

ULTRAVIOLET LIGHT

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ABSTRACT

Ultraviolet light (UV) is a recognized disinfection alternative to chlorine and ozone in many applications from drinking water to wastewater treatment. UV provides effective disinfection without production of problematic disinfection byproducts. Information on the mechanism and application of UV for drinking water disinfection is presented. Advantages and disadvantages of the technique are discussed with a view towards comparison with chemical disinfection. Practical information regarding UV system design, operation, and maintenance as well as capital, operating, and maintenance costs are indicated for a range of disinfection strategies.

1. Introduction

Ultraviolet light (UV) is an established and increasingly popular alternative to chemicals for the disinfection of drinking water, wastewater, and industrial waters of various qualities. UV disinfection systems can be engineered for a broad range of applications provided that due attention is paid to the quality of the water being disinfected and the disinfection objectives being sought. Table 1 provides a list of specific applications of UV disinfection.

The practice of UV disinfection for drinking water and its underlying theory has been well documented. Drawing from literature sources as well as direct experience, this paper attempts to provide a review of the current state of the art.

2. An Historic Perspective

An historic perspective on UV disinfection has been published in several review articles (Grocock, 1984; Schenck, 1981; USEPA, 1996). The germicidal effects of radiant energy from the sun was first reported by Downs and Blunt in 1878. Practical application of UV, however, required the development of the mercury vapor lamp as an artificial UV source in 1901 and the recognition of quartz as the ideal lamp envelope material in 1905. The first experimental attempts to use UV to disinfect water were made in Marseilles, France in 1910. Between 1916 and 1926, UV was used in the USA for the disinfection of drinking water and used on ships to provide potable water. However, the low cost of water disinfection by chlorine

combined with cost, operational, and reliability problems observed with early UV disinfection equipment slowed the growth in the application of UV until the 1950s.

Table 1. Applications of UV disinfection.

<p><u>Drinking Water</u></p> <ul style="list-style-type: none"> Municipal Communal <ul style="list-style-type: none"> Subdivisions Mobile home parks Camp grounds Hunting lodges Ski Resorts Hotels Ships Institutional <ul style="list-style-type: none"> Hospitals Schools Nursing Homes Community centers Residential <p><u>Wastewaters</u></p> <ul style="list-style-type: none"> Municipal Communal Institutional Residential 	<p><u>Commercial</u></p> <ul style="list-style-type: none"> Fish hatcheries Hydroponics Laboratories Aquaria Restaurants <p><u>Industrial</u></p> <ul style="list-style-type: none"> Breweries Pharmaceutical Bottlers Electronics Canneries Dairy Food Marine Distilleries Petroleum Textile Cosmetics Printing
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In 1955, practical installations of UV disinfection for drinking water occurred in Switzerland and Austria. By 1985, the number of installations in those countries had risen to 500 and 600 facilities, respectively. With the discovery of chlorinated byproducts, UV disinfection became popular in Norway with the first UV installation occurring in 1975. The first installation in the Netherlands occurred in 1980.

Today, there are over 2000 installations in Europe using UV to disinfect drinking water and over 1000 installations in the United States (USEPA, 1996). UV disinfection is popular in New York where it is used to disinfect over 6.4% of all groundwater systems. As well, 761 of the 10,700 public water systems in Pennsylvania were reported to use UV alone or in combination with chlorine. In the United Kingdom, UV disinfection using both low and medium pressure lamp technologies has been combined with chlorine at a 14.5 MGD water treatment plant in London for primary disinfection and residual maintenance (Wolfe, 1990).

3. Sources of UV Light

Ultraviolet light is that portion of the electromagnetic spectrum that lies between X-rays and visible light (Figure 1). Four regions of the UV spectrum have been defined – vacuum UV between 100 and 200nm, UVC between 200 and 280nm, UVB between 280 and 315nm, and UVA between 315 and 400nm (Meulemans,

1986). Practical application of UV disinfection relies on the germicidal ability of UVC and UVB.

Electromagnetic Spectrum

Cosmic Rays	Gamma Rays	X Rays	Ultra Violet	Visible Light	Infrared	Micro Waves	Radio Waves
			100	400			

Expanded Scale of Ultraviolet Radiation

X-Rays	Vacuum UV	UV C	UV B	UV A	Visible Light
100	200	254	280	315	400
Germicidal Wavelengths					
					800

Figure 1. The electromagnetic spectrum.

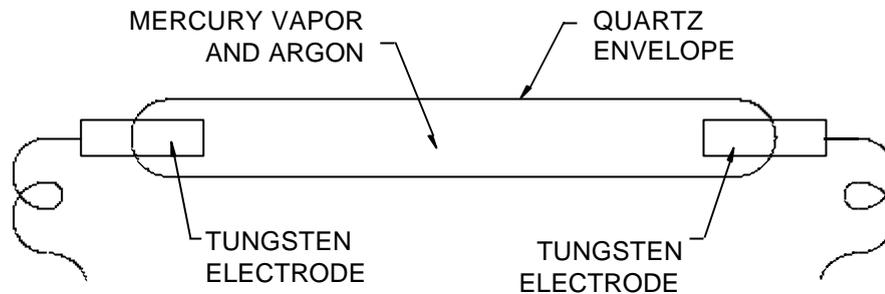
While the sun is a source of ultraviolet light, absorption of short wavelength radiation by the earth's ozone layer prevents significant quantities of UVB and UVC from reaching the earth's surface. Accordingly, practical application of UV disinfection depends on artificial sources of UV. The most common sources of UV are commercially available low and medium pressure mercury arc lamps.

A typical mercury arc lamp (Figure 2) consists of a hermetically sealed tube of UV - transmitting vitreous silica or quartz with electrodes at both ends (Phillips, 1983). The tube is filled with a small amount of mercury and an inert gas, usually argon. The electrodes are usually composed of tungsten with a mixture of alkaline earth metals to aid arc formation within the lamp. A gas discharge is struck by applying a high voltage across the electrodes. UV light is emitted from the lamp when mercury vapor, excited by the discharge, returns to a lower energy state. Argon is present to aid lamp starting, extend electrode life, and reduce thermal losses. Argon does not contribute to the spectral output of the lamp.

Due to the negative resistance electrical characteristics of gas discharges, stable operation of a mercury arc lamp requires a suitable ballast. If the lamp is operated using an A.C. supply, the ballast usually consists of both inductive and capacitive components. Ballasts may be characterized as either electromagnetic or electronic (O'Brian et al, 1995; Phillips, 1983) (Figure 2). Electromagnetic ballasts typically consist of an inductor in series with the lamp and a power factor correction capacitor in parallel. Power is delivered to the lamp at the line frequency of 50 or 60 Hz. Electronic ballasts, on the other hand, consist of a AC to DC rectifier followed by an inverter to convert the DC to high frequency AC in the kilohertz range. Compared to electromagnetic ballasts, electronic ballasts are more compact, reduce system cost, have a greater electrical efficiency, and can operate

at various power settings (O.Brian et al, 1995). As well, operation of the lamp at a higher AC frequency increases lamp output and extends lamp life (Phillips, 1983).

LAMP CONSTRUCTION



BALLAST DESIGN

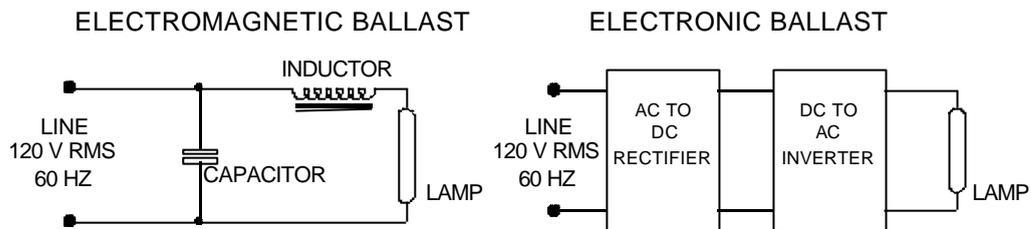


Figure 2. Mercury arc lamp construction and ballast design.

Figure 3 presents a comparison of the spectral output of low and medium pressure mercury arc lamps. Low pressure mercury arc lamps used in water disinfection vary in length from 35 to 163 cm and have a diameter between 1.2 and 1.9 cm. During lamp manufacture, mercury is introduced into the lamp as a single drop (50 – 100 mg Hg in a 1.5 m low pressure lamp; O’Brian et al, 1995). Lamps are designed to operate at optimal efficiency with a lamp wall temperature of 40°C and an electrical arc power near 0.3 W/cm (Phillips, 1983). Under these conditions, the mercury vapor pressure within the lamp is 0.9 Pascals and most of the mercury within the lamp exists in a liquid state. The construction, filling, and operation of a low pressure lamp is chosen to maximize the conversion of electrical energy to resonant UV radiation at 254nm and 185nm. Approximately, 85% of the light emitted from a standard low pressure lamp is resonant UV radiation. Including ballast losses, conversion of electrical energy to UV light is approximately 35 to 40% efficient (O’Brian et al, 1995). A 147 cm long standard low pressure lamp can be expected to produce 26.7 W of UV at 254nm given an electrical input of 75 W.

Medium pressure mercury arc lamps used in water disinfection vary in length from 25 to 70 cm and have a diameter near 2.2 cm. During lamp manufacture, a measured mass of mercury is introduced into the lamps (1.4 to 15 mg Hg/cm arc length). The lamps are designed to operate at a relatively high electrical arc power

of 48 to 126 W/cm (Phillips, 1983). Accordingly, the lamp wall temperature is between 650 to 850°C and all of the mercury within the lamp is vaporized to a vapor pressure near 13 kPa. Due to the high plasma temperature within the medium pressure lamp, vaporized mercury exists in a number of excited states. Transition of the excited states to a lower energy level results in the release of light at various wavelengths. Accordingly, the UV spectral output of a medium pressure lamps consists of numerous peaks with a continuum of UV below 245nm. Ignoring radiation below 248.3nm, Phillips (1983) reports that a medium pressure lamp operating at an electrical arc power of 107 W/cm produces 9.38 W/cm of UVC and 8.19 W/cm of UVB. Thus at least 44% of the total radiation emitted by a medium pressure lamp is UVB and UVC. Conversion of electrical energy to UVB and UVC is at least 16% efficient. Accordingly, a 25cm long medium pressure lamp can be designed to produce 450 W of UVB and UVC given an electrical input of 2.8 kW.

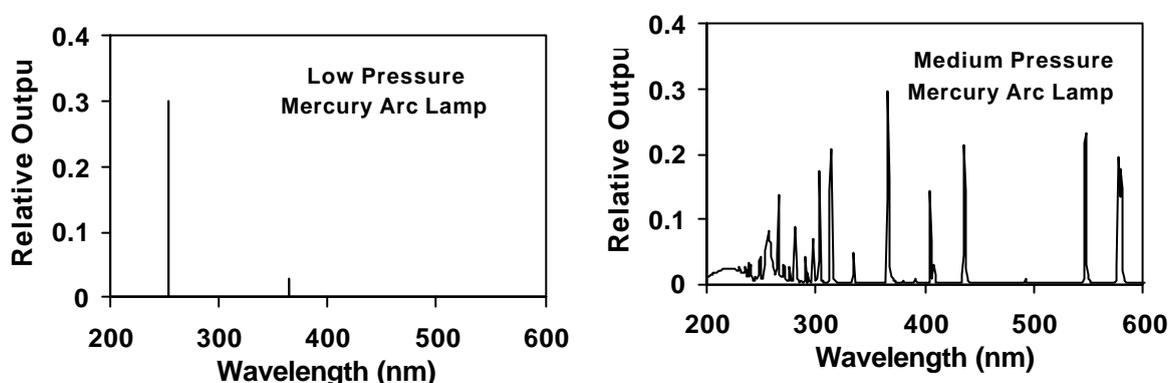


Figure 3. Spectral output of low and medium pressure mercury arc lamps.

While low pressure lamps are more electrically efficient than medium pressure lamps, medium pressure lamps produce a greater UV output per lamp. Accordingly, medium pressure UV systems can be expected to use fewer lamps, take up less space, and require less maintenance. As well, due to the reduced number of lamps, medium pressure UV systems can cost effectively incorporate automatic cleaning systems to remove fouling that accumulates on lamp sleeves during water disinfection, thereby significantly reducing labor associated with lamp maintenance. Whether a low or medium pressure system, or a combination of the two, is appropriate for a particular application will depend on site specific factors.

4. Mechanism of UV Disinfection

4.1 DNA Dimerization

Microorganisms are inactivated by UV light as a result of photochemical damage to their nucleic acids. UV radiation is absorbed by nucleotides, the building blocks of cellular RNA and DNA, in a wavelength dependent manner with peaks near 200

and 260nm (Sonntag and Schuchmann, 1992) (Figure 4). Absorbed UV promotes the formation of bonds between adjacent nucleotides, creating double molecules or dimers (Jagger, 1967). While the formation of thymine-thymine dimers are the most common, cytosine-cytosine, cytosine-thymine, and uracil dimerization also occur. Formation of a sufficient number of dimers within a microbe prevents it from replicating its DNA and RNA, thereby preventing it from reproducing. Due to the wavelength dependence of DNA UV absorption, UV inactivation of microbes is also a function of wavelength. Figure 4 presents the germicidal action spectra for the UV inactivation of *E. coli* (DIN, 1996). The action spectra of *E. coli* peaks at wavelengths near 265nm and near 220nm. It is convenient that the 254nm output of a low pressure lamp coincides well with the inactivation peak near 265nm.

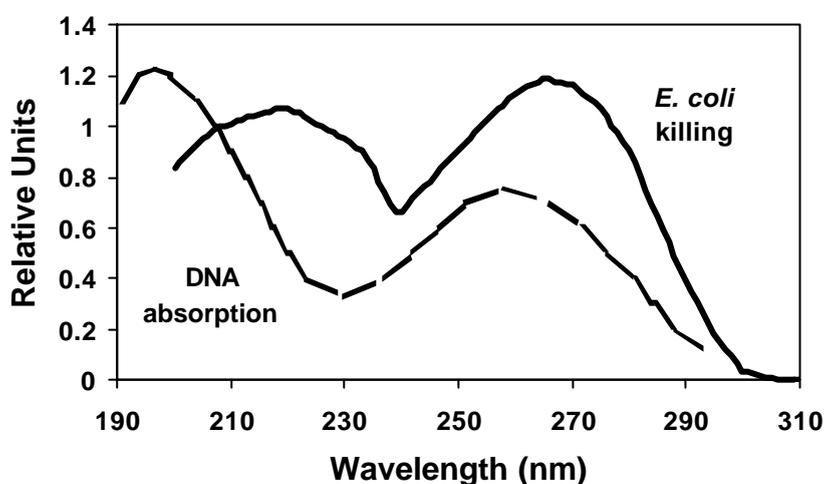


Figure 4. Comparison of the action spectrum for *E. coli* inactivation to the absorption spectrum of nucleic acids

4.2 Repair Mechanisms

Many microbes which have a functional metabolic system have various mechanisms for the repair of damaged nucleic acids (Jagger, 1967). The repair mechanism which is most unique to UV disinfection is the photoreactivation mechanism. The photodimerization of adjacent thymines resulting from UV absorption by nucleic acids can be reversed by a photoreactivating enzyme which uses light between 300 and 500 nm to activate cleavage of the dimer. Other UV induced transformations in the nucleic acids, including dimers involving cytosine, can not be repaired except by a dark repair mechanism in which entire damaged segments of nucleic acid are excised and the undamaged complementary strand is used as a template for repair and replacement of the damaged segment.

Viruses have no repair mechanisms to reverse the damage created by UV light. The ability of bacteria and other microbes to photorepair is directly related to the extent of the UV damage, the exposure to reactivating light between 300 and

500nm, and the pH and temperature of the water. A significant inverse relationship has been reported between applied UV dose and the photoreactivation of coliform bacteria with less repair at higher doses (Lindenauer and Darby, 1994). Exposure to light between 300 and 500nm must occur within two to three hours for photorepair to be encouraged (Grocock, 1984). Accordingly, residence time within a drinking water system will reduce photorepair potential.

4.3 Inactivation Kinetics and the Concept of UV Dose

$$N = N_0 e^{-kIt}$$

The kinetics of microbial inactivation by UV is often cited as following Chick's Law: where N_0 is the initial concentration of microbes prior to applying UV, N is the number of microbes remaining after exposure to UV, I is the UV intensity, t is the exposure time, and k is a microbial inactivation rate constant. UV dose is defined as the product of UV intensity and time. Figure 5 presents a graphical representation of Chick's law showing inactivation as a function of applied UV dose. A useful interpretation of Chick's Law is that for a UV dose increase equal to $2.30/k$, there is an order of magnitude reduction in the microbial population.

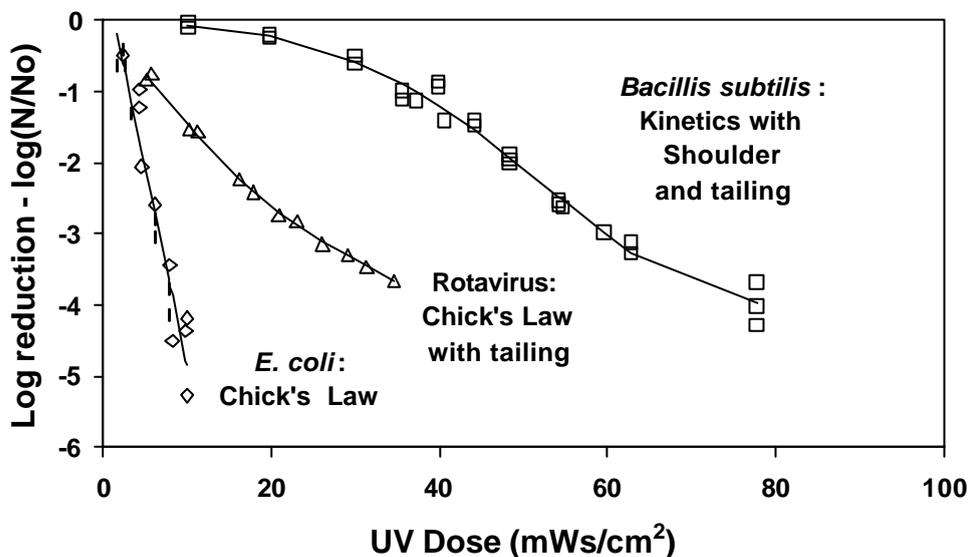


Figure 5. UV disinfection inactivation kinetics (adapted from Chang et al, 1985).

Deviations from Chick's Law are often observed as either a shoulder at low doses or tailing at high doses (Figure 5). Shoulders at low doses can be explained using series-event inactivation kinetics (Severin et al, 1984). In series-event kinetics, inactivation of a microbe occurs only after sufficient DNA damage has occurred

within the microbe. Accordingly, the onset of inactivation observed with a UV dose-response curve appears to require a threshold dose. Not all microbes demonstrate observable series-event kinetics in their dose–response curves. Severin et al (1984) and Harris et al (1987) observed virus inactivation following Chick’s law and bacterial inactivation followed series-event kinetics. Chang et al (1985) observed viral inactivation and the inactivation of some bacterial pathogens following Chick’s Law while the inactivation of cysts, spores, and other bacteria had shoulders.

Tailing occurs at high doses and can be attributed to the clumping of microbes, and the occlusion of microbes within particulates (Parker and Darby, 1995) and other microbes. Microbes occluded by particulate material and other microbes experience a lower UV dose compared to individual microbes in the bulk phase due to the UV absorbance of the particulate material and biomass. For example, the UV transmission through an E. coli cell is 70% at 254nm (Jagger, 1967). The UV transmission through particulates will depend on the composition of the particulate and the presence of UV absorbing compounds like iron.

Dose delivered by monochromatic low pressure mercury arc lamps has been traditionally defined as the product of the intensity at 254nm and the exposure time. No reference to the microbial action is included in this calculation. With polychromatic medium pressure mercury arc lamps, the contribution of each germicidal wavelength, weighted by the microbial action spectra, should be considered in the determination of dose (Meulemans, 1986). The germicidal dose delivered by a medium pressure mercury arc lamp can be defined as:

$$UV\ Dose = \sum_{I=200\ nm}^{I=315\ nm} I(I)G(I)t$$

Where $I(\lambda)$ is the wavelength-dependent output from the medium pressure lamp and $G(\lambda)$ is the wavelength-dependent action spectra of the microbe being inactivated. Since dose in UV disinfection has been traditionally cited for low pressure mercury arc lamps, microbial action spectra should be normalized at a wavelength of 254nm to a value of one. By normalizing the action spectra to one, UV dose calculated for the medium pressure lamps becomes comparable to doses calculated for low pressure mercury arc lamps.

4.4 Inactivation Rates

Table 2 presents a summary of UV inactivation observed using low pressure lamps with viral, bacterial, and protozoan pathogens as well as indicator microbial groups. Microbe inactivation rates vary depending on the microbe species, the microbe population, and the wavelength of UV light. In general, bacteria are less resistant to UV at 254nm than virus, which in turn are less resistant than bacterial spores. While protozoan cysts and oocysts are regarded as the most resistant pathogenic

microbes to UV at 254nm, there is some evidence that cysts are more susceptible to inactivation by polychromatic UV from medium pressure lamps (Bukhari et al, 1998). In general, gram positive bacteria are more resistant than gram negative bacteria. Water temperature and pH have little if any impact on the rate of microbe inactivation by UV (USEPA, 1996). pH effects observed with bacterial virus MS-2 inactivation have been attributed to pH-induced clumping of the microorganisms (Malley et al, 1995) as opposed to a change in the rate of DNA damage by UV.

Table 2 indicates that with few exceptions, the dose for inactivation of pathogenic bacteria are very similar to the dose required for the disinfection of fecal indicator groups such as fecal coliforms. This is not surprising given that the underlying mechanism of UV disinfection is similar within these organisms. The nature of the exterior of the bacterium also has a similar impact on UV transmittance into the micro-organism. Higher UV doses are required when the bacteria have a unique UV-absorbing protective exterior as is the case in some bacterial spores (Munakata et al, 1991).

Between 1971 and 1988, about 81% of the identified bacteria-associated waterborne disease outbreaks in the United States (Craun, 1990) were due to bacteria listed in or related to those in Table 2. Although it is not possible to determine the sensitivity of each and every bacterial pathogen to UV, the common mechanism of UV action on nucleic acids provides a high level of confidence that similar doses would be required for most bacterial pathogens likely to be encountered in drinking water.

Because of the low number of virus required for infectivity, careful consideration should be given to the UV dose requirement for virus inactivation. The most UV-resistant human pathogenic virus described by any author in the literature is the Rotavirus (Reovirus) which was reported to be 11 times more resistant to UV than *E. coli* (Harris et al, 1987). Other authors (Battigelli et al, 1993; Chang et al, 1985) have reported a greater susceptibility of Rotavirus to UV. Viruses such as poliovirus and hepatitis A are only 2 to 5 times as resistant as *E. coli*. Although some variation from study to study exists, the evidence summarised by the IAWPRC Study Group on Health Related Water Microbiology (IAWPRC, 1991) indicates less than a fourfold difference in UV resistance of *E. coli* and viruses. By comparison, the rotaviruses were observed to be similar to *E. coli* in sensitivity to chlorine, but poliovirus and some enteric viruses were reported to be 40 or more times more resistant to chlorine than *E. coli* (Engelbrecht et al, 1978; Scarpino et al, 1974). Victor Cabelli reports (personal communication) that the Norwalk virus which accounts for 20 to 40% of waterborne acute gastroenteritis, is over 100 times more resistant to chlorine than is *E. coli*.

There are several implications of the above mentioned observations. First, the most resistant microbe with one disinfection method is not the same for another. A meaningful comparison of disinfection methods should involve examination of a

broad range of microbial species which would include the most sensitive and most
Table 3. UV dose in mWs/cm² to inactivate a microbial population by 1 Log (90%) and 2 Log (99%).

MICRO-ORGANISMS	Log Reduction		MICRO-ORGANISMS	Log Reduction	
	1	2		1	2
BACTERIA			Fecal coliforms ¹⁰	3.4	6.8
Bacillus anthracis	4.5	8.7	Salmonella enteritidis	4	7.6
Bacillus subtilis, spores	12	22	Salmonella paratyphi ³	3.2	---
Bacillus subtilis	7.1	11	Salmonella typhi ⁵	2.1	---
Campylobacter jejuni ⁵	1.1	---	Salmonella typhimurium ¹⁰	3	---
Clostridium tetani ¹	12	22	Shigella dysenteriae	2.2	4.2
Corynebacterium diphtheriae ¹	3.4	6.5	Shigella flexneri (paradysenteriae)	1.7	3.4
Escherichia coli	3	6.6	Shigella sonnei ⁵	3	5
Klebsiella terrigena ⁵	2.6	---	Staphylococcus aureus	5	6.6
Legionella pneumophila ⁴	0.9	2.8	Streptococcus faecalis ⁵	4.4	---
Sarcina lutea	20	26.4	Streptococcus pyogenes	2.2	---
Mycobacterium tuberculosis	6	10	Vibrio cholerae (V.comma) ⁶	---	6.5
Pseudomonas aeruginosa ⁶	5.5	10.5	Yersinia enterocolitica ⁵	1.1	---
VIRUSES					
MS-2 Coliphage ⁵	18.6	---	Influenza virus ²	3.6	6.6
F-specific bacteriophage ²	6.9	---	Polio virus ^{5,6,9}	5 - 8	14
Hepatitis A ^{5,6}	7.3	---	Rotavirus ^{5,6,9,11}	6 - 15	15-40
PROTOZOA			ALGAE		
Giardia lamblia ^{6,7}	82	---	Blue Green ^{1,3}	300	600
Cryptosporidium parvum ⁸	80	120	Chlorella vulgaris ^{1,2}	12	22
YEAST					
Saccharomyces cerevisiae ¹	7.3	13.2			

References: 1. Legan (1980) 2. Jevons (1982) 3. Grocock (1984) 4. Antopol (1979)
5. Wilson et al (1993) 6. Wolfe (1990) 7. Rice and Hoff (1981) 8. Ransome et al (1993)
9. Harris et al (1987) 10. Trojan Technologies Ltd. 11. Battigelli et al (1993)

resistant for both disinfectants. Second, the range of resistance for bacteria and virus is much narrower when using UV than when using chlorine. This narrower range will provide more confidence when using UV as compared with chlorine that the level of disinfection achieved as indicated by the traditional indicator microbes is reflective of the disinfection level achieved for other microbes. This is a distinct advantage because of the ease, lower cost, and operator familiarity with standard coliform assays compared with viral or bacteriophage assays which are being proposed for monitoring of virus inactivation when chlorine is the disinfectant. Last, higher doses of either UV or chlorine can be provided to enhance disinfection of resistant microbes. With chlorine, this disinfectant dose will result in increased chloro-organic byproduct formation (Greiner et al, 1992).

There is presently some debate on the resistance of protozoa parasites to UV disinfection. Past work using low pressure mercury arc lamps indicates protozoan parasites like *Giardia Lamblia* and *Cryptosporidium parvum* are significantly more resistant to UV than bacteria and virus, requiring a UV dose of 80 mWs/cm² to achieve a one log reduction. Recent work by Bukhari et al (1998), however, indicates that a 3.9 log reduction of *Cryptosporidium*, measured using mouse infectivity studies, can be achieved with a low UV dose from a medium pressure mercury arc lamp. Significant reductions of *Cryptosporidium*, however, were not confirmed using *in vitro* assays. The results suggest that traditional enumeration techniques to measure protozoan cysts/oocyst inactivation by UV may be significantly underestimating the reduction in viability. As well, medium pressure mercury arc lamps may have advantage over low pressure mercury arc lamps with regards to protozoan inactivation. Given the significance of this work, further research over the next year will likely resolve these issues.

4.5 UV Dose Requirements

The minimum UV dose required for pathogen reduction is not universally agreed upon and neither should it be. Many site specific considerations come into play when selecting a UV dose considered sufficient to disinfect a drinking water supply to a level considered acceptable (Regli et al, 1991). Factors to consider include the source water quality and level of microbial contamination, the impact on microbial contamination of water treatment processes located upstream of the UV disinfection unit, the epidemiological information correlating microbial populations with the occurrence of disease, and the target risk level considered acceptable to protect the public from waterborne disease.

UV dose requirements can be determined using either a bench scale collimated beam apparatus in a laboratory or an on-site pilot scale UV disinfection unit. In a collimated beam study, a petri dish containing a water sample is irradiated in a controlled manner using a UV source of known intensity. UV dose-response relationships can be established by varying the time of exposure with the collimated beam apparatus or by varying the flow rate through the UV disinfection

pilot. The UV dose response curve will provide information on the sensitivity of the microbes to UV and the impact of particle associated microbes on achievable disinfection. Ideally, the UV dose-response curve is obtained for the poorest water quality expected – high suspended solids or turbidity, high microbial counts (No), and high levels of UV absorbing soluble and particulate compounds. A UV dose-response curve can serve not only to identify a UV dose requirements to achieve a particular level of disinfection but also serve to identify whether pretreatment of the water can lead to a more cost effective disinfection solution.

Various jurisdictions throughout the world specify different UV dose requirements (USEPA, 1996). The United States Department of Health, Education, and Welfare (DHEW) in 1966 proposed, as a guideline for UV disinfection on ships, a UV dose of 16 mWs/cm² at all points within the UV disinfection chamber. Pretreatment of the water to meet Drinking Water Standards with an emphasis on turbidity and color removal was also specified.

The National Sanitation Foundation (NSF) ANSI/NSF Standard 55-1991 defines two standards for Point-of-Use (POU) and Point-of-Entry (POE) UV disinfection systems. The first standard defines a Class A UV disinfection unit designed to disinfect virus and bacteria to safe levels. Class A units must provide a dose of 38 mWs/cm². The second standard defines a Class B UV unit designed for the supplemental disinfection of treated and disinfected public water. Class B units must provide a dose of 16 mWs/cm². NSF stated that a dose of 16 mWs/cm² would provide greater than 2 log removal of non-spore forming heterotrophic bacteria and a dose of 38 mWs/cm² would provide a 4 log removal of virus. The standard also requires that dose delivery by a UV reactor be validated by comparing the disinfection achieved in the reactor using a challenge microbe (either *Saccharomyces cerevisiae* or *Bacillus subtilis*) to the UV dose-response curve obtained using a lab-scale collimated beam apparatus. Similar to the DHEW guideline, NSF Standard 55 is not intended for the treatment of waters with an obvious contamination source like sewage. Furthermore, if surface waters are to be treated, a prefilter must be used for cyst reduction.

The Surface Water Treatment Rule of the United States EPA requires a UV dose of 21 and 36 mWs/cm² to provide, respectively, a 2 and 3 log removal of hepatitis A virus. The Rule notes that this dose requirement includes a safety factor of 3. The American Water Works recommends a dose of 40 mWs/cm² for small municipal systems. While the states of Utah, New Jersey, and Pennsylvania call for a dose requirement of 16 mWs/cm², Arizona, Delaware, Massachusetts, North Carolina, and Wisconsin require compliance to ANSI/NSF Standard 55 Class A. Both Wisconsin and Pennsylvania specify UV for the treatment of well water, and the Wisconsin requirement specifies a need for filtration prior to UV to remove sediments and cysts. In Europe, Norway, Austria, and France require doses of 16, 30 and 25 mWs/cm² respectively.

5. UV Reactor Design

UV disinfection reactor designs can be classified as either open-channel systems, closed-channel non-contact systems, or closed-channel contact systems. Open-channel systems are common in wastewater disinfection and consist of racks of UV lamps oriented horizontal or parallel within a wastewater flow. Flow is gravity fed and exposed to the atmosphere. Closed-channel non-contact systems involve water or wastewater flowing through UV transmitting tubes, typically Teflon. Lamps are external to the tubes and the flow is either pressurized or gravity fed. Closed-channel contact systems consist of UV lamps, housed within UV transmitting quartz sleeves, immersed within a water or wastewater flow. Closed-channel contact systems treating a pressurized flow are the most commonly encountered and preferred reactor designs for the UV disinfection of drinking water.

Components of a closed-channel contact UV reactor for drinking water disinfection may include lamps, ballasts, quartz sleeves, quartz sleeve cleaning mechanisms, reactor housing, UV intensity meters, flow sensors, command and control electronics, alarms, and flow control valves. Upstream water pretreatment devices may also be included as part of a complete disinfection package.

Quartz sleeves protect lamps from damage and, in the case of low pressure lamps, thermally insulate the lamps from the water, thereby allowing them to operate at an optimal temperature regardless of the water temperature. Quartz sleeve UV transmittance depends on the type of quartz used and is typically 90% at 254nm. During the disinfection of water, inorganic scale accumulates on the quartz sleeves reducing the transmission of UV light from the lamps into the surrounding water. Various automated mechanical cleaning mechanisms, including ultrasonics, Teflon ring wipers, high pressure jets, and wire brushes, have varying degrees of success removing scale accumulation from quartz sleeves (Kreft et al, 1986). Experience, however, shows that chemical cleaning is always required to completely remove the scale. Chemical cleaning using acid washes may be accomplished using either recirculation systems, manual cleaning, or automatic wipers incorporating chemical solutions.

The UV reactor housing should be made of materials that neither transmit UV nor corrode. Both the DHEW guideline and the NSF standard call for UV reactors that incorporate materials that do not impart taste, odor, color, or toxic materials to the water. NSF Standard 55 also specifies hydrostatic pressure performance to ensure reactors do not leak nor burst. UV reactor design should also ensure easy access for lamp replacement, quartz sleeve cleaning, and other maintenance.

Monitoring systems may include ports for safe visual verification of lamp operation, electronic UV intensity meters mounted to measure UV intensity at the reactor wall, transducers to monitor water and ballast temperatures, sensors to detect lamp failure, and flow sensors. Through command and control electronics, monitoring

systems should trigger audible and/or visual alarms to warn of low UV intensity, excessive flow, or over heating. Monitoring equipment can be used to shut off or divert flow under low dose conditions, or regulate flow through the UV system using flow control valves.

The ideal UV reactor is a turbulent plug flow reactor with complete transverse mixing. With plug flow, there is neither dispersion in the direction of flow nor short circuiting. Accordingly, all fluid elements leave the reactor with a residence time equal to the theoretical residence time. With complete transverse mixing, all fluid elements are exposed to the same average intensity within a cross section perpendicular to flow. Without such mixing, fluid elements close to the lamp would experience a high UV intensity and an overdose of UV while fluid elements far from the lamp would experience a low UV intensity and be underdosed.

While the concept of an ideal UV reactor incorporates two contradictory principles – no longitudinal mixing yet complete transverse mixing – UV reactors can and should be designed to approximate these conditions. Inlet conditions to the reactor can be designed using baffles to ensure short circuiting and dead zones are minimized. High flow rates through the reactor can be maintained to promote turbulence and transverse mixing. Reactor aspect ratios, the ratio of reactor length to hydraulic radius, can be kept high to minimize longitudinal dispersion.

When a UV reactor has been designed hydraulically to approximate an ideal UV reactor, the UV dose delivered by the reactor can be calculated using:

$$Dose = I_{average}^{reactor} \times t_{residence} = I_{average}^{reactor} \times Vol / Q$$

Where $t_{residence}$ is the residence time of the reactor with an effective volume, Vol, passing a water flow, Q. The effective volume within a UV reactor is the volume of water exposed to UV light and the average intensity within the reactor is calculated for the effective volume. Note that UV dose calculated using average intensity is often greater than dose calculated using the measured intensity at the reactor wall.

The UV intensity within a UV reactor depends on the UV output of the lamp, reflectance, refraction, and absorption of UV light as it passes through the quartz sleeve, and absorption of UV light by organic and inorganic chemicals as it passes through the water. Transmission of UV light through quartz and water can be calculated using Lambert's Law. The UV intensity at a point within the water is the sum of the contribution of light from each point along the arc of each UV lamp immersed within the water. While determining the UV intensity within a UV reactor is complex, models for UV light intensity profiles around a mercury arc lamp have been developed (Jacob and Dranoff, 1970) and are the basis for the Point Source

Summation (PSS) software developed for the US EPA to calculate average UV intensities within UV disinfection reactors (USEPA, 1996).

6. Factors Impacting UV Dose Delivery

Operational factors that impact dose delivery by a UV reactor to the microbes include the supply of electricity, lamp aging, quartz sleeve fouling, reactor hydraulics, absorbance of UV by the water, water temperature, and the location of the microbes within particulate.

UV disinfection systems require a reliable source of electricity to operate sensors, valves, command and control electronics, and lamps. In the event of a power failure, UV systems should be designed to shut off water flow through the unit.

UV lamp output will decline over time due to lamp aging. Lamp aging may be attributed to three mechanisms – electrode failure, solarization of the lamp envelope, and mercury impregnation into the inside of the lamp envelope (Phillips, 1983). Electrode failure is directly related to the number of on/off cycles experienced by the lamp and is thus a controllable failure mechanism. UV lamps used in water disinfection can be expected to remain on 24 hours per day thereby reducing the potential for electrode failure. Solarization and mercury impregnation lead to a gradual loss in lamp envelope UV transmittance over time. It is expected that with normal operation, low pressure mercury arc lamps will have useful lives between 7000 and 14,000 hours.

Quartz sleeve fouling due to the accumulation of inorganic scale and organic biofilms will reduce the UV dose delivered to the water. Biofilms will form on the lamps when they are not in operation at a rate dependent on the presence of organic and inorganic nutrients in the water. Inorganic scale accumulation on the quartz sleeves will occur when the lamps are in operation. The rate of scale accumulation depends on the temperature at the quartz sleeve surface and the water concentrations of cationic iron, magnesium, calcium, aluminum, manganese and sodium and anionic carbonate, phosphate, and sulphate (Blatchley et al, 1993). With low pressure lamp systems and a typical drinking water quality, sleeve cleaning frequencies can be expected to vary from once a month to twice a year.

Reactor hydraulics will be a function of reactor design and the flow rate passing through the reactor. For a non-ideal reactor design, the impact of short circuiting, dead spaces, excessive longitudinal dispersion, and a lack of transverse mixing on UV dose delivery will vary with the flow rate through the reactor.

An increase in the UV absorbance of the water will lower the dose delivered by a UV reactor. UV absorbance in drinking water can be attributed to the presence of iron, humic acids, and tannins within the water and can be expected to vary

seasonally and temporally. UV absorbance may be measured using a spectrophotometer. With UV disinfection systems using low pressure mercury arc lamps, the UV absorbance at 254nm is of interest. With medium pressure systems, the UV absorbance at all of the germicidal wavelengths has an impact on UV dose delivery. With treated drinking waters, UV absorbing compounds in the water often result in a UV transmittance at 254nm of 70 to 98 % over a 1 cm pathlength.

While water temperature does not have an impact on the rate of microbial inactivation by UV, water temperature can have a direct impact on the UV power output from a low pressure mercury arc lamp. The impact will depend on heat transfer from the lamp to the surrounding water and thus depends on how well the design of the quartz sleeve maintains the lamp near its optimal operating temperature. Since medium pressure mercury arc lamps operate at temperatures well above the temperature of the water, the UV output from a medium pressure lamp is unaffected by changes in water temperature.

The dose delivery to the microbes in the water will vary depending on whether the microbes are present as individual cells or whether they are occluded within particulates. Individual microbes will be more amenable to disinfection than particulate associated microbes. The inactivation of microbes within particles will depend on the particle size, structure, and composition. The presence of UV absorbing materials (iron and humic acids) within the particulates will shield occluded microbes from UV. Larger particles will be more difficult to disinfect than smaller particles. Particle counters can be used to quantify the presence of particulates in drinking water. TSS and turbidity measurements can also be used to assess the presence of particulate. Like UV absorbance, the concentration of particulates in the water can be expected to vary seasonally and temporally.

7. Practice of UV Disinfection

7.1 Strategies for Drinking Water Disinfection

While reduced rates of bacterial growth have been reported in drinking water following UV disinfection (Lund and Omerod, 1995), UV does not produce a disinfectant residual that can offer protection of a municipal distribution line against microbial growth and biofilm formation. While this fact has been used to support the use of chlorine over UV, there is scientific evidence that if the water contains sufficient nutrients to support microbial growth, the presence of 1ppm free chlorine residual in a municipal distribution line is no guarantee that biofilms will not be formed on pipe surfaces and fecal coliforms will not be found at the tap (Rice et al, 1991; Herson et al, 1991). In fact, chlorine may react too quickly with the surface molecules of the biofilm and not penetrate into the biofilm to inactivate deeper microbes. Chloramine, on the other hand, is less reactive and provides better control of biofilms and heterotrophs within a distribution line (Neden et al, 1992).

Since chloramine is not a good primary disinfectant, an appropriate strategy may be to use UV as a primary disinfectant and chloramine as a residual to control microbial growth in the distribution lines.

While chloramine produces fewer trihalomethanes than does free chlorine, chloramine like chlorine does promote the formation of higher molecular weight chloro-organics. An alternate strategy towards controlling microbial growth within a distribution line may be to treat the water to remove the nutrients that would later promote microbial growth. Biologically active filters may be used upstream of a UV disinfection unit to reduce the concentration of assimilable organic carbon (AOC), lower weight organic compounds that microbes readily uptake as food and use to promote growth. This strategy has been successfully applied in Europe where UV disinfected water with low AOC levels is pumped into a well maintained distribution system and heterotrophic plate counts are maintained below 500 colonies/mL.

With well water, the ground acts as a massive biofilter reducing the concentration of AOC and filtering out protozoan cysts, bacteria, and viruses. In the case of ground water not under the influence of surface water, UV disinfection can be used directly on the water with minimal pretreatment. A possible concern is the presence of inorganic ions that could contribute to the formation of scale on the lamp sleeves. In the case of surface waters, the presence of protozoan cysts, TSS, and higher AOC has to be addressed. While high doses of chlorine can be used to inactivate Giardia cysts, chlorine is not effective against Cryptosporidium. Unless current research into the ability of medium pressure lamps to inactivate cysts and oocysts proves differently, filtration offers the most practical solution for the removal of protozoan cysts. Accordingly, an appropriate disinfection strategy for surface waters would be to filter the water to remove TSS and protozoan cysts, apply UV to inactivate pathogenic bacteria and virus, and use either chloramines or AOC control to protect the distribution system from microbial growth.

UV disinfection systems may be used either at a municipal water treatment plant or closer to the tap. Point-of-Entry or Point-of-Use UV units can be installed at a home, business, or institution to provide disinfected drinking water. Locating a UV unit closer to the tap results in a shorter distribution system. Household pipes can be flushed using chemical disinfectant to ensure UV disinfected water is delivered to the tap without either chemical residuals or heterotrophic bacteria.

7.2 Performance Validation

Many manufacturers of UV disinfection equipment make claims on equipment performance – dose delivery, lamp life, and cleaning mechanisms performance. Performance validation ensures UV disinfection equipment performs as stated.

A simple approach towards validating the dose delivery of a UV reactor is the use of bioassays where the annihilation of a challenge microbe achieved by a UV

reactor is compared to the disinfection achieved using a collimated beam apparatus (Qualls and Johnson, 1983). NSF Standard 55 describes a bioassay protocol using either *Saccharomyces cerevisiae* or *Bacillus subtilis* as a challenge microbe. Wilson et al (1993) suggested the use of MS-2 bacteria virus as a challenge microbe for testing UV disinfection systems. Each of these organisms serve well as a challenge microbe due to their relatively high UV dose requirement for inactivation, ease of preparation, low cost of enumeration, and non-pathogenic nature. Bioassays should be performed at the design water flow rates (low and high) and under the poorest water quality conditions expected for the drinking water application under consideration.

Residence time within a UV reactor may be validated using tracer studies. In a tracer study, a conservative tracer chemical like salt is injected into the water flow upstream of the UV reactor. The presence of the tracer chemical is monitored downstream of the UV reactor. Analysis of the change in tracer concentration as a function of time can be used to estimate the actual residence time distribution and provide information on hydraulic conditions within the reactor. While residence time distributions can be used to provide insight into the axial dispersion along a reactor, it does not provide insight into transverse mixing and accordingly cannot provide the same insight into reactor performance as does the bioassay.

Cleaning mechanisms may be validated using on-site pilot testing or by relying on the manufacturer's track record applying the UV disinfection equipment under similar circumstances.

7.3 Operation and Maintenance

UV disinfection units should be located to facilitate easy access for maintenance. Operators need to be able to calibrate monitoring sensors, check failsafe devices, clean lamp sleeves, inspect and clean reactor inner surfaces, examine seals, replace aged lamps, and monitor water quality. Flushing of the UV disinfection unit and the distribution system using a chemical disinfectant should be performed prior to UV system startup and on an as needed basis thereafter. Typically, 3 to 5 hours of maintenance per week can be expected with a UV system providing drinking water to 3,300 people at a peak flow rate of 250 GPM. Adequate spare parts, including at least one lamp, sleeve, and ballast, should be available to facilitate maintenance. Spent mercury lamps should be properly disposed of.

UV system startup and adequate operator training can be usually completed within one day. Operators should have access to equipment manuals that include operating and maintenance instructions, system drawings, and information on how to order and obtain replacement parts. Manufacturers should provide information on the peak design flow for the system, water quality limitations (turbidity, TSS and UV absorbance), expected lamp life, and the UV dose at the end of lamp life.

During maintenance, flow through the UV unit is shut off and the system is drained of water. In order to provide continual disinfection, redundant UV units, either in series or in parallel, may be used. Power generators may be considered to guarantee UV disinfection during power outages. Shutoff valves installed upstream and downstream of the UV unit should be normally in the closed position when power to the unit is off. Contingency plans should be drawn up in the event of power failures. Remote telemetry monitoring of system operation and alarm conditions may be considered with multiple UV units at various locations.

7.4 Disinfection Byproducts

The ability of UV light to promote photochemical reactions underlies two UV-based environmental technologies – UV disinfection and advanced oxidation. Advanced oxidation uses the energy of UV light, alone or in combination with added oxidants, to promote the destruction of hazardous organic chemicals. Advanced oxidation, however, uses a greater UV dose than UV disinfection to obtain practical oxidation rates with a wide variety of organic compounds.

Several studies have identified and characterized UV disinfection byproducts arising from photochemical reactions other than DNA dimerization. Awad et al (1993) observed the formation of formaldehyde, glyoxal, and acetaldehyde, and the reduction of 8 to 12 carbon hydrocarbons when irradiating reclaimed wastewater with UV from low pressure mercury arc lamps. Formaldehyde increased from a background level of 3.54 $\mu\text{g/L}$ to 5.9 and 9.62 $\mu\text{g/L}$ after an applied dose of 45 and 147 mWs/cm^2 . These formaldehyde levels were well below the US EPA health advisory of 1 mg/L for a lifetime exposure for a 70kg adult. Accordingly, it has been concluded that the health risk posed by the observed formaldehyde levels was insignificant (US EPA, 1996). Oppenheimer et al (1996) compared byproduct formation in reclaimed water disinfected using a UV dose of 300 mWs/cm^2 and disinfected using chlorine. While significant increases in trihalomethanes were observed with chlorine disinfection, no UV disinfection byproducts were formed. Using a UV dose of 120 mWs/cm^2 to disinfect Rhine River water, Zoeteman et al (1982) reported the formation of a few disinfection byproducts and some compound destruction. An increase in water mutagenicity was not observed. Further work by Kool et al (1985) and Kruithof and van der Leer (1990) confirms that UV disinfection does not result in the formation of mutagenic or carcinogenic byproducts and does not cause the oxidative breakdown of sugar-based microbial polymers. Unlike chlorine and ozone (Rice et al, 1991; Akhlaq et al, 1990), UV does not result in the formation of AOC that can promote microbial growth in distribution lines.

UV radiation below 240nm can promote the conversion of nitrate to nitrite. Grocock (1984) reported a 1% conversion of nitrate-to-nitrite during drinking water disinfection using UV. Nitrite formation is not a concern with UV disinfection systems using monochromatic low pressure mercury arc lamps (Sonntag and

Schuchmann, 1992). Nitrate-to-nitrite conversion with polychromatic medium pressure mercury arc lamps can be prevented by using lamp sleeves that absorb UV wavelengths below 240nm.

In summary, disinfection byproduct formation during the UV disinfection of drinking water is negligible and no measurable increase in drinking water toxicity has ever been attributed to UV disinfection byproducts.

8. Costs of UV Disinfection

Due to the lack of UV disinfection byproducts and the ability of UV to meet environmental water regulations, the UV disinfection industry is taking away market share from the chlorination equipment industry. Approximately 56% of chlorine alternative installations are forecasted to be UV technologies, in which 20% market is for municipal potable water supply. Overall, the US market for UV disinfection equipment and systems will grow from \$20 million annually to \$100 million from 1995 to 2000 (Miller et al, 1995). UV disinfection equipment held an estimated 2.4% share of the total US water treatment equipment market in 1994 and the market growth rate is predicted to be between 12.8% and 14% (Frost and Sullivan, 1995). In western Europe, the clean water market is expected to grow between 20 to 25% per year. The water treatment market in the rest of the world is also huge. The World Bank estimates that water and sanitation needs in Asia will be over \$150 billion over the next decade (USEPA, 1997).

The range of UV disinfection equipment prices vary widely, from less than US\$1,000 to over US\$400,000 depending on flow rate. Approximately two-thirds of UV equipment is purchased via a contractor; 19% direct from a manufacturer; and 14% through a distributor or other third party. Since the equipment cost is a major part of the capital cost, the capital cost is chosen as the equipment cost plus 20 percent. The average capital costs are from US\$2.07/m³ to US\$1.08/m³ for a UV dose of 40 mWs/cm² treating a flow rate from 91 to 6814 m³/day (USEPA, 1996).

Major operation and maintenance costs include part replacement cost, power cost and labor cost. For a flow rate from 91 to 6814 m³/day and a UV dose of 40 mWs/cm², costs are estimated between US\$0.53/m³ and US\$0.19/m³ for part replacement, between US\$0.45/m³ to US\$0.17/m³ for power, and between US\$0.11/kgal to US\$0.026/kgal for labor. Overall, the operation and maintenance costs averaged from three UV disinfection manufacturers are from US\$1.09/m³ to US\$0.39/m³ for dosage of 40 mWs/cm² (USEPA, 1996). Note that labor and power costs will vary from location to location.

Costs for using UV disinfection for primary disinfection have been compared to the costs of using either chlorine or ozone. Because a residual disinfectant is required

in the distribution systems in North America, costs were based on supplementing ultraviolet disinfection with chlorination as a secondary disinfectant. A residual concentration of 1 mg/L was assumed based on regulations. Ozonation costs are based on a dose of 1 mg/L and assumed that the contact time of 10 minutes. Chlorination costs are based on a 5 mg/L dose with an assumption of residual concentration above 0.5 mg/L and a labor requirement of seven to ten hours per week. At a UV dose of 40 mWs/cm², over a flow range of 64 LPM to 6813 m³/day the total costs for UV plus chlorine residual were from US\$44.9/m³ to US\$2.6/m³ and were never higher than that for ozone or chlorine alone (USEPA, 1996). The EPA concluded that the costs of using UV at a dose of 40 mWs/cm² are far lower than using ozone or chlorine for flow rates ranging from 64 LPM to 6813 m³/day. When a disinfectant residual is not required, the total costs will be lower. The United States EPA (1996) concluded that ultraviolet disinfection is an economically viable and feasible technology, particularly for small water system. Based on the energy and capital costs in different countries or regions in the world, the average annualized cost estimated for comparable systems may vary as much as 50%.

9. Summary and Conclusions

UV disinfection of drinking water offers many unique and significant advantages. Unlike chemical disinfectants, UV does not add any toxic chemicals to the drinking water nor promote the formation of carcinogenic and mutagenic byproducts. UV does not promote the oxidative breakdown of microbial polymers resulting in the formation of AOC that can promote biofilm growth in distributions systems. UV does not leave unpleasant tastes and odors in the treated drinking water. While an increase in the dose of chemical disinfectants results in additional disinfection byproducts and aesthetic impacts, no negative water quality impacts can be associated with an overdose of UV.

Use of UV removes the need to transport, store, and handle dangerous chemicals. Costs associated with such practices can add 30% to the cost of disinfection when such activities are regulated by rules like the Uniform Fire Code of the United States. The Uniform Fire Code calls for accident insurance, ventilation and storage requirements, and treatment facilities capable of dealing with an accidental release of chlorine gas or caustic liquid spill.

UV disinfection is effective for a wide variety of virus and bacteria over a narrower dose range than chlorine and ozone. Unlike chemical disinfectants, microbial inactivation rates by UV are neither pH nor temperature dependent. While protozoan cysts are resistive to UV disinfection using low pressure mercury arc lamps, cryptosporidium oocysts cannot be inactivated by a normal dose of chlorine or ozone. Accordingly, unless current research into protozoan inactivation by medium pressure mercury arc lamps proves otherwise, filtration will continue to be the most practical solution for cyst removal.

Since UV disinfection systems only require short residence times, UV systems occupy a smaller footprint than chemical disinfection systems. UV disinfection systems are modular, thereby facilitating easy expansion and upgrades. UV systems can be easily designed for small and large flows making them suitable for use at homes as well as at large municipal water treatment plants. UV systems are simple to operate and maintain with minimal exposure hazard to workers. Monitoring sensors, command and control electronics, and alarm systems are incorporated into UV disinfection systems thereby guaranteeing reliable dose delivery to the water and ensuring pathogen removal.

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