Enhance Water Treatment Processes with **UV Advanced Oxidation**

TROJAN UV

Contents

Introduction

The UV advanced oxidation process (UV AOP) is a water treatment method often employed for the treatment of less pristine sources of drinking water, such as treated wastewater in the case of potable reuse, or contaminated groundwater aquifers in the case of groundwater remediation. Regardless of the application, the commonality of UV AOP treatment sites is the treatment of micropollutants.

When UV technology is used for other purposes, such as pathogen treatment, installed UV equipment often requires less intense amounts of ultraviolet light. With UV AOP applications, UV intensity levels are significantly higher. In addition, many other factors can influence UV equipment's performance and delivery of UV intensity and dose. As a result, the successful implementation of UV AOP for advanced water treatment requires experienced knowledge of both the science of the treatment and the engineering behind the equipment used to deliver the treatment.

Trojan Technologies has supplied UV equipment for municipal-scale water treatment systems under the TrojanUV brand for nearly half a century. Backed by world-class research and engineering teams, Trojan Technologies is a global leader in the design and execution of UV AOP systems for multiple contaminant treatment applications.

Water treatment stakeholders, including consulting and process engineers, operators and equipment owners, and permitting and regulatory agencies, can use this eBook to understand the science that drives UV AOP treatment. This resource provides quick and accurate information about UV AOP to assist stakeholders with smooth project decisions and development transitions. The following topics will be reviewed at a general level:

- Definitions
- Equipment requirements
- Project development recommendations
- Site-specific situational guidance
- Comparisons with competing technologies

To learn more about UV AOP technology and TrojanUV systems, contact a Trojan Technologies expert on our website.

What are micropollutants?

Micropollutants (also called environmental contaminants, trace organics, and emerging contaminants) can refer to chemicals in soil, air, and water. **This eBook focuses on micropollutants that can impact water sources.**

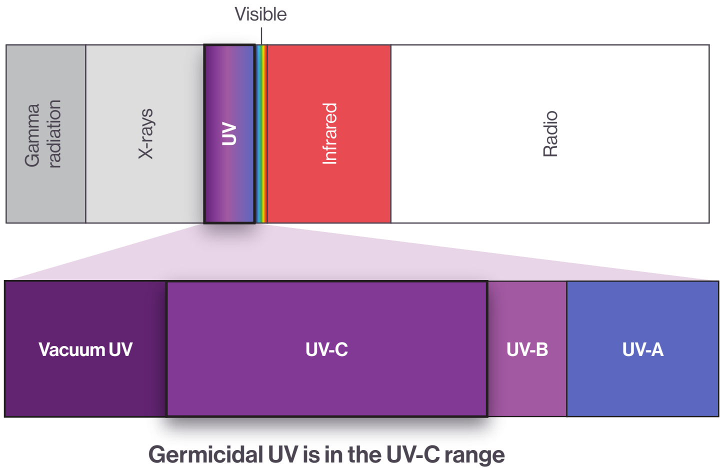
Several micropollutants, including industrial solvents and byproducts, pesticides, and pharmaceuticals, exist at trace concentrations in streams, lakes, rivers, and groundwater. Micropollutants may enter the water directly from human activities, such as industrial manufacturing, agriculture, and wastewater discharge. They may also originate from natural sources, such as algal blooms that release toxins and taste- and odor-causing molecules. Many micropollutants can have carcinogenic, endocrine-disrupting, or other harmful properties. Further, removing micropollutants can be challenging through conventional water treatment processes like filtration. Some micropollutants are difficult to remove even with advanced membrane technologies like microfiltration (MF) and reverse osmosis (RO).

The UV advanced oxidation process

For over a century, UV technology has successfully been applied to treat various pathogens in municipal drinking water and wastewater. Over the last several decades, UV treatment applications have expanded to include the treatment of micropollutants, either independently or in combination with pathogen treatment. Some micropollutants can be treated using UV energy alone, but most are broken down more readily with the addition of an oxidant. This treatment is the UV advanced oxidation process (UV AOP). UV AOP offers significant advantages over other technologies, including ozone-based AOPs, for the treatment of micropollutants. But how does UV AOP work?

Ultraviolet light

All light exists in the form of photons. Photons are "packages" of energy with properties of waves and particles. The human eye can detect wavelengths of light between 400 nanometers (nm) and 700 nm, referred to as the visible light range. Ultraviolet light is the term used for high-energy, non-visible light with wavelengths between 10 and 400 nm (**Figure 1**).



Germicidal UV is in the UV-C range

Figure 1: The inset represents the electromagnetic spectrum with the UV range.

The wavelength range of UV has four subranges: Vacuum-UV, UV-A, UV-B, and UV-C. Most commercial UV lamps emit light in the UV-C range with wavelengths between 200 and 280 nm. Light emitted in the UV-C range is commonly referred to as "germicidal" light as it is absorbed by and consequently damages genetic material (e.g., DNA), resulting in inactivation of the organism (inability to reproduce) (**Figure 2**). These same wavelengths are also effective for destroying micropollutants through UV photolysis and UV oxidation.

UV photolysis

UV photolysis refers to "direct UV attack." It is a photochemical reaction that only requires ultraviolet light (**Figure 3**) and is initiated by the absorption of ultraviolet light by micropollutants, resulting in the breakdown of their molecular bonds. The degradation or breakdown of a micropollutant by UV photolysis is a function of the following characteristics:

- **Molar absorption coefficient (ε):** The amount of light absorbed by a 1-molar (M; mol/Liter) solution of the micropollutant at a specific light wavelength over a 1-cm pathlength of water. The larger the number, the more photons a micropollutant absorbs at that wavelength.
- **Quantum yield (Φ):** The ratio of resulting molecules being produced when compared to the number of molecules absorbing light. For example, if the quantum yield is 1, then 1 product molecule is produced for every micropollutant molecule that absorbs light.

Some micropollutants might absorb less ultraviolet light (i.e., have low molar absorbance). However, if they have a high quantum yield, they can still be treated effectively through UV photolysis, and vice versa.

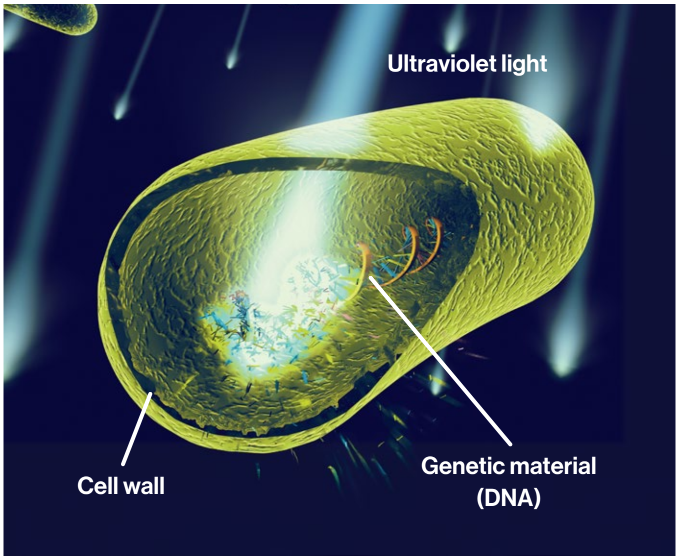


Figure 2: UV is an established water treatment process, where ultraviolet light is absorbed by microorganisms, resulting in their inactivation.

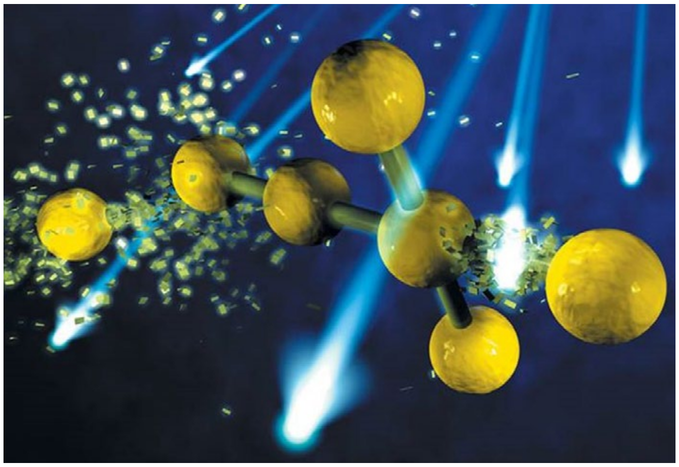


Figure 3: UV photolysis is a process where the chemical bonds of micropollutants are broken due to the direct absorption of ultraviolet light.

UV oxidation

Oxidation refers to the loss of electrons from a molecule, which are taken by another molecule during a chemical reaction. The UV oxidation reaction is a powerful type of oxidation reaction that occurs when combining ultraviolet light and oxidizing agent, such as hydrogen peroxide.

The UV oxidation reaction is illustrated in **Figure 4**. An oxidation precursor or oxidant, such as hydrogen peroxide (H_2O_2), is added to the contaminated water ahead (upstream) of a UV chamber. Once the water enters a UV chamber, the oxidant absorbs ultraviolet light. The UV photolysis process converts the oxidant into more powerful oxidants called free radicals (e.g., one molecule of hydrogen peroxide can become two hydroxyl radicals when exposed to ultraviolet light). Other oxidants, including free chlorine, can be used instead of hydrogen peroxide to produce additional free radical species. Radicals are highly reactive chemical species that immediately "attack" and steal electrons from nearby molecules, resulting in their oxidation, ultimately destabilizing and degrading their molecular structure.

Radicals, including hydroxyl radicals, are some of the most effective oxidizing agents known (**Table 1**). Free radicals generated through UV oxidation react immediately and non-selectively with micropollutants and other undesirable molecules in the water. The rate at which these reactions occur is described by a second-order rate constant specific to each micropollutant and free radical:

- **Reaction rate constant (k):** A measurement of how fast a chemical reaction takes place. In UV AOP systems, reactions with hydroxyl radicals (·OH) generally follow second-order kinetics, so the units are expressed as $M^{-1}s^{-1}$. For example, the value of $k_{\cdot OH}$ represents the rate at which a compound reacts with hydroxyl radicals, in terms of molecular concentration per second.

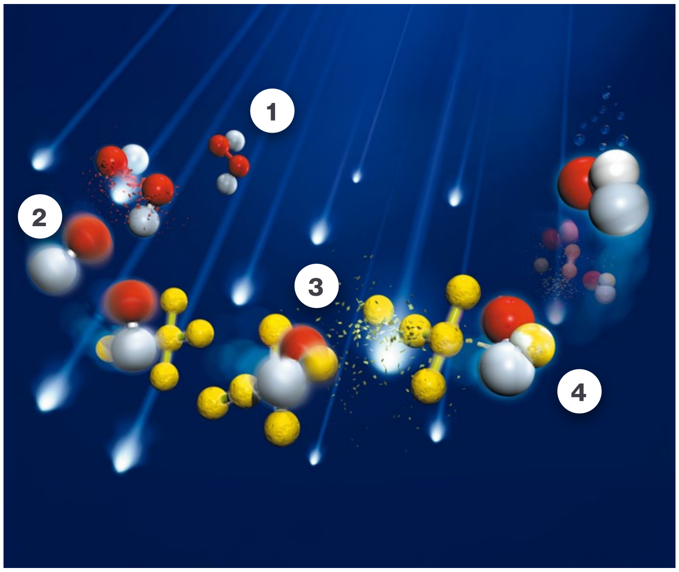


Figure 4: UV oxidation is a process where an oxidation precursor like hydrogen peroxide *(1)* is converted to free radical species *(2)*, which interact with micropollutants *(3)*, resulting in their oxidation and breaking of their chemical bonds *(4)*.

Oxidant	**Oxidation potential** (volts)
Fluorine	3.0
Hydroxyl radical	2.8
Chlorine radical	2.1
Ozone	2.1
Hydrogen peroxide	1.8
Chlorine	1.4

Table 1: The oxidation potential of several common oxidizing agents

UV AOP combines UV photolysis and UV oxidation

The UV oxidation process enhances but does not fully replace treatment provided by direct UV photolysis of a micropollutant. Micropollutants are treated differently by a combination of these processes. For example, *N*-nitrosodimethylamine (NDMA) is a micropollutant treated almost exclusively through UV photolysis. In contrast, other micropollutants like 1,4-dioxane are treated almost exclusively by radical oxidation through UV oxidation.

For most micropollutants, including taste- and odor-causing compounds (e.g., 2-methylisoborneol and geosmin), algal toxins (e.g., microcystin), pesticides (e.g., atrazine), and others, providing the desired treatment through UV AOP requires an optimum balance between UV photolysis and UV oxidation. This balance is managed by the UV AOP programmable logic controller (PLC) and is highly influenced by the natural characteristics of the water being treated (refer to what affects and influences UV AOP treatment). **Figure 5** illustrates the relative contribution of each photochemical process for some micropollutants.

Remember that UV photolysis and UV oxidation occur simultaneously and almost immediately when the water enters the UV chamber during AOP treatment. No extended contact basins are needed after the UV chamber to complete treatment.

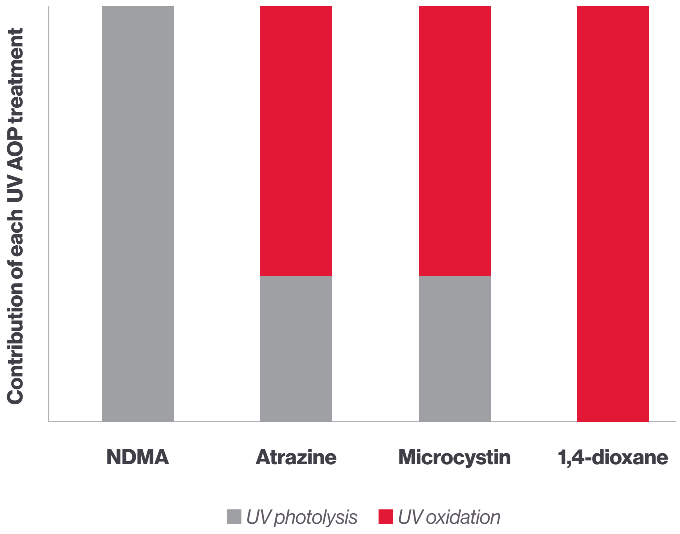


Figure 5: Contribution of UV photolysis and UV oxidation to the treatment of selected micropollutants during UV AOP

Want to investigate a UV AOP system for a particular micropollutant? Contact a Trojan Technologies representative.

What micropollutants can UV AOP target and treat?

Any micropollutant that can have its molecular structure compromised through either UV photolysis or oxidation reactions can potentially be treated by a UV AOP system (**Table 2**). Trojan Technologies uses published values or values determined through internal research for molar absorption coefficients (Φ), quantum yields (ε), and radical rate constants

(k) to determine the appropriate amount of UV dose and oxidant (if needed) required to deliver the desired treatment of single or multiple micropollutant targets.

Using UV AOP to treat pathogens

Before being used in applications like UV AOP, ultraviolet light for decades has been, and continues to be, recognized as a solution for treating pathogens, including various types of bacteria (e.g., *E. coli*), protozoa (e.g., *Cryptosporidium*), and viruses (e.g., *adenovirus*). A significant difference between these two UV applications is that the amount (intensity) of ultraviolet light required to carry out UV AOP treatment is significantly higher than the amount of ultraviolet light needed to treat pathogens. This means that properly designed UV AOP installations targeting micropollutants can provide enough ultraviolet light power to simultaneously achieve pathogen treatment.

The requirements for pathogen treatment can vary significantly from one application of UV AOP to another. Treatment sites of surface water or groundwater considered under the direct influence of surface water (GUDI) can benefit from using UV treatment to achieve the required 4-log virus credit in place of chlorine treatment, which although common, can lead to the formation of regulated chemical disinfection byproducts (DBPs). *Cryptosporidium parvum* is a common pathogen resistant to chlorine treatment that can be easily inactivated with ultraviolet light at sites that detect this pathogen in their source water. Lastly, advanced wastewater treatment and potable reuse UV AOP applications have stringent pathogen treatment requirements, and ultraviolet light can achieve as high as a 6-log treatment credit for viruses, *Cryptosporidium*, and *Giardia* in these applications.

Micropollutant type	Example(s)
Industrial volatile organic compound (VOC) stabilizers	1,4-dioxane
Industrial VOCs	Trichloroethylene (TCE), tetrachloroethylene (PCE)
Disinfection and oxidation byproducts	*N*-nitrosodimethylamine (NDMA)
Pharmaceuticals	Various antibiotics
Polycyclic aromatic hydrocarbons	DDT
Pesticides, herbicides, fungicides	Atrazine, metaldehyde, chlorothalonil
Algal toxins	Microcystin-LR, anatoxin
Taste- and odor-causing compounds	Methylisoborneol (MIB), geosmin
Cyanide	Free cyanide
Munitions	RDX
Endocrine disruptors	Bisphenol A, nonylphenol, carbamazepine, estradiol
Industrial contaminants	MTBE, TBA, hydrazine

Table 2: Examples of micropollutants treated by TrojanUV's UV AOP systems. Each system carried its own unique contaminant mix and desired amount of treatment. Trojan Technologies uses established kinetic modeling to guarantee the removal of a micropollutant of concern.

Equipment supplied with a UV AOP system

UV chamber

UV AOP treatment reactions occur in the UV chamber (**Figure 6**). The chamber houses the ultraviolet light-emitting lamps, which are contained in quartz sleeves to protect them from the water. The appropriate size of a UV chamber is determined by several factors, including the amount of water to be treated, its quality and characteristics, the micropollutant target(s), and the desired amount of micropollutant removal (often expressed as $\log_{10}$ reduction of the micropollutant).

Types of UV lamps used in UV chambers

Commercial UV systems typically use one of two lamp types: low-pressure (LP) and medium-pressure (MP) lamps. One critical difference between these two lamps is their UV emission output. LP lamps emit ultraviolet light at a single wavelength (254 nm), which is ideal for treating microorganisms (DNA absorbs light principally at 260 nm). MP lamps emit UV light across a range of wavelengths (**Figure 7**) and are called polychromatic.

Figure 6: A TrojanUVFlex® 200 AOP chamber with 144 lamps

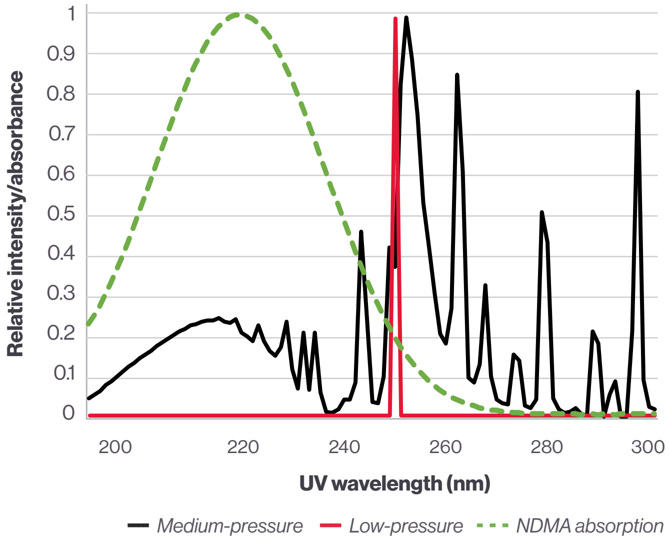


Figure 7: Relative MP and LP UV lamp emissions across the relevant range. Relative absorption of UV for the micropollutant *N*-nitrosodimethylamine (NDMA) is also shown.

When evaluating different lamp technologies, several factors affect the overall treatment efficiency and should be carefully considered. For some micropollutants, peak UV photolysis (higher molar absorption coefficient) may occur at wavelengths other than 254 nm, which may give MP lamps a greater capacity to carry out UV photolysis contaminant breakdown. MP lamps also have higher energy output than LP lamps, allowing fewer lamps and a smaller UV chamber footprint to be used. This can lower capital expenses.

However, despite the higher energy output, MP lamps are less efficient, meaning less UV energy is produced per watt of power needed by the lamp. UV AOP systems using MP lamp technology require more power to operate than equivalent UV AOP systems using LP lamps and can result in more than 3-fold higher power costs.

Oxidant, oxidant storage, and dosing equipment

Oxidant molecules are the source for even more powerful oxidizing free radicals after exposure to ultraviolet light. Two oxidants are commonly used in UV AOP applications: hydrogen peroxide (H_2O_2) and free chlorine. Selecting the best oxidant depends significantly on the water's characteristics and the UV AOP application (refer to choosing an oxidant).

Stock solutions of oxidant are stored in high-density polyethylene (HDPE) or metal tanks until the system signals the dosing equipment to inject the correct amount into the water treatment stream. To ensure thorough mixing before the water enters the UV chamber, static mixers are typically installed just before or after the injection point.

Programmable logic controller

The programmable logic controller (PLC) is an industrial computer that controls the UV AOP process and, most critically, the balance between the dose of ultraviolet light and oxidant needed to treat the desired micropollutants. The PLC can also collect and analyze measurements from online instruments that monitor for critical water characteristics (refer to what affects and influences UV AOP treatment) to determine the amount of ultraviolet light and oxidant needed at a given time. Depending on the control program used and measured values for these characteristics, such as flow rate or pH change, the PLC may modify the amount of ultraviolet light or oxidant dosed to maintain treatment of the target micropollutant.

Critical control setpoint treatment PLC

The critical control setpoint (CCS) program or "fixed dose" program utilizes predetermined targets for the UV and oxidant doses, which are programmed into the PLC. To ensure treatment targets are always achieved, these predetermined targets are often evaluated based on expected worst-case treatment conditions.

Over time, a treatment plant might experience situations that result in even worse treatment conditions, necessitating increased targeted doses for ultraviolet light or the oxidant. The CCS philosophy will not automatically make these adjustments and requires manual operator intervention, which might increase the risk of non-compliant, off-spec water.

Active control treatment PLC

Active control uses established photokinetic models programmed into the PLC to adjust targets for UV and oxidant doses in response to changes in UV AOP influencers (**Figure 8**). Online instrumentation—for example, monitors installed for pH, free chlorine, total chlorine, and others—can rapidly detect any worsening conditions, allowing the PLC to immediately respond by increasing UV or oxidant dose accordingly without operator intervention.

Active control approaches can also adjust doses if the treatment conditions become more favorable. In this case, UV and oxidant dose targets are lowered to allow the entire UV AOP system to operate more cost-effectively.

Residual oxidant quenching agent

Some of the oxidant added to the system may pass through the UV chamber without being converted into free radicals. To ensure water safety and quality, this residual oxidant may need to be removed through quenching. This can be achieved using a granular activated carbon (GAC) filter or by adding a suitable dose of free chlorine. Trojan Technologies can help recommend the most effective quenching approach for a specific application.

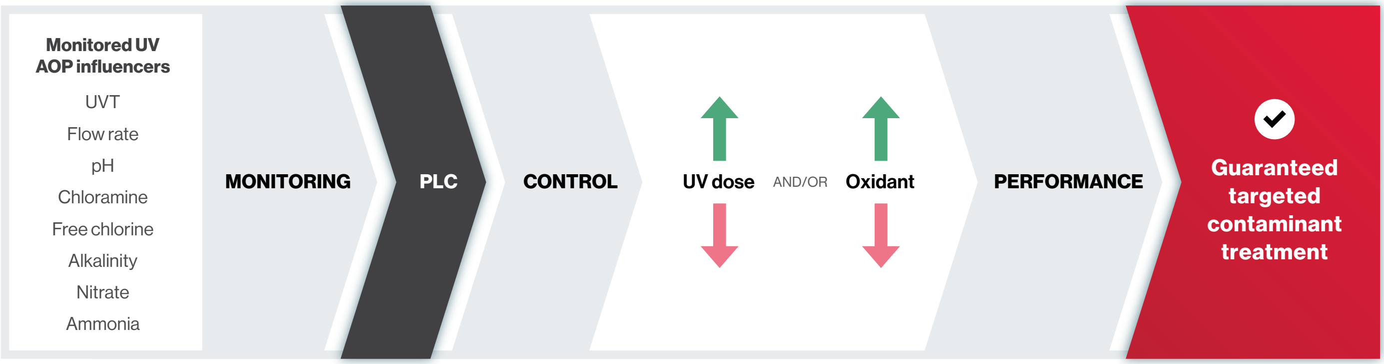


Figure 8: Embedded in the system's PLC, Trojan Technologies' active control program for UV AOP systems monitors critical water characteristics. It establishes appropriate dose targets for ultraviolet light and the oxidant in real time. The result is continual UV AOP performance where the desired removal of micropollutants is always achieved.

UV AOP applications

Groundwater remediation

Groundwater is generally a very clean source of drinking water. Soil acts as a natural filter and removes most micropollutants and pathogens. Extracted groundwater is typically ready to drink with little to no additional treatment. However, industrial contamination, landfill leachate, septic systems, and other pollution sources could contaminate clean groundwater with micropollutants.

As understanding of the public health risks posed by micropollutants in contaminated groundwater grows, regulations are evolving, and water providers are becoming more motivated to address these emerging compounds in their treatment processes. In 2020, for example, the State of New York implemented an enforceable maximum contaminant level (MCL) for the micropollutant 1,4-dioxane, a probable human carcinogen often detected in groundwater in areas of historic industrial activity (**Figure 9**). 1,4-dioxane is particularly challenging to remove from groundwater due to its ability to evade advanced membranes and air-stripping methods. Advanced oxidation is considered the best available treatment for the 1,4-dioxane micropollutant.

Other recognized groundwater micropollutants, including volatile organic compounds (VOCs) such as trichloroethylene (TCE) and tetrachloroethylene (PCE), can also be remedied through UV AOP treatment.

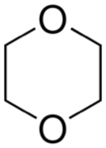
Properties of 1,4-dioxane	
Formula	$C_4H_8O_2$
Molecular weight	88.15
Structure	
	

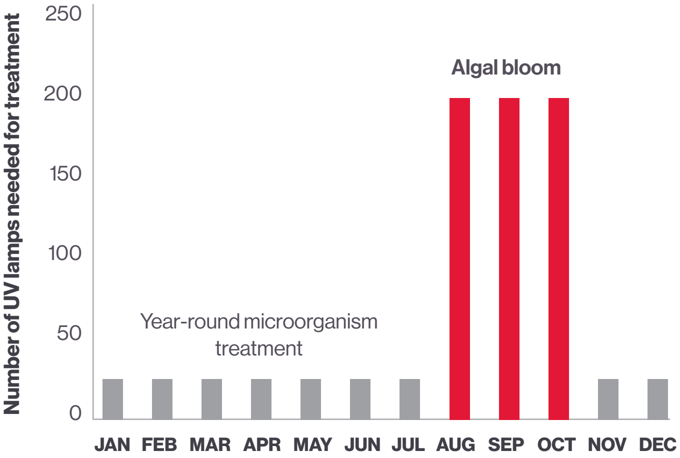
Figure 9: A micropollutant often found in groundwater, 1,4-dioxane is treated very effectively with UV AOP.

Surface water remediation

Unlike groundwater, surface water is more directly exposed to human and environmental influences and, therefore, more likely to become contaminated with micropollutants and pathogens. Agriculture can significantly contribute to surface water contamination, with a common occurrence being fertilizer and pesticide run-off into lakes and rivers during rainfall events.

Many regions maintain stringent regulations for pesticides in drinking water. In Europe, for instance, individual pesticides are limited to having a concentration of no higher than 0.1 micrograms per liter (µg/L) of water, with total pesticide limits being 0.5 µg/L. Further, when fertilizers enter surface waters through run-off events, they can provide the necessary nutrients for cyanobacteria (blue-green algae) growth. These algal blooms can produce cyanotoxins like microcystin, which have been proven harmful to health. Algae can also produce other compounds, including MIB and geosmin, which can negatively impact drinking water's aesthetic qualities, primarily taste and odor, often resulting in consumer complaints.

Many surface water remediation applications are seasonal. For example, cyanotoxins and taste- and odor-causing compounds generated by algal blooms are often a nuisance during late summer and autumn. If a treatment facility is experiencing these issues and also requires pathogen treatment for *Cryptosporidium* or viruses, then these lower UV intensity pathogen treatment requirements are most often needed throughout the year. For many UV AOP systems, the PLC can lower the UV intensity delivered during times of the year when UV AOP treatment is unnecessary. This convenient control approach can save owners significant operating costs (**Figure 10**).



Treatment	Type	Months	UV lamps	Oxidant	Power savings/yr
1-log methyllisoborneol and 1-log geosmin	UV AOP	Aug-Oct	192	Needed	–
4-log virus	UV	Jan-Jul; Nov-Dec	96	Not needed	$130,680
3-log *Cryptosporidium*	UV	Jan-Jul; Nov-Dec	24	Not needed	$174,960

Figure 10: Monthly representation of the number of UV lamps needed to treat 1-log (90%) of methylisoborneol and geosmin produced from a seasonal algal bloom and 3-log (99.9%) *Cryptosporidium* for the remaining months when algae are not present. The table shows the power cost savings possible by turning off unnecessary lamps when UV AOP treatment is not needed during the year.

Potable reuse

High population density and growing water scarcity have resulted in several regions with declining drinking water sources (surface and groundwater), especially if those regions are more exposed to drought conditions.

To ensure sustainable drinking water supplies, many of these regions are turning to domestic wastewater as a source of drinking water. To ensure this wastewater is treated to an advanced level of purity for reintroduction into the drinking water supply, specialized wastewater treatment plants, called advanced wastewater treatment facilities (AWTF), are constructed. AWTFs are often required to include UV AOP as a part of the advanced wastewater treatment process due to its ability to treat chemical micropollutants found in wastewater sources (**Figure 11**) and provide additional treatment for pathogens.

Water is naturally reused through the global hydrologic cycle. Potable reuse uses treatment systems to accelerate this natural process. AWTFs can send their advanced treated wastewater to an environmental buffer, such as a surface water basin or groundwater aquifer, before it goes to a drinking water treatment facility. This is indirect potable reuse (surface water augmentation and groundwater augmentation). Water from AWTFs that bypasses the environmental buffer and is sent directly to a drinking water treatment facility is direct potable reuse (raw water augmentation).

AWTFs typically use advanced membrane technology like MF and RO to remove small solids, some micropollutants, and some pathogens. However, even the most advanced membrane technologies, including RO, do not remove all micropollutants of concern. Advanced oxidation technology is considered a necessary treatment step at AWTFs to treat micropollutants that are not easily filtered from the water. For example, California, an established leader in implementing potable reuse and constructing AWTFs, requires targeted UV AOP treatment for 1,4-dioxane. NDMA, a recognized byproduct of wastewater treatment, is also a commonly targeted micropollutant treated with UV AOP systems at AWTFs.

Dual-treatment applications with UV AOP

In many advanced treatment scenarios, utilities and water providers must address multiple treatment objectives. A common requirement, for instance, is the treatment of pathogens, including bacteria and viruses. Since UV technology is a well-established and validated method for pathogen inactivation, this function can be simultaneously achieved with the same equipment as the UV AOP process. By doing so, utilities can achieve micropollutant and pathogen treatment objectives in a single step, streamlining treatment processes and reducing the need for additional equipment.

A. Full advanced treatment (FAT) typically used in California AWTFs

B. Carbon based advanced treatment (CBAT)

Figure 11: Examples of AWTF treatment train processes, including FAT treatment (A) and an alternative CBAT when RO brine discharge options are limited (B).

Choosing an oxidant for UV AOP: hydrogen peroxide or free chlorine

Hydrogen peroxide

Hydrogen peroxide (H_2O_2), on its own, is a strong oxidizing agent, but when hydrogen peroxide molecules absorb ultraviolet light, the result is the formation of two hydroxyl radicals. These radicals more rapidly oxidize targeted micropollutants of concern.

Advantages

Hydrogen peroxide is stable in most waters. For example, water properties like pH can influence the structure of some molecules but have less impact on the overall structure of hydrogen peroxide, making it easier to use across a range of treatment environments. Stock hydrogen peroxide is also stored as a liquid instead of a compressed gas, allowing for safer chemical storage.

Risks and drawbacks

Hydrogen peroxide handling requires basic personal protective equipment, especially if stored in highly concentrated stock solutions (27%, 35%, 50% w/w). Photolysis of hydrogen peroxide to hydroxyl radicals is not 100% efficient. Most hydrogen peroxide will not be converted into hydroxyl radicals and will remain in the water after the UV chamber. This residual hydrogen peroxide typically needs to be removed before the water can be safely used for purposes like drinking.

Free chlorine

Free chlorine is produced when chlorine stock solutions (sodium hypochlorite or chlorine gas) are added to the water. Free chlorine molecules are in one of two forms: hypochlorous acid (HOCl) or the hypochlorite ion (OCl-). Both free chlorine molecules can absorb ultraviolet light and produce free radicals.

Advantages

Free chlorine molecules have a higher molar absorption coefficient (at most UV wavelengths) than hydrogen peroxide, meaning more free radicals can be produced using free chlorine than with equivalent amounts (moles) of hydrogen peroxide. Furthermore, different species of radicals can be generated, adding another oxidation mechanism during the UV AOP process. Chlorine is also a widely used chemical in water treatment, and water providers often use it for other purposes, including secondary (residual) treatment in their distribution infrastructure. This means that any residual free chlorine not converted to radicals can often practically remain in the solution and does not require quenching.

Risks and drawbacks

The advantages of using free chlorine instead of hydrogen peroxide are situational. More specifically, the pH of the water needs to be within a range (refer to what affects and influences UV AOP treatment) that is principally only achieved after water has passed through RO membranes. Therefore, free chlorine's advantages are best realized in potable reuse UV AOP applications, and it is not recommended for other applications such as groundwater or surface water remediation.

What affects and influences UV AOP treatment?

The overall performance of UV AOP using either hydrogen peroxide or free chlorine depends on the UV equipment used and, more importantly, on the characteristics of the water being treated. This section details how water "influencers" can impact hydrogen peroxide and free chlorine in UV AOP systems.

UV transmittance

UV transmittance (UVT) measures how well ultraviolet light travels through water (**Figure 12**). As the value for UVT, often measured as a percentage transmittance through 1 cm of water, decreases, more background water constituents absorb or block the ultraviolet light, preventing UV from reaching the target micropollutants and oxidant.

How does UVT affect UV AOP with hydrogen peroxide?

As the UVT of treated water increases, more ultraviolet light can penetrate the water and photolyze hydrogen peroxide molecules, producing more hydroxyl radicals. Lowering UVT values has the opposite effect and reduces the efficiency of the UV AOP system.

How does UVT affect UV AOP with free chlorine?

As the UVT of treated water increases, more ultraviolet light can penetrate the water and photolyze free chlorine molecules, producing more free radical species. Lowering UVT values has the opposite effect and reduces the efficiency of the UV AOP system. Other influencers, such as ammonia and chloramines, can directly affect the UVT of water when free chlorine is used, and conversely, have less impact when hydrogen peroxide is used.

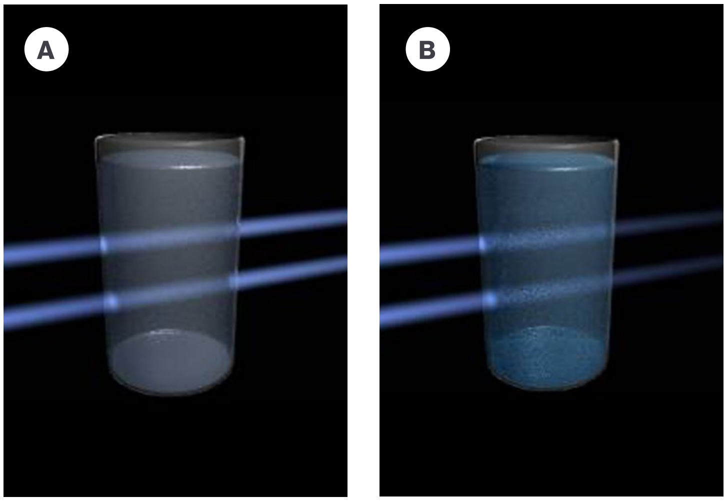


Figure 12: High UVT water (A) and low UVT water (B)

pH

The water's pH can significantly impact the structure of molecules, including oxidants added to the UV AOP system, potentially influencing their ability to generate free radicals. The structure of other molecules can also be altered, impacting the efficiency of the UV AOP.

How does pH affect UV AOP with hydrogen peroxide?

The pH does not directly impact the form of hydrogen peroxide, allowing hydrogen peroxide to be a more suitable UV AOP oxidant across a range of pH values. However, a small but noticeable correlation exists between rising pH and lower AOP performance. This is because pH impacts the form of other molecules, notably carbonate species commonly found in surface water and groundwater sources. Bicarbonate (HCO_{3-}) has a higher reaction rate constant with hydroxyl radicals compared to its conjugate acid, carbonic acid (H_2CO_3), and competes for the free radicals that are produced. This unwanted competition, typically called "scavenging," inhibits the UV AOP process. Bicarbonate concentrations increase and carbonic acid concentrations decrease as pH levels pass neutral (pH>7). Therefore, as pH increases, there are often more molecules that remove free radicals and inhibit the UV AOP system.

How does pH affect UV AOP with free chlorine?

pH significantly influences the molecular form of free chlorine in water. While both forms of free chlorine (hypochlorous acid [HOCl] or the hypochlorite ion [OCl-]) can absorb ultraviolet light, hypochlorous acid produces more free radicals than the hypochlorite ion. The hypochlorite ion has an over 10-fold higher affinity for free radicals than hypochlorous acid; therefore, it competes for the free radicals produced, acting as a free radical scavenger.

Hypochlorous acid is found at higher concentrations than the hypochlorite ion when the water becomes more acidic (pH<7). For free chlorine to be a suitable oxidant in a UV AOP system, nearly all free chlorine should be in its hypochlorous acid form, which happens when the pH falls below 5.5 (**Figure 13**). The pH of natural groundwater and surface water is often higher, but as previously mentioned, acidic pH values like this are usually measured in RO effluent water in potable reuse applications.

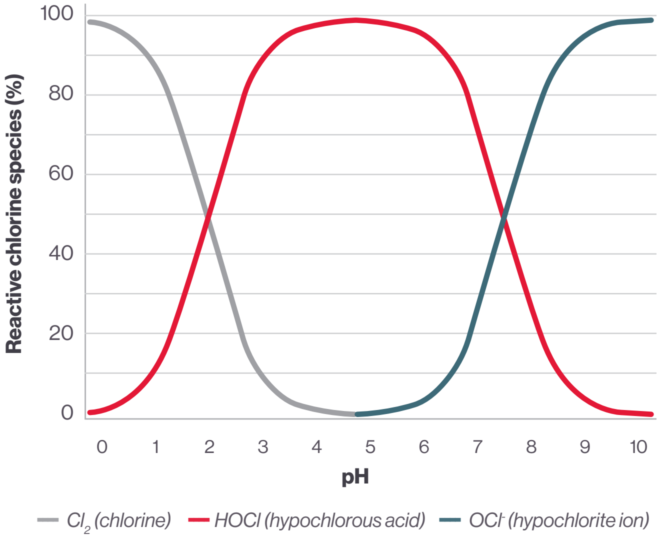


Figure 13: Graph showing free chlorine speciation across pH values. At a pH of 5 to 5.5, free chlorine speciation is close to 100% HOCl (hypochlorous acid), the ideal free chlorine species for producing free radicals for UV AOP treatment.

Alkalinity

Alkalinity is the buffering capacity of water, and more generally, a measurement of how resistant water is to a change in pH. It is often measured in terms of carbonate concentrations.

How does alkalinity affect UV AOP with hydrogen peroxide?

As alkalinity (carbonate) levels rise, a reduction in AOP treatment often occurs. This is because certain carbonate species, namely bicarbonate, act as hydroxyl radical scavengers and compete for hydroxyl radicals. As mentioned, this effect can be exacerbated as pH increases past neutral levels.

How does alkalinity affect UV AOP with free chlorine?

The effects of alkalinity are the same with free chlorine, but as mentioned above, free chlorine is most often used for UV AOP at potable reuse sites that treat RO membrane permeate. RO permeate water is very clean and generally has low levels of carbonate species. In addition, the acidic pH would result in more carbonic acid than bicarbonate, which has a lower affinity for radicals and is less of a scavenging risk.

Nitrate

Nitrate (NO_3-), naturally found in many waters, absorbs specific wavelengths of ultraviolet light (**Figure 14**) and can reduce the number of UV photons available for UV photolysis and free radical production. Wavelengths less than or equal to 240 nm are principally absorbed by nitrate. Since LP UV lamps (refer to UV lamp types) emit light principally at 254 nm, they are less influenced by nitrate. Approximately 20% of the UV emissions from MP lamps are affected by nitrate absorbance and are more impacted by higher nitrate concentrations.

"Scavenging" is a term used to describe unwanted competition for the free radicals produced in the UV AOP system. Scavenging potential varies significantly by water type. Trained Trojan Technologies staff can determine the background risk of scavenging in a site's water, which will ensure a successful full-scale design backed by the Trojan Technologies Performance Guarantee.

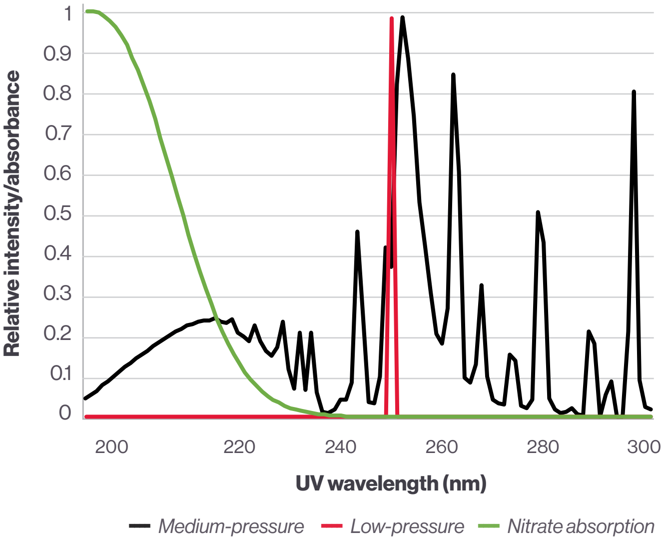


Figure 14: Relative MP and LP UV lamp emissions across the relevant range. Relative absorption for UV for nitrate is also shown.

How does nitrate affect UV AOP with hydrogen peroxide?

When nitrate absorbs ultraviolet light, it is partially photolyzed into another molecule called nitrite (NO_2-). The nitrite molecule has a high reaction rate constant with hydroxyl radicals, making it a strong hydroxyl radical scavenger that competes for free radicals that are produced, thus reducing the overall efficiency of the UV AOP system.

How does nitrate affect UV AOP with free chlorine?

When nitrate absorbs ultraviolet light, it is partially photolyzed into another molecule called nitrite (NO_2-). The nitrite molecule has a high reaction rate constant with free radicals, making it a strong hydroxyl radical scavenger that competes for free radicals that are produced, thus reducing the overall efficiency of the UV AOP system. Since free chlorine is used most frequently as a UV AOP oxidant for potable reuse applications after treatment with RO membranes, RO should remove many nitrate molecules, so they will likely not be as influential.

Ammonia and chloramines

While ammonia (NH_3) can be found naturally in water, its influence on UV AOP treatment is often present when it is intentionally added with free chlorine before membranes (including RO membranes) to produce chloramines for membrane pretreatment and the prevention of biological growth. Chloramines are also used for pathogen treatment in wastewater and drinking water applications.

How do ammonia and chloramines affect UV AOP with hydrogen peroxide?

Rising concentrations of monochloramine (NH_2Cl) can have an inhibitive impact on UV AOP treatment because, when present, it lowers the UVT of the water, negatively impacting the amount of UV photolysis and free radical generation. However, monochloramine is not found naturally in most groundwaters or surface waters, and the risk of it affecting UV AOP with hydrogen peroxide is low.

How do ammonia and chloramines affect UV AOP with free chlorine?

Monochloramine is challenging for UV AOP with free chlorine and potable reuse applications due to its frequent use as an upstream RO membrane pretreatment. Any residual monochloramine in the RO permeate can lower UVT and inhibit the downstream UV AOP system. Furthermore, additional free chlorine added for the UV AOP treatment process can react with any residual ammonia to produce more monochloramine, further propagating interference with the treatment process.

However, additional free chlorine does convert monochloramine to dichloramine ($NHCl_2$), the latter molecule not having the same inhibiting characteristics. So-called “breakpoint chlorination” kinetics, which account for the multiple reactions involving chlorine and monochloramine species, are critical to understand when designing a UV AOP system using free chlorine. Understanding these kinetics principles and programming them into an active control PLC (refer to equipment supplied with a UV AOP system) helps accurately determine the values of UVT and chlorine species concentrations needed for compliant micropollutant treatment.

Micropollutant treatment technology comparisons

Air stripping

Air stripping is valuable in treatment applications where targeted micropollutants can be easily "volatized" or taken out of water and transferred into the air.

- Air stripping transfers a micropollutant to the vapor phase and does not remove it from the environment. Discharge of the resulting contaminated air may require permits and treatment of off-gases (with carbon filters or biofilters, for example).
- Air stripping is ineffective at treating NDMA, 1,4-dioxane, vinyl chloride, and other micropollutants that are not easily volatized.
- Air-stripping systems may not be suitable at sites with height or noise constraints, as they typically require tall towers and produce significant noise from high-powered air blowers.
- No pathogen treatment is achieved with air stripping.

Ozone

Ozone treatment, like UV AOP, is an example of oxidation treatment where micropollutants are broken down through the oxidation and degradation of their chemical bonds. Unlike UV AOP, ozone does not require ultraviolet light to deliver treatment, and this can make ozone more practical when treating waters with reduced clarity.

- Ozone is a weaker oxidizing agent than the free radicals produced through UV AOP systems. A contact time (CT) of several minutes in the water is necessary before treatment can be considered complete. The fast-acting free radicals produced with UV AOP treatment provide instant treatment with negligible CT.
- Due to the CT requirement, ozone needs contact basins, ozone generators, ozone destruction units, compressors, and liquid oxygen storage tanks, which can require a larger initial investment than UV AOP.
- Many waters have some naturally occurring bromides that can react with ozone to form bromate, a regulated treatment byproduct and known carcinogen.
- Ozone is ineffective against NDMA, a byproduct of wastewater treatment and a common target of UV AOP systems in potable reuse applications.
- NDMA can be produced as a byproduct of ozone treatment in potable reuse applications if the prerequisite precursors are present in the wastewater supply.

Activated carbon (powdered and granular)

Activated carbon is a filtration technology where an organic substance, such as coal, is subjected to extreme heat, making the material porous. These pores or adsorption sites can trap small molecules, including micropollutants. The use of activated carbon has been a well-established method of removing a variety of micropollutants in several applications.

- Activated carbon filters micropollutants, removing them from the water but not the environment. Disposal of saturated “spent” carbon requires landfill shipping and disposal or direct regeneration of the spent carbon through reactivation. Both processes can have negative environmental impacts.
- Replacement of carbon filter vessels can be costly.
- Powdered carbon is very cumbersome to work with.
- Activated carbon’s ability to remove NDMA, 1,4-dioxane, many pesticides, vinyl chloride, and other micropollutants with a low affinity for carbon is limited. Breakthrough detections can be rapid, resulting in frequent media change-outs at a considerable expense.
- Activated carbon has a lower impact on pathogens such as *Cryptosporidium*, *Giardia*, and viruses.

Membranes

Membrane technology includes several different types of filters made from synthetized fibers that can remove extremely small molecules and ions. Examples include MF, nanofiltration (NF), and RO.

- Certain molecules treated by UV AOP, namely 1,4-dioxane and NDMA, can pass through membranes, including RO, the membrane technology with the highest rejection and best ability to filter contaminants.
- The filtrate (called “brine” in RO applications) collected off membranes must be backwashed and disposed of. This waste management step adds complexity to treatment plant design and operation. RO brine often requires disposal in an ocean outfall or evaporation pond. UV AOP treatment generates no side waste stream and does not require brine disposal.
- Electricity consumption and power costs are much higher for membranes, as pumps are used to produce high enough pressure to force water through membranes.

In-situ chemical oxidation (ISCO)

ISCO uses injection wells to dose oxidizing chemicals (e.g., hydrogen peroxide) directly into soil and groundwater, where they reduce chemical micropollutants. Minimal surface infrastructure is needed, which can lead to a lower-cost remediation solution.

- The success of ISCO depends on an accurate survey map of the contamination plume and its flow direction.
- ISCO is not always 100% effective, and several weeks or months must pass before monitoring wells can collect samples and test for efficacy. With UV AOP, influent and effluent samples can be immediately collected and analyzed to confirm micropollutants are being appropriately removed.

The Trojan Technologies advantage with UV AOP

Experience

Installations

Trojan Technologies has been researching, developing, and delivering UV AOP offerings for more than 20 years and has 250 TrojanUV UV AOP installations on five continents. The most impressive aspect of these installations is their variety. Ranging in flow capacity from less than 100 gallons per minute to over 130 million gallons of water a day, these sites represent the full spectrum of UV AOP applications. The TrojanUV installation portfolio includes sites dedicated to groundwater remediation, surface water remediation, and potable reuse, targeting multiple different micropollutants.

Today, TrojanUV UV AOP installations help deliver cleaner water to more than 6 million people, removing an estimated 2 tons of contamination from the environment each year.

Research

Trojan Technologies' success with UV AOP solutions is built on the world-class expertise of its research and development team, which includes globally recognized leaders in photochemistry and molecular kinetics. This team, comprising Ph.D. holders and seasoned researchers, has dedicated their careers to advancing the science behind TrojanUV's cutting-edge UV AOP systems.

This team pioneered the active control program, which continues to be the standard in ensuring compliant, cost-efficient UV AOP control and is advancing the applicability and attractiveness of the technology.

Services

Laboratory and water analysis

Water characteristics, including pH, alkalinity, UVT, nitrate concentration, and hydroxyl radical scavenging potential, impact the design of a successful UV AOP system. To ensure the success of a UV AOP installation, it is critical to have a firm understanding of the water characteristics. The Trojan Technologies laboratory is staffed with experienced technicians and scientists who analyze customers' water at no charge to establish the critical baseline water characteristics for proper UV AOP system design.

Piloting and demonstration services

In many applications, it is necessary to determine whether UV AOP is a suitable solution before proceeding to a full-scale design and installation. Trojan Technologies maintains a fleet of mobile, pilot-scale UV AOP equipment (**Figure 15**), including an industry-first UV AOP demonstration system that expands traditional piloting by enabling performance testing and research, operator training, and public outreach.

Trojan Technologies' experienced service staff can install pilot systems on-site, and the research team is available to design and carry out customized pilot testing protocols when needed. Support for final report preparation and regulatory engagement is also available to help secure approval of UV AOP technology and ensure a smooth transition to full-scale implementation.

Figure 15: A mobile UV AOP system used for on-site pilot and performance testing.

Products

TrojanUV's systems for UV AOP include some of the world's most advanced engineered UV chambers. These include the various models of the TrojanUVFlex AOP product line. Featuring Solo Lamp® technology, an LP lamp that maintains a higher UV output, the TrojanUVFlex AOP requires fewer overall lamps compared to previous-generation LP UV lamps. The lower lamp count minimizes the size of a UV chamber, similar to MP lamps, but maintains the lower power and ownership costs of LP lamps. These compact UV chambers have a smaller footprint, minimizing the infrastructure required to house the systems.

The TrojanUVFlex AOP UV chambers can be engineered to carry as few as 16 lamps, requiring approximately 8 kW of power, to as many as 384 lamps, requiring approximately 384 kW. During operation, individual sections of lamps can be turned off (**Figure 16**) when treatment conditions become more favorable. For instance, when UVT increases or chloramines concentrations are lower, the Trojan Technologies Active Control Program reduces the UV dose delivered by the system and turns off any UV lamps considered unnecessary or redundant. Any lamps in operation can also be dimmed to lower power levels, further minimizing operational costs.

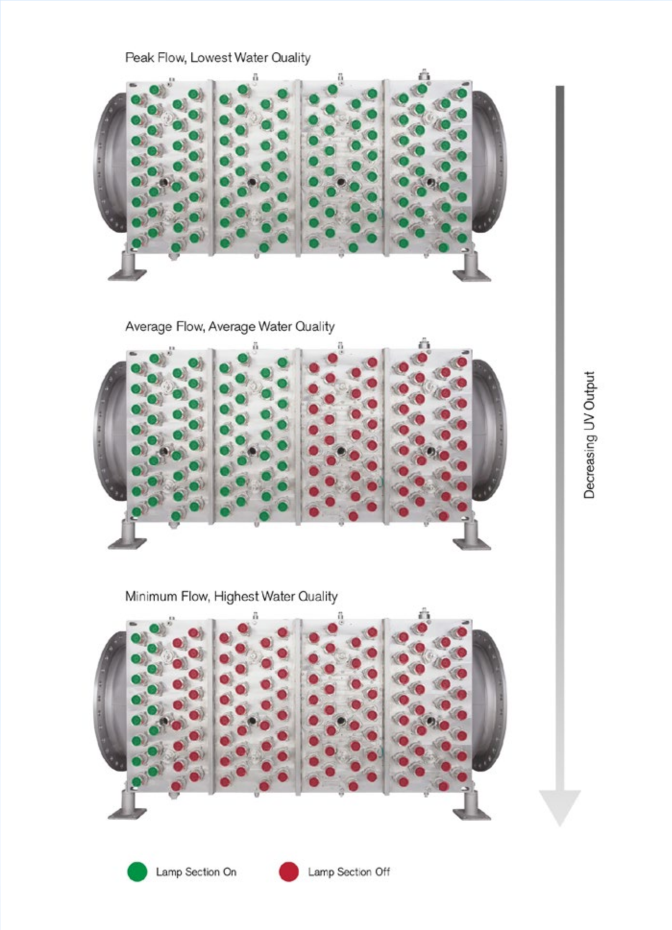


Figure 16: TrojanUVFlex100 AOP UV chamber shows selected sections of lamps in operation. The Trojan Technologies Active Control Program automatically turns off any unneeded lamps in response to improving treatment conditions.

LIFETIME
★ GUARANTEE ★
PERFORMANCE

The Trojan Technologies Performance Guarantee

Trojan Technologies is confident in its UV AOP experience and products. As a result, Trojan Technologies' commitment to customers is to provide a performance guarantee that promises the desired micropollutant treatment targets will always be met. This is in addition to Trojan Technologies' standard warranties guaranteeing the equipment's mechanical integrity.

Frequently asked questions

1. What is UV AOP?

UV advanced oxidation process (UV AOP) is a form of advanced oxidation where ultraviolet light treats micropollutants directly and indirectly by generating powerful free radicals, which remove micropollutants through oxidative chemical reactions.

2. What is UV photolysis?

A part of the UV AOP treatment process, UV photolysis occurs when micropollutants are directly treated with ultraviolet light. In many cases, micropollutants treated through photolysis do not require an oxidant. UV photolysis is also necessary to produce free radicals when the oxidant absorbs UV.

3. What is UV oxidation?

A part of the UV AOP treatment process, UV oxidation occurs when species of free radicals with high oxidation potential are produced as an oxidative precursor (e.g., hydrogen peroxide or free chlorine) interacts with ultraviolet light. These radicals oxidize (remove electrons) from micropollutants in the water, breaking them down into smaller constituents. UV photolysis and oxidation occur simultaneously to break down micropollutants in a UV AOP system.

4. What micropollutants are treated by UV photolysis and UV oxidation?

Many micropollutants are candidates for UV AOP treatment, including *N*-nitrosodimethylamine (NDMA); 1,4-dioxane; trichloroethylene (TCE) and chlorinated solvents other than alkanes; taste- and odor-causing compounds, such as MIB and geosmin; pesticides; methyl tert-butyl ether (MTBE); and a variety of pharmaceuticals. There are also many others. Contact Trojan Technologies representatives with specific questions regarding micropollutants of concern.

5. What are the advantages of UV AOP systems?

UV AOP treats micropollutants by removing them from the environment rather than transferring them to another medium (e.g., air in air stripping or solids in carbon filtration) that moves the micropollutant to a different phase in the environment where further (off-site) treatment is often required.

UV AOP treatment is placed in-line with other treatment technologies. Waste streams, such as brine or backwash water, are unnecessary and need not be considered in plant design.

Treating pathogens, including bacteria, protozoa, and viruses, is achieved simultaneously with ultraviolet light. Such treatment is commonly needed in addition to micropollutant treatment in potable reuse and certain surface water and groundwater remediation applications.

6. What are the advantages of TrojanUV UV AOP systems?

Trojan Technologies has decades of experience in the science and application of UV technology for UV AOP applications and has the largest installation base of UV AOP systems worldwide.

TrojanUV systems for UV AOP operate with an active control program, where the targeted UV and oxidant doses are adjusted immediately in response to changes in critical influencers of the water. This ensures cost-effective and compliant treatment is always achieved with minimal strain on operators.

A fleet of demonstration and pilot units enables customers to carry out proof of concept testing or enhance operator familiarity. These efforts are supported by Trojan Technologies' experienced staff. UV chambers are engineered to deliver a high-intensity UV dose in a small overall footprint, reducing building space and capital expenditures.

7. Where should a UV AOP system be installed in a treatment plant?

UV AOP systems are versatile in that they can be installed at many different points in a water treatment plant. The preferred location depends on the application, but in general, the best location is where the water is the cleanest with the highest UV transmittance (UVT) and the lowest concentration of solids. Contact Trojan Technologies experts or engineering consultants to learn how to integrate UV AOP into a new or existing facility.

8. Will Trojan Technologies analyze my water?

Yes, Trojan Technologies' laboratory facilities will conduct routine analyses of the critical influencers in water, such as UVT, pH, nitrate, alkalinity, and others, to design a reliable, customer-specific, full-scale UV AOP system backed by the Trojan Technologies Performance Guarantee. Analyses regarding new systems are conducted free of charge for customers.

9. What water quality parameters affect the performance of UV AOP systems?

The most important water quality parameters affect UV transmittance (UVT). Other parameters can promote free radical scavenging and unwanted competition for generated free radicals, making them less available to treat the micropollutants of interest.

Trojan Technologies' scientists evaluate the impacts of each parameter through an analysis of the site's water.

10. Will Trojan Technologies supply UV AOP systems with a guaranteed performance?

Yes. If provided with a representative water sample for testing in the design phase, Trojan Technologies guarantees its UV AOP sizing recommendations and the treatment performance at that site.

11. Is pilot testing necessary?

While pilot testing may demonstrate that the technology is effective, it is not required to design a UV AOP system. Hydraulic and optical conditions with pilot-scale systems can change when moving to full-scale UV AOP systems, which means different UV and oxidant doses are often used.

12. Are there any byproducts of the UV AOP reactions?

In most cases, byproduct formation in a UV AOP system is negligible. The potential for byproduct formation is evaluated on a case-by-case basis, and if there is significant potential, steps can be taken to eliminate any potential impacts. Typical reaction byproducts are low molecular weight aldehydes and carboxylic acid. These compounds are not generally a problem from a health or regulatory perspective. Bromate is not typically produced when using hydrogen peroxide as an oxidant.

13. Can microorganisms be treated with UV AOP?

Yes. The doses of ultraviolet light generally required to reduce micropollutants through the UV AOP process are often significantly higher than those needed to treat microorganisms. Therefore, microorganism treatment is simultaneously achieved with typical AOP applications when required.

14. How do you know how much ultraviolet light and oxidant precursor are needed?

Trojan Technologies has decades of experience designing and operating UV AOP systems. Trojan Technologies' experts use specialized models and algorithms that consider all the relevant chemical reactions, the water's characteristics, the amount of micropollutant treatment needed, and the efficiency of the UV chamber to find the right balance between ultraviolet light and oxidant. Because too much of one can result in an uneconomic operation, the Trojan Technologies Active Control Program ensures the appropriate treatment balance.

To learn more about the brands and affiliates of Trojan Technologies, please visit www.trojantechnologies.com