Pioneering Ultraviolet Treatment of Potable Water From High-Organic Surface Water in Florida

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The City of West Palm Beach (City) plans to upgrade its 47-mil-gal-per-day (mgd) conventional surface water treatment plant (WTP) treatment train by adding a new ultraviolet (UV) disinfection treatment system. A simplified process flow diagram of the existing system is provided in Figure 1. In 2008, the local health department required the City to improve the treatment facility to include low-pressure membranes as an additional barrier to pathogens. The UV disinfection was accepted as a more economical alternative treatment process that fulfills the regulatory intent to install a secondary barrier, while providing additional protection from pathogens.

The UV treatment system is planned downstream of the existing rapid gravity filters but upstream of any post-chemical additions. As part of the project, an additional powdered activated carbon (PAC) treatment system is also planned directly downstream from the raw water pump stations. The new UV system will be designed with a validated UV dose to achieve 4-log *Cryptosporidium* inactivation. This UV dose will also provide some level of inactivation of other pathogens, such as *Giardia lamblia*, E. coli, viruses, and bacteria. High organics, with a typical total organic carbon (TOC) of 11 mg/L, were expected to produce lower UV transmittance (UVT), posing a challenge for UV treatment. The UVT, a major UV design criterion, was in actuality much lower at 79 percent than typical applications. Fouling is a well-known phenomenon that was not understood for this water quality, although known UV foulants, calcium, and iron are added during treatment.

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The City decided to perform a pilot study to proactively determine the extent of fouling and to make informed decisions about the full-scale UV installation. As the first large drinking water UV installation in the state, the Florida Department of Health also wanted a pilot study to ensure that fouling could be overcome during full-scale treatment.

The specific objectives of the UV pilot study were the following:

1) Characterize fouling/scaling of quartz sleeves surrounding UV low- and medium-pressure lamps with softened/filtered water from the City's existing WTP.
2) Quantify UV quartz sleeve fouling and cleaning requirements.
3) Compare effectiveness of two different automated mechanical cleaning systems with external chemical cleaning from two different manufacturers.
4) Quantify bacterial inactivation effectiveness of the UV systems as part of the overall water treatment process.

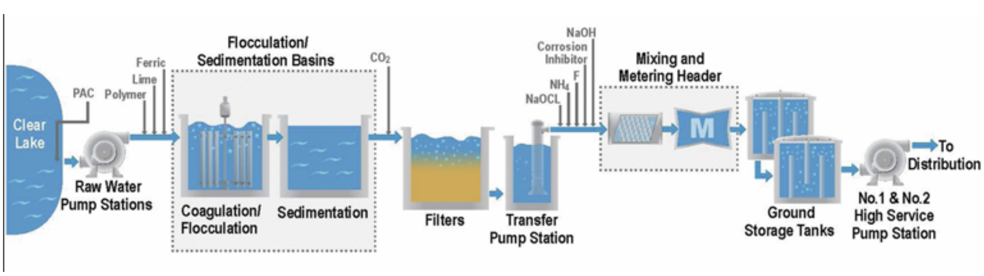

Figure 1. Simplified Existing Treatment Plant Process Flow Diagram

Table 1. Summary of Ultraviolet Reactors Piloted in Parallel

UV Lamp System	Name of UV Unit	Reactor Body Diameter (in.)	UV Lamp Power (W per Lamp)	No. of Lamps	Cleaning System
Low-Pressure High-Output (LPHO)	Trojan B03	8	165	3	Automatic Mechanical (Viton Rings)
Medium-Pressure (MP)	Calgon 3x4kW Sentinel	12	4000	3	Automatic Mechanical (SS Wire Brush)

Testing Methodology

Pilot Overview

Two UV reactors of different classes, medium-pressure and low-pressure high-output (LPHO), were run in parallel over 12 weeks of testing (Table 1 and Figure 2). The UV transmittance through the sleeve was measured spectrophotometrically to determine fouling using UV intensity sensor measurements, with lamps running at a constant power level.

Feed water for the UV reactors was pumped from the filtered water flume using a self-priming centrifugal pump and split into two parallel UV reactors (Figure 3). The UV reactor effluents were pumped back into the main process at the filter influent channel. The chlorine injection point used in phase 2 was located before the UV influent pump and the first sample point.

Flow rates were set to match the 4-log *Cryptosporidium* dose in accordance with the full-scale design and assuming 80 percent UVT. The LPHO unit was only validated using the older German DVGW standard to the 3-log inactivation dose, and was assumed to be conservative enough to be equivalent to 4-log inactivation of the newer Ultraviolet Disinfection Guidance Manual from the U.S. Environmental Protection Agency (EPA). The flow rate was maintained and the maximum power level was set throughout the pilot operation. The UV dose was allowed to drop as fouling and lamp aging occurred in order to use the UV intensity decline to measure fouling.

This mode of operation is contrary to full-scale operation where lamp power would be increased to compensate for changes in fouling, lamp aging, and UVT to maintain the required UV dose. The UV operation was divided into two phases: phase 1 without cleaning, and phase 2 without cleaning but with free chlorine pretreatment (Table 2). Phase 2 was originally planned to include regular cleaning at different time intervals, but was changed when fouling was discovered to be low.

Data Collection and Analytical Methods

The UV sleeve fouling, water quality, UV intensity readings, metal concentrations in acid used to clean fouled sleeves, and microbial activity before and after the UV reactors were recorded during the pilot operation. Sleeve fouling was measured with offline UV transmittance measurements using an Agilent Cary 60 UV-Vis spectrophotometer optics bench (Figure 3b). The three sleeves from each UV reactor were removed, rinsed with deionized (DI) water and left to air dry, then measured along with a spare reference sleeve of both types on the optics bench on a biweekly basis. A fouling factor (FF) was calculated for each sleeve measurement using the following equation:

FF = (Tmeasurement /Treference)0.5

Where Tmeasurement is the UV transmittance (percent) through the sleeve and Treference is the UV transmittance (percent)

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Figure 2. Photos of Installed Ultraviolet Pilot Reactors

(a) (b)

(a) Low-Pressure High-Output and (b) Medium-Pressure

Figure 3. Pilot Testing Photos

(a) (b)

(a) Ultraviolet Pilot Setup and (b) Cary 60 Optics Bench for Measurement of the Ultraviolet Sleeve

Table 2. Schedule of Testing Phases

Phase	Name	Duration (Weeks)
-	Burn-In	0.5
1	No Cleaning	6
2	No Cleaning with Free Chlorine Pretreatment	6

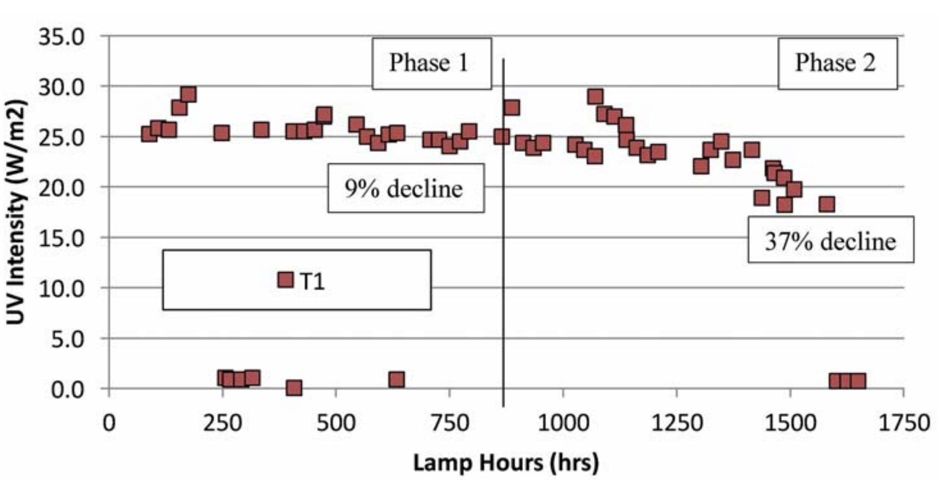

Figure 4. Ultraviolet Intensity Sensor Measurements for Low-Pressure High-Output Reactor

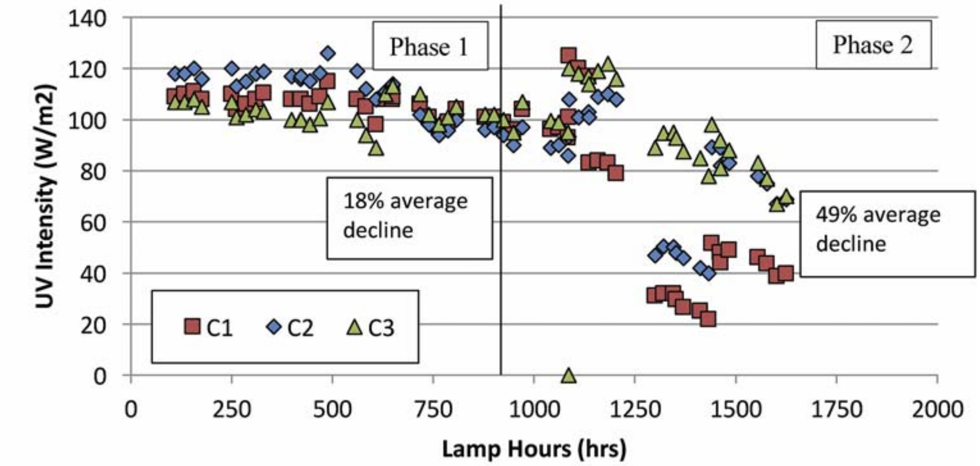

Figure 5. Ultraviolet Intensity Sensor Measurements for Medium-Pressure Reactor

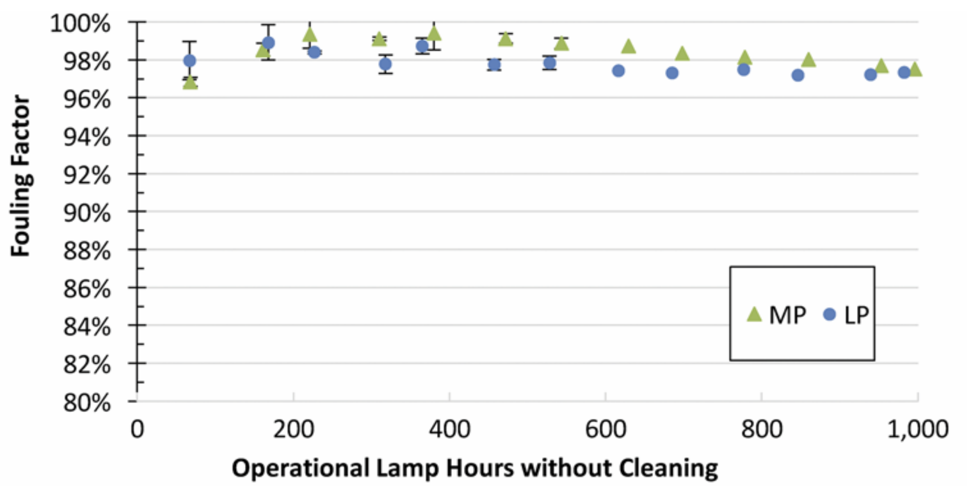

Figure 6. Ultraviolet Reactor Sleeve Fouling for Phase 1 – No Cleaning

Note: Error bars represent the standard deviation of the three sleeve fouling factors. After the measurement at 540 lamp hours without cleaning, one sleeve from each reactor broke and was replaced. Therefore, the sleeve measurements after 540 hours are shown as the average of the remaining two sleeves and do not show standard deviations.

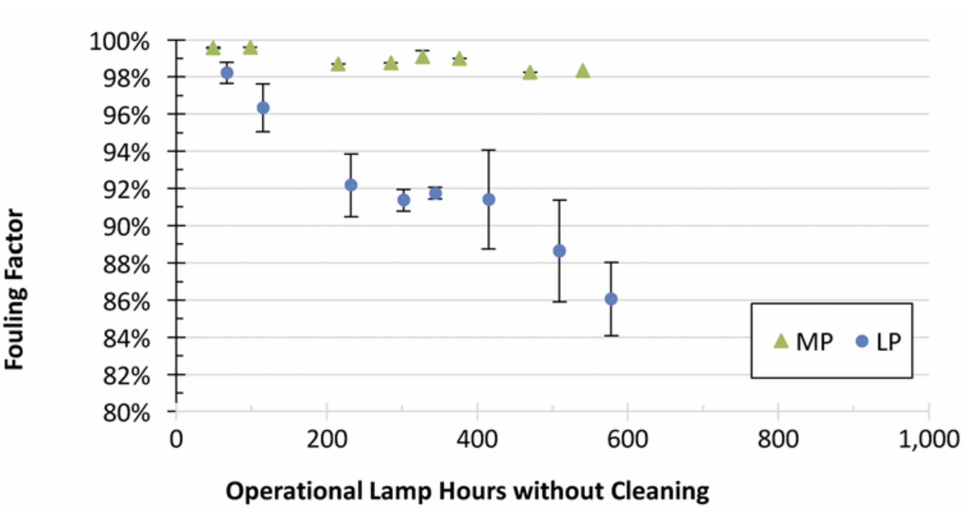

Figure 7. Ultraviolet Reactor Sleeve Fouling for Phase 2 – No Cleaning

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through a spare reference sleeve as measured on the optics bench.

Bacterial activity was tested at five different locations at the water treatment plant using three tests:

1. Colilert - total coliform and E. coli presence/absence
2. MI Agar - colony counts of total coliform and E. coli
3. Heterotrophic plate counts (HPC) - colony counts of total heterotrophic bacteria

At the end of phases 1 and 2, one sleeve from each reactor from each UV system was rinsed with 12 percent phosphoric acid and analyzed for metals. The impact of PAC pretreatment of raw water on the UVT of settled and filtered water was simulated using jar tests.

Results: Ultraviolet Intensity Sensor Measurements

The UV intensity sensor measurements over the course of the UV pilot operation for the LPHO reactor and medium-pressure (MP) reactor are provided in Figures 4 and 5, respectively. Both LPHO and MP reactor UV intensity decreased steadily during phase 1, and decreased at a greater rate during phase 2. At the beginning of phase 2, there was a sharp increase in UV intensity of both reactors. One possible explanation for the increase in UV intensity could be biofilm removal of the pilot with the free chlorine clean and subsequent free chlorine residual through the reactors (biogrowth in the pump and piping was suspected as detailed in the discussion section under phase 1).

Results: Phase 1 Sleeve Fouling – No Cleaning

Average values of fouling factors of the sleeves from MP and LPHO reactors are summarized over phase 1 in Figure 6.

The average fouling factors of both systems remained above 97 percent over 1000 lamp hours during phase-1 operation, which indicates low fouling. Lamp hours in the graph have been adjusted by subtracting the burn-in period hours for each reactor of approximately 85 hours. At the end of the burn-in period, all sleeves were to be cleaned according to vendor recommendation with Lime-A-Way and denatured alcohol; however, the cleaning left a residue that was recorded as a drop in UV transmittance on the optics bench as shown on the first data point. This method of cleaning was discontinued after the initial cleaning at the end of the burn-in period; instead, the sleeves were completely replaced after phase 1. Flow decreased slowly, day to day, on the LPHO unit, and valves were adjusted twice to compensate, indicating a possible increase in headloss in the pipes.

Results: Phase 2 Sleeve Fouling – No Cleaning with Free Chlorine Pretreatment

Average values of fouling factors of the three sleeves of MP and LPHO reactors are summarized over the course of phase 2 in Figure 7.

The average fouling factor of the MP system remained above 98 percent after 540 hours, while the average fouling factor of the LPHO system decreased to approximately 86 percent after 540 hours without cleaning. The LPHO sleeves were more fouled toward the end that was closer to the reactor inlet as measured using the optics bench.

Results: Fouling Characterization

Concentrations of some known foulants in the feed water to the UV reactors were:

- Iron ~220 µg/L
- Total hardness 115 mg/L as calcium carbonate ($CaCO_3$)
- TOC 6.5 mg/L

In the acid rinsate of LPHO and MP sleeves, absolute concentrations were measured at the end of phase 1 and phase 2, as well as the blank, which are presented in Figure 8. The exact absolute concentrations were not important, but the relative magnitude of concentrations show that the acid rinsate measured from the sleeves was significantly greater than the blank.

The major metal foulants measured in the acid rinsate of fouled sleeves in phase 1 were primarily iron (~40 percent) and zinc, followed by aluminum, and copper to a lesser extent (Figure 9). The major metal foulant measured in the acid rinsate of fouled sleeves in phase 2 was iron (~75 percent), and the remainder foulants were zinc and copper on the MP sleeves, and calcium on the LPHO sleeves (Figure 10).

Results: Powdered Activated Carbon Jar Testing

The UVT of settled water after pretreatment with PAC ranging from 0 to 40 mg/L is presented in Figure 11. It increased about 1

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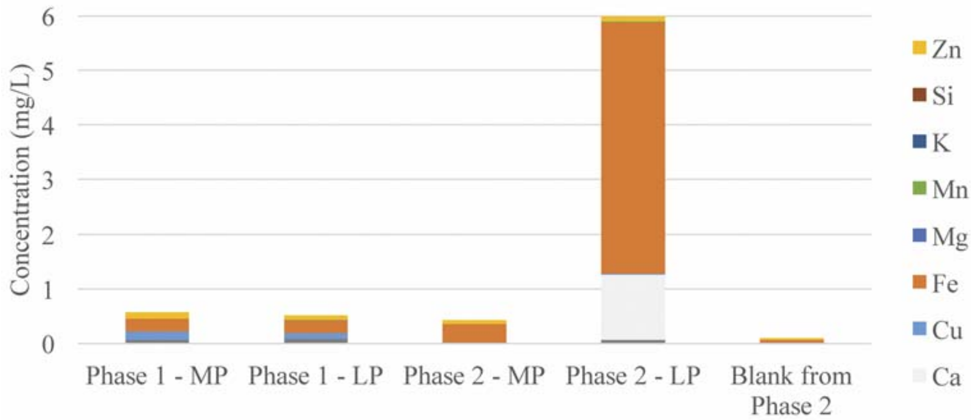
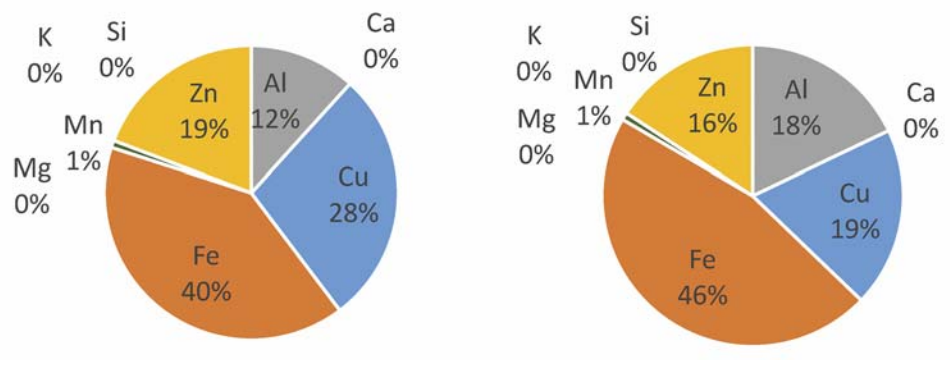


Figure 8. Concentrations of Metals in the Acid Rinsate

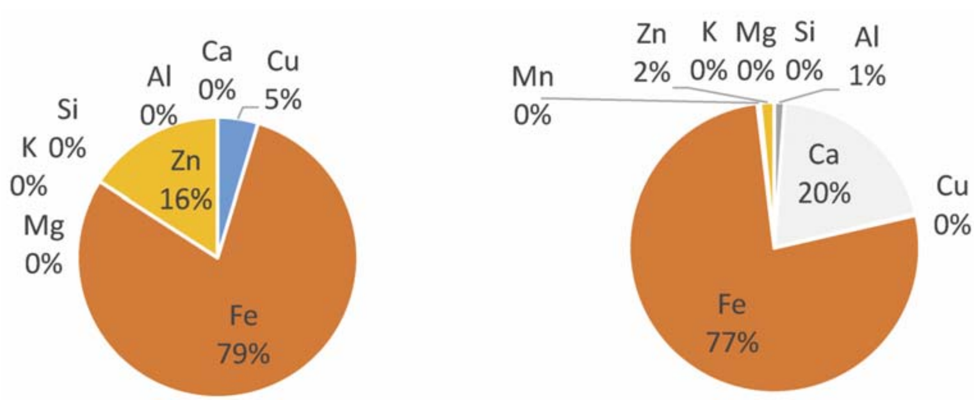
Note: The blank was measured in phase 2 only. The 6 percent phosphoric acid was used as acid rinsate in phase 1, and 12 percent phosphoric acid was used in phase 2.

Figure 9. Foulant Characterization on the Sleeve Acid Rinsate – End of Phase 1



(a) MP (b) LPHO

Figure 10. Foulant Characterization on the Sleeve Acid Rinsate – End of Phase 2



(a) MP (b) LPHO

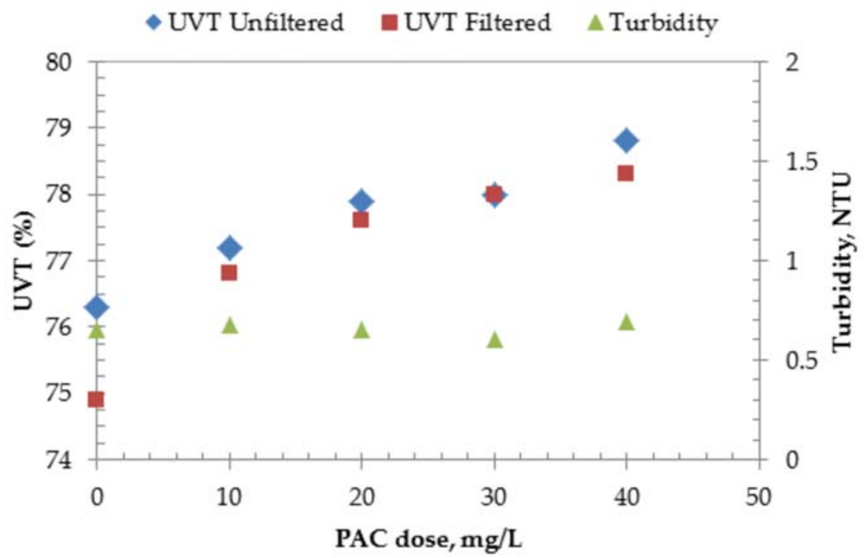


Figure 11. Settled Water Turbidity at Various Powdered Activated Carbon Pretreatment Doses

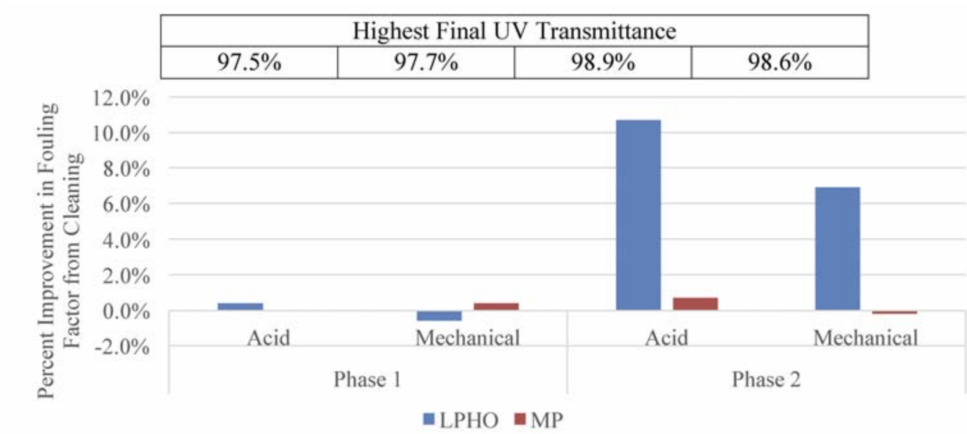


Figure 12. Comparison of Ultraviolet Sleeve Cleaning Methods

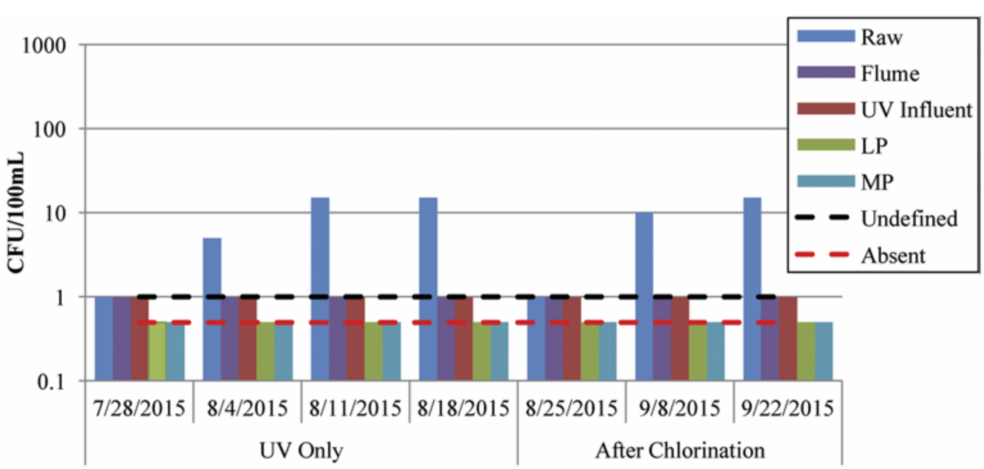


Figure 13. MI E. coli Test Results

Note: Undefined values varied depending upon the volume of the sample tested: 7/28: <10 CFU/100mL; 8/4 - 8/25 : <5 CFU/100mL: 9/8 - 9/22: <2 CFU/100mL.

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percent with 10 mg/L PAC and about 2.5 percent with 40 mg/L PAC on unfiltered water.

Results: Cleaning Method Comparison

The UV transmittance measurements taken before and after the sleeves were cleaned are presented in Figure 12. The 'Fouled' column shows fouling factors of sleeves operated without cleaning for approximately 1000 hours and 600 hours for phases 1 and 2, respectively. The mechanical clean for the LPHO unit malfunctioned during phase 1, so only approximately one-third of the sleeve was cleaned. Fouling factors of 'fouled' sleeves were similar between LPHO sleeves (e.g., T1 and T2) and similar between MP sleeves (e.g., C1 and C2).

Sleeve UV transmittance was improved by acid rinsing between 0 and 10.7 percent and changed by mechanical cleaning by -0.6 to 6.9 percent. In all cases, except the phase-1 MP mechanical clean, acid rinsing improved sleeve UV transmittance more than mechanical cleaning. None of the cleanings improved sleeve UV transmittance to the same UV transmittance of the reference sleeve (100 percent fouling factor).

Results: Microbiological Testing

The MI agar testing results at various places in the WTP process train are graphed in Figures 13 and 14 for E. coli and total coliform, respectively.

In general, the number of colony forming units (CFU) of total coliform and E. coli decreased as the water progressed through the treatment process. E. coli was absent in all samples measured after the UV reactor, and undefined (where a colony was not found during a test that tested <100 mL of sample) in all samples after the raw water. Total coliform was present in measurable quantities in the raw water, decreased in the flume sample, and then increased in the UV influent pump sample. Total coliform was measured after the UV reactors at 3 CFU/100mL or less on three separate days at the end of phase 1 and the beginning of phase 2. The HPC results at the various sampling locations in the plant are provided in Figure 15.

The HPC results from MP and LPHO UV reactor effluent water were significantly less than the samples obtained from other locations in the full-scale plant. The data showed higher HPC in the UV influent pump

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location than the flume during phase 1 and a step decrease in HPC at the UV influent after chlorination began in phase 2 to below 1000 CFU/mL. Log reduction over the UV reactors was 1-log to 2-log of plate counts of bacteria, which are not the same as true log inactivation. The HPC results were well within the EPA-recommended limit of 500 CFU/ml for potable water. During microbiological testing, E. coli was not detected in any sample after both UV reactors, total coliform colonies were less than 3 CFU/100 mL after the UV reactors, and HPC results showed significant reduction of total bacteria after both UV reactors.

Discussion of Results

Phase 1

Sleeve fouling measurements declined less than 3 percent over 1000 hours during phase 1. This represents low fouling; for comparison, the fouling factors in the Hetch Hetchy pilot study of MP systems decreased to 80 percent in less than 100 hours (Kim et al, 2009). The UV intensity decreased by 9 and 18 percent for LPHO and MP systems, respectively, in that period. Based on sleeve UV transmittance and UV intensity measurements, fouling is considered low during Phase 1. Low fouling has positive implications on maintenance efforts and cost of the full-scale UV plant.

Biogrowth during phase 1 was suspected due to several indicators:

- Increase in TOC and color a week after Phase 1 began.
- Increase in headloss to the LPHO unit characterized by decreasing flow and required adjustments of valves.
- Observed odor when pump and upstream piping was opened.
- Step increase in UV intensity after initial chlorination.
- Greater bacterial presence via MI total coliform and HPC in the UV influent pump than in the filtered water flume.
- On the second day of operation with prechlorination, total coliform up to 3 CFU/mL were detected in the LPHO and MP UV reactors, even though total coliform was not detected in the UV influent pump. Possible biogrowth in piping could be the source for total coliform hits.

Phase 2

In Phase 2, with free chlorine addition, sleeve fouling increased greatly for the LPHO unit, but not for the MP unit. Fouling characterization showed that the increased fouling was ~75 percent iron, and ~ 20 percent calcium. The increased oxidation potential of chlorine may have oxidized Fe^{2+} to Fe^{3+}, which could have contributed to increased fouling. Surprisingly, sleeve fouling measurements showed greater fouling in the LPHO system, but UV intensity showed a greater rate of decline in the MP system. It appears that temperature was not the strongest indicator of fouling as previously hypothesized because MP fouling would have been consistently greater. The difference in velocity may have led to the different results between sleeve measurements and UV intensity readings. The UVT did not correlate with any other water quality parameter tested (data now shown because of space constraints).

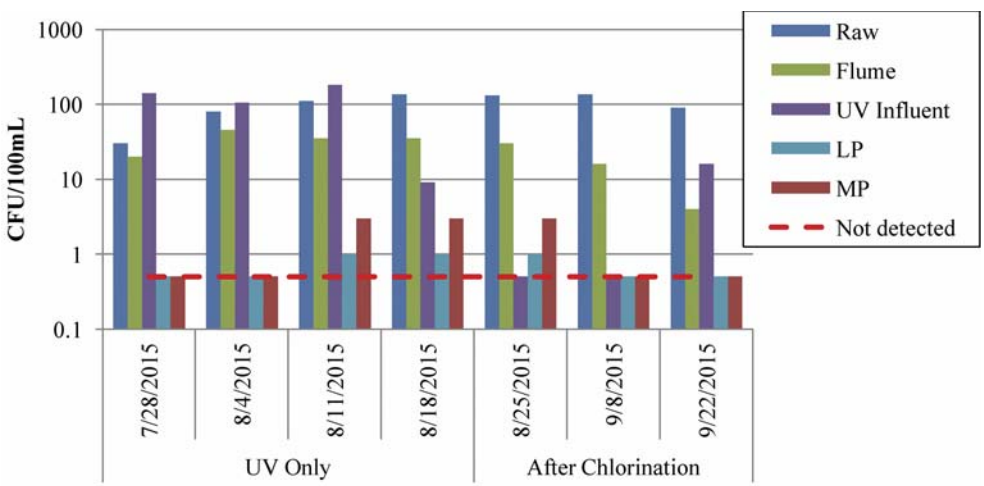

Figure 14. MI Total Coliform Test Results

Note: The UV Influent samples on 8/25 and 9/8 were undefined because they were tested using less than 100mL. Therefore, the results of these tests were <5 and <2 CFU/100mL, respectively.

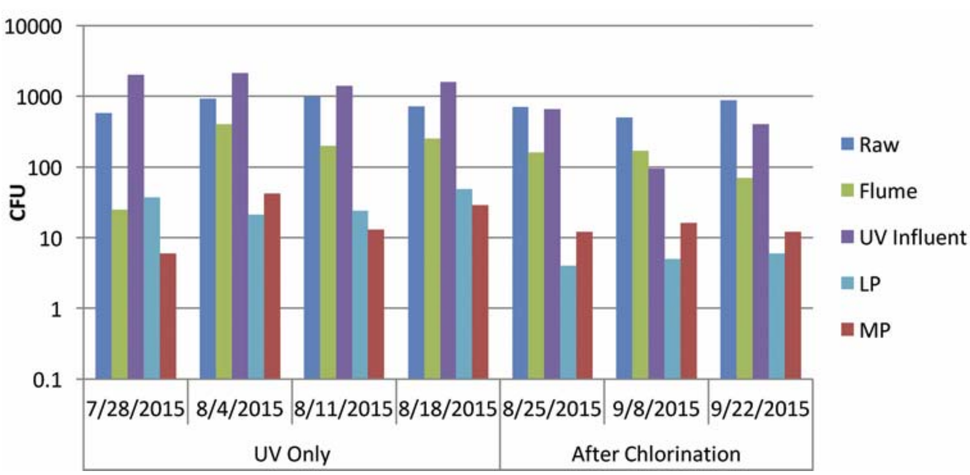

Figure 15. Heterotrophic Plate Count Results

Conclusions

A UV disinfection pilot study was conducted to evaluate preliminary operational data on a small-scale UV unit in order to verify the effectiveness of UV disinfection and to make decisions about the full-scale UV installation. Two UV reactors of different classes, one medium-pressure and one low-pressure high-output, were run in parallel over 12 weeks of testing. The UV sleeve fouling, water quality of the feed water, UV intensity readings, and microbial activity before and after the UV reactors were measured. The major findings of the study were:

- The fouling rate of filtered water without online cleaning was low as measured by sleeve fouling (<3 percent fouling factor decline) and UV intensity sensor readings (percent decline of 9 and 18 percent for LPHO and MP, respectively) over 1000 hours, even with biogrowth present upstream (phase 1).
- The fouling rate of filtered water without online cleaning was increased by free chlorine pretreatment as measured by sleeve fouling (fouling factor decline of 16 percent and 4 percent for LPHO and MP, respectively) and UV intensity sensor readings (percent decline of 18 and 49 percent for LPHO and MP, respectively) over ~600 hours (phase 2).
- The major metal foulants were primarily iron, and to a lesser extent, copper, zinc, and aluminum during phase 1, primarily iron during phase 2, and to a lesser extent calcium (LPHO) or zinc and copper (MP). Relative to the overall foulant amount, the percentage of iron and calcium increased during phase 2 when a prechlorine dose was applied to the reactors.
- Offline acid cleaning improved sleeve UV transmittance more than online mechanical cleaning, but up to 3 percent of the fouling factor was irreversible. Periodic online cleaning is suggested to proactively prevent irreversible fouling.
- The UV reactors were effective in inactivating a significant portion of bacteria, as shown in the total coliform, E. coli, and HPC tests. The HPC results were well within the EPA-recommended limits of 500 CFU/mL for potable water.
- In jar tests, PAC addition prior to coagulation improved the settled water UVT. The UVT increased about 1 percent with 10 mg/L PAC and about 2.5 percent with 40 mg/L PAC.
- For full-scale, low fouling is expected for either MP- or LPHO-type UV reactors, and both types provided adequate cleaning solutions without need for additional pretreatment. Prechlorination is expected to increase fouling rates significantly if used in full-scale.