Disinfection of biological agents in the field using a mobile advanced oxidation process

by

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Abstract

As an alternative to traditional disinfection methods, the use of an advanced oxidation process (AOP) was investigated for exercise in theatre to expediate water usability. The system utilized for this study was a mobile combination of UV irradiation and ozonation, which provided multiple mechanisms for treatment without the addition of chemicals. As a compact and transportable apparatus, the proposed unit would treat water for secondary purposes including vehicle washing, equipment cleaning, and other demands not involving consumption or personal hygiene. Several varying dilutions of hog farm lagoon water and military vehicle wash water were combined with microbial concentrations up to 9.10E+04 mpn/mL. The inoculant tested was Escherichia coli for frequency of occurrence and similarities to microbes of bioterrorism. The overall results for the AOP treatment do not indicate a connection between inactivation and suspended solids, but there does exist a significant relationship to contact time as indicated by changes in the flow rate. The experimental data showed a correlation to increased inactivation with lower flow rates. Although inactivation was not complete, the once through flow system could be adjusted to recirculate water for additional treatment. Due to time constraints additional testing was not possible, but the benefit could be examined in future research. The relationship of TSS to inactivation was not evident as inactivation occurred in similar distributions whether suspended solids were elevated or reduced.

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Chapter 1 - Introduction

The Army's Net Zero initiative seeks to reduce water consumption and improve reuse on military installations both locally and globally. In response to the necessity of water security to protect against contamination, promote control, and the handling of large volumes of wastewater following an event involving biological agents the following research to optimize a mobile Advanced Oxidation Process (AOP) was developed. The research seeks to evaluate the limitations, applicability, and advantages of such a process and how well it performs under varying water quality conditions.

The use of a mobile system is key for situations in theatre where local treatment and fresh water is not readily available. Such water could be hazardous due to elevated levels of TSS, nutrient pollution, harmful microorganisms, or chemical contamination. In dire situations, water reuse may be necessary and precautions exercised to ensure contamination does not occur from wash water that might be recycled. In the field, immediate access to chemical chlorination may not be available. While effective, the transport of treatment chemicals could prove hazardous in the event of an attack. The design of the AOP eliminates the need for additive chemicals, concerns for chlorine residual, undesired reactions between chemical treatment and possible contaminants, and transportable from one station to the next.

Convoys traveling in desert regions with extensive open space and routinely followed trails make for easy targets. Convoys carry vital supplies including sustenance, medical equipment, and fresh water between operations. When convoys are not available, or become delayed soldiers must rely on local sources for provisions. Advanced filtration, chemical

treatment options, and fresh sources are frequently scarce. Soldiers who have access to a local system or well water may be fortunate, but the water cannot be guaranteed for safe consumption or secondary utilization without additional treatment.

The Army and Environmental Protection Agency (EPA) are partnering to promote and demonstrate innovative technologies on military installations in support of the Net Zero initiative. Through the Office of Research and Development (ORD), EPA scientists and engineers are working with the Army to identify specific technology needs. One challenge of interest is containment, control and disposal of large volumes of wastewater following an event involving biological or agents. Wash racks, or areas where military vehicles are washed after field exercise, are a source of water contaminated with oil, grease, heavy metals and suspended solids (dirt and mud). Access to the wash rack water provides a unique opportunity to evaluate disinfection of biological agents in the field with water quality that might influence the disinfection process.

The proposed AOP for this project consists of ozone and ultraviolet radiation in combination to produce three treatment measures encompassing direct and indirect ozonation, and UV irradiation. Produced ozone is injected into the water stream, which is then exposed to UV radiation to induce the formation of H2O2 and indirect oxidation. The limitations of an AOP are not fully understood while limitations of the individual processes have been examined in previous studies. The combined effects of UV and Ozone together potentially overcome these limitations by advancing the rate of oxidation and speeding inactivation of microorganisms.

The potential of this process as designed has not been extensively studied in the combination proposed nor with respect to contact time and water quality interference. This investigation has been designed to evaluate the operation of the AOP system as it performs relative to elevated TSS and flowrates.. All components are within parameters suggested by existing literature including the intensity of the medium pressure UV lamp at 254 nm and an ozone concentration of 5.8 mg/L.

This report examines the inactivation and/or removal of biological agents in wash water using portable treatment processes. Wash water will be sourced from the vehicle wash racks at Fort Riley in Kansas. Biological contaminants will be spiked into tanks of clean tap water and dirty water of various dilutions. The effect of dirt and grime on biological agent removal efficiency will be determined and compared with results from clean tap water.

The objectives of this investigation aim to evaluate the limitations of an Advanced Oxidation Process treatment with set values of UV irradiation and Ozone concentration, and optimize the performance of the system according to those limitations. Experimentation was proposed to analyze the influence of total suspended solids and flowrate on the ability of the system to inactivate high levels of inoculum in the form of Escherichia coli. Based on the proposed source water from military field vehicle wash operations other possible parameters that might cause differences of inactivation include temperature, bio-solids, nutrient load, and pH.

Chapter 2 - Methods & Procedures

AOP System Design

The AOP system consists of a 1-inch stainless steel (SS) pipe loop system, a variable speed recirculation pump, a MP UV lamp and a LP UV lamp, an oxygen (O2) concentrator, an O3 generator, an ozone injection system, and an O3 destructor (Figure 1). Influent samples were removed from the blend tank used to feed the AOP unit, and just after initial entrance to the unit to establish fluctuations during loading. Effluent samples were removed from the sampling port immediately before the treated water was discharged. Water with biological agents was exposed to the ozone and UV light as it passed through the AOP unit.

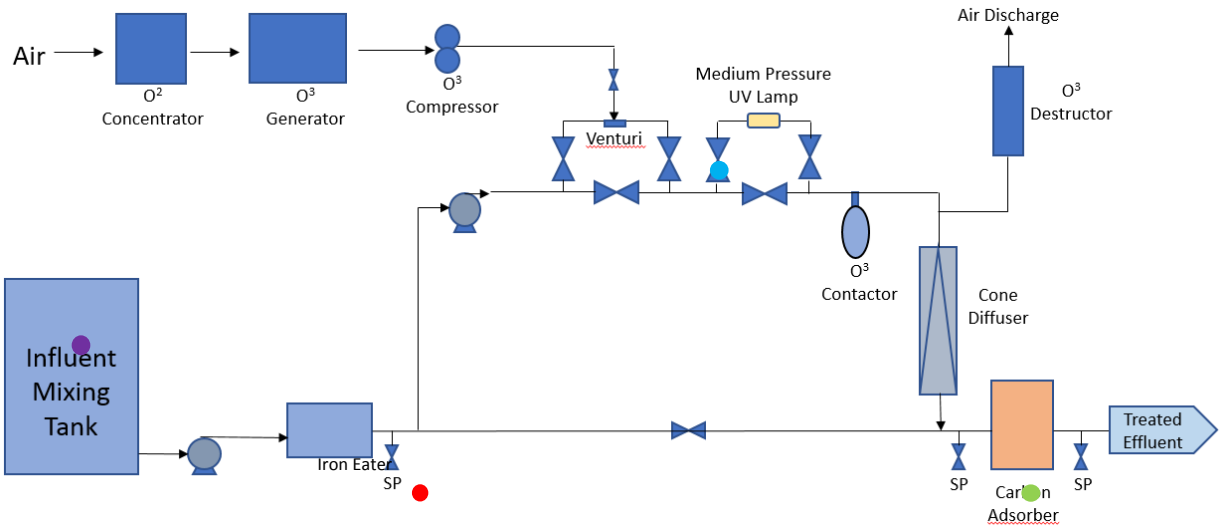


Figure 1 - Schematic Diagram of Pilot Scale AOP System

UV radiation was provided by a medium pressure (MP) UV reactor (Aquionics InLine 20 UV System, Aquionics, Inc., Erlanger, KY) in Figure 2. O3 was generated using an O2

concentrator and an O3 generator. The O2 concentrator separates O2 from compressed air through a pressure swing adsorption (PSA) process. The PSA process uses a molecular sieve (a synthetic zeolite), which adsorbs nitrogen and other impurities from the air at high pressure and desorbs them at low pressure. The O2 concentrator is designed for a maximum airflow rate of 6.6 standard cubic feet per hour (scfh). The O2 is then fed into the O3 generator. In the reaction chamber of the O3 generator, the feed gas is exposed to multiple high-voltage electrical discharges, producing O3. The O3 is injected into the system through a venturi-type, differential pressure injector (Mazzei ¾-inch MNPT Model 684) located on the discharge side of the system recirculation pump (¾-horsepower G&L Pump NPE/NPE-F). When the contaminated water enters the injector inlet, it is constricted towards the injection chamber and emerges as a high-velocity jet stream. The increase in velocity through the injection chamber results in a decrease in pressure, thereby enabling O3 to be drawn through the suction port and entrained into the motive stream. The venturi is assisted by an ozone compressor (Air Dimensions, Inc. DiaVac pump) to allow the system to operate at lower differential pressures while maintaining a high ozone concentration in the system. The ozone concentrations are further increased by the use of an ozone cone diffuser shown in Figure 3. Excess O3 is converted back to O2 using an O3 destruct unit before it is vented into the atmosphere. The recirculation pump is connected to a variable-speed controller (1AB2 AquaBoost II Controller), which enables the flow rate in the loop to be set to any desired value.

Treatment Process

The AOP disinfection technology is UV irradiation combined with O3. Due to the high molar extinction coefficient of ozone, UV radiation can be applied to ozonated water to form highly reactive •OH. Because photolysis of O3 generates H2O2, the UV/O3 process involves

the disinfection mechanisms present in O3/H2O2 and UV/H2O2 AOPs. For instance, H2O2 in conjunction with O3 can enhance the formation of •OH. H2O2 is a weak acid that partially dissociates into hydro-peroxide ion (HO2-) in water. The HO2- ion can rapidly react with O3 to form •OH. Meanwhile, hydroxyl radicals are produced from the photolytic dissociation of H2O2 in water by UV radiation. Disinfection can occur either by direct photolysis or by reactions with •OH.

Figure 2 - Medium-Pressure UV Lamp System

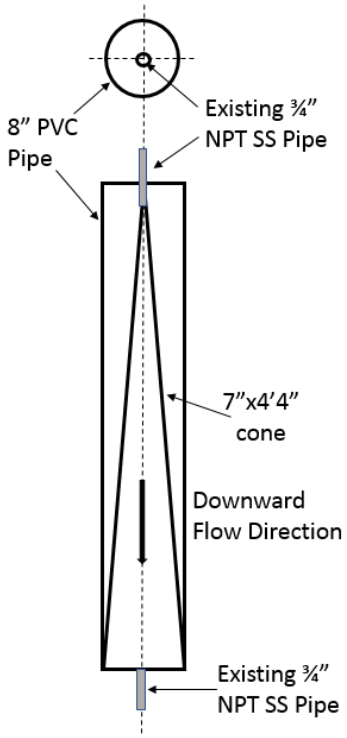


Figure 3 - Cone Diffuser for Ozone Concentration

Experimental Design

The investigation consisted of the treatment of Escherichia coli in clean tap water, dirty water from Fort Riley wash racks, and naturally sourced water from a local runoff collection pond using the mobile AOP trailer.

All tests were conducted on the Kansas State University campus in the Biological and Agricultural Engineering workshop. Water from the wash racks was used directly without dilution to establish whether an interference of turbidity existed. Carboys of water from the wash racks at Fort Riley were collected as needed along with water from a local runoff pond. Additional treatment analysis consisted of the influence of flowrate, bacteria interaction with suspended particles, and water quality.

The MP-UV lamp installed in the AOP system provided UV radiation at an emission spectrum between 200 nm and 300 nm with a power requirement of 0.9 kW and a UV dose >10 mg/cm2. The UV unit had one setting, so UV conditions were constant for all experiments in the study. Preliminary tests were performed by running carbon-filtered tap water and ozone through the AOP system to test the capacity of the ozone generator and to determine the ozone concentration in the AOP system. The setting of the ozone generator was adjusted during the preliminary tests to achieve the target ozone concentration of approximately 5.8 mg/L or greater in the AOP system. The levels of ozone were never definitively established due to the high reactivity of O3. Settings for the ozone generator were left at the highest values possible, but could not be recorded conclusively. The presence of ozone was observed throughout testing, but a true value of concentration was never determined. Unable to establish; consistent presence confirmed.

Experiments were conducted by filling the feed tank with E. coli inoculum at a minimum microbial density of 1.14E+05 mpn/ml. Propagation of the inoculant was carried out by incubating 100 mL of broth (Figure 4) with 1 mL of concentrated E. coli solution at 37°C for 24 hours.

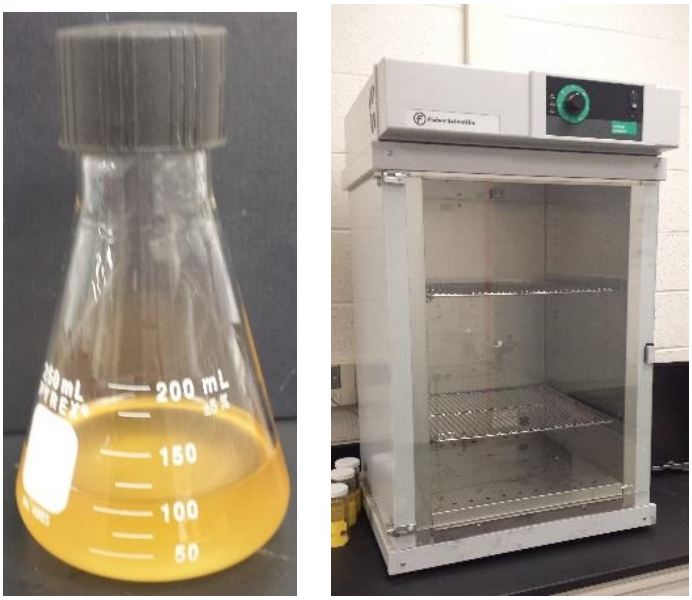


Figure 4 – Inoculated flask of 100 mL broth solution and incubation oven

Water was fed to the AOP unit at two different rates, 6 gpm or <4gpm. One sample was removed from the feed tank to determine the initial concentration (Ti). Water exiting the AOP unit (effluent samples) were sampled at the last sampling point before the water left the AOP unit (Ce). Samples were removed at 1, 5, 10, 15, and 20 minutes after the contaminated water feed to the AOP unit started. Disinfection was assessed by examining the log reduction (LR) of samples taken at 1, 5, 10, 15, and 20 minutes compared to the initial microbial density in the feed tank using the following equation:

Equation 1 - Microbial Density

$$LR = -log\frac{C_e}{T_i}$$

Table 1 lists the experimental design parameters for AOP disinfection of E. coli. Clean tap water was pumped through the AOP trailer for 20 minutes prior to each experiment to clear

the disinfection unit of particulates and residual bacteria. During this same time bacteria inoculum was circulated in the mixing tank for consistent distribution.

Table 1 - Experimental Design Parameters

Parameters	Designed Values
Source Water	Pond/Lagoon water, Dechlorinated tap water
dilution water	Pond/Lagoon water, Dechlorinated tap water
target contamination	*Escherichia coli*
Concentration of contaminant	10^3-10^5 mpn/mL
AOP method	UV irradiation/O3
Type of UV lamp	Medium-pressure UV lamp
UV Intensity	preset level kept constant
Ozone concentration	approx. 5.8 mg/L (indeterminate)
Temperature Range	20-23°C
Flow rates	less than 4 gpm and 6 gpm
Recirculation ratio	once-through flow
Collection Points	T, C0, C5, C10, C15, C20, E5, E10, E15, E20
Test Duration	20 minutes

Evaluation objectives

Measurement analyte, location, reporting units, and sampling frequency for critical measurements are summarized in Table 2. Table 3 summarized the measurement analyte, reporting units, sampling type, sample location, and frequencies for non-critical measurements.

Table 2 - Critical Parameter Measurement Summary

Measurement	Reporting Unit [a]	Sampling Location	Measurement Purpose
E. coli	mpn/ml	Supply tank, and Influent to Cart and Effluent from Outlet of AOP System at 0, 1, 5, 10, 15, and 20 minutes after the start of a test run.	Primary microbial contaminant for study
Ozone	mg/L	Outlet sampling port, 2 grab sampling events per test run (at the beginning and end of the test run)	Disinfectant concentration

a: cfu = colony forming units, mpn = most probably number, mg/L = milligrams per liter

The information in Table 2 highlights critical parameters for treatment. The initial bacteria concentration was required to evaluate inactivation rates. The presence of ozone, while difficult to measure precisely was identified in treatment grab samples to verify effectiveness of the system. A total of 10 samples were collected per run: 5 initial samples were drawn from the AOP cart at the intake, 1 sample directly from the mixing tank, and 4 treated samples were drawn from the effluent. Ozone sampling was tested prior to treatment and following. Neither sample provided consistent results suitable for reporting. Due to the rapid reactivity of ozone the ability to accurately sample was diminished and at time resulted in complete absence.

Table 3 - Non-Critical Experimental Measurements

Measurement	Reporting Unit[A]	Sample Type	Sampling Location	Sampling Frequency
Total Suspended Solids	mg/L	Each sample per run	Supply tank and outlet sample ports	10 sampling events per test run (T, C0, C5, C10, C15, C20, E5, E10, E15, E20)
Temperature*	ºC	Analog gauge reading	On-line gauge	2 readings per test run (at the beginning and end of the test run)
Flow rate*	gpm	Digital flow meter reading	On-line meter	2 readings per test run (at the beginning and end of the test run)
Water pressure*	psi	Analog gauge reading	On-line gauge	2 readings per test run (at the beginning and end of the test run)
Air flow into the ozone generator*	scfh	Flow meter	On-line meter	2 readings per test run involving ozone (at the beginning and end of the test run)

A: mg/L = milligrams per liter; gpm = gallons per minute; psi = pounds per square inch; scfh = standard cubic feet per hour, * = Process data

The experimental measurements indicated in Table 3 are indications of quantifiable characteristics monitored for each test run. Total suspended solids were observed for each sampling event drawn during a treatment run. This provided 10 incidences of TSS observation to evaluate how sediment behaved in the system. Temperatures were controlled by the ambient conditions of the day and did not fluctuate drastically. Flowrate, water pressure, and air flow were determined by inline sensors on the AOP cart. Maintaining consistent measurements provided uniformity by which to compare results.

Table 4 - Water Quality Measurements

Measurement	Reporting Unit[A]	Sample Type	Sampling Location	Sampling Frequency
*TDS	mg/L	Sample from supply tank	Mixing Tank	1 sampling every test run
*Conductivity	m S/cm	Sample from supply tank	Mixing Tank	1 sampling every test run
*Total N	ppm	Sample from supply tank	Mixing Tank	1 sampling every test run
*Total P	ppm	Sample from supply tank	Mixing Tank	1 sampling every test run
COD	mg/L	Sample from supply tank	Mixing Tank	1 sampling every test run
pH	Standard unit	Sample from supply tank	Mixing Tank	1 sampling every test run
TSS	mg/L	Sample from supply tank	Mixing Tank	10 samplings every test run

A: mg/L = milligrams per liter; ppm = parts per million; m S/cm = micro Siemens per centimeter

*Conducted by Kansas State Soil Testing Lab

The measurements in Table 4 are indicative of the water quality between test batches. Depending on source, settling time, and the discrete sampling these values fluctuated throughout testing. Correlations of these measurements with inactivity were used to compare water quality as it affects AOP treatment.

Chapter 3 - Sampling and Measurement Approach and Procedures

Sampling Procedures

The sampling points were in the supply tank and two outlets of the AOP system as shown in Figure 1. Samples for critical parameters (microbial contaminants) as well as non-critical parameters were collected at the frequency presented in Table 2 and Table 3. Sampling containers, preservation techniques, and holding times for grab sample measurements are presented in Table 5. As soon as practical, each sample was aliquoted into the proper containers and the appropriate preservation technique were applied in accordance with the guidelines in Table 5. Each container was labeled with the date and time sampled, sample location (inlet or outlet), and the parameters for analysis as seen in Figure 5 and Figure 6.

Table 5 – Parameters for Grab Sample

Parameter	Sample Container	Preservation Method	Holding Time
E. coli	Sterile 200 ml glass sample bottle	Cool to 4 ± 2 °C	24 hours from collection
Ozone	200-ml glass bottle	None	Samples analyzed immediately in the field
pH	200-mL glass bottle	Cool to 4 ± 2 °C	Samples analyzed immediately, or held for no more than 4 hours
TSS	200 ml glass sampling bottle	Cool to 4 ± 2 °C	Samples analyzed immediately, or held for no more than 48 hours

Figure 5 - Treated samples with high TSS

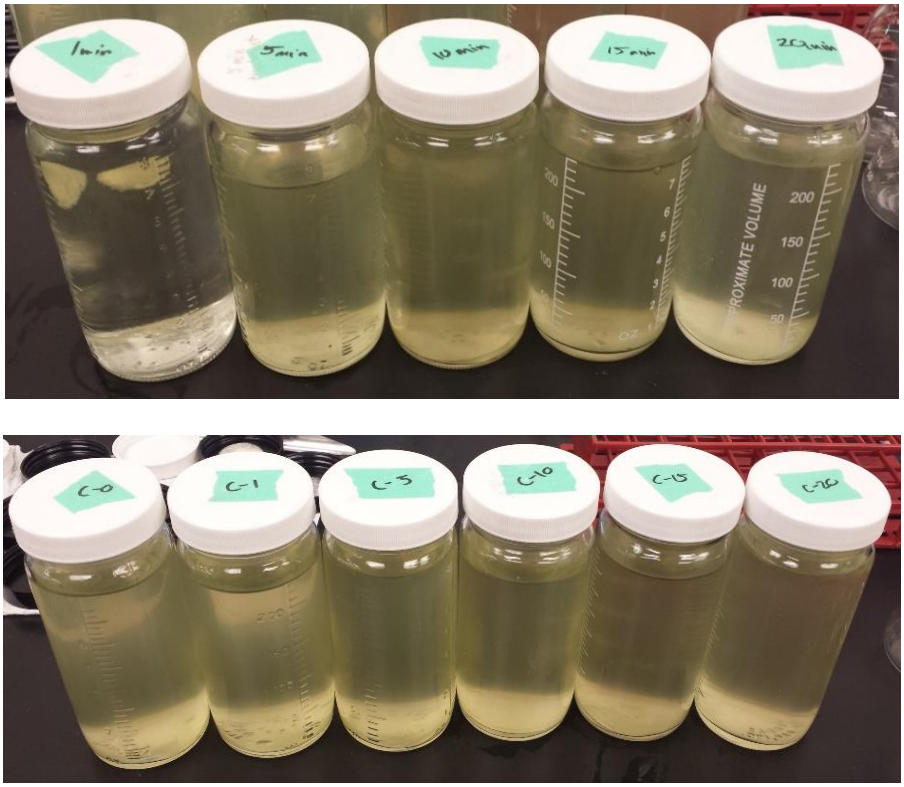


Figure 6 - Treated samples with low TSS

Enumeration Procedure

Microbial samples from the supply tank and AOP unit influent/effluent were collected in 200 ml glass sampling bottles. Once the bottles were full the samples were immediately analyzed or placed in a refrigerator at 4 ± 2 °C until analysis. Sample analysis was conducted by the Colilert-18 Method using vacuum sealed Quanti-Tray technology, shown in Figures 9 through 13, for enumeration of initial culture concentration and treated samples.

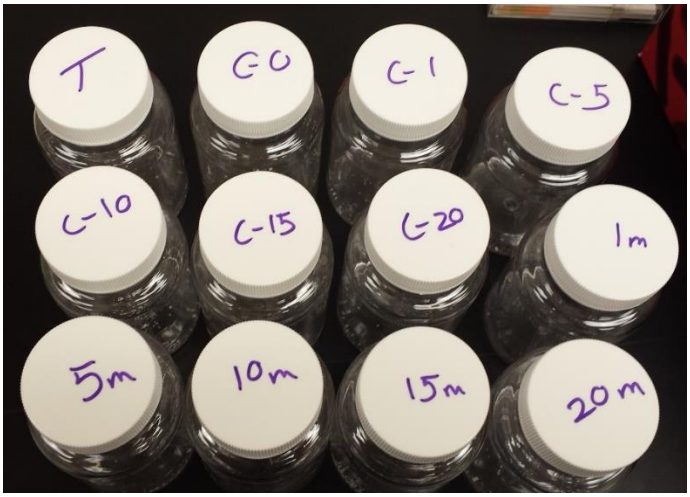


Figure 7 - Colilert-18 120 mL vessels with Sodium Thiosulfate labeled for enumeration

Figure 8 - Colilert-18 sodium thiosulfate vessels, reagent snap packets, and Quanti-trays

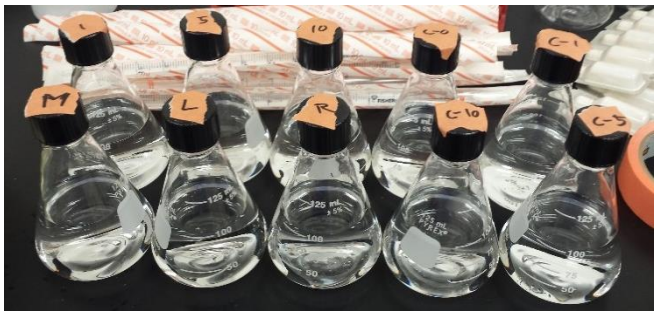


Figure 9 - Treatment sample dilution flasks

Figure 10 - Colilert-18 Quanti-Tray Sealer

Figure 11 - Activated Colilert-18 method Quanti-Trays

Analytical Laboratories

All analyses and measurements listed in tables 2 and 3 were conducted at Kansas State University with the Kansas State University Soil Testing Lab performing additional analysis to characterize the water samples. The testing of chemical oxygen demand (COD) and total suspended solids (TSS) were carried out in the Environmental Lab at Kansas State University (Figure 12, Figure 13).

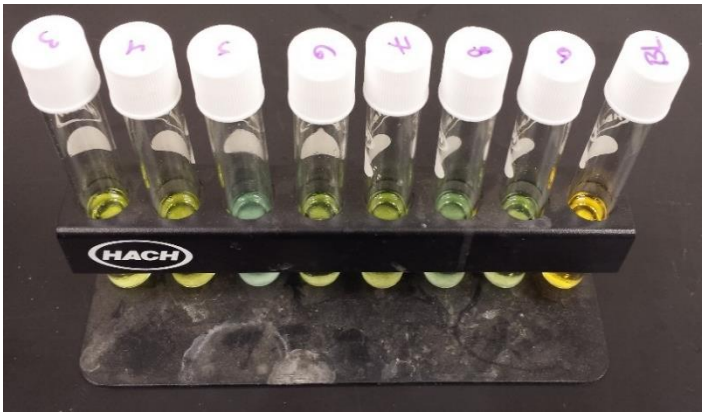


Figure 12 - Water Quality: COD Testing

Figure 13 - Water Quality: Total Suspended Solids

Sampling and Analytical Procedures

Analytical procedures are summarized in Table 6. The AOP system is outfitted with inlet and outlet sample taps. When collecting a grab sample, the sample tap was opened and water allowed to flow for approximately 10 seconds to flush the sampling port.

Table 6 - Analytical Methods for Grab Sample Parameters

Parameter	Unit[A]	Method	Citation	Method Summary
E. coli	mpn/ml	9221 B, C	Standard Methods for Examination of Water and Wastewater, 22nd Edition	Colilert reagent and Quanti-tray 2000
Ozone	mg/L	4500-O_3-B	Standard Methods for Examination of Water and Wastewater, 22nd Edition	Colorimetric, Indigo dye method
pH	pH units	150.1	EPA/600/4-79-020, Methods for the Chemical Analysis of Water and Waste, March 1983	Litmus paper strips
TSS	mg/L	SM 2540 D	Standard Methods for Examination of Water and Wastewater, 22nd Edition	
*TDS	mg/L	SM 2540C	Standard Methods for Examination of Water and Wastewater, 22nd Edition	
COD	mg/L	SM 5200D/Hach 8000	Standard Methods for Examination of Water and Wastewater, 22nd Edition	
*Conductivity	µS/cm	SM 2510	Standard Methods for Examination of Water and Wastewater, 22nd Edition	
*Total N		USGS WRIR 03-4174	USGS WRIR 03-4174	
*Total P		USGS WRIR 03-4174/EPA 365.2	USGS WRIR 03-4174	

A: mg/L = milligrams per liter., mpn=most probable number, cfu=colony forming units

* Conducted at the Kansas State University Soil Testing Lab (http://www.agronomy.k-state.edu/services/soiltesting/)

Samples were labeled in accordance with the following identification scheme: date, sample location, sample time, and experiment number. Temperature, flow and pressure readings were recorded 2 times per test run (at the beginning and the end of the test run). The number of tests completed is delineated in Table 7.

Table 7 - Test Run Summary

Test Run	Source Water	Flowrate (gpm)	TSS (mg/L)	Source Volume	Run Time
BL	Tap	6	0	100	10
LW1	Lagoon	4	197	100	20
LW2	Lagoon	4	121	100	20
LW3	Lagoon	3.5	70	100	20
PW10	Pond	6	52	150	20
PW11	Pond	6	110	150	20
PW12	Pond	6	70	150	20
PW2	Pond	6	49	100	10
PW3	Pond	5.5	65	150	20
PW5	Pond	6	682	150	20
PW6	Pond	3	155	150	20
PW7	Pond	6	50	150	20
PW8	Pond	3	278	100	20
PW9	Pond	3	176	100	20
TW1	Tap	4	67	100	20
TW3	Tap	4	210	100	20

The information in Table 7 lists the source for each test batch of water, its characteristic properties, and flowrate maintained during treatment. Tests were labeled according to the sequence of the batch and the associated source of water. The extended runtime of 20 minutes was applied to all, but two tests to provide additional sampling times as the 1 minute sampling time was omitted after verification that tap water chloramines were interfering with AOP inactivation.

Preparing and running the AOP trailer for an individual test required approximately 2 hours per run with 24 hours of preparation between tests for bacteria propagation and final

enumeration. Pretreatment maintenance of the AOP trailer entailed flushing of the system for 20 minutes with tap water, loading of source water to supply tank from storage tank at 15-23 minutes, mixing of inoculum bacteria and source water was 20 minutes and 30 minutes for 100 and 150 gallons respectively, and configuration of outlet and inlet hoses to appropriate locations. Setup and decommissioning of equipment for each test run was labor intensive as the area utilized was a common space for multiple projects.

The supply pump from mixing tank to AOP trailer provided a flowrate of ~11 gpm while the small mixing pump circulated water or transferred from the source tank to the mix tank at ~7 gpm.

Chapter 4 - Results and Discussion

Resultant Data

Decreased flow rates resulted in a longer period of exposure to the AOP treatment including time for higher levels of –OH ions to form, and H2O2 molecules the opportunity to react prior to O3 destruction. The difference in flow rates from 6 gpm to 4 gpm is not a large gap, but the results demonstrate a significant rate change of inactivation. Increases in flow rate were not tested, but data suggests the recirculation would be necessary for flow rates above 6 gpm.

The information in Table 8 expresses the water quality data provided by results from the Kanas State University Soil Testing Lab. Tests with incomplete data were not submitted for evaluation, but whose values were determined by standardized lab protocol mentioned in the methods section. Complete water quality evaluations were not conducted for TW1 and TW3.

Table 8 - Water Quality Results

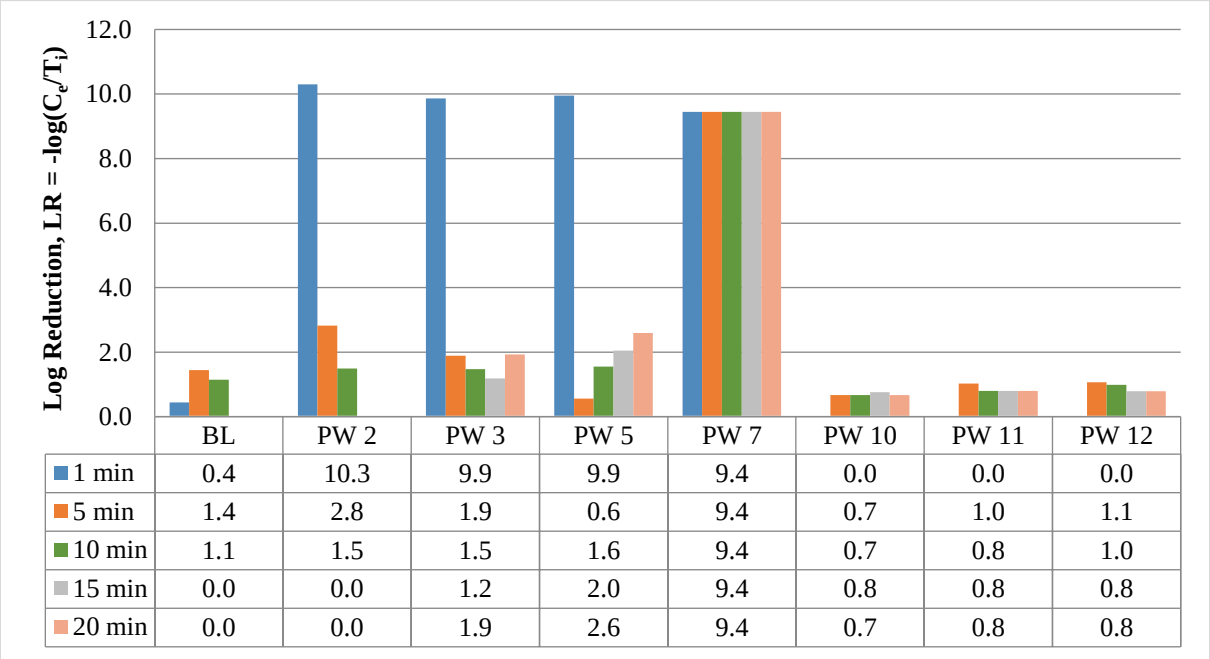
Test	TSS (mg/L)	TDS (mg/L)	Conductivity (m S/cm)	Total N (ppm)	Total P (ppm)	COD (mg/L)	pH
BL	0	0	-	-	-	-	7
PW2	38	-	-	-	-	-	-
PW3	65	648	0.93	11.03	0.9	123	8
PW5	682	569	0.813	15.91	1.66	150	8
PW6	155	616	0.88	13.48	1.22	142	8
PW7	52	571	0.816	15.68	1.17	143	8
PW8	278	591	0.844	17.42	1.36	150	7
PW9	176	601	0.858	15.95	1.23	150	8
LW1	197	356	0.509	4.17	0.33	47	8
LW2	121	368	0.525	4.41	0.34	60	8
LW3	70	365	0.521	3.99	0.29	37	8
PW10	52	573	0.819	10	1.01	145	8
PW11	110	591	0.844	12.71	1.46	150	8
PW12	70	604	0.863	12.18	1.31	155	8
TW1	67	-	-	-	-	-	-
TW3	120	-	-	-	-	-	-
Statistical Variation							
Average	141	496	0.77	11	1.02	121	8
Minimum	0	0	0.509	3.99	0.29	37	7
Maximum	682	648	0.93	17.42	1.66	155	8
Median	90	573	0.8315	12.445	1.195	144	8
Std Deviation	155	174	0.15	4.66	0.45	43	0.36

Inconsistent inactivation for E1 compared to remaining time intervals was prevalent among all flow rate samplings (Table 9). This observation lead to the disregard of E1 sampling times based on the conclusion that chloramine rich tap water was still present in the system at the 1 minute effluent sample time leading to incomparable inactivation. Due to the uncertainty of chloramine level fluctuations prior to the 1-minute sampling times were considered outliers.

Table 9 - Sequential order of testing and log reductions based on sampling time

Test	1 min	5 min	10 min	15 min	20 min		Std Deviation
BL	0.4	1.4	1.1	-	-		0.4
PW 2	10.3	2.8	1.5	-	-		***3.9***
PW 3	9.9	1.9	1.5	1.2	1.9		***3.3***
PW 5	9.9	0.6	1.6	2.0	2.6		***3.4***
PW 6	9.7	9.7	9.7	9.7	9.7		0.0
PW 7	9.4	9.4	9.4	9.4	9.4		0.0
PW 8	4.8	5.1	5.1	5.3	5.0		0.1
PW 9	6.1	5.8	6.3	5.1	5.0		0.5
LW 1	9.6	5.8	6.3	6.2	6.3		***1.4***
LW 2	4.2	4.2	6.0	5.5	5.2		0.7
LW 3	7.0	5.8	5.6	5.7	5.5		0.5
PW 10	-	0.7	0.7	0.8	0.7		0.0
PW 11	-	1.0	0.8	0.8	0.8		0.1
PW 12	-	1.1	1.0	0.8	0.8		0.1
TW 1	-	2.7	3.8	3.4	2.7		0.5
TW 3	-	3.2	2.8	3.2	2.8		0.2
Average	*7.4*	4.8	4.9	5.6	5.6		

Because inactivation outliers for E1 samples were most common among higher flowrate tests, the data was broken down into two sets for observation. The information in Figure 14 demonstrates the performance of the AOP for flow rates exceeding 5 gpm. The reduction observed at 1 minute sampling times expresses the effect of chloramines remaining in the system prior to complete circulation of the batch influent. The system at 1 minute had not yet been purged of tap water used to flush the system before testing.

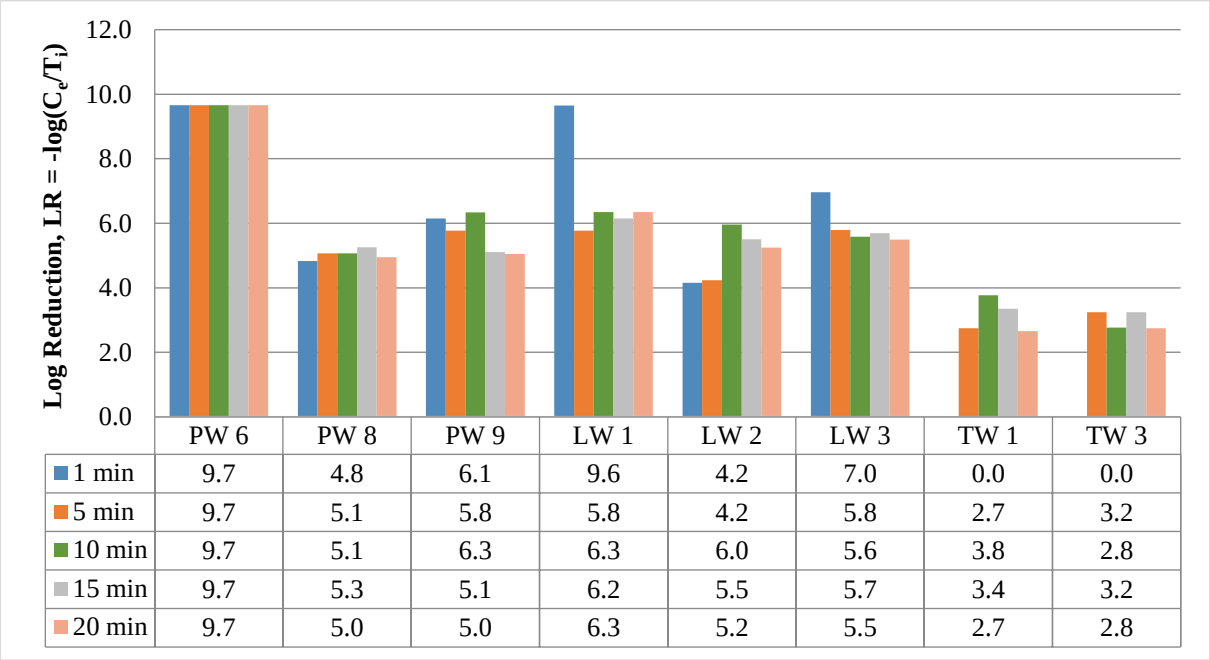


	BL	PW 2	PW 3	PW 5	PW 7	PW 10	PW 11	PW 12
1 min	0.4	10.3	9.9	9.9	9.4	0.0	0.0	0.0
5 min	1.4	2.8	1.9	0.6	9.4	0.7	1.0	1.1
10 min	1.1	1.5	1.5	1.6	9.4	0.7	0.8	1.0
15 min	0.0	0.0	1.2	2.0	9.4	0.8	0.8	0.8
20 min	0.0	0.0	1.9	2.6	9.4	0.7	0.8	0.8

Figure 14 - Log Inactivation based on sampling time for High Flowrate

The information presented in Figure 15 expresses a similar trend to that of Figure 14 with inconsistent reduction for the 1-minute effluent sampling. The trend is not as common for all tests as it is with higher flowrates. The lower rate of reduction could be attributed to the difference between the recirculating pump pressure and the influent pressure. Influent pressure was regulated to determine a high or low flowrate while the circulating pump moved water at a continuous rate. The pump required a minimum pressure of 1 psi in order to continue operation

throughout the entire run. Dropping below 3 gpm would in effect lower the pressure to below this threshold.



	PW 6	PW 8	PW 9	LW 1	LW 2	LW 3	TW 1	TW 3
1 min	9.7	4.8	6.1	9.6	4.2	7.0	0.0	0.0
5 min	9.7	5.1	5.8	5.8	4.2	5.8	2.7	3.2
10 min	9.7	5.1	6.3	6.3	6.0	5.6	3.8	2.8
15 min	9.7	5.3	5.1	6.2	5.5	5.7	3.4	3.2
20 min	9.7	5.0	5.0	6.3	5.2	5.5	2.7	2.8

Figure 15 - Log Inactivation based on sampling time for Low Flowrate

Uniformity of inactivation indicates the chloramines would have to be evenly distributed throughout the system. The lower flow rate may have permitted slower introduction of bacteria to treatment and thus to chloramine presence. While the in-flow rate was lowered the recirculation pump on the cart was not altered. Flowrate to the system was adjusted by increasing or decreasing inlet pressure. The rate at which the circulation pump moves the water would not be changed. Chloramine would have had adequate time to be flushed from the system without mixing of the two streams. The inactivation of 1 minute sampling times were disregarded by this reasoning.

Table 10 - Influent and Average Effluent rates for individual test

Test	Initial (T) (mpn/mL)	Effluent (E_A) (mpn/mL)	Percent Reduction (%)	Log Reduction
BL	1.99E+05	1.06E+04	94.67	1.27
PW2	1.99E+05	3.31E+03	98.33	1.78
PW3	7.22E+04	2.24E+03	96.90	1.51
PW5	8.88E+04	6.93E+03	92.20	1.11
PW6	4.62E+04	1.00E+00	100.00	4.66
PW7	2.81E+04	1.00E+00	100.00	4.45
PW8	1.71E+04	1.45E-01	100.00	5.07
PW9	4.37E+04	2.07E-01	100.00	5.33
LW1	4.43E+04	3.65E-02	100.00	6.08
LW2	3.45E+05	5.82E+00	100.00	4.77
LW3	9.10E+04	2.15E-01	100.00	5.63
PW10	1.14E+05	2.31E+04	79.67	0.69
PW11	1.52E+05	2.17E+04	85.69	0.84
PW12	1.50E+05	1.92E+04	87.18	0.89
TW1	3.65E+05	4.21E+02	99.88	2.94
TW3	1.75E+04	2.03E+01	99.88	2.94

Effluent averages shown in Table 10 omitted the E1 sampling time due to incongruity throughout testing to the remaining sampling times. The pervasiveness of chloramine disinfection from the tap water used to prime the AOP cart contributed inconclusive results. The value for effluent (EA) was determined from the average of E5, E10, E15, and E20 treated samples. The percent reduction was based on the difference of the initial (T) and effluent average reduction (EA). Log Reduction values utilized the initial (T) and effluent average reduction (EA).

Data Analysis

The value of total suspended solids ranged from 0 mg/L to 682 mg/L between 16 treatment samples. Values for TSS were collected from water quality testing by the Kansas State University Soil Testing lab. The rate of reduction indicates the elimination of bacteria based on percentage of inactivation from original values. The standard error for log reduction within each grouping of TSS levels reinforced the evidence that particulates were not a significant hindrance to a UV/O3 AOP. Figure 16 illustrates groupings of TSS ranges and the relative inactivation rates. For 0-60 mg/L the reduction averaged 93.17% with similar rates for 60-100 mg/L and 100-160 mg/L at 95.99% and 95.23%. The highest TSS levels or <160 mg/L experienced the highest rate of inactivation with 98.42%. The various groups represent 3-5 tests without distinguishing flowrate. The error bars represent standard deviation within the data groups. Reduction values were based on the average of inactivation for all associated effluent sampling times.

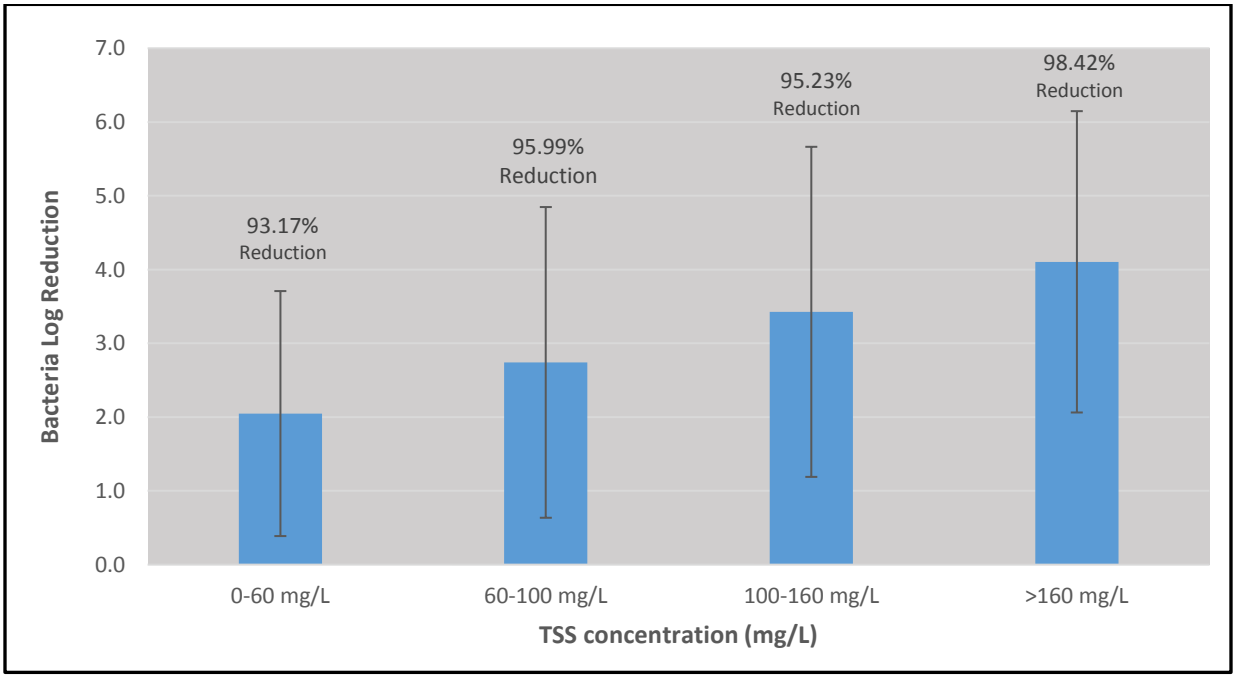


Figure 16 - Log Inactivation of Bacteria relative to TSS concentration in mg/L

Experimentation involved direct evaluation of highly turbid water from a runoff collection pond. Test sampling was expanded to 20 minutes with 150 gallons of water and 10 vials of 100 mL E. coli. To establish a baseline for comparison a dechlorinated tap water test was run with the 100 gallons of water and 8 vials of 100 mL E. coli with Tank samples reduced to a singular sample drawn from the middle. Bacteria concentrations and TSS levels were determined as consistent through several split samplings using Left, Right, and Middle collection points. One of the most important notes of the literature review dictates that contact time with ozone disinfection is vital. By reducing the flowrate to just above 3 gpm the level of inactivation was increased by 2-3 logs. Figure 17 illustrates the data as separated by difference of flowrate relative to percent inactivation. The two groupings, 6 gpm and 4 gpm, each consist of 8 individual tests and their average reduction. The error bars represent the standard deviation of inactivation within the two groups. Average reduction at a flowrate less than 4 gpm was significantly different than of flowrates of 6 gpm.

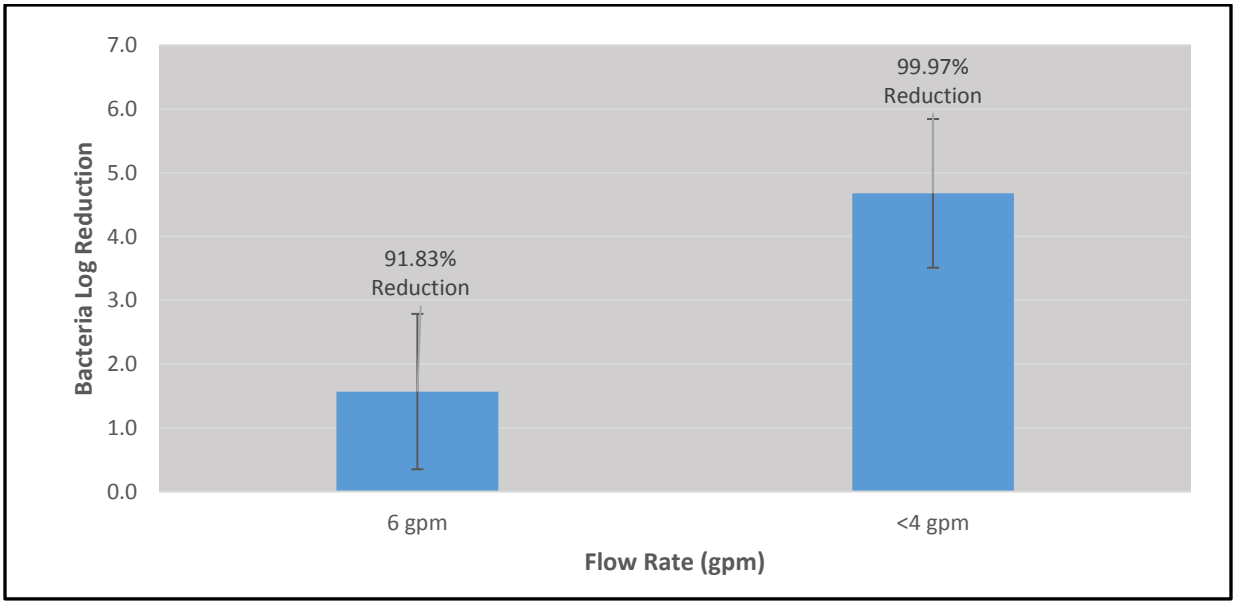


Figure 17 - Log Inactivation of Bacteria relative to Flow rate in gpm

Relation of Suspended Solids

The question of whether TSS was influential to the treatment process required closer observation of TSS levels and distribution. Analysis of TSS values, from 100 mg/L to 600 mg/L, resulting in similar reduction. Despite the increase of TSS the reduction ability of the AOP trailer remained uninhibited. In addition, higher TSS correlated with lower flowrates expressing the possibility of settling within the equipment, which would be expected to further hinder inactivation. At higher flowrates the relative TSS levels averaged 135 mg/L while at lower flowrates 160 mg/L.

Statistical Analysis

Is bacteria inactivation dependent on flow rate? The independent variable of flowrate was compared against the response variable, level of inactivation (Table 11). The high F value indicates a greater variation between the two scenarios rather than within the samples groups indicating flowrate is a significant contributor to inactivation. Flowrate can be observed as a relation to contact time, or the time of exposure to the treatment process. The connection between contact time and inactivation has been well established in the literature in reference to oxidation reactions and the advanced oxidation reactions occurring in the UV/O3 system. By reducing the flowrate, even marginally by 2 gpm, the rate of inactivation increased substantially. In a system requiring additional contact time the alternative to reducing flowrate would be repeated treatment or recirculation through the treatment system. This holds potential for future research on the matter.

Table 11 - Single Factor ANOVA: Flow Rate

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Low	8	37.42194	4.677743	1.360293
High	8	12.54557	1.568197	1.484671

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	38.67711	1	38.67711	27.18988	0.000131	4.60011
Within Groups	19.91475	14	1.422482			
Total	58.59186	15				

Variation between groups is lower than variation within groups of high and low TSS (Table 12). The low F statistic illustrates this relationship indicating that TSS does not have a significant influence on inactivation. The variation within the data shows that whether or not TSS is elevated does not influence effectiveness of the UV/O3 AOP to inactivate E. coli. The same principle is established in the literature in reference to ozonation, but not for UV irradiation. Because an AOP works in combination of the effects of UV and ozone the deficiency of ultraviolet irradiation as it is interfered with by particulate matter is overcome by the presence of ozonation and oxidation products.

Table 12 - Single Factor ANOVA: Total Suspended Solids

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Low	8	19.15929	2.394912	3.220706
High	8	30.80822	3.851028	3.937974

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.481098	1	8.481098	2.369459	0.146022	4.60011
Within Groups	50.11076	14	3.57934			
Total	58.59186	15				

Chapter 5 - Conclusions

From the results of the AOP treatment, the most imperative parameter can be isolated as the contact time, which is limited by flow rate. The ability of the AOP system to overcome interference of particulates from a variety of water sources demonstrates the potential of the system and its applicability across a broad spectrum.

Many studies have been conducted to reinforce the ability of an AOP to degrade chemicals, particularly organics, but the verification of its multiplicity as it applies to pretreated sources has not been examined as here in.

In addition to the work performed in this study further testing could be used to evaluate the definitive capacity of the system to inactivate bacteria by recirculation, and therefore longer treatment contact. The ability to rule out interference from sediment and particulate matter is a valuable time saving tool. Filtration of water usually precludes treatment to eliminate reactivity consumption by particulates, but within the UV/O3 system this may not be necessary initially. Depending on use of the water source the need to filtrate may be secondary to disinfection.