

An Overview of UV-based Advanced Oxidation Processes for Drinking Water Treatment

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ABSTRACT

This paper begins by presenting the regulatory interest behind the growth of UV-based Advanced Oxidation Processes (AOPs). The main focus of the paper will be a detailed look at the use of four UV-based AOPs (direct photolysis, UV/H₂O₂, UV/O₃, and UV/TiO₂ photocatalysis) in drinking water applications. For each treatment technology, the following are considered: (1) the general mechanism by which it achieves contaminant removal, (2) factors affecting its performance, (3) some relevant recent literature and research projects, and (4) some current commercial activities.

Keywords: Ultraviolet radiation; advanced oxidation process; photocatalysis; photooxidation; drinking water.

INTRODUCTION

The practice of UV disinfection of water dates back to the early twentieth century. More recently, UV has begun to replace chlorine as a primary disinfectant (Oliver and Carey 1976) largely due to the fact that it has been demonstrated to be more effective at inactivating *Cryptosporidium parvum* and *Giardia lamblia* (Bukhari et al. 1999; Craik et al. 2001). With the increased use of UV in drinking water treatment plants, much attention has been placed on developing UV-based advanced oxidation processes (AOP) for the removal of taste and odor compounds, micropollutants, or natural organic matter (NOM) from raw drinking water (Parsons and Byrne 2004).

An AOP typically involves the formation of hydroxyl radicals (•OH) that carry out the oxidation and degradation of target species. For UV-based AOPs this involves the addition of an oxidant or catalyst (e.g. O₃, H₂O₂, TiO₂) that UV photolyzes or activates leading to the formation of •OH radicals (Bolton and Cater 2004; Legrini et al. 1993).

UV-based AOPs date back to as early as 1899 when Bach (1899) observed the photolysis of carbonic acid. Much of the early work focused on the principles and theory behind photooxidation (i.e. quantum yields, reaction pathways). Currently, the main focus is on the full-scale application of AOPs, including reactor design and optimization. In the following, we present the drinking water regulations that have spurred the current interest in AOPs and discuss the current state of direct photolysis, UV/H₂O₂, UV/O₃, and UV/TiO₂ photocatalysis in research and commercial drinking water applications.

REGULATORY INTEREST

Environmental and health organizations place strict regulations on the maximum allowable concentration (MAC) of a number of organic chemicals in potable water to protect consumer safety. Table 1 summarizes the water quality guidelines of the United States Environmental Protection Agency (USEPA), Health Canada, the European Union (EU), and the World Health Organization (WHO) for selected contaminants whose removal by AOPs has been studied.

A certain class of halogenated derivatives, namely disinfection by-products (DBPs), trihalomethanes (THMs) and haloacetic acids (HAAs), enter the potable water via reaction between chlorine and NOM. UV-based AOPs are capable of reducing the concentration of NOM while also achieving primary disinfection. Thus, the reduced chlorine demand for maintaining a residual in the distribution system leads to an overall decrease in the formation of DBPs.

N-nitrosodimethylamine (NDMA) is a nitrosamine that is not currently regulated by national regulatory agencies. However, localized agencies such as the Ontario Ministry of Environment and the State of California have set drinking water guidelines of 0.009 ppb and 0.002 ppb NDMA, respectively. Because of its low molecular weight, low volatility, and poor adsorption characteristics, conventional treatment processes such as membranes, air stripping, and granular activated carbon (GAC) do not adequately remove NDMA. In addition, NDMA is not readily biodegradable so biological treatments are ineffective. Recently, much research has focussed on the removal of NDMA (Mitch et al. 2003) and commercial AOPs exist specifically for the removal of NDMA from drinking water.

Another contaminant for which much attention has been focussed on its removal (Deeb et al. 2003) and is not currently regulated by national regulatory agencies is methyl tertiary-butyl ether (MTBE). MTBE is not efficiently treated by activated carbon or air stripping since it is highly soluble in water and has a low Henry's law constant, 0.022 at 25 degrees Celsius (Squillace et al. 1998). In addition, biodegradation of MTBE under aerobic and anaerobic conditions is slow. Low levels of MTBE can make drinking water supplies undrinkable due to its turpentine-like taste and odour that are detectable at low taste and odour detection thresholds (Water Quality Branch 2001). Present data shows that MTBE is potentially carcinogenic but more research is necessary to determine concentration thresholds.

Taste and odor (T&O) are arguably the most important characteristics of drinking water, since they are the most

tangible for the consumer. Geosmin and 2-methylisoborneol (MIB), compounds commonly found in drinking water reservoirs with high algal bloom activity, are often the source of earthy and musty odors present in drinking water. Typically, powdered activated carbon (PAC), ozonation, or GAC filtration is implemented for geosmin and MIB control. However, T&O episodes are variable depending on the season and climate, therefore treatment is only required on an as-needed basis. An alternative is the UV/H₂O₂ AOP (Koratgere et al. 2005; Linden et al. 2004; Paradis et al. 2005). During a T&O event, a drinking water facility equipped with a UV system designed for disinfection and T&O treatment can switch from "Disinfection-Only" mode to "Disinfection + T&O control" mode by energizing additional UV lamps and dosing H₂O₂ upstream of the reactors, potentially resulting in significant cost savings (Royce et al. 2005).

Conventional treatment technologies are limited in their ability to remove a wide variety of contaminants and each has its drawbacks. The main advantages AOPs hold over current technologies are:

1. They are not specific to any one contaminant, and
2. The target contaminant is permanently eliminated and not transported from water to another medium.

Table 1: USEPA, Health Canada, EU, and WHO drinking water regulations

Contaminant	Maximum Allowable Concentration (MAC) ($\mu\text{g/L}$)			
	USEPA ^a	Health Canada ^b	EU ^c	WHO ^d
Organic Chemicals				
Atrazine	3	5	0.1	2
Benzene	5	5	0.10	10
Benzo(a)pyrene	0.2	0.01	0.01	0.7
Carbofuran	40	90	0.1	7
Chlorobenzene	100	n/a	0.1	n/a
1,2-Dichlorobenzene	600	200	0.1	1000
1,4-Dichlorobenzene	75	5	0.1	300
2,4-D	70	100	0.1	30
1,2-Dichloroethane	5	5	3	30
1,1-Dichloroethylene	7	14	n/a	30
Dioxin (2,3,7,8-TCDD)	0.00003	n/a	0.1	n/a
Ethylbenzene	700	n/a	n/a	300
Polychlorinated biphenyls	0.5	n/a	n/a	n/a
Pentachlorophenol	1	60	0.1	9
Tetrachloroethylene	5	30	10	40
Toluene	1000	n/a	n/a	700
2,4,5-T	n/a	n/a	0.1	9
1,1,1-Trichloroethane	200	n/a	n/a	n/a
Trichloroethylene (TCE)	5	50	10	70
Vinyl chloride	2	2	0.5	0.3
Xylenes (total)	10000	n/a	n/a	500
Disinfection Byproducts				
Haloacetic acids (HAA)	60	n/a	n/a	n/a
Trihalomethanes (TTHM)	80	100	100	460

^a – USEPA 2003; ^b – Health Canada 2004; ^c – European Union 1998; ^d – World Health Organization 2004

On the other hand, the disadvantages of AOPs are (Suty et al. 2004):

1. The water to be treated should have low bicarbonate/carbonate and natural organic matter (NOM) concentrations so that •OH radicals are reserved for the oxidation of organic contaminants,
2. The oxidation of some compounds may lead to the generation of more toxic by-products,
3. The oxidation by-products are generally more biodegradable so downstream treatment may be necessary to improve the biological stability of the water.

UV PHOTOLYSIS

Direct UV photolysis can provide effective removal of pollutants that exhibit large molar absorption coefficient and high quantum yields over the lamp's emission spectrum (Stefan and Williamson 2004). For vacuum UV (VUV) irradiation (185 nm), •OH radicals can be produced by the photolysis of water (Gonzalez and Braun 1995). The degradation pathway by UV photolysis varies depending on the pollutant and water conditions. In general, homolytic bond scission is the predominant mechanism (Stefan 2004).

A number of factors affect the performance of process involving direct photolysis. As stated by the First Law of Photochemistry, such treatment can only be carried out if the target contaminant is able to absorb UV. Additionally, once absorbed, the energy must be greater than the

energy of the weakest bond in the molecule to initiate a photochemical reaction (Bolton 2001). With these factors in consideration, the UV source must be carefully considered to ensure the spectrum emitted by the lamp is best suited for the application. Water quality may also contribute to the performance by way of indirect or sensitised photolysis as suggested by Stefan (2004). Photosensitisation involves the photolysis of NOM and nitrates to form reactive species, including •OH radicals, which encourage the degradation of pollutants.

Commercial Application: Low- and medium-pressure UV systems for NDMA removal

NDMA is effectively photolyzed by UV in the 200 nm to 260 nm range, thus eliminating the need for oxidant addition. Calgon Carbon's Rayox™ system, featuring 20 kW medium-pressure UV lamps designed to emit UV in the 200 to 260 nm absorbance spectrum range have been installed in a number of applications for NDMA removal from drinking water sources (Lem 1999).

Trojan's TrojanUVPhox™ is a reactor based on low-pressure amalgam lamp technology emitting UV primarily at 254 nm. A recent study has shown that low-pressure UV is as effective as medium-pressure UV for the photolysis of NDMA (Sharpless and Linden 2003). Therefore, due to the significantly lower energy requirements and life-cycle costs, low-pressure lamp-based reactors are currently the technology of choice for NDMA removal applications.

Table 2: 21st century studies involving UV direct photolysis of compounds found in drinking water

Compound	UV Source	Reference
NOM	VUV ₁₈₅ , LPUV UVC UVA, UVB, UVC LPUV, MPUV, Pulsed-UV MPUV	Buchanan et al. 2004; Thomson et al. 2002a; Thomson et al. 2004 Thomson et al. 2002b Parkinson et al. 2003 Liu et al. 2002a Hofbauer and Andrews 2004
TCE	MPUV	Li et al. 2003
PAHs	UVA, UVB Polychromatic LPUV, MPUV	Bertilsson and Widenfalk, 2002 Fasnacht and Blough, 2002 Miller and Olejnik 2001
NDMA	MPUV Pulsed-UV LPUV, MPUV	Stefan and Bolton 2002; Stefan et al. 2002 Liang et al. 2003 Sharpless et al. 2003
Herbicides & Pesticides	Various MPUV 250-750 nm LPUV HPUV	Burrows et al. 2002; Koratgere et al. 2005; Linden et al. 2004 Kruithof et al. 2001; Sharpless et al. 2003; Zheng and Ye 2001 Panadés et al. 2000 Rayne et al. 2002 Benitez et al. 2002
Phenols	MPUV	Esplugas et al. 2002
Dioxins	LPUV	Konstantinov et al. 2000
MIB & geosmin	LPUV, MPUV	Koratgere et al. 2005; Linden et al. 2004

Table 3: Design parameters for UV photolysis installations for NDMA treatment

Installation (year)	Parameter	Value
First Nations reserve, ON, Canada (early 1990s) ^a	Reactor	Rayox™
	Flow rate	270 GPM
	Influent NDMA concentration	100 ppt
	Effluent NDMA concentration	<5 ppt
	Operating cost (USD)	US\$0.40/1000 gallons
Suburban Water, Covina, CA, USA (1999) ^b	Reactor	Rayox™
	Flow rate	3,000 GPM
	Influent NDMA concentration	90 ppt
	Effluent NDMA concentration	<2 ppt
California Domestic Water, El Monte, CA, USA (2004) ^c	Reactor	TrojanUVPhox™
	Flow rate	14.4 MGD
	Influent NDMA concentration	200 ppt
	Effluent NDMA concentration	<2 ppt
Alamitos Barrier recycled water project, CA, USA (2004) ^c	Reactor	TrojanUVPhox™
	Flow rate	3 MGD
	Influent NDMA concentration	420 ppt
	Effluent NDMA concentration	<10 ppt
	Operating cost (USD)	US\$0.06/1000 gallons

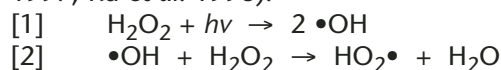
a - case study provided by Calgon Carbon Corporation 2005; *b* - Lem 1999; *c* - case studies provided by Trojan Technologies Inc. 2006

THE UV/H₂O₂ PROCESS

Based on the relevant literature available, UV/H₂O₂ is the most widely studied UV-based AOP for drinking water applications (Tuhkanen 2004; Stefan and Williamson 2004). The theory, kinetics, and mechanisms of oxidation are well understood (Tuhkanen 2004; Crittenden et al. 1999).

The dominant pathway of •OH formation in UV/H₂O₂ AOPs is the photolysis of H₂O₂ (Baxendale and Willson 1957). At first glance (Reaction 1), this process looks highly efficient since one mole of H₂O₂ yields two moles of •OH.

However, two main factors limit the efficiency of the process. First, the molar absorption coefficient of H₂O₂ at 254 nm is very low ($\epsilon_{254} = 19.6 \text{ M}^{-1} \text{ cm}^{-1}$), so a high concentration of H₂O₂ is required to have sufficient •OH production. However, this leads to the second problem, that is H₂O₂ itself scavenges •OH radicals (Reaction 2). Therefore, high concentrations of H₂O₂ can reduce the effectiveness of the process (Wang et al. 2000; Wang et al. 1997; Ku et al. 1998).

**Table 4: 21st century studies involving UV/H₂O₂ treatment of compound found in drinking water**

Compound	UV Source	Reference
NOM	HPUV	Wang et al. 2000
	VUV ₁₈₅ , UVC	Thomson et al. 2004
	MPUV	Speitel et al. 2000; Hofbauer and Andrews 2004
	UVC	Kleiser and Frimmel 2000; Parkinson et al. 2001
	MPUV, LPUV, Pulsed-UV	Liu et al. 2002b
	LPUV	Berube et al. 2004; Toor and Mohseni 2005
Phenols	MPUV	Esplugas et al. 2002
	Polychromatic	Fasnacht and Blough 2002
NDMA	MPUV	Stefan and Bolton 2002
	LPUV, MPUV	Sharpless et al. 2003
MTBE	LPUV, MPUV, PUV	Kavanaugh et al. 2003
	MPUV	Cater et al. 2000; Stefan et al. 2000
	LPUV	Chang and Young 2000
Herbicides & Pesticides	MPUV	Kruithof et al. 2001; Kruitof et al. 2002; Kruithof et al. 2005; Martin et al. 2005; Stefan et al. 2005; Williams et al. 2005
	LPUV	Müller and Jekel 2001
	HPUV	Benitez et al. 2002
	LPUV, MPUV	Koratgere et al. 2005; Linden et al. 2004;
MIB & gesomin	LPUV, MPUV	Koratgere et al. 2005; Linden et al. 2004; Paradis et al. 2005; Royce et al. 2005

Commercial Products: TrojanUVPhox™ and TrojanUVSwift™ECT

Trojan Technologies has a number of drinking water installations, treating a range of compounds, using the UV/H₂O₂ AOP. Depending on the application, either a TrojanUVPhox™, which implements low-pressure amalgam lamp technology, or a TrojanUVSwift™ECT based on medium-pressure lamp technology is selected. H₂O₂ concentrations range from 1 to 15 ppm.

Included are two water reuse projects (Orange County Water District and West Basin Municipal Water District), a drinking water well protection application (Stockton), and several drinking water treatment plant installations (PWN Treatment Plant Andijk, City of Cornwall, La Puente Valley County Water District, Valley County Water District, and San Gabriel Valley Water District).

Table 5. Design parameters for Trojan's UV/H₂O₂ installations

Installation (year)	Parameter	Value
Orange County Water District, CA, USA (2004) ^a	Reactor	TrojanUVPhox™
	Flow rate	100 MGD peak
	Target compounds	NDMA; 1,4-dioxane
	Influent NDMA concentration	150 ppt
	Effluent NDMA concentration	10 ppt
	Design electrical energy per order (EE/O)	<0.20 kWh/1000 gallons/order
West Basin Municipal Water District, CA, USA (2005) ^a	Reactor	TrojanUVPhox™
	Flow rate	12.5 MGD
	Target compound	NDMA
	Design influent NDMA concentration	100 ppt
	Target effluent NDMA concentration	<10 ppt
Stockton, CA, USA (2001) ^a	Reactor	TrojanUVPhox™
	Target compound	1,4-dioxane
The La Puente Valley County Water District, CA, USA (2002) ^a	Flow rate	3.6 MGD
	Target compounds	NDMA; 1,4-dioxane
	Influent NDMA concentration	1,500 ppt
	Effluent NDMA concentration	<1 ppt
	Influent 1,4-dioxane concentration	3.4 ppb
	Effluent 1,4-dioxane concentration	<0.5 ppb
PWN Treatment Plant Andijk, Netherlands (2004) ^{b,c,d,e}	Reactor	TrojanUVSwift™ ECT
	Flow rate	25 MGD peak
	Effluent micropollutant concentration	80% reduction of influent micropollutant concentration
City of Cornwall, ON, Canada (2006) ^{f,g}	Reactor	TrojanUVSwift™ ECT
	Peak flow rate	26.4 MGD
	Target compounds	MIB & geosmin
	Design influent geosmin concentration	50 ppt
	Target geosmin reduction	>1-log
Valley County Water District, CA, USA (2006) ^a	Reactor	Trojan Low Pressure
	Flow rate	11.2 MGD
	Target compounds	NDMA; 1,4-dioxane
	Influent NDMA concentration	3,000 ppt
	Effluent NDMA concentration	<2 ppt
	Effluent 1,4-dioxane concentration	<0.5 ppb
San Gabriel Valley Water Company, CA, USA (2006) ^a	Reactor	TrojanUVPhox™
	Flow rate	11.2 MGD
	Target compounds	NDMA; 1,4-dioxane
	Influent NDMA concentration	700 ppt
	Effluent NDMA concentration	<2 ppt
	Effluent 1,4-dioxane concentration	<0.5 ppb

a – case studies provided by Trojan Technologies Inc. 2006; *b* – Kruithof et al. 2005; *c* – Martin et al. 2005; *d* – Stefan et al. 2005; *e* – Williams et al. 2005; *f* – Royce et al. 2005; *g* – Paradis et al. 2005

Commercial Product: Calgon's Rayox™ based UV/H₂O₂ systems

In addition to the above-described Rayox™ installations used for direct photolysis of NDMA, Calgon has an application combining Rayox™ technology with hydrogen peroxide. Tetrachloroethylene (PCE), in the range of 0.5-4.5 ppb, was detected in the drinking water supply,

from a groundwater source, for the Salt Lake City Department of Public Utilities. Although, this was below the USEPA's TCE MAC of 5 ppb, treatment was preferred. This was the first UV/H₂O₂ system for treating a public drinking water supply in North America.

Table 6. Design parameters for the Calgon Rayox™ UV/H₂O₂ installation

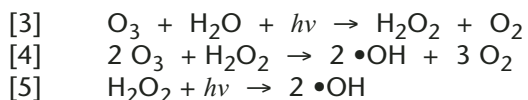
Installation (year)	Parameter	Value
Salt Lake City Department of Public Utilities, UT, USA (1998) ^a	Reactor	12 lamp tower (300 kW)
	Flow rate	3000 gpm
	Target compound	PCE
	Influent PCE concentration	2.3 ppb average
	Effluent PCE concentration	<0.05 ppb
	Operating and maintenance cost (USD)	US\$0.15/1000 gal

a - case study provided by Calgon Carbon Corporation 2005

THE UV/O₃ PROCESS

The use of ozone in drinking water treatment applications involving disinfection, oxidation and removal of micropollutants, NOM, taste and odour compounds, and colour has been extensively reviewed (e.g. Camel and Bermond 1998; Langlais et al. 1991; Gottschalk et al. 2000; Graham 1999). Ozone has a high oxidation potential but it is selective and may not completely oxidize some species. Therefore, AOPs that combine O₃ with UV or H₂O₂ to enhance •OH production are often more effective than O₃ alone (Camel and Bermond 1998).

The O₃/UV AOP is initiated by the photolysis of O₃ by UV to form H₂O₂ and O₂ (Peyton 1988). •OH production is carried out by the reaction between O₃ and H₂O₂.



The oxidation potential of UV/O₃ AOPs with UV of 254 nm wavelength is high due to the high molar extinction coefficient of O₃ ($\epsilon_{254} = 3300 \text{ M}^{-1} \text{ cm}^{-1}$) (Gottschalk et al. 2000). In addition, O₃ decays rapidly so the problem of residual concentrations in treated water is not of concern (Guittonneau et al. 1991). A great advantage of the UV/O₃ AOP is that it offers multiple barriers for contaminants in that both •OH and O₃ are available oxidants. A major drawback of the UV/O₃ AOP is, however, the requirement of O₃ production, generating high capital and operational costs. Additionally, as with all liquid phase O₃ processes, mass transfer limitations of O₃ into the liquid phase can severely decrease process efficiency and increase operating costs (Andreozzi et al. 1999). Another drawback of using O₃ arises when treating waters containing bromide, leading to the formation of bromate, a regulated carcinogenic byproduct.

Table 7. 21st century studies involving UV/O₃ treatment of compounds found in drinking water

Compound	UV Source	Reference
MIB & geosmin	LPUV	Collivignarelli and Sorlini 2004
Herbicides & Pesticides	LPUV	Collivignarelli and Sorlini 2004; Müller and Jekel 2001
	UVC	Ma et al. 2002
	HPUV	Benitez et al. 2002
MTBE	LPUV	Garoma and Gurol 2004; Graham et al. 2004
NOM	LPUV	Latifoglu and Gurol 2003; Mischuk et al. 2003; Collivignarelli and Sorlini 2004; Berube et al. 2004; Chin and Berube 2005
THMs	UVC	Liu and Sun 2003
MTBE	LPUV	Ramakrishnan et al. 2004
Phenols	MPUV	Teo et al. 2003; Esplugas et al. 2002

Commercial Activity: Development of UV/O₃ systems

Commercial UV/O₃ AOP systems are being developed but no commercial applications currently exist for drinking water treatment. However, UV/O₃ systems have been applied for municipal wastewater treatment by Wedeco (Ternes et al. 2003) and Hydroxyl Systems (www.hydroxyl.com) offers UV/O₃ systems that disinfect and remove colour and odor from wastewaters.

THE UV/TiO₂ PHOTOCATALYSIS PROCESS

The ideal semiconductor photocatalyst for UV-based water purification should be chemically and biologically inert, easy to produce and use, and activated by UV (Mills and Lee 2004). The semiconductor that comes closest to meeting these criteria is titanium dioxide (TiO₂), the most studied semiconductor photocatalyst today (Bhatkhande et al. 2001).

TiO₂ is a semiconductor with a band gap energy of ~3.2-3.0 eV, so UV of wavelengths less than 400 nm can excite pairs of electrons and holes. The photogenerated electrons then react with O₂ to produce predominantly superoxide radical anions (•O₂⁻), and the photogenerated holes react

with water to produce •OH. These two types of reactive radicals, along with other oxidants and radical species, work together to decompose organic compounds. The longer the photocatalyst film is illuminated with UV, the more organic material can be decomposed. The efficiency of most processes is low, typically <1% due to reflection and scattering losses and significant electron-hole recombination at light intensities typically found in photoreactors (Mills and Lee 2004; Fujishima et al. 2000; Hoffmann et al. 1995). Another drawback of the UV/TiO₂AOP is the quantum yield of •OH is only about 4% (Sun and Bolton 1996).

The key advantage of the UV/TiO₂ AOP is that no chemical addition (e.g., O₃, H₂O₂) is required to generate •OH radicals. Additionally, studies have shown the ability of UV/TiO₂ processes to disinfect water (Zhang et al. 1994; Ireland et al. 1993; Matsunaga et al. 1995; Curtis et al. 2002; Dunlop et al. 2002; Otaki et al. 2000; Wist et al. 2002) and this topic was reviewed by Blake et al. (1999). Yet, the design of photocatalytic reactors for water treatment is still in development. Slurry-based reactors are common but require separation of the TiO₂ slurry from the water stream. More promising are reactors with TiO₂ coated surfaces, but certain engineering challenges must be overcome before these types of systems are commercially available.

Table 8. 21st century studies involving UV/TiO₂ treatment of compounds found in drinking water

Compound	UV Source	Reference
NOM	MPUV	Palmer et al., 2002
	max @ 365 nm	Bekbolet et al., 2002
	max @ 365 nm 300-400 nm	Kerc et al., 2004, 2003a, 2003b; Uyguner et al., 2004 Gonenc and Bekbolet, 2001
Chlorinated benzaldehydes	UVC	Bekbolet and Getoff, 2002
Herbicides & Pesticides	MPUV	Hequet et al., 2001
	Xenon arc lamp	Konstantinov et al., 2001
	1000W Hg lamp	Daneshvar et al., 2004
Phenol	sunlight	Toyoda et al., 2000

Commercial Activity: Photocatalytic reactors for water treatment

Mills and Lee (2004) included a table of companies that currently promote photocatalytic systems for water purification. The most note-worthy product is Purifics' Photo-Cat™, a TiO₂ slurry-based photocatalytic reactor that Purifics claims is capable of treating water down to level exceeding drinking water standards as well as having a quarter of the operating and maintenance costs of other AOPs. However, Purifics is yet to install the Photo-Cat™ reactor for a drinking water application (private communication with T.P., Purifics ES Inc. 2006).

In Europe, much attention has been focused on the development of low-cost, fully autonomous water treatment systems for disinfection and removal of trace organic pollutants for use in remote locations and developing countries. Photocatalytic reactors driven by sunlight have emerged as the technology best suited for such applications (Galvez and Rodriguez 2002). Two groups, The Plataforma Solar de Almería (PSA), a dependency of the Center for Energy, Environment and Technological Research (CIEMAT) in Spain, and France's Laboratoire d'Application de la Chimie à l'Environnement (LACE) are respectively overseeing two major projects, SOLWATER (www.psa.es/webeng/solwater) and AQUACAT (Chapelon and Herrmann 2004).

ACKNOWLEDGEMENTS

For contributing to the relevant commercial applications and his editorial comments, the authors acknowledge Adam Festger of Trojan Technologies Inc. The authors acknowledge Scott Frenz of Calgon Carbon Corporation, Siva Angappam of Hydroxyl Systems, Achim Reid of Wedeco, and Tony Powell of Purifics ES Inc. for contributing to the relevant commercial applications.

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