pathogen of interest is cultured under controlled and reproducible laboratory conditions.
2. The pathogens are exposed to UV light under controlled laboratory conditions.
3. The culture is then exposed to a known UV intensity, of known wavelength, for a fixed period of time, thereby delivering a known UV dose to a known area of the presentation plate – hence dose and intensity are measured per cm^2 (area) rather than cm^3 (volume). The apparatus used to perform this test is called a Collimated Beam apparatus.
4. The exposed area of the plate is re-cultured to quantify the survival of the pathogen.
5. This procedure is replicated many times at systematically increasing doses in order to build a Dose Response Curve. This curve enables the log survival (and by inference, log reduction) for the pathogen of interest to be determined for any given UV dose. This entire procedure is then replicated at every UVT level across the required UVT range.
6. After the various Dose Response Curves have been constructed in the laboratory, these then need to be applied to test an actual UV disinfection system in order that it might be validated. The pathogens used to test the UV system are cultured (albeit in much higher volumes) under exactly the same conditions as used in the laboratory.
7. A sample of the water is taken at the inlet to and exit from the UV system and re-cultured to determine how many pathogens have survived.
8. The observed log survival of the pathogen is then compared to the pathogen's Dose Response Curve (see Step 5) and the actual UV dose delivered read off from the curve. This dose is termed the Reduction Equivalent Dose – RED.

A large "in-channel" UV system.

Who Determines the Rules for UV System Validation?

It all sounds relatively simple and sensible to this point, however, there are a number of different validation systems. The internationally recognised validation protocols for drinking water are:

- O-Norm (Austrian)
- DVGW (German)
- USEPA (USA – as per the *UV Disinfection Guidance Manual – UVDGM*)

(Interestingly, there is as yet no internationally recognised validation protocol for wastewater.)

Of these protocols, the USEPA and DVGW are the clear leaders. In general, Australian state health authorities will accept UV systems validated against an internationally accepted validation protocol, which includes either of these two protocols. Table 3 compares these two validation protocols. It is important to recognise that this table is not intended to be exhaustive, but rather it is intended to compare some of the most fundamental aspects of the two protocols.

Currently, the only internationally recognised water reuse validation protocol is:

USEPA – National Water Reuse Institute (NWRI)

This validation protocol is administered in a similar way to the UVDGM protocol for drinking water. The main difference is that the dose required to meet the validation standard is affected by the nature of the pre-treatment of the water upstream of the UV system. This introduces the concept of "log credits". This concept is best illustrated by way of the following example.

Two smaller "in-pipe" UV systems.

Let's assume that a pathogen requires a 7-log reduction on its passage through a water reuse disinfection system. The filter system in use upstream of the UV system has been validated to provide a 3-log reduction in the pathogen (i.e. it provides a "3-log credit"), therefore the UV system is required to provide only a 4-log reduction to achieve the 7-log target. The filter system would have been validated in some way similar to the biodosimetric method described above described for the UV system.

Various filter media perform better than others when it comes to providing log credits. In general media filters are less efficient than membrane filters, which are in turn less efficient than, say Reverse Osmosis (RO).

So, in summary, to have a UV system work for you, you need to know the following:

1. The minimum UVT of the water.
2. The peak, instantaneous maximum flow rate of the water passing through the UV system.
3. The log reduction requirement with respect to the pathogen(s) of interest.

The consequence of overestimating the minimum UVT or underestimating the instantaneous maximum flow, while making the system cheaper, will be failed UV disinfection that is not the fault of the system. Therefore, don't rush the specifications. Take the time to collect quality data and achieve a system that delivers that extra barrier to pathogens and reduced risk to public health.

References

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