Pergamon

Wat. Sci. Tech. Vol. 40, No. 4–5, pp. 203–213, 1999

0273–1223/99 $20.00 + 0.00

PII: S0273-1223(99)00502-8

ADVANCED WASTEWATER DISINFECTION TECHNOLOGIES: STATE OF THE ART AND PERSPECTIVES

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ABSTRACT

Chlorination/dechlorination and advanced disinfection processes (UV irradiation, ozonation, membrane filtration) have been reviewed in terms of their efficiency, regrowth potential, design parameters, experimental set-up, scale-up and industrial experiences. Existing results show the great influence of water quality, in particular of suspended matter concentration and organic content.

The efficiency and reliability of these processes are evaluated for different reuse applications. The critical analysis of the literature data and experimental results highlights UV irradiation as an effective and competitive advanced disinfection process. Ozonation is a viable solution in case of higher requirements for water quality including virus and protozoa removal. Ultrafiltration is a highly efficient process producing an excellent quality and totally disinfected effluent, particularly recommended for groundwater recharge and potable wastewater reuse. The choice between these advanced disinfection technologies depends on wastewater quality, existing standards, specific reuse applications and wastewater treatment work capacity.

KEYWORDS

Wastewater disinfection; chlorination/dechlorination; UV irradiation; ozone; membrane filtration; process evaluation.

INTRODUCTION

The increasing concern for pathogenic related water diseases promotes the implementation of more and more stringent standards on microbiological pollution of wastewater effluents. Although conventional treatment processes such as sedimentation, activated sludge or trickling filters are known to remove up to 90-99% of some microorganisms, their efficiency is not sufficient to meet existing requirements for wastewater discharge, bathing area protection and wastewater reuse (Yanko, 1993). Therefore, specific disinfection steps have to be included in the treatment chains.

Wastewater disinfection levels are determined by standards and recommendations that are specific to each country and region (Lazarova *et al.*, 1997). In general, these standards are becoming more and more stringent in order to ensure better public health and environmental protection. It is important to underline that the choice of a given disinfection process is not only a function of the water quality objectives. Other factors have to be considered, such as costs, equipment retrofitting or residual effluent toxicity. The purpose of this paper is to review feasible intensive disinfection technologies in terms of technical, economical and environmental criteria.

CHLORINATION/DECHLORINATION

As the most universally practised wastewater disinfection method since the late 1940s, chlorination plays a major role in preventing waterborne infectious diseases throughout the world. Several chlorine derivatives can be applied such as gaseous chlorine, hypochlorite or chloramine compounds. During the last years, numerous WWTPs in the USA have replaced gaseous chlorine by hypochlorite in order to improve operator safety and decrease operation and maintenance (O&M) costs.

Wastewater chlorine requirements vary considerably depending on effluent quality. Organic compounds, industrial wastes, as well as ammonia concentration, can strongly affect chlorine demand. The effectiveness of chlorination can be enhanced by improving mixing characteristics of chlorine contactors and process control strategy. Typical chlorine doses for municipal wastewater disinfection are about 5-20 mg/l and 30-60 minutes contact time, and usually allow for compliance with permits on conventional bacterial indicators (coliforms, *E. coli*). Higher doses are required for low quality wastewater such as primary or trickling filter effluents.

Many authors have reported about the inactivation of microorganisms by chlorination. It emerges that bacteria are usually well removed, although the presence of suspended solids may affect the process. On the contrary, very high free chlorine concentrations may be needed to inactivate cysts and some viruses of concern. King *et al.* (1988) observed that both *ciliates* and *amoebia* could withstand free chlorine residuals of 4 and 10 mg/l (pH 7.0, 25°C), respectively, and were still motile in chlorine solutions with lower residual concentrations after 30 to 60 minutes of exposure. Venczel *et al.* (1997) found that free chlorine produced no measurable inactivation of *Cryptosporidium parvum* oocysts in 4 or 24 hours.

Several studies also suggest that the efficiency of chlorination is strongly affected by nitrification (organic, ammonia, nitrite and nitrate concentrations), and in particular in presence of nitrite or lack of ammonia. Calmer *et al.* (1998) provide an analysis of existing literature data and guidance for better operation of chlorination/dechlorination with nitrification related problems.

The main disadvantage of chlorine is the generation of toxic by-products (DBP). This phenomenon has been discovered and discussed since the 1970s, when naturally occurring organic matters in some water sources were found to react with chlorine and form carcinogen trihalomethanes and other compounds (haloacetic acids and dissolved organic halogens). DBPs have been identified as potential human carcinogens and harmful for the environment even at low concentrations, less than 0.1 mg/L (Abarnou and Miossec, 1992, Szal *et al.*, 1991). It is important to stress that the presence of small concentrations of residual ammonia and low DOC reduces by-product concentration. Rebhun *et al.* (1997) have shown that the potential of dissolved organic halogens formation is up to 4 times lower in completely nitrified effluents compared to ammonia-containing effluents.

Another important concern is the impact of chlorinated effluents on receiving water ecosystems. It is confirmed that the major source of acute toxicity in chlorinated effluents is residual chlorine. For this reason, dechlorination with S(IV) compounds is often requested on such effluents. Historically, most municipal wastewater treatment plants used sulphur dioxide gas to dechlorinate their effluents. In addition to being a toxin, sulphur dioxide has been recently recognised as a carcinogen, and many plants are now using other sulphur-based reactants. Sodium bisulfite solutions are now commonly applied, and have proved to provide reliable dechlorination. However, after considerable research and full-scale demonstrations, some issues persist. Although most toxicological studies have shown that dechlorination reduces the toxicity of chlorinated effluents, some residual chlorine exceeding EPA regulatory limits may remain in dechlorinated effluents (Helz and Nweke, 1995). Moreover, dechlorination increases the salinity and consumes dissolved oxygen, requiring sometimes additional reaeration.

The main disadvantages of chlorine disinfection can be summarised as follows: (1) production of toxic by-products; (2) poor inactivation of spores, cysts and some viruses at the low dosages used for coliform removal; (3) stringent safety regulations leading to high investments for scrubbing systems and other safety equipment; (4) need for dechlorination increasing thus disinfection costs by 20-30%.

Chlorine dioxide exhibits some serious advantages as an alternative to chlorine. It has been tested and applied for wastewater disinfection before reuse in China, France, Israel and in the USA (Narkis *et al.*, 1988). Many studies labelled chlorine dioxide as "a more effective disinfectant than chlorine", both for bacteria and viruses in a broad range of pH (Huang *et al*, 1997, Junli *et al.*, 1997, Warriner *et al.*, 1985). Spores and cysts may also be well inactivated. The required pathogen removal (up to 4-5 log fecal test germs) has been achieved with ClO_2 doses of 2-5 mg/L and contact times of 5-15 min. These design parameters allow us to remove enterobacteria by 2.4 to 4 log and *Clostridium perfringens* spores by 1.5 to 2 log (Dernat *et al.*, 1997). Huang *et al.* (1997) and Junli *et al.* (1997) report a higher disinfection efficiency of ClO_2 in the inactivation of highly resistant viruses such as *Adenovirus, Coxsackie, Poliovirus, Herpes simplex*, etc. Another important advantage is that the germicidal efficiency of chlorine dioxide is not affected by the presence of ammonia.

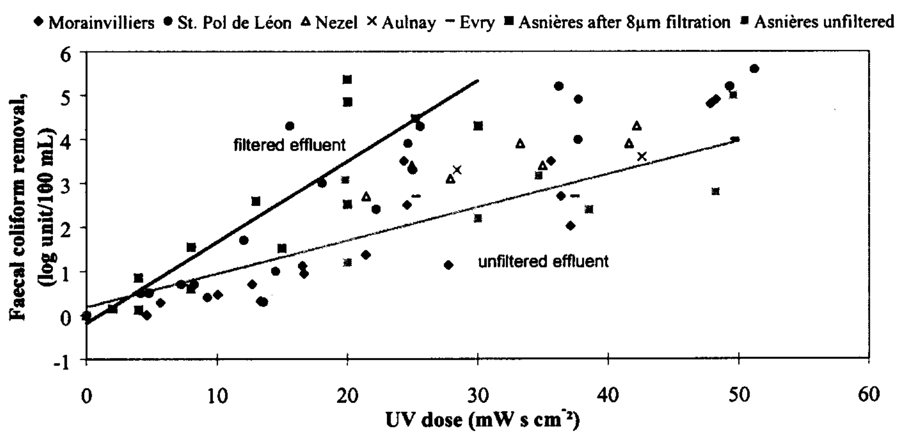

Figure 1. Influence of UV dose and filtration on fecal coliform inactivation for different effluents in French WWTP (collimated beam experiments).

UV IRRADIATION

Ultraviolet irradiation becomes the most commonly used alternative to chlorination with a comparable and often more effective disinfection efficiency for viruses and bacteria (EPA, 1992). Presently, thousands of installations world-wide practice UV disinfection using open channel equipped with low or medium pressure mercury arc lamps. The success of the UV technology is largely attributable to low costs, as well as the absence of toxic by-products (Linden *et al.*, 1998). Numerous pilot and full-scale studies have demonstrated that UV disinfection can consistently achieve the objective of 200 FC/100 mL (Braunstein *et al.*, 1996, Lazarova *et al.*, 1997, Whitby *et al.*, 1984, Whitby and Palmateer, 1993). Moreover, some industrial UV systems have now received the agreement of the state of California to achieve the Title 22 requirements of 2.2 TC/100 mL.

Disinfection data obtained on various types of secondary and tertiary treated wastewater showed that 30-45 mW s/cm^2 doses of UV radiation were sufficient to ensure 3 to 5 log removal of total and fecal coliforms and fecal streptococci. The required doses could be higher (up to 112-140 mW s/cm^2) in the case of more stringent standards, for example 2.2TC/100mL based on the 7-day median sample (Braunstein *et al.*, 1996). The required UV doses for a given pathogen log removal are significantly influenced by wastewater quality. In a number of studies (EPA, 1992, Whitby and Palmateer, 1993, Mandra *et al.*, 1996, Wright *et al.*, 1998), pathogen inactivation has been found to decrease significantly as the total suspended solids concentration of the effluent increases. The effect of filtration before disinfection was drastic (Fig. 1): the UV dose required for a given-log inactivation could be more than halved. Primary effluents, including chemically enhanced primary processes require significantly higher UV doses.

Darby *et al.* (1995) reported that *E.Coli* bacteriophage, *Poliovirus* type 1 and *Coxsackie* A2 viruses, as well as *Staphylococcus* bacterial strains, are more sensitive to UV irradiation than to chlorination. At the Langford UV plant, UK, a low UV dose (32 mWs/ cm^2) enabled the total removal of 2 log enterovirus and 4-5 log F-specific bacteriophages (Walker, 1997). However, it is important to stress that UV radiation virucidal efficiency varies with the virus type. High doses from 75 mWs/ cm^2 (Oppenheimer *et al.*, 1993) to 100-200 mWs/cm^2 (Braunstein *et al.*, 1996, Havelaar *et al.*, 1990, Nieuwstad *et al.*, 1991, Lazarova *et al.*, 1997) are required to inactivate 2 to 5 logs of the highly resistant bacteriophage MS2.

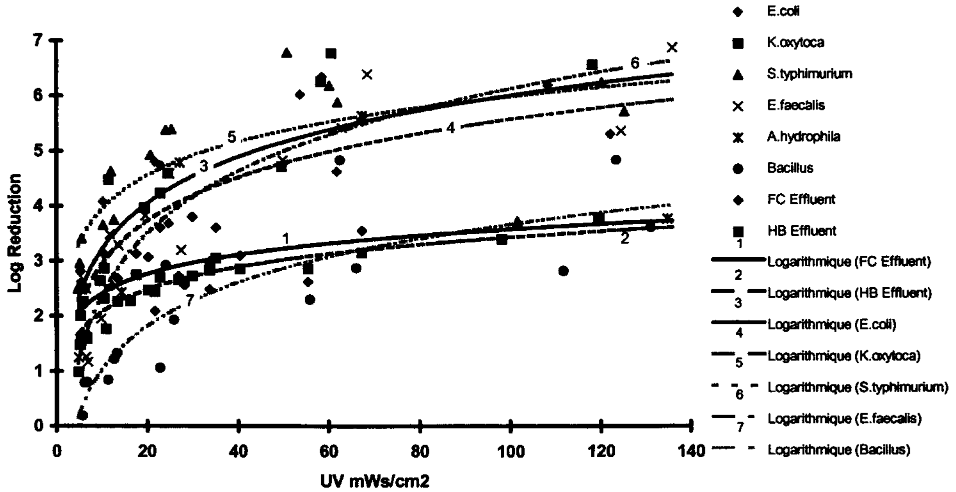

Figure 2. Reduction of indigenous bacteria (lines 1-2) and pure bacterial cultures (lines 3-7) after UV disinfection (collimated beam experiments).

The choice of the microbial culture also influences the UV dose (Fig. 2). Pure cultures of Enterobacteria and *Enterococci* (lines 3-6) are more sensitive than *Bacillus* strain (line 7): 3 log removal is ensured by 3 times smaller dose of 20 mWs/cm^2. The indigenous faecal coliforms and heterotrophic bacteria (lines 1 and 2) are more resistant than pure bacterial cultures.

Photoreactivation and dark repair have been reported as disadvantages of UV disinfection (Lindenauer and Darby 1994; Chan and Killick, 1995; Kashimada *et al*, 1996). Baron (1997) reported that regrowth depends on UV dose and reaches a maximum 1 log increase after irradiation up to 40 mWs/cm^2. No relationship was observed between repair and suspended solids or UV transmittance in the range of 10-60 mg/l and 10-80% respectively (Whitby and Palmateer, 1993). It is important to underline that no significant repair is observed for microorganisms with health risk such as *Fecal streptococci, Salmonella* and *Somatic coliphages.* A consensus does not exist within engineers and regulatory agencies regarding the inclusion of repair in UV system design.

The lack of standardization in determining UV dosage in UV systems makes accurate design very difficult and affects the result comparison from different studies. Collimated beam experiments are one of the proposed methodologies for sizing UV disinfection for a given wastewater effluent (Tchobanoglous *et al.*, 1996). In this bench-scale test, a shallow water sample is exposed to UV radiation in tightly-controlled conditions of UV exposure. As a result, the UV dose applied to the microorganisms may be considered as uniform. From these results, industrial design doses can be adjusted taking into account lamp age and fouling, as well as reactor hydrodynamic characteristics.

However, real full-scale inactivation behaviour cannot be directly deduced from collimated beam tests. Indeed, industrial reactors do not provide single "average" doses because of spatial variations of the intensity and velocity fields. For that reason, the sizing of full-scale UV plants is usually achieved based on experience or empirical correlations (Wright *et al.*, 1998). This often results in over- or undersizing.

Recent advances in process modelling have allowed for accurate predictions of process behavior on the basis of the UV dose distribution concept (Blatchley *et al.*, 1997, Chiu *et al.*, 1997, 1998; Do-Quang *et al.*, 1997). The high potential of this new method to predict UV disinfection performances has been demonstrated in a vertical lamp pilot-scale system. Collimated beam tests were also performed on the pilot plant influent (Fig. 3). In parallel with these experiments, the UV intensity field within the irradiated zone of the pilot system was modelled. The velocity field inside an identical reactor was measured with the Laser Doppler Velocimetry technique (LDV). These fields were then combined together with a random walk computer model which simulated the injection of 10 000 particles. The result was a calculated dose-distribution curve that spanned a broad range of doses (Fig. 4). This graph represents the number of bacteria that have encountered a given dose [$\Sigma I(t)\Delta t$] during their detention in the UV contactor. Of particular significance was the portion of this distribution which represented particles found to encounter doses lower than 7.5 mWs/cm^2 (from 51 to 260 particles). While only a relatively small fraction of the particles were found to experience these low doses, they accounted for a large fraction of the total number (or concentration) of "particles" which retained viability following irradiation. The particle trajectories which accounted for the low end of the dose distribution were found to be in the vicinity of the reactor walls, where the intensity was minimal and the velocity was relatively high. The combination of dose-response curves (Fig. 3) and of the calculated dose-distribution curve (Fig. 4) made it possible to predict coliform inactivation inside the pilot-scale UV unit. Predicted and measured inactivation responses are given in Table 1.

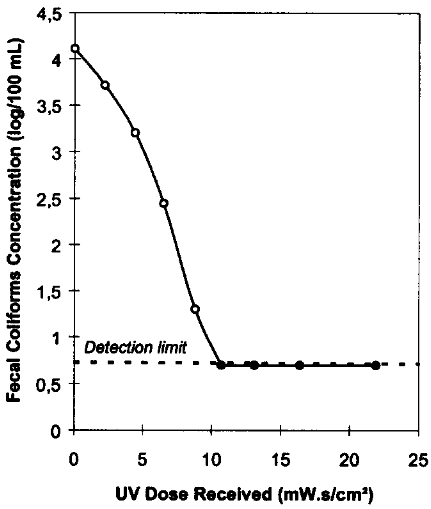

Figure 3. Example of dose-response curve (collimated beam test)

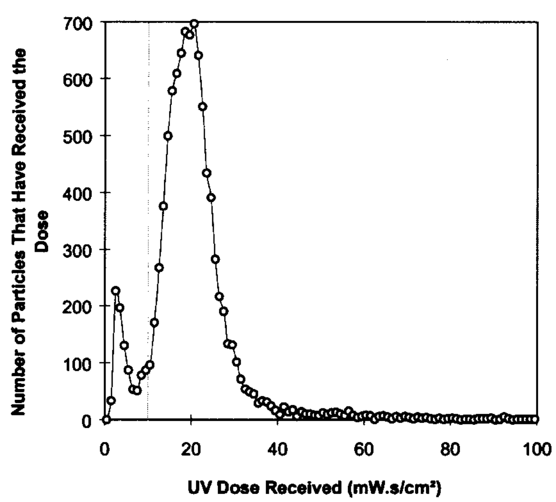

Figure 4. Calculated dose-distribution curve for the UV reactor.

The combination of the LDV measurements, the intensity field simulation and the collimated beam dose-response curve yielded a prediction of inactivation that was in close agreement with the pilot tests (Table 1). In all cases, the error was within the uncertainty of the faecal coliform analyses. This method may be applied for rational sizing of UV facilities. It does require ample efforts to experimentally establish the dose-distribution curve, but this work only has to be done once. Then, easy-to-perform collimated beam tests may be used to predict full-scale inactivation, taking into account the variations in wastewater quality.

Table 1. Comparison of measured and predicted faecal coliform (FC) inactivation responses for a UV pilot system

Test N°	Influent FC, *CFU/100 mL*	Effluent FC, *measured*	*CFU/100 mL* (log removal) *calculated*
1	12380	213 (1.76)	187 (1.82)
2	7000	151 (1.66)	64 (2.04)
3	900	11 (1.89)	13 (1.84)
4	6667	53 (2.10)	73 (1.96)
5	1250	12 (2.01)	18 (1.83)
6	2350	17 (2.14)	25 (1.97)
7	125000	119 (3.02)	171 (2.86)
8	7333	224 (1.52)	150 (1.69)
9	5333	24 (2.35)	30 (2.26)

Existing studies investigating UV disinfection by-product formation in various wastewater show no significant change in the organic composition of irradiated effluents either with low (Oppenheimer *et al.*, 1997) or medium pressure lamps (Linden *et al.*, 1998). Slight increases in aldehyde and formaldehyde concentration have been reported and explained by oxidation of glycerol in the lipid cell membranes (Linden *et al.*, 1998).

Numerous studies reported that overall costs of UV systems are similar, or even lower than costs of chlorination/dechlorination for plant sizes in the range of 20 000-1 000 000 p.e. (Blatchley *et al.*, 1996; Lazarova *et al.*, 1997). The operating costs include mostly lamp replacement and cleaning and are about 50% of total annual costs. For low pressure lamps, energy costs are about 15-20% of the operating costs. Major advantages of UV disinfection are its simplicity, minimal space requirement and absence of toxic by-products. As with chlorine, amoebic and protozoan cysts are the most difficult to inactivate. Neverthless, recent studies have shoun the ability of medium pressure UV lamps to reduce the infectivity of *Cryptosporidium* (Clancy *et al.*, 1998). UV systems can be recommended as a competitive solution for disinfection of secondary and tertiary effluents.

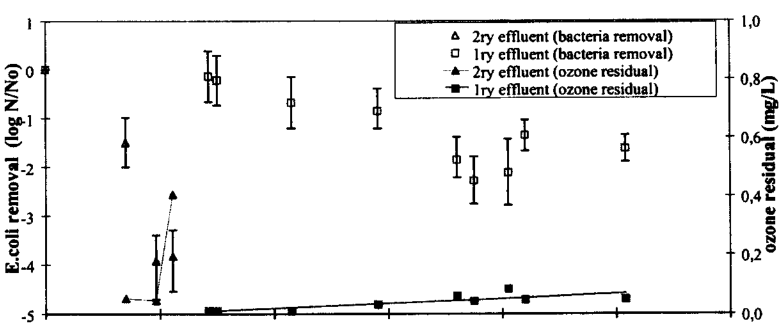

Figure 5. *E.coli* removal on primary PE and secondary SE effluents (PE: COD=446 mg O2/L, SS=107 mg/L; SE: COD=55 mg O2/L, SS=30 mg/L).

OZONATION

Developed in Europe for drinking water treatment for almost one century, ozonation has been used for wastewater disinfection since 1975 in the USA. Ozone is a strong oxidising agent, effective in destroying bacteria, viruses (Roy *et al.*, 1982, Warriner *et al.*, 1985), but also cyst-forming protozoan parasites like *Giardia* and *Cryptosporidium* which are particularly resistant to most other disinfectants (Perrine, 1990). Despite the complexity of the mechanisms involved, it was confirmed that dissolved molecular ozone was primarily responsible for *E. coli* inactivation in drinking water (Hunt and Mariñas, 1997). The high efficiency of ozone towards viruses, as described by Tyrrell *et al.* (1995) who worked on indigeneous populations in secondary sewage effluents, makes it especially attractive when regulations for reuse or discharge involve viruses.

As for other processes, the quality of the wastewater to be treated highly influences the efficiency of ozonation. Competitive reactions of the water matrix contribute to the "ozone demand", which can be evaluated as the transferred dose of ozone required to get a measurable residual in the effluent. Experiments conducted on different effluents led to values of ozone demand ranging from a few mg of ozone/L of water for several secondary and a tertiary effluents, up to more than 10 mg/L for a primary effluent. It was shown that a significant inactivation of *E.coli* (2 logs) could be reached before the ozone demand was met, that is when concentrations of ozone residual in the effluent are almost 0 mg/L (Lazarova *et al.*, 1997). This was also found to be true for the primary effluent (Fig. 5). Slightly higher residuals (0.4 mg/L) could lead to a 4 log reduction in the secondary effluent.

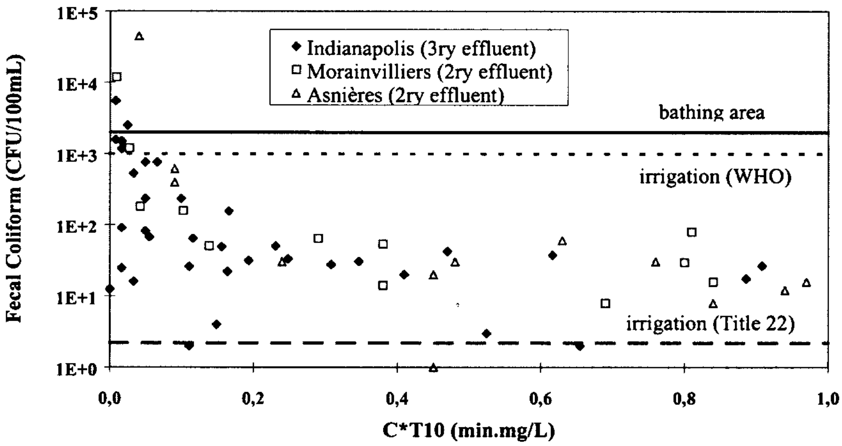

Figure 6. Faecal Coliform concentration after ozonation compared to reuse standards.

The design of ozone disinfection units is usually based on the CT concept, product of the residual ozone concentration by the hydraulic contact time. In order to compare data from effluents with various ozone demands and various hydraulic characteristics, disinfection results obtained on two secondary and a tertiary effluent were studied as a function of $C.T_{10}$ (Fig. 6). The parameter T_{10} depends on T and represents the time after which 10% of the effluent has exited the reactor. It was shown that $C.T_{10}$.values higher than 0.2 min mg/L were enough to meet the requirements for bathing areas in Europe and the USA or the WHO standards for irrigation. Nevertheless, in order to meet higher objectives like the stringent Title 22 regulation (2.2 total coliforms/100mL), much higher ozone doses up to 40-50 mg/L were required (Legan 1982). 3 log *Giardia cyst* removal has been achieved with C.T value of 2.9 min mg/L and residual ozone concentration about 0.3 mg/L (Hunter and Rakness, 1997).

No toxic compounds have been found in an ozonated secondary effluent (Langlais *et al.*, 1992). Several studies on wastewater ozonation reported an enhancement of water quality with up to 20% of COD reduction and decrease of color (Lazarova *et al.*, 1997). Most mutagenicity studies show that ozonation reduces or removes mutagenicity in water.

Literature data on regrowth potential after ozonation are contradictory. Cipparone *et al.* (1997) reported substantial increase in bacteria count after ozonation, while Lazarova *et al.* (1998) showed that ozone treated effluent did not support *E. coli* growth contrary to the significant regrowth of this strain in chlorine and peracetic acid disinfected effluents.

The main advantage of ozonation is the very high disinfection efficiency for all pathogens of concern in wastewater (bacteria, viruses and parasites). Ozonation also enhances water quality and is an acceptable solution for large treatment plants and stringent requirements on virus removal.

MEMBRANE FILTRATION

Microfiltration (MF) and Ultrafiltration (UF) are being intensively studied in France and the USA for wastewater disinfection and removal of colloids and larger molecular weight organics. These technologies are based on a physical barrier concept. Because of the high quality of the treated water, membrane filtration is used in Australia, Japan, and the USA for specific water reuse applications, such as groundwater recharge, grey water recycling and industrial wastewater recycling (Renaud *et al.*, 1997). Moreover, the absence of bacterial regrowth and residual toxicity may give membranes important advantages over other processes for groundwater recharge and potable reuse.

UF pilot tests performed with hydrophilic membranes (cut-off 0.01 μm) on different effluents showed complete removal of coliforms, *Streptococci, Salmonella, Clostridium,* enteric viruses and bacteriophages (Mandra *et al.*, 1993). More recently, the removal of parasites and virus from tertiary effluent was compared on MF (0.2 μm cut-off), UF and RO membranes for the San Diego Water Repurification Project (Adham *et al.*, 1998). With integer UF fibers, total elimination of virus was consistently achieved, whereas MF reached 0.1 to 3.2 log removal with performances highly depending on the membrane fouling status. Fluxes around 50 L/h m^2 are standardly adopted for both UF and MF. However, effluent quality alterations may result in changes of membrane cleaning periodicity (Langlais *et al.*, 1993). It is important to stress, however, that in the case of UF disinfection, performances are less affected by variations in wastewater quality or fouling.

As a new application, the use of low pressure membranes for pretreatment to reverse osmosis is being investigated for the production of high quality water, such as required for indirect potable reuse in California, USA. For such applications, pilot tests conducted at Orange County (California) showed that unlike MF, UF could provide SDIs consistently under 1. UF was able to decrease by 30% the pressure required to operate the downstream RO unit with a given flux (Leslie *et al.*, 1996).

UF disinfection could also be successfully combined with intensive biological treatment in membrane bioreactors (Manem and Sanderson, 1996). This technology is advantageously used for complete wastewater treatment in compact units before recycling or reclamation either for municipal or industrial wastewater.

GUIDELINES FOR DISINFECTION PROCESS SELECTION

The choice of a given disinfection process is generally driven by several criteria, such as cost-effectiveness, safety, environmental impact and public health related issues. Systematic procedures can not be used to ease the choice, because site-specific constraints (permit or safety regulations, existing treatment chain, etc.) prevail in many cases. However, some general trends, advantages and disadvantages can provide helpful guidelines for disinfection process selection. The good definition of appropriate criteria for process selection is especially important nowadays, when new indicators or pathogens other than bacteria are often issued in wastewater discharge and reuse permits (viruses, *E. coli*, etc).

The purpose of this section is to evaluate the efficiency of several disinfection processes based on selected process characteristics and criteria (Table 2). A cost evaluation study was performed for two disinfection objectives and design parameters given in Table 3. The evaluation procedure and assumptions associated with the capital and operating costs were described in more details elsewhere (Lazarova *et al.*, 1997).

Table 2. Comparison of technical-economic characteristics of advanced disinfection technologies

Characteristics/ criteria	Chlorination/ dechlorination	UV	Ozone	MF	UF
Safety	+	+++	++	+++	+++
Bacteria removal	++	++	++	+++	+++
Virus removal	+	+	++	+	+++
Protozoa removal[1]	-	-	++	+++	+++
Bacterial regrowth	+	+	+	-	-
Residual toxicity	+++	-	+	-	-
By-products	+++	-	+	-	-
Operating costs	+	+	++	+++	+++
Investment costs	++	++	+++	+++	+++

"-" none ; "+" low ; "++" middle ; "+++" high

[1]in vitro analysis of *Cryptosporidium*

Table 3. Design parameters[1] (dose/contact time) in the case of secondary effluent disinfection and two water quality objectives

Process	Objective I *<10⁴ TC/100mL; < 2 10³ FC/100mL*	Objective II *<10² FC/100mL; no enterovirus in 10L*
Chlorine	[2]4 (3-8) mg/L; 30 min	10 (8-15) mg/L; 30-60 min
UV	35 (25-40) mW s/cm^2	65 (50-100) mWs/cm^2
Ozone	5 (3-10) mg/L; 10 min	7 (5-10) mg/L; 10 min
MF	50 (40-80) L/h m^2, 20°C, *2 backwashes/h*	*Not possible for total virus removal*
UF	50 (40-60) L/h m^2 at 20°C, *2 backwashes/h*	

[1]Design values depending strongly on wastewater effluent quality

[2]mean value (minimum-maximum value)

The analysis of these results shows that chlorination has proved to be a reliable means of removing bacteria and respecting conventional permits for disinfection of primary, secondary and tertiary effluents. However, toxic by-products may present a risk for public health. In most cases, the presence of chlorine residual represents a threat to the environment (discharge in water streams, groundwater recharge), so dechlorination has to be implemented increasing thus disinfection costs. Also, the effectiveness of chlorine on some viruses is questionable. Protozoa are not affected by the commonly applied chlorine doses and residence times.

The reliability of UV disinfection is also well established for secondary and tertiary effluent disinfection. Its main advantage on chlorination/dechlorination is the absence of toxicity and by-product formation and comparable costs. Moreover, UV systems require no specific safety control and equipment. Theses numerous advantages make UV irradiation particularly suitable for wastewater disinfection and various reuse applications. With slightly higher costs, ozonation may be recommended for large plants when viruses and/or protozoan parasites are targeted. This might be more and more the case because the increasing concern about some epidemic microorganisms such as viruses and *Giardia* and *Cryptosporidium.*

Membrane filtration is a highly efficient process for wastewater disinfection. The excellent water quality of the effluent makes is favourable to high stringent reuse applications. It is especially adapted to groundwater recharge, where low microbial regrowth, as well as low suspended solids concentrations are needed. Its main disadvantage is still relatively high costs, but it is the only technology that guarantees reliability, absence of toxicity and total disinfection required by advanced applications such as potable reuse.

CONCLUSIONS

Despite chlorine efficiency against bacteria and some viruses, the potential toxicity of chlorination by-products makes this process less and less attractive for wastewater disinfection. The critical analysis of the literature data and experimental results reported in this paper highlighted UV irradiation as a highly efficient and cost competitive advanced disinfection process. The higher cost of ozone is outbalanced by the better water quality and virus removal. Therefore, ozone may be recommended as a viable technical solution for large scale plants, especially when viruses and/or protozoa cysts are targeted. Low pressure membrane filtration, in particular ultrafiltration, ensures excellent water quality and total disinfection with a high reliability. These advantages make membrane process the only acceptable technology for advanced reuse applications such as indirect potable reuse, groundwater discharge and some industrial uses. The final choice between different disinfection technologies will depend on the wastewater effluent quality, the existing standards, the specific applications, the capacity of the wastewater treatment works, as well as on the local specific factors.

REFERENCES

Abarnou, A. and Miossec, L. (1992) Chlorinated waters discharged to the marine environment chemistry and environmental impact. An overview. *The Science of Total Environment*, **126**, 173-197.

Adham, S.S ., Gagliardo, P.F., Trussell, R.R., Olivieri, A.W. (1998) Removal of microorganisms in water repurification. *Proc. Conf. Disinfection '98, Spec. WEF Conf.*, Baltimore, MD, USA, 19-22 April 1998, 375-390.

Baron, J. (1997) Repair of wastewater microorganisms after ultraviolet disinfection under seminatural conditions. *Wat. Environ. Res.*, **69**, 5, 992-998.

Blatchley, E.R., Bastian, K.C., Duggirala, R.K., Alleman, J.E., Moore, M. and Schuerch, P. (1996) Ultraviolet irradiation and chlorination/dechlorination for municipal wastewater disinfection: assessment of performance limitations. *Wat. Environ. Res.*, **68**, 2, 194-204.

Blatchley, III, E. R., Do-Quang, Z., Laîné, J.M. (1997) Process Modelling of ultraviolet Disinfection. *WEF Conf.*, Chicago, Oct. 18-22.

Braunstein, J.L., Loge, F.J., Tchobanoglous, G., and Darby, J.L. (1996) Ultraviolet disinfection of filtered activated sludge effluent for reuse applications. *Wat. Environ. Res.*, **68**, 2, 152-161.

Calmer, J., Neethling J.B. and Murbach D. (1998) Nitrification effects on chlorination and disinfection. *Proc. Conf. Disinfection '98, Spec. WEF Conf*, Baltimore, MD, USA, 19-22 April 1998, 59-70.

Chan, Y. Y. and Killick, E. G. (1995) The effect of salinity, light and temperature in a diposal environment on the recovery of E. coli following exposure to ultraviolet radiation. *Wat. Res.*, **29**, 5, 1373-1377.

Chiu, K.P., Lyn, D.A. and Blatchley. III, E.R. (1997) Hydrodynamic behavior in ultraviolet disinfection systems: Effects on microbial inactivation. *Proc. CSCE-ASCE Environ. Eng. Conf.*, Edmonton, Alberta, Canada, 22-26 July 1997.

Chiu, K.P.; Lyn, D.A.; Blatchley III, E.R. (1998) Measurements and modeling of microscale hydrodynamic behavior in UV disinfection systems: Application for improvement of process performance. *Proc. Conf. Disinfection '98, Spec. WEF Conf*, Baltimore, MD, USA, 19-22 April 1998.

Clancy, J.L., Hargy, T.M., Marshall, M.M., Dyksen, J.E. (1998) UV light inactivation of Cryptosporidium oocysts. JAWWA, 90, 9, 92-102.

Cipparone, L. A., Diehl, A. C. and Jr, G. E. S. (1997) Ozonation and BDOC removal: effect on water quality. *J. AWWA*. 89(2), 84-96.

Darby, J., Heath, M., Jacangelo, J., Loge, F., Swaim, P. and Tchobanoglous, G. (1995) Comparison of UV irradiation to chlorination: guidance for achieving optimal UV performance. WERF project 91-WWD-1, Alexandria, VA.

Dernat, M. ; Choupeaux, J. ; Pouillot, M. ; Massechelein, W.J. (1997) Le dioxide de chlore, un oxidant efficace pour la désinfection des eaux résiduaires urbaines, *L'eau, l'industrie, les Nuisances*, **204**, 63-70.

Do-Quang, Z., Djebbar, R., Blatchley III, E. R. and Laine, J. M. (1997) Computational Fluid Dynamics (CFD) modeling of UV disinfection reactor performances: Optimization of the flow in vertical lamps open channel. *Proc. CSCE-ASCE Environ. Eng. Conf.*, Edmonton, Alberta, Canada, 22-26 July 1997.

EPA (1992) Ultraviolet Disinfection Technology Assessment. EPA/832/R-92/004. US EPA, Washington D.C.

Junli, H., Li, W., Nenqi, L., Li, L.X., Fun, S.R. and Guanle, Y. (1997) Disinfection effect of chlorine dioxide on viruses, algae and animal planktons in water. *Wat. Res.*, **31**, 3, 455-460.

Havelaar, A.H., Meulemans, C.C., Pot-Hogeboom, W.M., and Koster, J., (1990) Inactivation of bacteriophage MS2 in wastewater effluent with monochromatic and polychromatic ultraviolet light. *Wat. Res.*, **24**, 1387.

Heltz, G.R. and Nweke A.C. (1995) Incompleteness of wastewater dechlorination. *Env. Sci. Tech.* **29**, 4, 1018-1022.

Huang, J.L.,; Wang, L.,; Ren, N.Q. , Liu, X.L.,; Sun, R. F. and Yang, G. L. (1997) Disinfection effects of chlorine dioxide on viruses, algae and animal planktons in water. *Wat. Res.*, **31**, 3, 455-460.

Hunt, N. K. and Mariñas, B. J. (1997) Kinetics of Escherichia coli inactivation with ozone. *Wat. Res.*, **31**, 6, 1355-1362.

Hunter, G. and Rakness, K. (1997) Start-up and optimization of the ozone disinfection process at the Sabago lake water treatment facility. *Ozone Sci.Eng.*, **19**, 255-272.

Kashimada, K., Kamiko, N., Yamamoto, K. and Ohgaki, S. (1996). Assessment of photoreactivation following ultraviolet light disinfection. *Wat. Sci. Tech.* **33**, 10-11, 261-269.

King, C.H.; Shotts, E.B. ; Wooley R.E. ; Porter, K.G. (1988) Survival of coliforms and bacterial pathogens within protozoa during chlorination. *Appl. Environ. Microbiol.*, **54**, 12, 3023-3033.

Langlais, B., Legube, B., Beuffe, H. and Doré, M. (1992) Study of the nature of the by-products formed and the risks of toxicity whan disinfecting a secondary effluent with ozone. *Wat. Sci. Tech.*, **25**, 12, 135-143

Langlais, B., Denis, Ph., Triballeau, S., Faivre, M., and Bourbigot, M. M. (1993) Microfiltration used as a means of disinfection downstream: A bacterial treatment stage on fixed-bed bacteria. *Wat. Sci. Tech.*, **27**, 7-8, 19-27.

Lazarova V., J.C. Bourdelot, M.L. Janex and J.M. Laîné (1997) Advances in wastewater disinfection: technical and economic evaluation and large scale operation. *Proc. WEFTEC Asia'98*, Singapore, March 8-11, 1998, **2**, 129-139.

Lazarova V., Janex M.L., L. Fiksdal, C. Oberg, I. Barcina and M. Pommepuy (1998) Short and long term efficiency of different disinfection technologies. *Proc. 19th IAWQ Conf.*, Vancouver, 21-26 June, 1998.

Legan, R .W. (1982) Alternative disinfection methods : a comparison of UV and ozone. *Ind. Wat. Eng.*, Mar/Apr 12-21.

Leslie G.L., Dunivin W.R., Gabillet P., Conklin S.R., Mills W.R., Sudak R.G. (1996) Pilot testing of microfiltration and ultrafiltration upstream of reverse osmosis during reclamation of municipal wastewater. *Proc. Amer. Desalination Ass. Nat. Conf.*, Monterey, CA, Aug. 4 1996.

Linden K.G., Soriano G.S. and Darby J.L. (1998) Investigation of disinfection by-product formation following low and medium pressure UV irradiation of wastewater. *Proc. Conf. Disinfection '98, Spec. WEF Conf*, April 19-22, Baltimore, USA, 137-147.

Lindenauer, K. G. and Darby, J. L. (1994) Ultraviolet disinfection of wastewater: efffect of dose on subsquent photoreactivation. *Wat.Res.*,**28**, 4, 805-817.

Mandra, V., Lefevre, F., Anselme, C. and Audic, JM. (1993) Use of ultrafiltration for disinfection of urban wastewater. *Proc. Hydrotop '93*, May 1993, Marseille, France.

Mandra, V., Lazarova, V., Dumoutier, N., and Audic, J.M. (1996) Etude comparative de la désinfection des eaux résiduaires urbaines par l'acide peracétique, l'irradiation UV et l'ozone. *Proc. Colloque Journées Information Eaux, 18-20 septembre 1996, Poitiers*, vol. **2**, 61/1.

Manem, J., and Sanderson, R., (1996) Membrane Bioreactors. In: *Water treatment membrane processes*, ed. by Mallevialle J., Odendaal P., and Wiesner M.R., McGraw-Hill, AWWA, pp. 17.1.

Narkis, N., Offer, R. and Betzer, N. (1988) Chlorine dioxide as a disinfectant at each step of the advanced treatment of effluents intended for reuse. *Proc. 61th Ann. Conf. of WPCF*, Dallas, USA.

Nieuwstad, Th.J., Havelaar, A.H., and Van Olphen, M., (1991) Hydraulic and microbiological characterization of reactors for ultraviolet disinfection of secondary wastewater effluent. *Wat. Res.*, **25**, 775.

Oppenheimer, J.A., Hoagland, J.E., Laîné, J.M., Jacangelo, J.G., and Bhamrah, A., (1993) Microbial inactivation and characterization of toxicity and by-products occuring in reclaimed wastewater disinfected with UV radiation. *Proc. WEF Speciality Conf. Series*, TT043,13.

Oppenheimer, J. A., Jacangelo, J. G., Laîné, J-M and Hoagland, J. E. (1997) Testing the equivalency of ultraviolet light and chlorine for disinfection of wastewater to reclamation standards. *Wat. Environ. Res.*, **69**, 1, 14-24

Perrine, D. (1990) Cinétiques d'action du chlore et de l'ozone sur les trophozoïtes et les kysts d'amibes libres de germes *Naegleria* et *Acanthamoeba*. *J. Français d'Hydrol.*, **21**, 1, 113-121.

Rebhun, M., Heller-Grossman, L. and Manka, J. (1997) Formation of disinfection byproducts during chlorination of secondary effluent and renovated water. *Water Environ. Res.*, **69**, 6, 1154-1162.

Renaud, P., Lazarova, V., Levine, B. and Manem, J. (1997) *Water reuse International Report. Proc. IWSA World Congress, Madrid*, IR8-1/IR8-7.

Roy, D., Englebrecht, R. S. and Chian, E. S. K. (1982) Comparative inactivation of six enteroviruses by ozone. *J. AWWA*. Dec. 660-664.

Szal, G.M., Nola,, P.M., Kennedy, L.E., Barr, C.P. and Bilger, M.D. (1991) The toxicity of chlorinated wastewater: instream and laboratory case studies. *Res. J. WPCF*, **63**, 6, 910-920.

Tchobanoglous G., Loge F., Darby J. and Devries M. (1996) UV design : comparison of probabilistic and deterministic design approaches. *Wat. Sci. Tech.*, **33**, 10-11, 251-260.

Tyrrell, S. A., Rippey, S. R. and Watkins, W. D. (1995) Inactivation of bacterial and viral indicators in secondary sewage effluents, using chlorine and ozone. *Wat. Sci. Tech.* **29**, 11, 2483-2490.

Venczel L.V., Arrowood M., Hurd M. and Sobsey M.D. (1997) Inactivation of Cryptosporidium parvum oocysts and Clostridium perfringens spores by a mixed-oxidant disinfectant and by free chlorine, *Appl. Environ. Microbiology*, **63**, 4, 1598-1601.

Walker D. (1997) Personal communication.

Warriner, R., Kostenbader, K.D., Cliver, D.O. and Ku, W.C. (1985) Disinfection of advanced wastewater treatment effluent by chlorine, chlorine dioxide and ozone using seeded poliovirus. *Wat. Res.*, **19**, 12, 1515-1526.

Whitby, G.E. and Palmateer, G. (1993) The effect of UV transmission, suspended solids and photoreactivation on microorganisms in wastewater treated with UV light. *Wat. Sci. Tech.*, **27**, 3-4, 379-386.

Whitby, G.E., Palmateer, G., Cook, W.G., Maarschalkerweerd, J., Huber, D. and Flood, K. (1984) Ultraviolet disinfection of secondary effluent. *JWPCF*, **56**,7, 844-851.

Wright H., DeVries M. and Sakamoto G. (1998) A systematic approach to designing and costing of UV disinfection systems. *Proc. Conf. Disinfection '98, Spec. WEF Conf*, Baltimore, MD, USA, 19-22 April 1998, 11-23.

Yanko, W.A. (1993) Analysis of ten years of virus monitoring data from Los Angeles County treatment plants meeting California wastewater reclamation criteria. *Wat. Environ. Res.*, **66**, 5, 221-226.