UV-Oxidation: Municipal Case Studies and New Applications

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ABSTRACT

Increasingly, municipal water suppliers are seeking to treat both microbial and chemical contaminants. This is due, at least in part, to an increasing awareness of chemical contaminants in the water supply. Numerous recent studies have detailed the presence of chemical contaminants in streams, lakes, rivers, and groundwater. To address this concern, a multi-barrier approach is often used, applying a combination of conventional treatment techniques and other technologies including carbon, ozone, other oxidative methods, and/or membranes. UV technologies are often employed as a disinfection barrier to chlorine-resistant pathogens. In addition, UV technologies are increasingly being employed as a barrier to chemical contaminants such as the nitrosamines (e.g. N-nitrosodimethylamine, or NDMA), pesticides, taste and odor-causing compounds (e.g. MIB and geosmin), algal toxins, and pharmaceuticals. Using a combination of UV and hydrogen peroxide, "UV-oxidation" generates hydroxyl radicals, which, in conjunction with UV light itself, destroy chemical contaminants. Three case studies are presented describing the application of UV-oxidation for simultaneous disinfection and treatment of contaminants in drinking water and indirect potable reuse applications: the Aurora Reservoir Water Purification Facility (ARWPF) in Aurora, Colorado, the Orange County Water District's Groundwater Replenishment System in California and the drinking water treatment plant for the City of Cornwall, Ontario, Canada. Each uses or will use UV-oxidation to treat contaminants and to disinfect.

Keywords: UV-oxidation, Advanced Oxidation, ultraviolet disinfection, taste and odor, nitrosamine, emerging contaminants, hydrogen peroxide.

INTRODUCTION

Water providers, providing drinking water for public consumption or highly-treated wastewater for indirect potable reuse, must supply water that meets purity standards. In doing so, providers must address both microbial and chemical contaminants. These contaminants may have immediate or long-term health effects or, in drinking water, may impact the aesthetic quality.

Public awareness of contaminants in the water supply continues to grow. With recent research in the United States and Europe revealing the presence of trace environmental contaminants in the aquatic environment, there is also a growing desire to remove these contaminants at the drinking water treatment plant. Examples of these compounds include nitrosamines such as N-nitrosodimethylamine (NDMA), 1,4-dioxane, pesticides, pharmaceuticals, volatile organic compounds (VOCs), algal toxins (such as microcystin), and taste and odor-causing compounds (such as 2-methylisoborneol [MIB] and geosmin).

In addition, chlorine-resistant microbiological contaminants such as *Cryptosporidium* and spores of sulfur-reducing clostridia (SSRC) can also be present in source water supplies and have the potential to cause acute health impacts. Water providers are continually challenged to supply water free from these and other microbial contaminants. In many cases, plants employ multi-disinfectant strategies.

UV technologies are playing an increasing role in providing a barrier to both microbial and chemical contaminants in drinking water. The benefits of UV alone for disinfection are well understood, and the number of municipalities installing UV as a relatively inexpensive primary barrier to microbial contaminants (or as part of a multi-disinfectant strategy) continues to rise. In addition, UV in conjunction with hydrogen peroxide, a process known as UV advanced oxidation or simply UV-oxidation, enables the UV system to act as a barrier to chemical contaminants in addition to simultaneously disinfecting.

The emergence of this dual capability has led to the development of a number of new municipal-scale applications of UV technologies. UV-oxidation is now being used in a variety of applications to treat chemical and microbiological environmental contaminants simultaneously on a large scale (tens of millions of gallons per day and larger). UV, alone and in conjunction with hydrogen peroxide, destroys environmental contaminants through the photochemical processes known as UV-photolysis and UV-oxidation. These processes occur nearly instantaneously as water passes through a UV-oxidation system. Because more energy is required for contaminant treatment than for disinfection, disinfection is enhanced during treatment with UV-oxidation.

Introduction to Contaminants in the Environment

Contaminants are present in the world's water supply. For example, the pathogens *Cryptosporidium* and *Giardia* have the capability to cause widespread, acute illness, while trace chemical contaminants such as pesticides, industrial contaminants or disinfection by-products represent a more chronic, long term health threat. These compounds may come directly from human sources such as industrial manufacturing, agricultural run-off, and wastewater discharge; or they may originate from natural sources, such as the taste and odor-causing compounds in water generated by algae and bacteria blooms. Some contaminants are highly mobile in water, resistant to biodegradation, and are difficult to treat by conventional technologies such as carbon filtration or coagulation. In many cases UV-oxidation is effective where other technologies are not.

In what has become a landmark (and thoroughly cited) study by the United States Geological Survey, Kolpin et al. (2002) detected a wide variety of contaminants in water bodies in vulnerable watersheds (down-watershed from large cities, animal feeding operations, etc.). Other researchers have made similar observations (Funk 2003, Daughton and Ternes 1999, Halling-Sorenson et al. 1998). But with the increasing realization that many surface waters are either effluent impacted (under the influence of municipal or industrial wastewater) or in some cases, effluent dominated, the issue is not confined only to vulnerable watersheds.

The nitrosamine family of compounds, which includes N-nitrosodimethylamine (NDMA), has attracted increased attention from the water treatment community as potent and potentially wide-ranging water contaminants (Barrett et al. 2003). NDMA is a toxic compound that is formed as a disinfection by-product of chlorination and chloramination in water and wastewater treatment systems (Mitch and Sedlak 2002; Choi and Valentine 2001). Nitrosamines cannot be effectively treated with advanced water treatment technologies such as activated carbon, RO, or ozone. All nitrosamines, however, are effectively treated with UV light. A variety of regulatory agencies are acting to limit exposure to the nitrosamines. For example, at the federal regulatory level in the U.S., nitrosamines have recently been included on the EPA's proposed Unregulated Contaminant Monitoring Rule 2 (UCMR 2). At the state level, California has set a Notification Level for NDMA at 10 nanograms per liter (ng/L) and a Public Health Goal of 3 ng/L. Ontario has promulgated a 9 ng/L standard.

The issue of contaminants in the environment is a worldwide issue. For example, in Europe, a variety of water quality investigations have been performed (e.g. Ternes 1998). In one survey, completed in 2000-2001 by EUREAU, a European association of water suppliers and wastewater operators, found that in the UK, raw groundwater regularly exceeds water quality standards in 6% of resources while a further 5% of resources exceed the pesticide limits occasionally. When considering surface water (rivers and lakes) the percentage of resources exceeding water quality standards increases dramatically to 77% (EUREAU 2001). In another study by the UK's Department for Environment, Food, and Rural Affairs (DEFRA 2002), it was found that 29% of freshwater sites contained pesticide concentrations exceeding Environmental Quality Standards on at least one sampling occasion. The most commonly detected pesticide was isoproturon, followed by mecoprop and diuron.

In addition to anthropogenic contaminants, certain naturally-produced chemical contaminants can impact the aesthetic quality of drinking water. Organic chemicals resulting from algae blooms, primarily geosmin and MIB, are often responsible for earthy/musty tastes and odors in drinking water. In a typical case, algae and bacteria release MIB and geosmin into the water in the summer/early fall (Hoehn 2002). In addition to aesthetic impacts, certain types of blue-green alga produce algal toxins (such as microcystin) that can have both acute and chronic impacts on humans (Kuiper-Goodman et al 1999). Because, to the average consumer, the aesthetic quality of water is the most obvious indicator of overall quality, increased attention is being focused on solving taste and odor (T&O) problems. For some municipalities, conventional solutions such as powdered and granular activated carbon (PAC and GAC) are adequate. However, for many, large doses of PAC or frequent change-outs of GAC are required. In addition, the application of ozone technology can be cost prohibitive and incapable of meeting *Cryptosporidium* treatment requirements and limits on byproduct formation (specifically bromate) as set forth in the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) and the Disinfectant/Disinfection Byproducts Rule. For many utilities, UV technologies are the best option to comply with the treatment requirements of the LT2ESWTR. In addition, there is a growing awareness of UV-based oxidation processes for treating micropollutants in water. A variety of researchers over the last 15 years have identified UV-oxidation as an efficient technology to treat T&O-causing compounds and algal toxins in drinking water (e.g., Glaze et al. 1990, Stefan and Royce 2005). Further, numerous full scale UV-oxidation installations including the PWN Water Supply Company North-Holland (located in the Netherlands), are currently in operation treating a variety of environmental contaminants. Specifically, the PWN installation has been in continual operation for approximately two years disinfecting and acting as a barrier to pesticides, T&O-causing compounds and algal toxins.

ENVIRONMENTAL CONTAMINANT TREATMENT OPTIONS

A variety of treatment options have been employed to act as barriers to chemical and microbiological contaminants. Examples include ozone, PAC, GAC and membranes (from microfiltration to reverse osmosis). Each has advantages and limitations.

An additional option that in many cases provides cost effective multi-barrier capability is UV light (either alone or in conjunction with hydrogen peroxide). UV light-based water treatment systems have a variety of advantages.

- UV-based processes treat contaminants that may not be treatable by conventional (or even advanced) water treatment technologies alone due to a contaminant's relatively high solubility, small molecular weight, or resistance to degradation by chemical treatment.
- The use of some treatment options (chlorine or ozone, for example) can promote the formation of by-products such as trihalomethanes (THMs) or bromate, which have been identified as potential carcinogens and are strictly regulated at low levels in drinking water.

These advantages have encouraged a shift from chemical-based disinfection (chlorine, chloramines, ozone) to UV light-based disinfection.

How Does UV-Oxidation Work?

UV photolysis and UV oxidation are the photochemical processes that break down chemical contaminants. A brief description of each process follows.

UV photolysis is the process by which the chemical bonds of the contaminant are broken by the energy associated with UV light. When light is incident on an object, the photons may be reflected, transmitted, or absorbed. When UV photons enter water, they are both transmitted and absorbed by the water itself and its constituents (dissolved species including organic and inorganic substances). Photons that are absorbed may initiate a photolysis reaction. A contaminant molecule will undergo the photolysis reaction if 1) the contaminant molecules in water are capable of absorbing UV photons (measured by the contaminant's molar absorption coefficient) and 2) the energy holding the chemical bonds in the molecule together is less than the energy of the UV photons absorbed.

UV oxidation is a photochemical process that breaks down organic constituents in water by the process of oxidation, in this case initiated by the hydroxyl radical. UV oxidation begins with the scission (splitting) of the O-O bond in the hydrogen peroxide molecule through UV photolysis. Hydrogen peroxide is made up of two oxygen and two hydrogen atoms. When exposed to UV light, one hydrogen peroxide molecule splits into two hydroxyl radicals. The resulting hydroxyl radicals are highly reactive species that react unselectively with organic compounds (including contaminants) in the water. In addition, while the hydroxyl radical continues its reaction with the chemical contaminant, photolysis of the contaminant will in most cases also occur.

Some chemicals are preferentially treated by the UV-photolysis process; others are preferentially treated by the UV-oxidation process. Most are treated by a combination of both where UV photolysis and UV oxidation act simultaneously to break down the chemical contaminant.

Examples of the Application of UV-Oxidation

Drinking Water - The Aurora Water Purification Facility, Aurora, CO

Faced with a rapidly growing population and limited water resources, the City of Aurora is taking an innovative approach to prepare for the city's water future. This effort, known as the Prairie Waters Project, will enable the city to maximize its use of water it already owns from the South Platte River. A key component of this strategy is the construction of the Aurora Reservoir Water Purification Facility (ARWPF). An advanced treatment process will be utilized to ensure that the water is pure and free from microbial and chemical contaminants.

The 50 million gallon per day (MGD) ARWPF will utilize bank filtration, enhanced coagulation, the TrojanUVPhox™ UV-oxidation system, and granular activated carbon filtration. Testing has shown that this treatment process effectively purifies the water to a quality beyond drinking water standards. Trojan UV oxidation was selected as a cornerstone treatment process at this facility for its superior disinfection capabilities and for its ability to destroy micropollutants without forming harmful by-products.

The TrojanUVPhox™ will act as a barrier to a variety of environmental contaminants. Examples include taste and odor-causing compounds such as MIB and geosmin, algal toxins such as microcystin, pharmaceuticals such as ibuprofen and acetaminophen, hormones such as estrogens and testosterone, pesticides such as atrazine and isoproturon, and nitrosamines such as NDMA.

The TrojanUVPhox™ was selected after a cost-benefit evaluation of potential purification approaches was conducted by the engineer (CH2M Hill) and the City of Aurora. Other technologies such as ozone were also evaluated. Trojan UV-oxidation was selected for its ability to

- Provide superior disinfection,
- Accomplish treatment without creating disinfection by-products such as bromate, and
- Act as a barrier to multiple contaminant classes such as nitrosamines, taste and odor-causing compounds, pharmaceuticals, steroids, and pesticides.

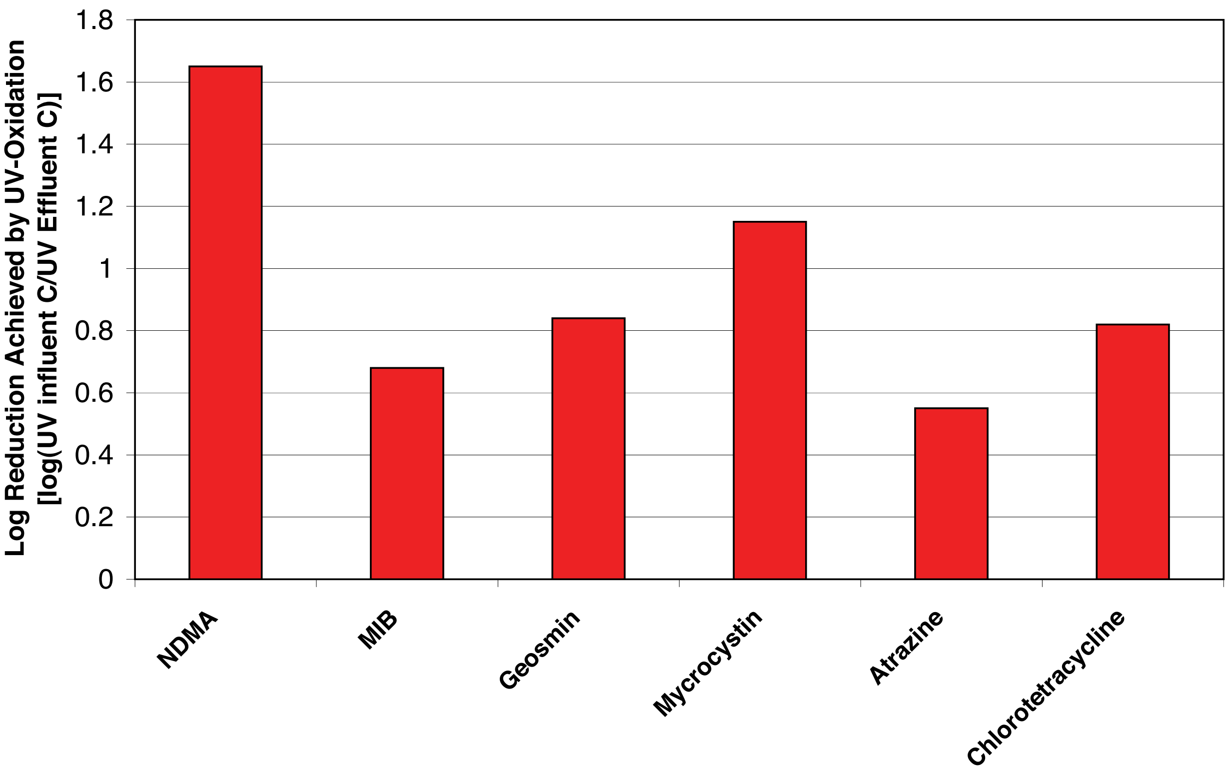
The use of UV-oxidation for contaminant treatment at Aurora is making it possible to reduce or eliminate a reliance on reverse osmosis (RO) membranes. RO systems can reject 10% to 20% of influent water as a brine waste stream. This waste stream is difficult to dispose of, especially in landlocked communities such as Aurora, Colorado. The TrojanUVPhox™ will perform many functions similar to that performed by RO. In addition, the UV-oxidation system will act as a barrier to nitrosamines, which cannot be fully removed by RO.

During the design of the TrojanUVPhox™ system for Aurora, CH2M Hill performed a number of experiments to simulate, using actual water from the source, the contaminant reduction through each of the treatment steps. Using various test-scale UV-oxidation systems, the log reduction of NDMA, MIB, geosmin, microcystin (an algal toxin), atrazine (a pesticide), and chlorotetracycline (a pharmaceutical) was determined by simulating the expected full scale operating conditions (i.e., full scale UV energy and hydrogen peroxide concentration). The results for treated water with an 86.5% UV transmittance and a pH of 7.5 are given in Figure 1. In the tests, log reductions varied from 0.55 for atrazine to 1.65 for NDMA (Swaim 2006).

Indirect Potable Wastewater Reuse - Orange County Water District

UV technology is also being applied at the Orange County Water District (OCWD) in Southern California. In a region known for its scarcity of water, OCWD is constructing a facility that will purify up to 100 MGD of wastewater per day for augmentation of regional groundwater supplies. This project, known as the Groundwater Replenishment (GWR) System, is the largest indirect potable reuse (IPR) project in the world. Following secondary wastewater treatment, water will pass through advanced treatment including microfiltration (MF), RO, and UV-oxidation using the TrojanUVPhox™. These treatment steps effectively remove any contaminants present in the water, making its quality better than that of most drinking water. The filtration steps MF and RO remove the larger molecular weight compounds and reduce TDS, while UV-oxidation destroys any remaining low-molecular weight and recalcitrant compounds such as NDMA and 1,4-dioxane. The UV-oxidation system will also provide >4 log-removal disinfection.

Figure 1. *Degradation of environmental contaminants by UV-oxidation in bench and pilot studies simulating full-scale operation at the ARWPF*



The UV system for OCWD was designed to treat 150 ng/L of NDMA to less than 10 ng/L. In addition, the system is required to disinfect delivering a UV dose of at least 100 mJ/cm^2. In order to obtain an operating permit from the regulating body with jurisdiction over the GWR System, the California Department of Health Services (DHS), a portion of the full scale system (capable of treating 5 MGD) was installed as a demonstration system in June 2004. This demonstration-scale TrojanUVPhox™ system underwent extensive testing to demonstrate both contaminant (NDMA) destruction and disinfection (MS2 coliphage used as a challenge organism). The UV system was tested at the designed flow of 5 MGD with an influent NDMA of 150 ng/L. The performance exceeded the requirements, as the effluent NDMA concentration was measured below 10 ng/L (Figure 2). The addition of H_2O_2 at a low level (3 mg/L) ensured the destruction of other contaminants such as volatile organic compounds or pharmaceuticals that may be present in the water.

Based on the performance data, the California DHS has granted a permit to operate the demonstration scale system for the delivery of water for injection into the groundwater aquifer. The construction of the full scale system is underway and scheduled for completion in 2007.

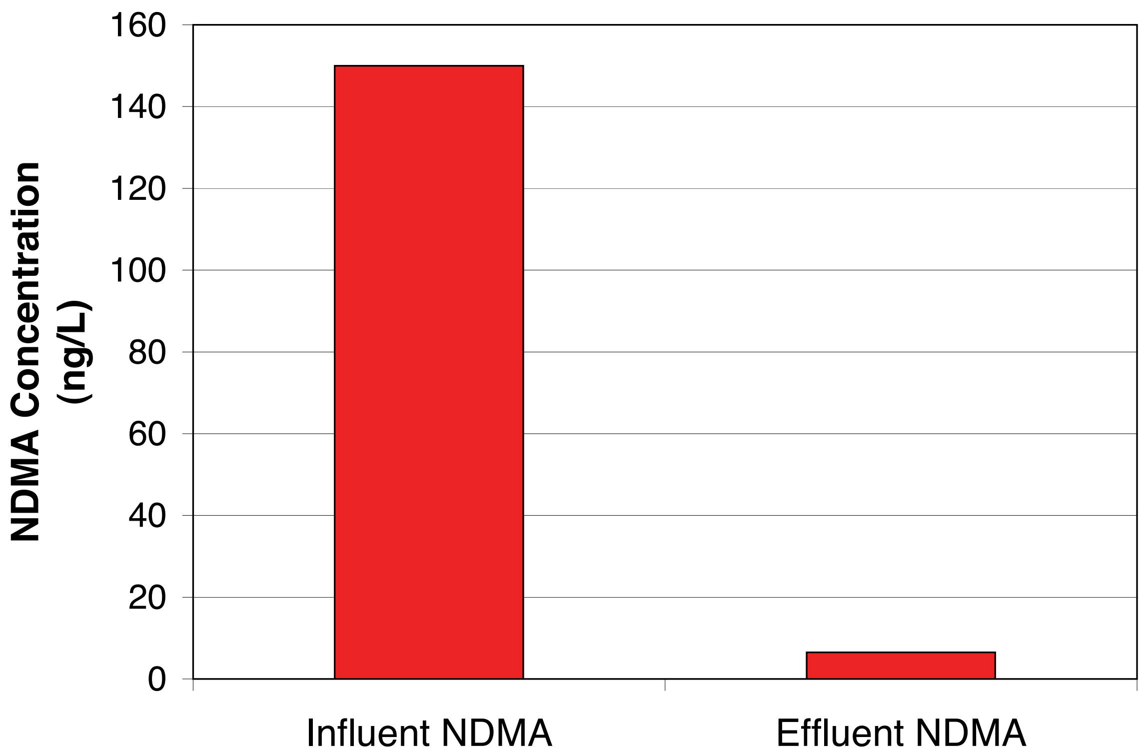
Drinking Water - Cornwall, Ontario, Canada

The city of Cornwall in Ontario, Canada is a city of nearly 60,000 people located on the St. Lawrence River. The city draws its drinking water from this river, a reliable and generally good-quality source. However, in the late summer and early fall, dying algae from algae blooms during the warmest months often leave an earthy and musty taste in the water. The city's conventional treatment process consisting of coagulation, sedimentation, and mixed-media filtration was unable to remove sufficient quantities of geosmin and MIB, the compounds responsible for the difficult-to-treat taste and odor (T&O) problem.

Concurrently, the city had a need to meet addition disinfection rules set forth by the Ontario Ministry of the Environment, rules intended to protect the public from *Giardia*. The existing chlorine disinfection system, in addition to introducing a negative chlorinous taste to the water, was inadequate to meet the new rules. The city made a decision to install UV disinfection to accomplish an additional 1-log reduction of *Giardia* to earn additional disinfection contact time (CT) credit.

The city chose a TrojanUVSwift™ ECT with a capacity of 26 MGD. The system is sized to accomplish a 1-log reduction in the concentration of geosmin while also delivering a disinfection dose to perform *Giardia* inactivation.

Figure 2. *Results of performance testing at Orange County GWR System*



The system will operate in two modes, Disinfection-Only Mode and T&O-Control + Disinfection Mode. In Disinfection-Only Mode, the UV system will operate at lower energy levels sufficient for inactivation of any microorganisms. This is the normal operating mode for year-round drinking water treatment. While in Disinfection-Only Mode, only a fraction of the total UV lamps and/or reactors installed will be operated thereby keeping the operating costs at a minimum while simultaneously meeting disinfection requirements. During a T&O event, the UV system is operated in T&O-Control + Disinfection Mode. In this mode, additional UV lamps/reactors are energized and hydrogen peroxide dosed into the water upstream of the UV system. The combination of UV and hydrogen peroxide initiates the oxidation reaction that destroys T&O-causing chemicals and increases the level of disinfection. This system offers a variety of benefits to the Cornwall treatment train, including the multiple-barrier capability of treating chemical and microbiological contaminants without forming bromate, a small footprint, and simple operation.

Construction of the new plant was completed in August 2006. Startup was in progress at the time of publication.

SUMMARY

Contaminants are present in water supplies. Some, like taste and odor-causing compounds derived from algae blooms, are formed by natural processes in the environment. Others enter the water supply from anthropogenic sources such as industrial or municipal wastewater. Water providers are continually challenged to provide safe, reliable and aesthetically-pleasing drinking water. UV-oxidation has emerged as a powerful technology that can play a multi-functional role in a multi-barrier water treatment system, simultaneously treating a variety of contaminants and providing highly effective disinfection.

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