Disinfection Alternatives for South Florida Water Management District's ASR Facility

Rafael E. Frias III, Heather Landis, and Robert Verrastro

The South Florida Water Management District (SFWMD) operates and maintains approximately 1,800 miles of canals and levees, 25 major pumping stations, and about 200 larger and 2,000 smaller water control structures in southern Florida. One program the district focuses on is watershed management to restore the Kissimmee-Okeechobee-Everglades ecosystem, coastal ecosystems, and their tributary watersheds.

During the 20th Century, much of the land around Lake Okeechobee was converted to agricultural use. Associated with the land use changes were large increases in the rate of nutrient (nitrogen and phosphorus) inputs to the lake, and detrimental changes occurred in the lake's water quality. The Lake Okeechobee & Estuary Recovery Program provides a storage/disposal option for phosphate-laden surface water before it enters Lake Okeechobee.

One potential source for storage and disposal is the Taylor Creek Aquifer Storage and Recovery (ASR) facility, which was placed in operation in April 1991. In August 1992, it was taken out of service and has remained inactive. A feasibility study to re-activate the facility was initiated in May 2006, with the objective of designing a new 10 million-gallon-per-day water treatment system at the original ASR site, incorporating as many of the original design features as possible.

The new system should consist of a combination of filtration and disinfection to produce recovered water that meets primary drinking water standards before injection. The current site does not meet the primary drinking water standards for total coliforms, fecal coliforms, and turbidity, and exceeds the maximum contaminant level for arsenic, iron, manganese, sulfate, and total dissolved solids.

The first step in the project was to evaluate filtration and disinfection for the site. Several disinfectants were bench tested, including chlorine, chlorine dioxide, ozone, ultraviolet (UV), peracetic acid and UV in combination with peracetic acid. Pilot testing of a UV reactor was also conducted at the site.

Rafael E. Frias III, P.E., is an engineering manager at the Tampa office of the engineering, consulting, and construction company Black & Veatch. Heather Landis, P.E., is a water process engineer in Black & Veatch's Boston office. Robert Verrastro, P.G., is a lead hydrogeologist for the South Florida Water Management District in West Palm Beach. This article was presented as a technical paper at the Florida Section AWWA Fall Conference in November 2007.

Water Quality

On May 4, 1989, and May 8, 2006, extensive water quality analyses were conducted near the site. The relevant parameters analyzed on those dates are shown in Table 1. For comparison, the water quality data from the bench and pilot scale testing is included.

Of interest is the variation in total coliform concentration from the historical water quality samples and during the testing period. The total coliform concentrations were low for the testing period compared to the concentration measured on May 8, 2006, and August 23, 2006.

The low concentration of coliforms in the water has been attributed to the drought conditions affecting South Florida. In fact, during pilot testing, one set of data collected after a rain event showed a noticeably higher concentration of bacteria than before, suggesting the impact of the weather on stormwater runoff and water quality.

According to the U.S. drought archives, in May 2006 the area around Taylor Creek was abnormally dry. From March 2007 to April 2007, the drought condition has been categorized as severe. Additional information from the National Climatic Data Center suggests that in May 1989, the area was experiencing a moderate drought.

Table 1: Comparison of Historical and Current Raw Water Quality

	Historical Data			Test Data March 20-April 25, 2007
	May 4, 1989	May 8, 2006	August 23, 2006	
Alkalinity, mg/L $CaCO_3$	95	110	NA	NA
Color, PCU	NA	80	350	NA
Bromide, mg/L	NA	0.61	NA	1.4-1.5
Hardness, mg/L $CaCO_3$	256	320	NA	NA
pH	7.8	8.1	7.85	7.5 – 8.4
Temperature, °C	NA	28.7	NA	22 – 26
Total coliform, cfu/100mL	30	2,700	1,500	<1 – 55
Fecal coliform, cfu/100mL	4	7	NA	1-10
Total organic carbon, mg/L	NA	NA	NA	19.2-20.9
TSS, mg/L	NA	38	9.0	6.8 – 10
Turbidity, NTU	14	23.4	8.89	5.13 - 12.3

Bench-Scale Test Results

Bench-scale testing was conducted on water filtered at the site through a 400-micron filter. The disinfectants tested included ozone, chlorine, chlorine dioxide, UV, peracetic acid, and chloramines. The first set of bench-scale testS took place in March 2007. It was during this testing that the low concentration of coliforms was measured.

Based on the analysis, all disinfectants were able to meet the treatment goal of less than 4 cfu/100mL for total coliforms and zero fecal coliforms, but because the concentration of coliforms was significantly low, the ability of the disinfectant to provide higher inactivation of the target organisms could not be established. As a result, heterotrophic plate count (HPC) bacteria were selected for study in addition to total and fecal coliforms for analysis.

Continued on page 28

Continued from page 26

Ozone

Ozone is an effective oxidant that can remove taste and odor, color, iron, and manganese. It is also effective for the inactivation of *Giardia* and viruses and can be effective for inactivation of *Cryptosporidium* at higher water temperatures.

The aqueous ozone stock solution for the bench study was produced using a Pacific Ozone Generator. The ozone doses selected for bench testing were 3, 4, 7 and 8 mg/L. Total and fecal coliform samples were sent to a certified laboratory for analysis.

The results of ozonation are shown in Table 2 and Figure 1. The maximum HPC log inactivation among the dose tested is 0.7-log at 8 mg/L as illustrated in Figure 3-1. It should be noted that the impact of ozonation to HPC inactivation leveled off after a dose of 7 mg/L.

Bromate is a potential byproduct of the ozonation process if bromide is present in the raw water. Bromate is considered a disinfection byproduct and its current maximum contaminant level (MCL) is 10 µg/L, based on an annual average.

The bromide concentration in the raw water that was measured in May 2006 was 0.61 mg/L, but during the testing period it was approximately 1.5 mg/L. Typically, if the raw water bromide concentration is less than 0.1 mg/L, bromate formation should be within the regulated value of 10 µg/L; however, because the bromide concentration is above 0.1 mg/L and the suggested ozone dose is 8 mg/L, bromate formation could be an issue, so bromate formation was monitored during the bench ozonation.

As shown in Table 2, even at the lowest ozone dose tested (3 mg/L), the bromate formation was greater than 10 µg/L, while the HPC log inactivation was only 0.2 at this dose.

O_3 Dose	Total Coliforms	Fecal Coliforms	HPC	Bromate
mg/L	(cfu/100mL)	(cfu/100mL)	(cfu/mL)	(µg/L)
0	6	2	2500	0
3	2	1	1410	11
4	4	1	1070	17
7	4	<1	410	35
8	<2	<1	390	63

Table 2: Ozone Bench-Scale Study Results (4/19/2007)

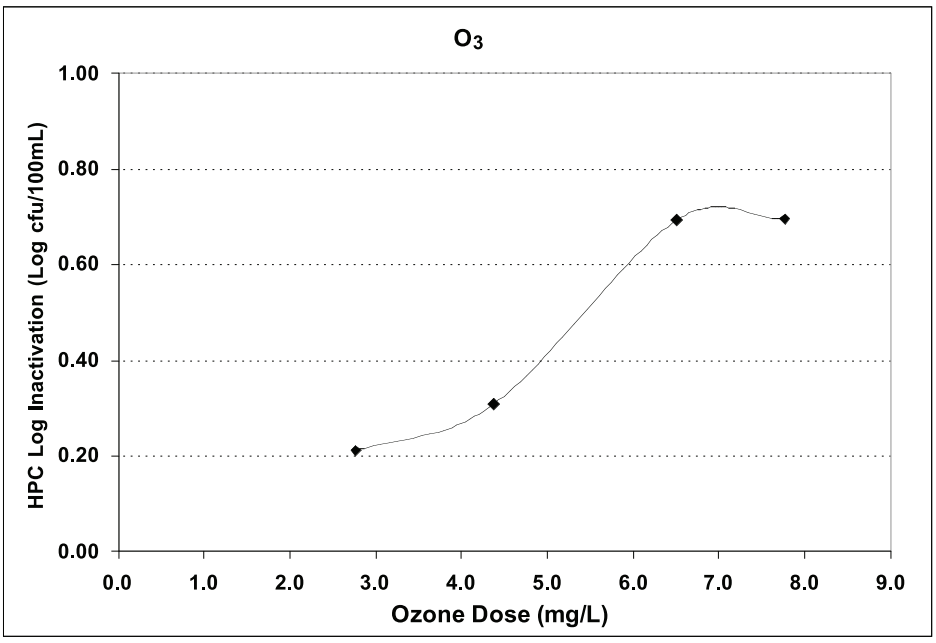

Figure 1. The Impact of Ozonation on Inactivation of HPC Bacteria

UV Disinfection

UV disinfection is effective for the inactivation of *Cryptosporidium*, *Giardia*, and bacteria, regardless of water temperature or pH. UV also does not form any known disinfection byproducts; however, the effectiveness of the UV system depends on the transmittance of the water. UV light can penetrate water with high transmittance and reach the target organism at a lower intensity than would be required for lower transmittance water.

The bench UV testing was conducted with a Wedeco collimated beam device.

Continued on page 30

Table 3: UV Bench-Scale Study Results

UV Dose	Total Coliforms	Fecal Coliforms	HPC
mJ/cm^2	(cfu/100mL)	(cfu/100mL)	(cfu/mL)
0	6	2	1060
10	<2	<1	280
20	<2	<1	400
40	<2	<1	160
60	<2	<1	850*
90	<2	<1	43
120	<2	<1	23
150	<2	<1	13

Figure 2. UV Dose Response of HPC

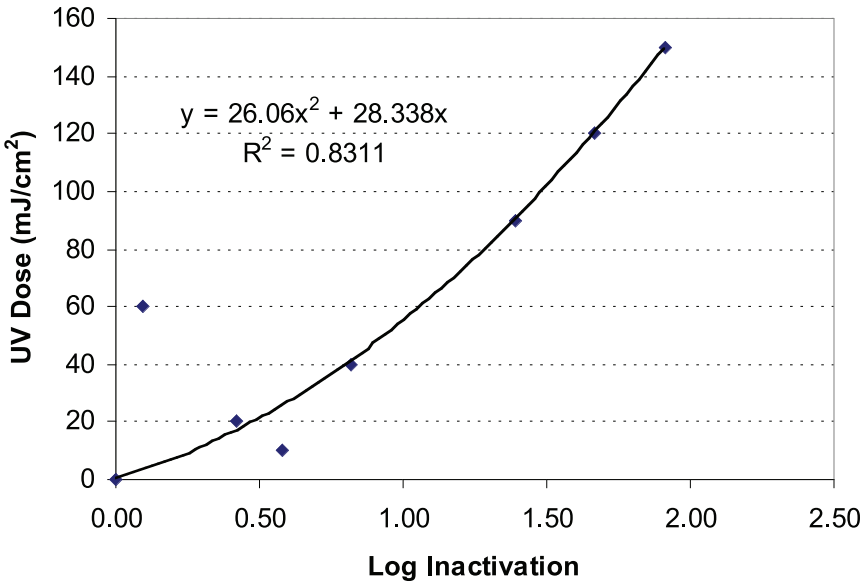

Table 4: Peracetic Acid Bench-Scale Study Results

Peracetic Acid Dose (mg/L)	Contact Time (min)	Total Coliforms (cfu/100mL)	Fecal Coliforms (cfu/100mL)
0	5	10	11
2		6	8
4		4	9
8		<4	0
12		4	2
0	10	20	14
2		268*	<1
4		<4	<1
8		<4	<1
12		<4	<1
0	30	20	14
2		<4	<1
4		<4	<1
8		<4	<1
12		<4	<1

* This point was an outlier and deleted from analysis.

Continued from page 28

Experiments were performed at dosages of 10, 20, 40, 60, 90, 120, and 150 mJ/cm^2. The water was exposed to the UV light for a calculated period of time to reach the target dose. The total coliform and fecal coliform samples were taken afterward and were sent immediately to a certified laboratory for analysis. Similar to ozonation, HPC bacteria were also measured as an indicator of disinfection efficiency.

The results of the UV disinfection bench study are shown in Table 3. At all doses tested, the total and fecal coliforms were inactivated to treatment goal levels, since the initial coliform concentration was only 6 cfu/100mL.

The UV disinfection efficiency as indicated by the log HPC inactivation is shown in Figure 2. Typically, a UV dose of 40 mJ/cm^2 is used for disinfection and will provide at least 3-log inactivation of *Giardia*, *Cryptosporidium*, and bacteria, but because of the significantly low UV transmittance of the water (22 percent), even after filtration, the required UV dose to achieve 3-log inactivation will be much higher than the typical dose. Figure 2 shows that the HPC log inactivation reached 2-log removal only at 150 mJ/cm^2.

Peracetic Acid

Peracetic acid (PAA) is made up of acetic acid and hydrogen peroxide. PAA is a desirable disinfectant because it does not have a persistent residual and has minimal byproducts; however, PAA is corrosive at concentrations above 10 percent and is regulated under 40 CFR 1910.119 at concentrations above 60 percent by weight.

Peracetic acid disinfection is a function of contact time and dose. According to research by Caretti and Lubello (2002), a PAA dose of 8 mg/L and a contact time of 30 minutes resulted in 4-log inactivation of total coliforms. Accordingly, the bench testing was performed at doses of 2, 4, 8 and 12 mg/L with contact times of 5, 10 and 30 minutes. Samples were quenched at each reaction time and total coliform and fecal coliform samples were sent to a certified laboratory for analysis.

The results of the peracetic acid tests are presented in Table 4. Again, low concentrations of total and fecal coliforms were present in the raw and filtered water. At a dose of 4 mg/L and a contact time 10 minutes, 0.7-log inactivation of total coliforms was achieved and about 1.15-log inactivation of fecal coliforms was achieved.

Continued on page 32

Continued from page 30

Peracetic Acid + UV Disinfection

Previous research conducted by Black & Veatch has shown a synergistic effect of PAA addition followed by UV disinfection. A bench-scale study demonstrated complete inactivation (about 5+ log) of total coliforms when using a PAA dose of 2 mg/L and a UV dose of 50 mJ/cm^2. The transmittance of the water tested was about 60 percent.

Therefore, bench-scale testing of PAA/UV was performed to determine the appropriate combination of PAA and UV dosages. Based on the low initial concentration of total coliform in the filtered water, a low dose of UV was selected for the total coliform inactivation. The water was first exposed to peracetic acid at the dosages and contact times listed in Table 5 and then exposed to UV light.

The results indicate similar inactivation compared to the inactivation results of using only peracetic acid. Based on the low concentration of total coliforms in the water, it was not possible to establish a greater inactivation that could have possibly been achieved using higher UV dosages in combination with peracetic acid.

Chlorine

The chlorine bench study was performed using liquid sodium hypochlorite (NaOCl) at three dosages of 5, 10, and 15 mg/L with contact times of 20, 40, 60, and 80 minutes for each dose. Because the effectiveness of chlorine as a disinfectant depends on pH and temperature, the pH of the water samples was decreased to 7 and the water sample was warmed to around 20 degrees Celsius.

At each specific reaction time, the residual of chlorine was measured. Then samples were quenched and sent to a certified laboratory for analysis of total and fecal coliform, TOC, and trihalomethane (THMs) and haloacetic acids (HAA5). The results are shown in Table 6. Because of the low concentration of total and fecal coliforms in the filtered water, all tested dosages and contact times met the treatment goal.

THM and HAA5 are the two major categories of DBPs formed during chlorination, with MCLs of 80 and 60 µg/L, respectively. The formation of THM and HAA5 depend on the water quality, chlorine dose, and contact time. Because of the high TOC (18.4 mg/L) of the filtered water and the high dose of chlorine, the formation of these DBPs exceeded the MCLs significantly—especially THM—as indicated in Table 6.

Lower dosages of chlorine were therefore tested to determine the maximum chlorine dose and contact time allowed without exceeding the MCLs for THMs and HAAs. The results of the low-dose chlorination experiment are shown in Table 7.

HPC bacteria also were measured to evaluate the effectiveness of chlorine disinfection. A chlorine dose of 5 mg/L and a contact time of 5 to 10 minutes resulted in about 0.7-log inactivation of HPC bacteria. The formation of disinfection byproducts is a function of chlorine dose and contact time, so based on the results of the bench-scale testing, a contact time of 10 minutes should not be exceeded if dosing with 5 mg/L of chlorine.

Chlorine Dioxide

Chlorine dioxide (ClO_2) is a neutral compound of chlorine in a high oxidation state (+IV). It is an

Table 5: Peracetic Acid & UV Bench-Scale Study Results

Peracetic Acid Dose (mg/L)	Contact Time (min)	UV Dose (mJ/cm^2)	Total Coliforms (cfu/100mL)	Fecal Coliforms (cfu/100mL)
0	--	--	20	10
2	5	10	4	1
4			<4	1
2	10		<4	<1
4			<4	<1

Table 6: Chlorine Bench-Scale Study Results

Dose (mg/L)	Contact Time (min)	CT (mg-min/L)	Total Coliforms (cfu/100mL)	Fecal Coliforms (cfu/100mL)	THM (µg/L)	HAA5 (µg/L)
0	--	--	10	8	--	--
5	20	NA	<4	<1	--	--
	40	NA	<4	<1	--	--
	60	1.2	<4	<1	--	--
	80	2.4	<4	<1	--	--
10	20	NA	<4	<1	--	--
	40	NA	<4	<1	--	--
	60	7.2	<4	<1	--	--
	80	3.2	<4	<1	--	91
15	20	NA	<4	<1	208	117
	40	NA	<4	<1	287	148
	60	45.6	<4	<1	--	--
	80	88.8	<4	<1	365	150

Table 7: Chlorine Bench-Scale Study Results

Dose (mg/L)	Contact Time (min)	CT (mg-min/L)	Total Coliforms (cfu/100mL)	Fecal Coliforms (cfu/100mL)	HPC (cfu/mL)	THM (µg/L)	HAA5 (µg/L)
0	--	--	6	5	1680	--	--
3	10	1.8	<2	<1	340	32.0	28.7
4	10	2	<2	<1	360	56.5	36.1
5	5	1.45	<2	<1	310	66.1	41.4
5	10	2.2	<2	<1	390	72.9	40.1

unstable gas that decomposes rapidly and therefore is usually generated onsite by mixing and reacting a chlorine solution in water with a solution of sodium chlorite.

One research study, Roberts et. al. (1980), determined that a chlorine dioxide dose of 10 mg/L was needed to provide 4-log inactivation of total coliform over a contact time of 5 to 15 minutes; therefore, three chlorine dioxide dosages—5, 10 and 15 mg/L—were tested with contact times of 5, 10, and 15 minutes for bench-scale study. Total coliform, TOC, and the disinfection byproduct chlorite were analyzed at a certified laboratory.

The results are shown in Table 8. Similar to other disinfectants, because of the low concentration of total and fecal coliforms in the filtered water, all chlorine dioxide dosages and contact times tested met the treatment goal. At a dose of 5 mg/L and a contact time of 10 minutes, 0.4-log inactivation of total coliforms was achieved.

The byproduct of chlorine dioxide is chlorite. Chlorite is currently regulated at an MCL of 1.0 mg/L. As shown in Table 8, the formation of chlorite was significantly higher than the MCL at a contact time of 15 minutes and a dose of 5 mg/L.

If chlorine dioxide were to be implemented, then chlorite reduction would be required. This can be achieved by adding either ferrous or sulfur-based chemicals at the contact basin. Additional contact time would be required for chlorite removal as well. The effectiveness of the chlorite removal will depend on pH.

Table 8: Chlorine Dioxide Bench-Scale Study Results

Dose (mg/L)	Contact Time (min)	CT (mg-min/L)	Total Coliforms (cfu/100mL)	Fecal Coliforms (cfu/100mL)	Chlorite (mg/L)
0	--	--	10	8	--
5	5	1.7	4	1	--
	10	29.5	<4	<1	--
	15	99.4	<4	<1	3.4
10	5	0.8	<4	<1	--
	10	26.4	<4	<1	--
	15	95.6	<4	<1	4.8
15	5	1.1	<4	<1	--
	10	17.8	<4	<1	--
	15	98.6	<4	<1	7.2

Chloramines

Chloramines are a weaker disinfectant than chlorine and chlorine dioxide, but chloramines are more stable, thus extending disinfectant benefits throughout a water utility's distribution system. Typically they are not used as the primary disinfectant for the water, but for maintaining a disinfectant residual in the distribution system. Since chloramines are not as reactive as chlorine with organic material in water, they produce substantially lower

Continued on page 34

Table 9: Chloramines Bench-Scale Study Results

Dose (mg/L)	Contact Time (min)	CT (mg-min/L)	Total Coliforms (cfu/100mL)	Fecal Coliforms (cfu/100mL)	HPC (cfu/mL)	THM (µg/L)	HAA5 (µg/L)
Chloramination							
0	--	--	6	3	1420	--	--
15	80	728	<2	<1	108	<MRL	43.0

Continued from page 33
concentrations of disinfection byproducts in the distribution system.

The purpose of the chloramines bench testing was to determine if chloramines have the same level of effectiveness as chlorine; therefore, pre-formed chloramines were used instead of dosing the sample with chlorine followed by ammonia. Only one test was conducted, at a dose of 15 mg/L and a contact time of 80 minutes. The samples were analyzed for total and fecal coliforms and HPC bacteria by a certified laboratory. The results are shown in Table 9.

As expected, because of the low initial concentration of coliforms, the results met the treatment goal. Chloramination provided 1.1-log inactivation of HPC bacteria based on the sample tested. Also, the THM concentration for the chloraminated sample was below the detection level. The HAA concentration, however, was 43 µg/L. This could be a result of the high concentration of bromide in the water, which was measured at 1.4 mg/L for that sampling event.

The chloramines residual after 80 minutes was 9 mg/L. The maximum residual disinfectant level (MRDL) for chloramines in the distribution system is 4 mg/L, so if chloramines were to be used at the high dose of 15 mg/L and if the drinking water guidelines are to be followed, then quenching of chloramines would be necessary.

Table 10: Bench-Scale Testing Results Summary

Disinfectant	Result
Ozone	At dose of 8 mg/L, 0.7-log inactivation of HPC was achieved. At a dose of 3 mg/L, 11 µg/L bromate was formed.
UV	UVT is only 22% for Taylor Creek. At a dose of 50 mJ/cm^2, 1-log inactivation of HPC was achieved. At a dose of 150 mJ/cm^2, 2-log inactivation of HPC was achieved.
PAA	At a dose of 4 mg/L and contact time of 10 minutes, treatment goal was met.
PAA / UV	At a PAA dose of 2 mg/L and contact time of 10 minutes followed by a UV dose of 10 mJ/cm^2, the treatment goal was met.
Chlorine	At a CT of about 2 mg-min/L, 0.7-log HPC inactivation was achieved. At a dose of 5 mg/L with contact time of 5 and 10 min, about 70 µg/L of THM was formed, which was close to the MCL of 80 µg/L.
Chlorine Dioxide	At a CT of 50 mg-min/L (dose of 5mg/L and contact time of 10 min.), treatment goal was met. At a dose of 5 mg/L with contact time of 15 min, 3.4 mg/L of chlorite was formed, while the MCL is 1.0 mg/L.
Chloramines	At a CT of 728 mg-min/L (dose of 15 mg/L and contact time of 80 min.), a 1.1-log HPC inactivation was achieved. THM formation was below detection limit and HAA formation 43 µg/L, which was below MCL of 60 µg/L.

Bench-Scale Testing Results Summary

Based on the raw-water quality measured during testing, any of the disinfectants tested could meet the inactivation of goal of less than 4 cfu/100mL for total coliforms. Table 10 provides a summary of the bench-scale test results.

Pilot-Scale Testing

The purpose of the UV pilot test was to determine if the UV system could achieve the required inactivation of total and fecal coliforms. The UV pilot coincided with the Gunderboom filtration study, and a process schematic of the pilot system is shown in Figure 3.

Raw water was collected from the L-63N Canal and was filtered through the Gunderboom system. Then the filtered water was pumped into the UV reactor, which was provided by Calgon Carbon Corporation. The flow rate of the system was adjusted and

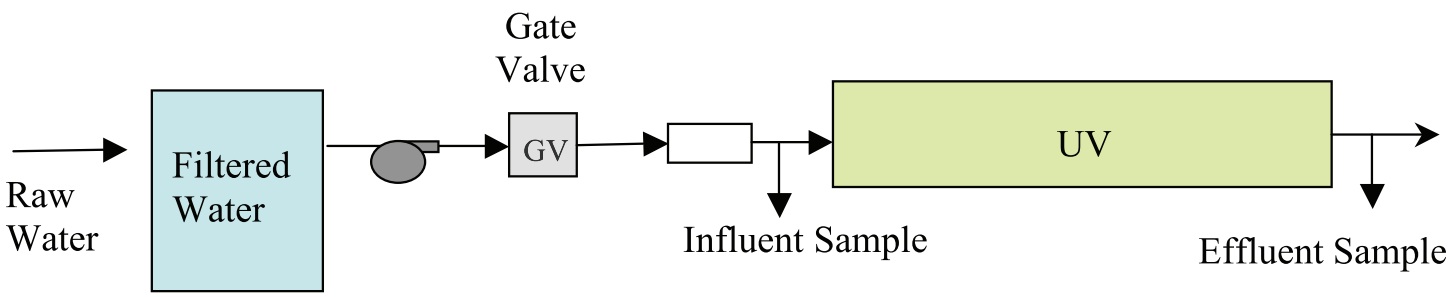

Figure 3. UV Pilot Schematic

monitored by a gate valve and flow meter. Samples were collected and sent to a certified laboratory within the necessary holding time for analyzing total and fecal coliforms and total suspended solids (TSS).

The UV pilot system provided by Calgon was an open-channel UV reactor equipped with four low-pressure high-output UV lamps. The flow rate through the reactor could be varied from 10.5 gpm to 150 gpm. Because of the pumping limitations at the site and the low transmittance of the water, the UV system was operated from 10.5 gpm to 40 gpm during the study.

Results

The UV system was operated at four different flow rates to establish a variation in UV dose applied to the filtered water. During these tests, total and fecal coliforms and HPC bacteria were measured. To determine the UV dose applied during the test period, the dose response curve developed for the HPC bacteria (Figure 2) was used to calculate the applied dose based on the log inactivation measured.

The applied UV dosages for the April 17th and 18th tests are shown in Table 11. During the April 17th testing, almost 1.5 log inactivation of HPC was achieved, which corresponded to an applied UV dose of 95.6 mJ/cm^2. For the other flow rates, the UV dose varied from 20 to 40 mJ/cm^2, which is the typical UV dose range in a drinking-water application, resulting in 0.5 to 0.7-log inactivation.

Based on the equation from the dose response curve, if 1.5-log inactivation of the target organism is required, then the UV dose applied would need to be about 100 mJ/cm^2, while 1.9 log inactivation would require a UV dose of 150 mJ/cm^2.

Unfortunately, the HPC dose response curve can not be used to determine the applied dose associated with total coliform inactivation data. A total coliform dose response curve could not be developed because of the low concentration of coliforms in the filtered water, but research has shown that HPC bacteria are slightly more resistant to UV light than total coliforms; therefore, based on the pilot-scale testing, a UV system designed around the data collected for the HPC bacteria would result in a conservative design.

Conclusions

The purpose of the bench-scale and pilot-scale testing was to demonstrate that the disinfectants could achieve the following goals:

- Total coliform concentration less than 4 cfu/100mL
- No presence of fecal coliforms in the treated water

	April 17, 2007		April 18, 2007	
Flow Rate (gpm)	**Log Inactivation**	**Applied UV Dose (mJ/cm^2)**	**Log Inactivation**	**Applied UV Dose (mJ/cm^2)**
10	1.448	95.6	0.908	47.2
20	0.615	27.3	0.688	31.8
30	0.661	30.1	0.656	29.8
40	0.641	28.8	0.508	21.1

Table 11: Applied UV Dose for the HPC Bacteria Testing on April 17 – 18, 2007

During the course of testing, it became apparent that the total and fecal coliform concentrations were much lower than anticipated, which is attributed to the drought conditions that persisted during the testing; therefore, it was necessary to use a surrogate organism to demonstrate the effectiveness of the different disinfectants to achieve the treatment goals. HPC bacteria were selected because they are slightly more resistant to UV light compared to total coliforms; therefore, the HPC bacteria provide a more conservative approach.

Based on the results of the pilot testing, the following conclusions can be made:

- The UV disinfection system could provide from 1-log inactivation (90 percent inactivation) to 1.5-log inactivation (96 percent inactivation), depending on the dose applied.
- Based on the developed dose response curve from the bench-scale testing, a UV dose of 54 mJ/cm^2 will provide 1-log inactivation and a dose of about 100 mJ/cm^2 will provide 1.5-log inactivation.

The bench and pilot data did demonstrate that with low concentrations of total and fecal coliforms, each disinfectant at a low dose would achieve the treatment goal of total coliforms <4 cfu/100mL and a fecal coliform concentration of zero; however, based on the historical data from Taylor Creek, the total coliform concentration can exceed 1,500 cfu/100mL. In this situation, at least two disinfectants would be required to meet the treatment goals.

References

- Caretti, C., C. Lubello, and R. Gori. 2002. "Comparison Between PAA/UV and H2O2/UV Disinfection for Wastewater Reuse" *Water Supply*. 2(1): 205–212.
- Roberts, P.V., E.M. Aieta, J.D. Berg, and B.M. Chow. 1980. "Chlorine Dioxide for Wastewater Disinfection: A Feasibility Evaluation." Stanford University Technical Report 251.