

**Los Angeles Department of Water and Power (DWP)  
North Hollywood West Well Field**

**TrojanUVFlex200™ - Advanced Oxidation System**

**Performance Test Report**

March 30, 2023

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## 1 INTRODUCTION/BACKGROUND

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The Los Angeles Department of Water and Power (DWP) has installed a UV advanced oxidation system at the North Hollywood West Well Field for the treatment of 1,4-dioxane. The system consists of four trains (1 duty+1 standby) of TrojanUVFlex200™ UV Advanced Oxidation Process (UV-AOP) chambers, along with a hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) dosing system. Each chamber contains 8 lamp sections, and each section is comprised of 24-1 kW Solo UV lamps.

Trojan Technologies, along with DWP and DWP's Owner's Agent (OA), completed on-site performance testing of the UV-AOP system December 6-9, 2022. This report describes the methods, procedures and test conditions used during the performance testing and summarizes the overall test results based on the analytical data from a third-party laboratory.

## 2 OBJECTIVES

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The primary objective of TrojanUVFlex200 UV-AOP system performance testing was to verify that the installed UV system is capable of meeting the treatment criteria at the design operating conditions, as summarized in Table 2-1. A secondary objective was to obtain performance data demonstrating removal of 1,4-dioxane treatment at reduced water UV transmittance (UVT) values and within guaranteed electrical power draw requirements.

**Table 2-1: Summary of UV-AOP Design Conditions.**

	Current	Future
Peak Design Total Flow, GPM	9,020	12,750
Duty Trains	3	4
Peak Design Flow, GPM/Train	3,007	3,188
Minimum Flow, GPM/Train	1,500	1,500
Minimum UVT at 254 nm, %	97	97
1,4-Dioxane Log <sub>10</sub> Reduction	≥1.9	≥1.6
Max. OH Radical Scavenging Demand (s <sup>-1</sup> )	90,500	90,500

## 3 UV-OXIDATION FUNDAMENTALS

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### 3.1 TREATMENT MECHANISMS

UV light-based advanced oxidation processes (UV-AOPs) rely upon the simultaneous mechanisms of direct UV photolysis and hydroxyl radical-induced oxidation to degrade chemical contaminants in water. UV-photolysis is the process by which chemical bonds in the contaminant structures are broken by the energy associated with the UV light absorbed by those compounds. UV-photolysis does *not* require the addition of H<sub>2</sub>O<sub>2</sub>. A UV-AOP process in the presence of an oxidant (*e.g.* H<sub>2</sub>O<sub>2</sub>) relies on the *in-situ* generation of hydroxyl radicals (•OH) through the UV-photolysis of H<sub>2</sub>O<sub>2</sub> which is dosed to the water, and the subsequent oxidation of chemical contaminants initiated by hydroxyl radicals.

Hydrogen peroxide is commercially available as aqueous solutions of varying strength. It is a relatively weak absorber of UV light having a molar absorption coefficient at 254 nm of 19.6 L mol<sup>-1</sup> cm<sup>-1</sup>. Nevertheless, the quantum yield of hydroxyl radical formation from hydrogen peroxide UV photolysis approaches unity. Therefore, the UV/H<sub>2</sub>O<sub>2</sub> process is one of the most efficient advanced oxidation processes.

Hydroxyl radicals are extremely reactive, short lived and unselective transient species. Due to their high reactivity in natural waters, especially in the presence of naturally occurring organic matter (NOM) and alkalinity, these radicals will instantly react with the water constituents and do not exist beyond the boundaries of the UV reactor volume.

Hydroxyl radicals can oxidize organic and inorganic compounds by various types of reactions, comprising electron transfer, hydrogen abstraction and electrophilic addition reactions. In UV oxidation treatment processes, the yield of hydroxyl radicals is optimized based on the H<sub>2</sub>O<sub>2</sub> required for a given contaminant treatment level for a given water quality, flow and UV system operating conditions.

### 3.2 WATER QUALITY PARAMETERS

#### 3.2.1 UV Transmittance

UV transmittance (UVT) is the spectral radiant power (P<sub>λ</sub>) transmitted through a medium (*e.g.* water sample) across a particular pathlength (l) divided by the spectral radiant power incident on the sample (P<sub>λ</sub><sup>0</sup>). UVT is measured using a UV spectrophotometer. Reagent grade water is used to zero the instrument (*i.e.*, UVT = 100%). UV absorbance (A) at a given wavelength (λ) correlates to the amount of light absorbed by a solution over a given pathlength (l). UVT and UV absorbance are related through the following equation:

$$\text{UVT}(\lambda, \%) = 10^{-A(\lambda)} \times 100$$

The typical cell pathlength is 1 cm and both transmittance and absorbance values are commonly reported per cm. A key reference wavelength and one at which UVT is often reported is 254

nm, which is also the radiation emitted from the excited state of mercury atoms in the low-pressure mercury vapor arc lamps. UV Transmittance depends on the concentration of UV light-absorbing compounds and particles (which also scatter the light) present in the water matrix. The higher the water background UV absorption, the lower is the UV light availability to H<sub>2</sub>O<sub>2</sub> for hydroxyl radical generation and to organic contaminants for the direct UV photolysis. The UV transmittance is one of the key water quality parameters used in the UV equipment sizing for a given application.

### 3.2.2 Hydroxyl Radical Scavenging Demand

While the desired reactions in UV oxidation processes are between photo-generated hydroxyl radicals and contaminant molecules, the non-selective nature and high reactivity of hydroxyl radicals result in reactions between these species and various organic and inorganic water constituents, which always occur at much higher concentrations than the target micropollutants. Examples of such hydroxyl radical scavengers are the dissolved natural organic matter (NOM), carbonate and/or bicarbonate ions, iron and manganese ions, etc. Hydrogen peroxide itself reacts with hydroxyl radical; thus, the kinetic model used to determine the UV/H<sub>2</sub>O<sub>2</sub> process conditions and to size the UV equipment optimizes the H<sub>2</sub>O<sub>2</sub> concentration required to generate the highest •OH yield, while affecting a minimum •OH demand. The •OH water background demand has a negative impact on the steady-state concentration of hydroxyl radicals in the water. Since the rate of contaminant degradation is proportional to the steady-state concentration of hydroxyl radicals, these hydroxyl radical scavenging reactions reduce the rate of contaminant degradation. The •OH water background demand (also known as ‘scavenging term’;  $\sum k_s[S]$  or S.T.) is water matrix-specific and must be determined experimentally through a properly developed and validated method. Trojan routinely determines the scavenging demand of water samples at its laboratory in London, Ontario. The •OH water background demand is another key water quality parameter used by the kinetic model for sizing the UV equipment for a given UV/H<sub>2</sub>O<sub>2</sub> AOP application.

In principle, the method for the •OH water background demand relies on the competition kinetics for the hydroxyl radicals between the water matrix constituents and a probe compound which is added to the sample (Zhou and Mopper, 1996; Rosenfeldt and Linden, 2007; Rosenfeldt, 2010; Lee and von Gunten, 2010; Keen *et al.*, 2014; Kwon *et al.*, 2014; Gerrity *et al.*, 2016; Wang *et al.*, 2020). The most commonly used probe compound is para-chlorobenzoic acid (pCBA) providing its well characterized rate constant for the OH radical reaction ( $5.0 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ ; Buxton *et al.*, 1988) and known quantum yield and molar absorption coefficient at 254 nm. Upon reviewing the literature published over the years and extensive use of pCBA for quantification of OH radical steady state concentration, Trojan adopted and used pCBA as a probe for the •OH water background demand determination in samples collected from water treatment plants in the past.

In a recent article, Kim *et al.* (2021) reported for the first time in the literature on a potential unidentified reaction of pCBA in the UV/H<sub>2</sub>O<sub>2</sub> process in addition to the known •OH- and direct photolysis-based degradation. The authors examined several chemical compounds of various structures as potential •OH chemical probes, among which, p-CBA. The experimental

data indicated that para-substituted benzoic acids, in particular, are vulnerable to attack by an unknown reactive species, leading to false quantification of •OH. As a result, the •OH water background demand measured using these probes, including pCBA, would be underestimated.

The authors postulated the triplet excited state of H<sub>2</sub>O<sub>2</sub> as the reactive species responsible for the degradation of pCBA in addition to the •OH and direct photolysis pathways. Although there is no direct experimental evidence in the public domain on the decay of H<sub>2</sub>O<sub>2</sub> excited states, Kim *et al.* advanced the idea of pCBA degradation *via* a H<sub>2</sub>O<sub>2</sub> triplet state based on the observed p-CBA byproducts containing the oxygen isotope (<sup>18</sup>O) atom when they used H<sub>2</sub><sup>18</sup>O<sub>2</sub>.

Based on their experimental results, Kim *et al.* concluded that the impact of the reaction of (H<sub>2</sub>O<sub>2</sub>)<sup>\*</sup> on the degradation kinetics of the •OH probe compound (*e.g.* pCBA) would be more significant under the following conditions: (a) presence of high concentrations of •OH scavengers; (b) high concentration of H<sub>2</sub>O<sub>2</sub> dosed to the water sample subject to •OH water background demand measurement; and (c) low concentration of dissolved oxygen. The higher the contribution of (H<sub>2</sub>O<sub>2</sub>)<sup>\*</sup> to the kinetics of pCBA decay, the greater the underestimation of the •OH water background demand.

Providing the recent literature information and additional in-house investigation on p-CBA suitability as a probe for the OH radical water matrix demand determination, Trojan decided not to use this compound as a probe anymore. Further proprietary research studies conducted at Trojan resulted in adopting a reliable probe compound for OH radical water matrix demand. That compound has been used over the past 3-4 years.

UV system sizing was based on water samples submitted to Trojan for hydroxyl radical scavenging demand determination in 2016. The results are listed in Table 3-1, and they were all determined using pCBA as an •OH probe compound. The maximum value measured was for the NH037 sample (90,500 s<sup>-1</sup>), so this is the value used for sizing and programmed into the PLC during commissioning.

**Table 3-1: Hydroxyl radical scavenging demand results.**

Trojan ID	Sample ID	Date Received	UVT <sub>254</sub> (%)	Nitrate (ppm as NO <sub>3</sub> <sup>-</sup> )	OH Radical Scavenging (s <sup>-1</sup> )
818	NH034	10/26/2016	98.0	31.8	79,000
819	NH037	10/26/2016	98.0	30.6	90,500

### 3.3 TROJAN UV/H<sub>2</sub>O<sub>2</sub> SYSTEM CONTROLS

The operation of Trojan UV-Oxidation Systems for contaminant treatment is based on the calculation of an instantaneous contaminant log-reduction (LR) as a function of the fundamental contaminant kinetic parameters, system flow, UV transmittance, hydroxyl radical scavenging demand, H<sub>2</sub>O<sub>2</sub> concentration and UV reactor intensity sensor values. The methodology is based

on a contaminant treatment kinetic model that combines a fundamental photochemical kinetic model with an empirically validated UV dose model to accurately predict the degradation of contaminants in a UV-oxidation system (i.e. UV alone or combined with an oxidant to generate hydroxyl radicals).

Therefore, the UV system control algorithm provides a dynamically-adjusted system based upon the identified process input parameters. These include flow rate, UVT, hydroxyl radical scavenging demand, and contaminant influent and target effluent concentration (to calculate target LR<sub>s</sub>). Further, by inputting the H<sub>2</sub>O<sub>2</sub> and electrical energy costs, the algorithm calculates the combination of lamp power and H<sub>2</sub>O<sub>2</sub> concentration that meets the contaminant treatment objective at the lowest operating cost. Specific constraints on the limits of the system operation can also constrain the operating conditions.

The fundamental photochemical kinetic model is based upon a contaminant-specific pseudo-first order UV fluence-based reaction rate constant ( $k'$ , cm<sup>2</sup> /mJ) that accounts for contaminant reduction due to both UV direct photolysis and hydroxyl radical oxidation. In addition to the contaminant-specific fundamental kinetic parameters (i.e., quantum yield ( $\Phi_C$ ), molar absorption coefficient ( $\epsilon_C$ ) & second order hydroxyl radical rate constant  $k_{C,OH}$ ), this fluence-based rate constant  $k'$  is dependent upon the H<sub>2</sub>O<sub>2</sub> concentration and the hydroxyl radical scavenging demand of the water ( $\sum k_s[S]$  or S.T.). Typically, the scavenging demand of the water is considered to be either a constant value (based upon historical measurements) or linked to certain measurable water quality parameters. The H<sub>2</sub>O<sub>2</sub> concentration is a control variable that can be monitored and adjusted together with the UV reduction equivalent dose (RED) to provide the target LR of the contaminant. The fluence-based rate constant for contaminant treatment with the UV/H<sub>2</sub>O<sub>2</sub> AOP is calculated using the following equation:

$$\frac{k_c}{I_{avg.}} = k'_c = \frac{\phi_c \epsilon_c LN(10)}{U} + \frac{LN(10) \phi_{OH} \epsilon_{H_2O_2} k_{c,OH} [H_2O_2]}{U(k_{H_2O_2,OH} [H_2O_2] + \sum k_{s,OH} [S])}$$

**Eq. 1**

where,

<u>Symbol</u>	<u>Description</u>
U	Photon energy at 253.7 nm (J/einstein)
$\phi_C$	Quantum Yield of contaminant at 254 nm
$\phi_{OH}$	Quantum Yield of OH radical formation from hydrogen peroxide photolysis
$\epsilon_C$	Molar absorption coefficient of contaminant at 254 nm, M <sup>-1</sup> cm <sup>-1</sup>
$\epsilon_{H_2O_2}$	Molar absorption coefficient of hydrogen peroxide at 254 nm, M <sup>-1</sup> cm <sup>-1</sup>
$k_{C,OH}$	Reaction rate constant of contaminant with OH radical, M <sup>-1</sup> s <sup>-1</sup>
$k_{H_2O_2,OH}$	Reaction rate constant of H <sub>2</sub> O <sub>2</sub> with OH radical, M <sup>-1</sup> s <sup>-1</sup>
$k_{s,OH}[S]$	Hydroxyl radical scavenging for various constituents S in the water matrix, s <sup>-1</sup>

Equation 1 is provided and discussed further by Stefan (2018). Inspection of equation 1 shows that for a given contaminant and water quality (i.e., ( $\sum k_s[S]$ ), the H<sub>2</sub>O<sub>2</sub> concentration is the only independent variable.

This rate constant has the units  $\text{cm}^2/\text{mJ}$ . The UV dose required to achieve 90% removal of a chemical pollutant ( $D_{10}$ ,  $\text{mJ}/\text{cm}^2$ ) is related to the fluence-based rate constant  $k_c'$  through equation (1):

$$D_{10} = \text{Ln}(10)/k_c' \quad \text{Eq. 2}$$

Therefore, for a given  $\text{H}_2\text{O}_2$  concentration, a target LR ( $\text{LR}_t$ ) is achieved by delivering the required UV dose i.e. the reduction equivalent dose (RED,  $\text{mJ}/\text{cm}^2$ ).

$$\text{RED}_t = D_{10} \times \text{LR}_t \quad \text{Eq. 3}$$

The RED delivered by a UV reactor is a function of various parameters among which the water flow rate and UVT, the lamp power level, the quartz sleeve transmittance (including fouling) and the UV reactor efficiency. The flowrate and UVT are measured parameters. The lamp power level is the controlled/independent variable.

In disinfection applications, the RED for a UV reactor is calculated using a bioassay-generated validated equation in which RED is a function of UV lamp power level/UV intensity measurement, flowrate, UVT and  $D_{10}$  (i.e. the dose per LR of a microorganism or contaminant). Similarly, for UV-AOP applications, Trojan has developed a RED equation for the TrojanUVFlex200 reactor using an empirically validated computational fluid dynamics (CFD) model to relate RED to the UV intensity sensor values, flowrate, UVT, and  $D_{10}$ .

The control algorithm evaluates various combinations of lamp power and related RED and  $\text{H}_2\text{O}_2$  dose and related  $D_{10}$ , all of which meet the contaminant LR target and selects that combination which represents the minimum operating cost.

## 4 METHOD

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### 4.1 EXPERIMENTAL SET UP

#### 4.1.1 1,4-Dioxane Dosing

To quantitatively demonstrate the required log reduction targets of 1,4-dioxane, effort was made to estimate the required 1,4-dioxane concentrations in the UV influent such that the contaminant concentrations could be accurately measured in both UV influent and UV effluent samples. Therefore, the influent contaminant concentrations needed to be high enough such that 1,4-dioxane concentrations in the UV effluent samples were greater than the analytical method reporting limit (MRL). The analytical method employed for 1,4-dioxane analysis was EPA Method 522, which has an MRL of  $0.070 \mu\text{g}/\text{L}$  and an MDL of  $0.028 \mu\text{g}/\text{L}$ . Since it was recommended to avoid working at concentrations approaching the MRL, a target UV effluent 1,4-dioxane concentration of  $\sim 0.1 \mu\text{g}/\text{L}$  was chosen.

The 1,4-dioxane injection stock was prepared by diluting 1g of  $>99.5\%$  pure 1,4-dioxane (Chemservice N-10220-1G lot#13649600) in 1.0 L of distilled water to prepare a 1000 mg/L



stock solution. This stock was injected into the UV influent piping just downstream of cartridge filter 2 using a Masterflex peristaltic pump.

#### 4.1.2 Achievement of Steady State Operation

A critical requirement is that the UV system be operating at steady state prior to collection of the UV reactor influent-effluent sample pairs. The method that was used to determine the time required to reach steady state was a tracer test with the UVT modifier Super Hume (UAS of America), which is a liquid concentrate natural organic matter. A step change in the UVT was made and samples were collected at specified time intervals at both the reactor influent and effluent sample ports. The reactor lamps were off during this test. The samples were analyzed on-site for UVT to determine the time required for the system to reach steady state following a change in process conditions.

## 4.2 TEST PROCEDURE

The general procedure for each test completed was:

- Warming up the UV system/lamps;
- Setting and verifying stable system flow at the target value for each test condition;
- Entering the desired lamp sections on, lamp power level and H<sub>2</sub>O<sub>2</sub> dose in manual mode
- Starting the pump to inject the 1,4-dioxane and/or UVT modifier;
- Waiting for steady state time to elapse;
- Recording the relevant data on a hard copy bench sheet;
- Collecting the influent and effluent sample pairs;
- Measuring hydrogen peroxide and UVT in the UV influent and UV effluent.

### 4.2.1 Test Matrix

Table 4-1 presents the original test matrix and summarizes the operational conditions. Testing was constrained by the discharge and storage capacity of the UV effluent water, which meant that only 60-90 minutes of test time was available each day. As a result of these constraints, all tests were completed at the minimum flow rate of 1500 gpm.

Ambient UVT was tested as well as the design UVT of 97%. Additional tests were completed at UVT values of 95% and 88% to examine the UV/H<sub>2</sub>O<sub>2</sub> process performance at 1,4-dioxane treatment in water of lower than design UVTs, should such conditions occur in the future. Super Hume was used to lower the water UVT to the desired values listed in Table 4-1.

All tests were completed using Train 2 with a maximum of 4 lamp sections on, since that was the train that was fully operational at the time of testing. All tests were completed in manual mode to ensure testing took place under the conditions tied to the maximum power draw and peroxide set out in the project specifications. To conduct these tests in manual mode, the number of lamp sections on, lamp power and H<sub>2</sub>O<sub>2</sub> dosage were manually set to the specified/desired values.

The control test was added to demonstrate the expected result that no 1,4-dioxane treatment occurred in the absence of UV and H<sub>2</sub>O<sub>2</sub>. This test was also included to judge sample collection, handling, and analysis quality control.

**Table 4-1: Sampling and injection locations.**

Test ID	Flow/ Train (gpm)	UVT <sub>254nm</sub> (%)	Lamp Sections On	Approx. Spiked 1,4-D Conc. (ug/L)	Required 1,4-Dioxane Log Red.	Max. [H <sub>2</sub> O <sub>2</sub> ] (mg/L)	Max. Lamp Power (%)	Max. EED (kWh/kgal*)
Ctrl	1,500±150	97±0.5	0	20	0	0	0	0
1	1,500±150	97±0.5	4	20	>1.9	25	100	1.11
2	1,500±150	97±0.5	4	10	>1.6	20	95	1.06
3	1,500±150	Background (97.5-98.5)	3	10	>1.4	18	100	0.84
4	1,500±150	Background (97.5-98.5)	2	5	>0.9	14	100	0.56
5	1,500±150	95±0.5	4	10	>1.4	25	100	1.11
6	1,500±150	88±0.5	4	5	>1.0	25	100	1.11
7	1,500±150	Background (97.5-98.5)	4	20	>1.9	21	100	1.11
8	1,500±150	Background (97.5-98.5)	3	15	>1.7	25	100	0.84

Note: Tests 5-8 were completed for informational purposes only and without any performance guarantee.

#### 4.2.2 Sample Handling

Sample bottles were provided by Weck Laboratories Inc. (Industry, CA). UV influent samples were collected first followed by the UV effluent samples, ensuring the steady-state operating conditions upon any change in the test variables (see Table 4-1). For each sample location, a 3L composite sample was taken in a clean, rinsed plastic vessel. The samples were then split among the required sample containers provided for each parameter by Weck. Care was taken to ensure no headspace was present in the 1,4-dioxane sample bottles. Separate containers were used to obtain UV influent and UV effluent samples for UVT and hydrogen peroxide on site analysis, with the analysis being completed by Trojan within approximately 10 minutes of sample collection. Samples were placed in a cooler with ice, and collected each day by the Weck sample courier, with Chain of Custody procedures followed.

#### 4.2.3 UV Transmittance (UVT)

Samples for the water UVT analysis (prior to H<sub>2</sub>O<sub>2</sub> injection but after UVT modification) were collected in the H<sub>2</sub>O<sub>2</sub> injection building. UV influent samples were drawn upstream of H<sub>2</sub>O<sub>2</sub> injection by the online Real Tech UVT meter. Grab samples for the background water and from the UV influent and effluent sample ports were measured using a 4cm path length quartz cell and a RealUVT™ 254nm portable photometer (RealTech Inc., Canada).

#### 4.2.4 Power Measurements

Power was measured at the system Power Distribution Center (PDC) such that lamp and driver power, as well as related auxiliary power (such as air conditioners) were included. The meter used was a Power Monitors Inc. Eagle 330 3-phase power analyzer provided by DWP.

#### 4.2.5 Hydrogen Peroxide

Hydrogen peroxide was measured using the DPD/peroxidase method described by Bader *et al.* (1988). In this procedure, hydrogen peroxide reacts with DPD reagent (Hach Company) through a reaction catalysed by the peroxidase enzyme (horseradish peroxidase, Millipore Sigma USA).

#### 4.2.6 Hydroxyl Radical Scavenging Demand

As mentioned in section 3.2.2, Trojan routinely determines the scavenging demand of water samples at its laboratory in London, Ontario. A probe compound is added for which the rate constant for the •OH reaction is available in the published literature and was also confirmed by Trojan. The spiked water samples are irradiated to precise UV doses at 253.7nm from a UV lamp mounted in a low-pressure collimated beam apparatus. The *quasi*-parallel UV light beam is perpendicular to the water sample surface. UV fluence rate at the water surface is measured using a calibrated radiometer (International Light Technologies Inc.) and the exposure times with NIST traceable stopwatches. The sample results are used to develop a UV dose-response relationship, from which the probe degradation kinetics is calculated, and subsequently the •OH water matrix scavenging capacity is determined.

#### 4.2.7 1,4-Dioxane and Remaining Parameters

All analyses were performed by Weck Laboratories (Industry, CA). Chain-of-custody forms were used, and the laboratory reports were sent to Trojan. 1,4-Dioxane analysis was performed using USEPA method 522 with an MRL of 0.070 µg/L and a method detection limit (MDL) of 0.028 µg/L. All parameter method details are listed in Table 4-2.

**Table 4-2: Analytical details for Weck methods.**

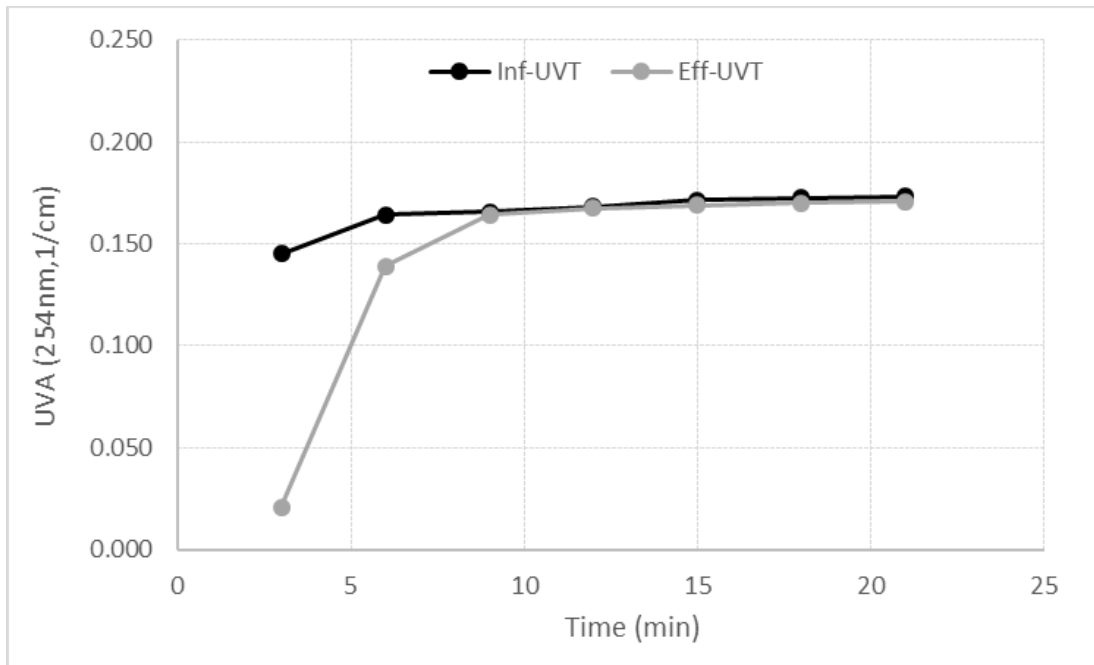
ANALYTE	METHOD	MDL	MRL	UNITS
1,4-Dioxane	EPA 522	0.028	0.070	ug/l
Alalinity as CaCO3	SM 2320B	1.9	5.0	mg/l
Calcium, Total	EPA 200.7	0.0234	0.500	mg/l
Dissolved Organic Carbon	SM 5310B	0.15	0.30	mg/l
Hardness as CaCO3, Total	Calculation	0.219	3.31	mg/l
Iron Total	EPA 200.7	0.0050	0.030	mg/l
Magnesium, Total	EPA 200.7	0.0390	0.500	mg/l
Nitrate as N	EPA 300.0	8.3	110	ug/l
Nitrite as N	EPA 300.0	9.0	150	ug/l
pH	SM 4500H	0.10	0.10	pH Units
Sulfate as SO4	EPA 300.0	0.72	1.5	mg/l
Total Dissolved Solids	SM 2540C	4.0	10	mg/l
Total Organic Carbon (TOC)	SM 5310B	0.19	0.30	mg/l
Turbidity	EPA 180.1	0.017	0.10	NTU

## 5 RESULTS

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### 5.1 MIXING AND STEADY STATE

A mixing/steady state test was completed prior to the 1,4-dioxane tests. The test was completed at 1,556 gpm with the UV reactors off and using Super Hume as the tracer compound. At time t=0 min Super Hume was injected and samples were taken from the UV influent and UV effluent ports simultaneously at 3-minute intervals. The test results are shown in Figure 5-1 and indicate that steady state was reached at approximately 9 minutes. Therefore, at least 9 minutes was used as a steady state time for each test prior to sampling. The results also show that the influent samples match the effluent samples at 9 minutes and onward, which demonstrates that the influent sample location provided representative (fully mixed) samples.



**Figure 5-1 Mixing/steady state test results.**

## 5.2 WATER QUALITY

Results for the NHW water samples sent to Trojan just prior to (November 2022) and during the performance testing (December 2022) are listed in Table 5-1. Well 37 was used for all performance tests completed. Of note are the hydroxyl radical scavenging results, which show an average value of  $54,400 \pm 5510 \text{ s}^{-1}$  for all samples listed. This value is much lower than the design scavenging value of  $90,500 \text{ s}^{-1}$  that was entered into the HMI prior to testing. Nitrate concentrations in the submitted samples are low, which is favorable as nitrate photolyzes forming nitrite, which is a strong hydroxyl radical scavenger. The UVT results for the samples taken from the UV influent during testing (December 6-9<sup>th</sup>) include the absorbance of  $\text{H}_2\text{O}_2$  and UVT modifier, and therefore are not representative of ambient UVTs.

**Table 5-1: Trojan water quality results for NHW samples.**

Sample ID	pH	Alkalinity (mg/L as CaCO <sub>3</sub> )	UVT (%)	TOC (mg/L)	Total Iron (mg/L)	Nitrate (mg/L as NO <sub>3</sub> <sup>-</sup> )	H <sub>2</sub> O <sub>2</sub> at Sampling (mg/L)	Scavenging Term (s <sup>-1</sup> )
Well 45 (11/18/22)	8.11	192	95.0	0.874	0.32	5.38	N/A	52,000
Well 37 (11/21/22)	8.05	180	97.0	0.824	0.03	4.99	N/A	52,700
Well 34 (11/23/22)	7.52	201	97.9	0.722	0.14	6.18	N/A	52,700
Well 34 (11/30/22)	7.93	203	98.2	0.356	0.03	6.49	N/A	47,800
Well 37 (12/06/22)	8.00	180	96.0	0.800	0.07	5.93	20.4	50,200
Well 37 (12/07/22)	8.01	181	93.6	0.465	0.05	6.22	24.7	54,300
Well 37 (12/08/22)	7.94	182	94.5	0.433	0.03	5.99	19.1	62,500
Well 37 (12/09/22)	7.87	182	98.3	0.334	0.04	5.17	0.15	63,000

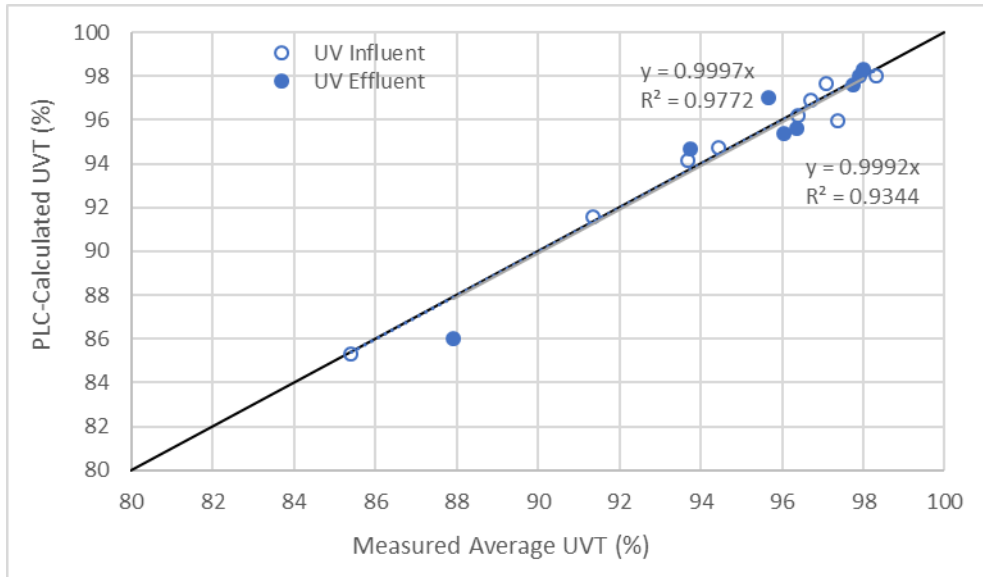
Notes: samples taken during testing (Dec 6-9) have UVT, TOC, nitrate, and scavenging values affected by the H<sub>2</sub>O<sub>2</sub> and Super Hume added during testing. Well 37 was used for the performance tests.

### 5.3 ON-SITE DATA AND MEASUREMENTS

Table 5-2 presents the critical on-site measurements recorded for each test run. These include the measured flow, the number of lamp sections operating and the percent lamp power level, the required influent H<sub>2</sub>O<sub>2</sub> concentration and predicted effluent H<sub>2</sub>O<sub>2</sub> concentration. The predicted 1,4-dioxane, TCE, and PCE log reductions are also listed, along with the sensor readings for each 24-lamp section.

Table 5-3 lists the benchtop analyses, including measured UVTs and H<sub>2</sub>O<sub>2</sub> concentrations for 3 consecutive samples taken during contaminant sampling. This data was used to demonstrate how accurately the UV system control algorithm predicts the UV influent UVT. To do this, the H<sub>2</sub>O<sub>2</sub> absorbance measured in the UV influent was added to the background absorbance.

Figure 5-2 shows the comparison between measured average UV influent and effluent UVT and PLC-predicted influent and effluent UVT. The agreement is very good for the influent data, thereby providing confidence in the system control calculation method for influent UVT. The effluent results also show good agreement, with 1 notable outlier at the low UVT (88%). For this point the measured value is high relative to the predicted value, which is likely due to the inability to predict the increase in UVT through the reactor that results from any reduction in the humic and fulvic acids present in the UVT modifier (Super Hume).



**Figure 5-2: Comparison between measured and PLC-predicted influent UVT.**

Target (manually entered) and measured UV influent and PLC-predicted and measured UV effluent H<sub>2</sub>O<sub>2</sub> results are plotted on Figure 5-3. Additional confidence in the PLC calculations for typical (automatic mode) operation can be gained by examining the UV effluent H<sub>2</sub>O<sub>2</sub> data. The system calculates the UV effluent H<sub>2</sub>O<sub>2</sub> concentration using the UV influent concentration and H<sub>2</sub>O<sub>2</sub> destruction through the reactor. The UV influent and effluent H<sub>2</sub>O<sub>2</sub> concentrations are then used to determine the average H<sub>2</sub>O<sub>2</sub> concentration through the UV chamber, and subsequently the log reductions for chemical targets. Figure 5-3 shows that measured and the PLC-calculated UV effluent H<sub>2</sub>O<sub>2</sub> concentrations agree very well, which provides confidence in the PLC calculations.

**Table 5-2: HMI data for each test completed.**

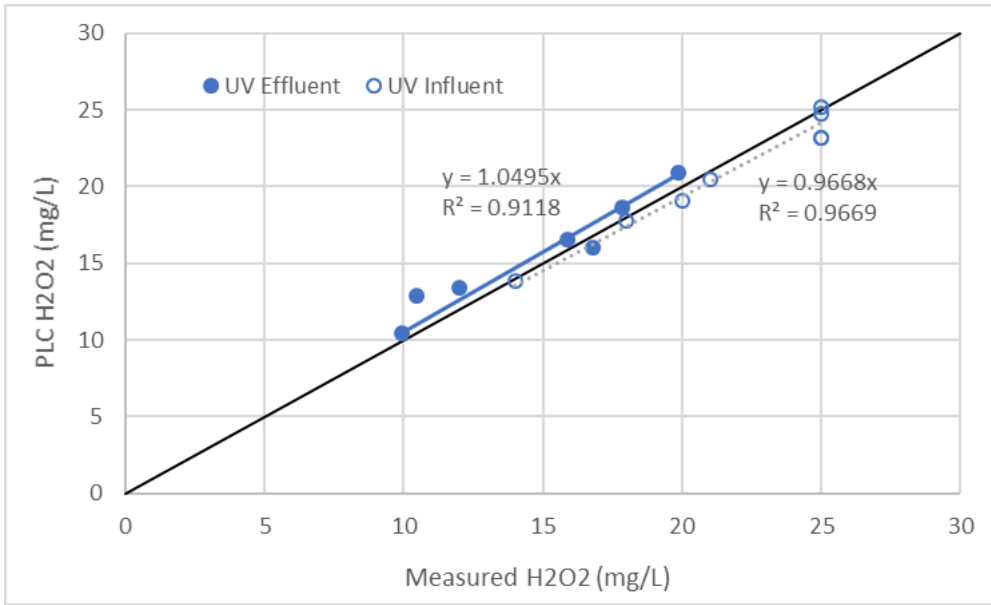
Test	Date	Time	Sections on	Power (%)	UVT (%)	Flow (gpm)	Inf H2O2 (mg/L)	Eff H2O2 (mg/L)	HMI-Predicted Log Reductions			UVI Sensors (mW/cm <sup>2</sup> )							
									1,4-D	TCE	PCE	1	2	3	4	5	6	7	8
Control	9-Dec	11:53	0	100	98.05	1538						0.01	0.01	0.00	0.01	0.03	0.01	0.02	0.01
1	7-Dec	3:31	4	100	97.21	1528	25	16.51	2.29	2.34	2.04	6.24	6.35	6.63	6.4	0.25	0.03	0.02	0.01
2	8-Dec	5:25	4	95	99.22	1566	20	13.44	1.97	2.02	1.89	6.18	6.31	6.68	6.34	0.3	0.03	0.02	0.01
3	8-Dec	5:45	3	100	98.44	1429	18	12.87	1.93	1.98	1.8	7.43	7.64	7.83	0.38	0.2	0.03	0.00	0.00
4	8-Dec	5:59	2	100	98.34	1533	14	10.45	0.74	1.27	0.97	7.6	7.5	0.64	0.06	0.06	0.02	0.02	0.01
5	9-Dec	10:56	4	100	93.72	1479	25	18.62	1.68	1.75	1.52	5.55	5.65	5.89	5.73	0.13	0.01	0.02	0.01
6	9-Dec	11:32	4	100	87.5	1464	25	20.88	1.0	1.15	1.0	4.04	4.15	4.36	4.26	0.03	0.00	0.02	0.01
7	6-Dec	1:07	4	100	98.74	1524	*	*	*	*	*	7.47	7.73	8.18	7.47	0.73	0.08	0.06	0.02
8	7-Dec	3:49	3	100	99.22	1521	25	16.04	2.41	2.55	2.24	7.13	7.29	7.37	0.39	0.14	0.03	0.03	0.01

\*data not displayed on HMI for manual mode until a program change was made

**Table 5-3: Measured UVT and H<sub>2</sub>O<sub>2</sub> results.**

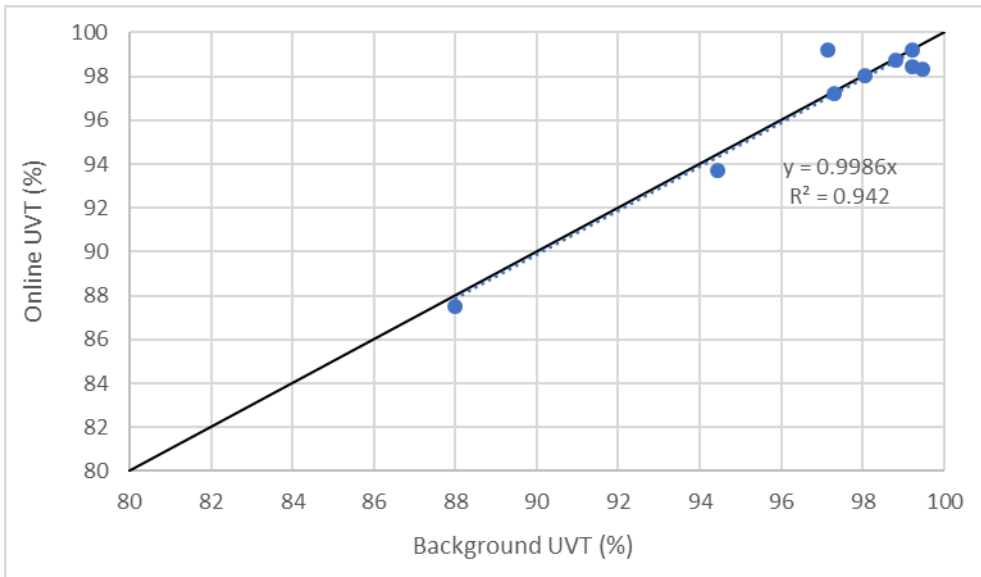
Test	UVT (%)									H <sub>2</sub> O <sub>2</sub> (mg/L)							
	Pre-H2O2	UV Inf r1	UV Inf r2	UV Inf r3	Avg UV Inf	UV Eff r1	UV Eff r2	UV Eff r3	Avg UV Eff	UV Inf r1	UV Inf r2	UV Inf r3	Avg UV Inf	UV Eff r1	UV Eff r2	UV Eff r3	Avg UV Eff
Control	98.05	98.29	98.30	98.35	98.31	98.25	98.32	98.30	98.29	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
1	97.30	93.70	93.71	93.60	93.67	96.01	96.01	96.09	96.04	24.90	24.80	24.50	24.73	15.84	15.86	15.91	15.87
2	97.14	94.32	94.31	94.70	94.44	96.35	96.35	96.36	96.35	19.12	19.24	18.99	19.12	12.24	11.86	11.94	12.01
3	99.23	96.70	96.68	96.74	96.71	98.03	97.58	98.06	97.89	17.76	17.72	17.76	17.75	10.32	10.56	10.56	10.48
4	99.47	97.14	97.11	96.99	97.08	98.00	98.01	97.97	97.99	13.92	13.92	13.68	13.84	10.08	10.08	9.69	9.95
5	94.45	91.27	91.43	91.35	91.35	93.71	93.78	93.78	93.76	23.28	23.28	23.04	23.20	17.76	17.76	18.00	17.84
6	88.00	85.36	85.28	85.56	85.40	87.87	87.99	87.84	87.90	23.28	23.04	23.28	23.20	19.92	19.68	19.92	19.84
7	98.81	96.35	96.46	96.40	96.40	97.45	97.88	97.87	97.73	20.40	20.50	20.40	20.43	10.80	10.80	10.80	10.80
8	99.22	97.36	97.34	97.40	97.37	95.83	95.59	95.60	95.67	25.20	25.10	25.30	25.20	16.80	16.90	16.70	16.80





**Figure 5-3: Comparison between measured and PLC H<sub>2</sub>O<sub>2</sub> concentrations.**

Figure 5-4 compares the Real Tech online UVT measurements to the background UVT grab samples measured using the bench-top photometer. The results are in very good agreement, with the online meter reading slightly low overall, which provides slight conservatism for treatment.



**Figure 5-4: Comparison between online UVT and measured background UVT.**

## 5.4 1,4-DIOXANE TREATMENT

The 1,4-dioxane data reported by Weck Laboratories are listed in Table 5-4, along with the measured power data and a summary of key operational data for each test. For each of the tests that had a power guarantee (Tests 1-4), the measured power was below the guaranteed value.

The average values of 1,4-dioxane log reduction data calculated for each test conducted during the performance testing far exceeded the guaranteed values (Table 4-1) for all tests. That is in part explained by the way the UV/H<sub>2</sub>O<sub>2</sub> system was run during the performance testing, namely, using the UV power and H<sub>2</sub>O<sub>2</sub> concentration estimated as needed to meet the target log-reduction for each run considering the high OH radical matrix demand of 90,500 s<sup>-1</sup>. As mentioned above, the OH radical scavenging demand measured for the well water treated during the performance testing was much lower (~54,400 s<sup>-1</sup> as an average) than the value of 90,500 s<sup>-1</sup> measured in samples from 2016 (see Table 3-1) and included in the design criteria.

As shown in Table 5-4, 1,4-dioxane was dosed to the UV influent such that, based on the log-reduction target, its concentration in the UV effluent exceeds the 1,4-dioxane MRL of 0.070 µg/L in all tests, except for test #6. However, 1,4-dioxane was reported as not detected (ND) i.e., “not detected at or above the MDL” (Weck Laboratories description of ND) in all UV effluent samples apart from Test 4.

The average 1,4-dioxane log reduction value for each test represents the average of the three log-reduction values calculated from each UV influent-UV effluent pair data, using the MDL of 0.028 µg/L for the UV effluent concentration of 1,4-dioxane, with exception of Test 4. Therefore, apart from Test 4, the actual log-reduction values were higher than the values shown in Table 5-5 and ranged from >1.3 in test #6 which was performed at the lowest UVT (88%) to >2.6 in test #7 (high UVT, high H<sub>2</sub>O<sub>2</sub> dose, maximum UV system operating power).

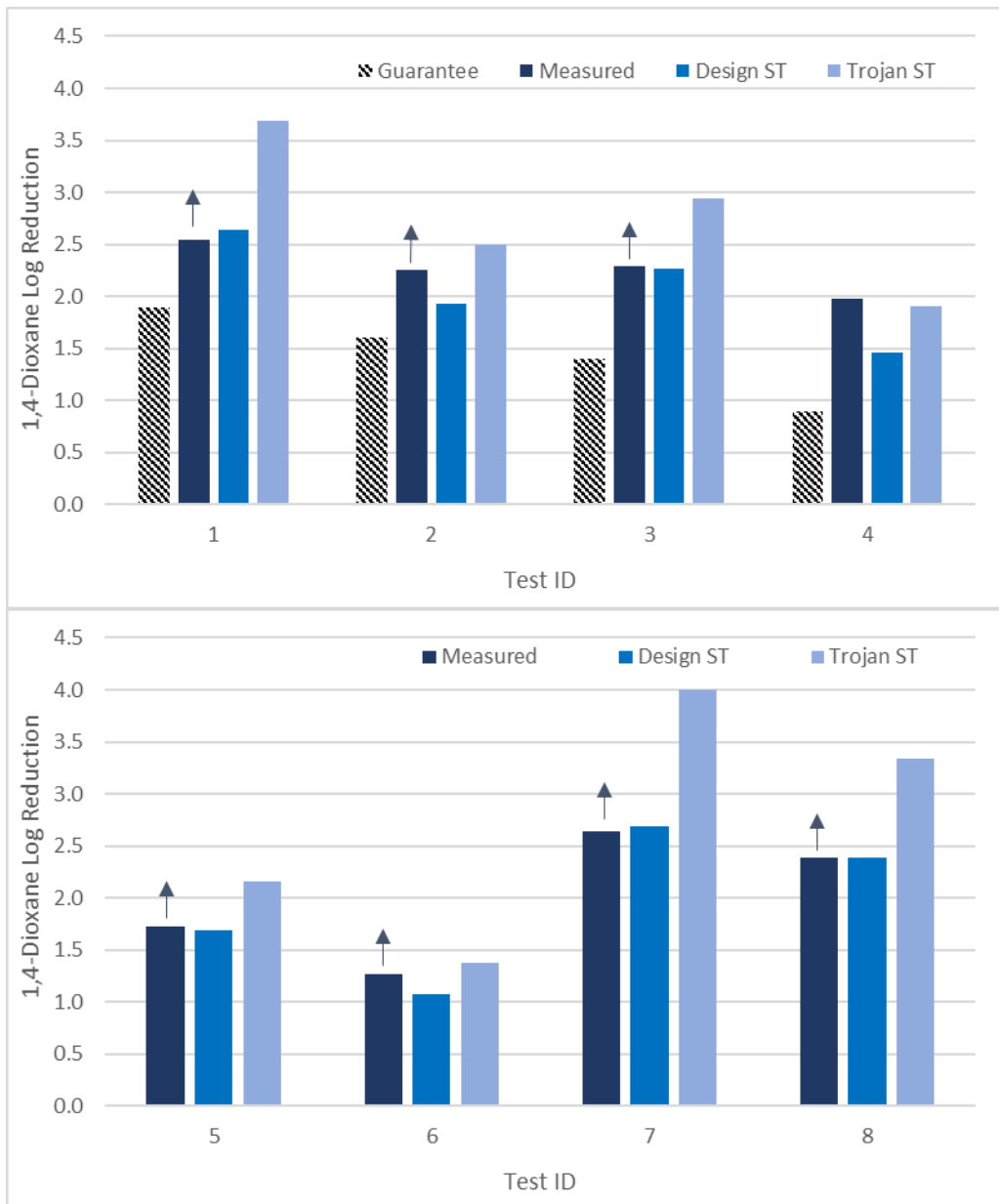
To compare the measured 1,4-dioxane log reductions for each test to predicted values, the Flex200 control equation was used. Test-specific inputs of flow rate, influent UVT, number of lamp sections on, lamp power, nitrate concentration, and UV influent H<sub>2</sub>O<sub>2</sub> concentration were used. Hydroxyl radical scavenging for the design (90,500 s<sup>-1</sup>) and Trojan measured day-specific values were also used for the calculations.

Figure 5-5 shows the measured and predicted 1,4-dioxane log reductions for each test, with the guaranteed value for relevant tests (1-4). Since the measured log reductions are all greater than the reported values due to the non-detect UV effluents, it isn't possible to demonstrate which scavenging value is most accurate. Of note for Test 4, the predicted log reduction using the Trojan day-specific scavenging value is slightly lower than the measured log reduction, which demonstrates slight conservatism for the control predictions.

**Table 5-4: 1,4-Dioxane and power data for each test.**

Test	Sections on	Power (%)	Online UVT (%)	Flow (gpm)	Measured UVT (%)			[H2O2] (mg/L)		Measured 1,4-dioxane (ug/L)						1,4-dioxane (ug/L)				Total Power (kW)	
					Backgrnd	Avg Inf.	Avg Eff.	Avg Inf.	Avg Eff.	UV Inf-1	UV Inf-2	UV Inf-3	UV Eff-1	UV Eff-2	UV Eff-3	Avg. Inf.	Avg. Eff.	Avg. LR	Guarant. LR	Measured	Max. Guarant.
Control	0	100	98.1	1538	98.1	98.3	98.3	0.2	0.2	3.7	4.3	3.5	3.3	3.1	3.4	3.8	3.3	0.07		1.15	
1	4	100	97.2	1528	97.3	93.7	96.0	24.7	15.9	9.6	11	8.4	<0.028	<0.028	<0.028	9.7	<0.028	>2.54	1.90	104.20	110
2	4	95	99.2	1566	97.1	94.4	96.4	19.1	12.0	5.6	4.6	4.7	<0.028	<0.028	<0.028	5.0	<0.028	>2.25	1.60	99.20	102
3	3	100	98.4	1429	99.2	96.7	97.9	17.7	10.5	6.4	4.5	5.3	<0.028	<0.028	<0.028	5.4	<0.028	>2.29	1.40	79.10	80.6
4	2	100	98.3	1533	99.5	97.1	98.0	13.8	10.0	5.0	3.8	4.3	0.031	0.054	0.052	4.4	0.046	1.98	0.90	53.82	57.9
5	4	100	93.7	1479	94.5	91.4	93.8	23.2	17.8	1.5	1.4	1.6	<0.028	<0.028	<0.028	1.5	<0.028	>1.73		104.20	
6	4	100	87.5	1464	88.0	85.4	87.9	23.2	19.8	0.59	0.5	0.48	<0.028	<0.028	<0.028	0.5	<0.028	>1.27		102.10	
7	4	100	98.7	1524	98.8	96.4	97.7	20.4	10.8	14	11	12	<0.028	<0.028	<0.028	12	<0.028	>2.64		104.70	
8	3	100	99.2	1521	99.2	97.4	95.7	25.2	16.8	6.7	7.1	6.9	<0.028	<0.028	<0.028	6.9	<0.028	>2.39		78.97	

Note: Test 7 UV Inf-3 and UV Eff-2 values were switched relative to the lab report (assumed to be a sample label or transcription error); MDL =<0.028 ug/L



**Figure 5-5: 1,4-Dioxane results (“measured”) and predictions for various scavenging values (top-guaranteed tests and bottom-remaining tests).**

## 5.5 OTHER ANALYTES

UV Influent and UV effluent sample pairs were collected during the performance testing for the purpose of analysis of selected non-target analytes. These included alkalinity, calcium, DOC, hardness, total iron, Mg, Mn, nitrate, nitrite, pH, sulfate, TDS, TOC, and turbidity. The results are listed in Table 5-5.

**Table 5-5: Analytical data for non-target parameters.**

Analyte	Units	1-INF	1-EFF	2-INF	2-EFF	3-INF	3-EFF	4-INF	4-EFF	5-INF	5-EFF	6-INF	6-EFF	7-INF	7-EFF	8-INF	8-EFF	C-INF	C-EFF
Alkalinity	mg/l	180	180	170	170	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Calcium	mg/l	122	123	119	119	119	119	118	119	121	119	122	120	119	122	123	121	119	121
DOC	mg/l	0.48	0.39	0.45	0.43	0.37	0.56	N/A	0.49	0.44	0.49	0.49	0.55	0.41	0.42	0.51	0.44	0.53	0.6
Hardness	mg/l	427	429	415	411	416	415	413	415	423	417	424	417	417	425	427	423	416	421
Total Iron	mg/l	0.052	0.045	0.046	0.1	0.04	0.056	0.044	1.4	0.046	0.083	0.047	0.14	0.25	0.17	0.11	0.058	0.047	0.14
Mg	mg/l	29.4	29.6	28.7	28.4	28.7	28.6	28.5	28.6	29.2	28.8	29.2	28.8	28.7	29.3	29.5	29.1	28.8	29.1
Mn	mg/l	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NO3-N	ug/l	1100	1100	1100	1100	1100	1100	1100	1100	1200	1200	1200	1100	1100	1100	1100	1100	1200	1200
NO2-N	ug/l	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
pH	pH units	7.87	7.85	7.96	7.96	8.01	8.00	7.99	8.00	8.00	7.93	8.00	7.97	7.88	7.91	7.85	7.88	8.00	8.00
SO4	mg/l	350	350	340	350	350	350	350	350	360	360	360	360	350	350	270	340	360	350
TDS	mg/l	820	820	780	780	780	780	780	770	790	790	790	790	830	820	820	810	790	790
TOC	mg/l	0.47	0.50	0.41	0.59	0.38	0.33	N/A	0.45	0.61	0.54	0.76	0.74	0.38	0.38	0.45	0.48	0.56	0.37
Turbidity	NTU	0.30	0.25	0.25	0.45	0.20	0.35	0.15	19	0.40	0.90	0.65	1.0	0.60	0.35	0.30	0.15	0.20	0.75

## 6 CONCLUSIONS & RECOMMENDATIONS

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This report documents the on-site performance tests for the TrojanUVFlex200 AOP system installed at the LADWP North Hollywood West well site. The data demonstrate successful treatment at the “scaled-back” design conditions providing >2.5 log reduction of 1,4-dioxane at 1,528 gpm of 97.3% UVT water with 24.7 mg/L H<sub>2</sub>O<sub>2</sub> compared with the maximum design target of 1.9 log reduction of 1,4-dioxane. Furthermore, the tests covered a range of conditions including flowrates from 1,429 gpm to 1,510 gpm (i.e., ~1/6<sup>th</sup> of design but using 1 of 3 trains and up to 4 out of 8 lamp sections on), UVT values from 88 to 99.5%, influent H<sub>2</sub>O<sub>2</sub> concentrations from 13.8 mg/L to 25.2 mg/L, and 1,4-dioxane log reductions from >1.3 to >2.6. All UV effluents were non-detect (<0.028 ug/L) except for test #4, in which the average 1,4-dioxane concentration was 0.046 µg/L.

All tests with power guarantees (1-4) had measured power draw values below the project guaranteed values. Similarly, the measured 1,4-dioxane log reduction values were all greater than the guaranteed values. This is partly because the scavenging values measured for samples taken during testing were 50,200-63,000 s<sup>-1</sup> which are much lower than the design hydroxyl radical scavenging value of 90,500 s<sup>-1</sup>.

Data from the tests was also used to validate the Trojan PLC program. Results presented demonstrate how the system accurately calculates UV influent UVT from the sum of the background UVT and the absorbance contribution from injected H<sub>2</sub>O<sub>2</sub>. Further, the results demonstrate that the measured and PLC-calculated UV effluent H<sub>2</sub>O<sub>2</sub> concentrations agree very well and the calculated H<sub>2</sub>O<sub>2</sub> concentrations are slightly high. This makes the calculated average H<sub>2</sub>O<sub>2</sub> slightly high, and therefore the calculated average UVT slightly low (conservative).

It is also recommended that representative water samples be periodically sent to Trojan specifically for nitrate ion concentration and scavenging term evaluation. The nitrate ion concentration and scavenging terms are both critical inputs for the control algorithm. Based upon the Trojan sample results, Trojan recommends that the current inputs should be 6.5 mg/L (as NO<sub>3</sub><sup>-</sup>), which is slightly higher than Trojan measured in the samples, and a scavenging term

of  $69,300 \text{ s}^{-1}$  ( $63,000 \text{ s}^{-1} + 10\%$ ). Trojan recommends that samples be shipped monthly for 1 year to establish a baseline of expected water quality. Assuming that variations in the water quality results for these samples are minimal, the frequency of sampling can be subsequently reduced.

Overall, the TrojanUVFlex200 AOP performance test results described in this report demonstrate that the system is properly designed to meet and exceed the guaranteed contaminant treatment and maximum electrical power draw requirements. The data presented has also shown that select calculations used for the automatic control system are accurate based on measured results, and this provides confidence that the system can reliably operate over a broad range of flows, water qualities and treatment targets.

## 7 REFERENCES

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Bader *et al.*: Photometric method for the determination of low concentrations of hydrogen peroxide by the peroxidase catalyzed oxidation of N,N-diethyl-p-phenylenediamine (DPD). *Water Res.* **22** (9), 1109-1115, 1988.

Buxton *et al.*: Critical Review of Rate Constants for Reactions of Hydrated Electrons, Hydrogen Atoms and Hydroxyl Radicals ( $\bullet\text{OH}/\bullet\text{O}^-$ ) in Aqueous Solution. *J. Phys. Chem Ref. Data* **17**, 513-886, 1988.

Gerrity *et al.*: Emerging investigators series: prediction of trace organic contaminant abatement with UV/H<sub>2</sub>O<sub>2</sub>: development and validation of semi-empirical models for municipal wastewater effluents. *Environ. Sci.: Water Res. Technol.* **2**, 460-473, 2016.

Keen *et al.*: Identifying the factors that influence the reactivity of effluent organic matter with hydroxyl radicals. *Water Res.* **50**, 408, 2014.

Kim *et al.*: Occurrence of Unknown Reactive Species in UV/H<sub>2</sub>O<sub>2</sub> System Leading to False Interpretation of Hydroxyl Radical Probe Reactions. *Water Res.* **201**, 117338, 2021.

Kwon *et al.*: Prediction of the removal efficiency of pharmaceuticals by a rapid spectrophotometric method using Rhodamine B in the UV/H<sub>2</sub>O<sub>2</sub> process. *Chem. Eng. J.* **236**, 438-447, 2014.

Lee *et al.*: Impact of groundwater quality and associated byproduct formation during UV/hydrogen peroxide treatment of 1,4-dioxane. *Water Res.* **173**, 115154, 2020.

Lee Y. and von Gunten U.: Oxidative transformation of micropollutants during municipal wastewater treatment: comparison of kinetic aspects of selective (chlorine, chlorine dioxide, ferrate<sup>VI</sup>, and ozone) and non-selective oxidants (hydroxyl radical). *Water Res.* **44**, 555-566, 2010.

Rosenfeldt E.J. and Linden K.G.: The  $R_{OH,UV}$  concept to characterize and to model UV/H<sub>2</sub>O<sub>2</sub> process in natural waters. *Environ. Sci. Technol.* **41**, 2548-2553, 2007.

Rosenfeldt E.J.: Rapid method for measuring background hydroxyl radical scavenging for impacts on design of advanced oxidation processes. *Proceedings of AWWA Water Quality and Technology Conference and Exhibition*, November 14-18, Savannah, GA, USA, 2010.

Stefan, M.I. (ed): *Advanced Oxidation Processes for Water Treatment*, IWA Publishing, 2018.

Zhou X. and Mopper K.: Determination of photochemically produced hydroxyl radicals in seawater and freshwater.

Wang *et al.*: External Standard Calibration Method To Measure the Hydroxyl Radical Scavenging Capacity of Water Samples. *Environ. Sci. Technol.* **54**, 1929, 2020.