Incorporation of High-Level Ultraviolet Disinfection to Meet Stringent Effluent Discharge Disinfection Byproducts Limits

Lynn Spivey, Sean Chaparro, Steve Schaefer, and William Harrington

The South Cross Bayou Water Reclamation Facility (SCBWRF) in Pinellas County was originally constructed in 1960 with a 15-mil-gal-per-day (mgd) average capacity. A 12-mgd expansion and other improvements were implemented in the 1970s and 1980s. In 2004, the County completed a project to expand the facility to an average flow of 33 mgd, with a peak hourly flow of 66 mgd. Effluent from the facility is currently disinfected with chlorine gas, and on average, 20 to 30 percent of the effluent is discharged via surface water to the Joe's Creek outfall, a Class III water body, with the remaining used for beneficial reuse.

In 2010, the County entered into a consent order with the Florida Department of Environmental Protection (FDEP) that required the surface water discharge from the facility via the Joe's Creek outfall to meet regulatory limits by June 30, 2013 (subsequently amended to Sept. 30, 2014), for trihalomethanes (THMs), which are disinfection byproducts (DBPs) of chlorination. Specifically, water discharged to Joe's Creek must contain less than 34 micrograms per liter (µg/L) of chlorodibromomethane (CDBM), and less than 22 µg/L of dichlorobromomethane (DCBM). Both limits are running annual averages (RAA) based on grab samples collected monthly. These limits do not apply to the reuse and land application systems.

In order to meet these limitations, a new advanced disinfection system consisting of

Lynn Spivey is principal engineering consultant and Sean Chaparro, P.E., is senior environmental engineer with ARCADIS-US Inc. in Tampa. Steve Schaefer, P.E., is principal engineer with Parsons Water & Infrastructure Inc. in Tampa. William Harrington, P.E., is engineering support services supervisor—planning and design section, with Pinellas County.

high-level ultraviolet (UV) disinfection for surface water discharges was planned and designed. Due to a tight consent order compli-

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ance schedule, only prevalidated UV systems for reuse applications were considered, and a prepurchase of the selected UV system was completed to ensure that the tight compliance schedule could be met. The new UV system is currently under construction and will be retrofitted in the facility's existing automatic backwash filter basins.

This article discusses the methodology and results of the evaluation completed to confirm the required UV system capacity and the assessment of the major available prevalidated UV systems that will meet the high-level disinfection requirements of the facility. To minimize costs, a split stream treatment approach was used, where the UV system would only treat a portion of the flow and then be blended with the chlorinated/dechlorinated stream prior to discharge. Various UV system capacities were assessed to determine the "optimum" UV system capacity that will meet disinfection requirements at a UV transmittance (UVT) below the minimum prevalidated level, and ensure that the blended stream can comply with the running annual average surface water discharge DBP limits. Provisions included in the contract documents to verify and confirm that the UV system will meet disinfection requirements at a design UVT below the minimum prevalidated levels are also presented.

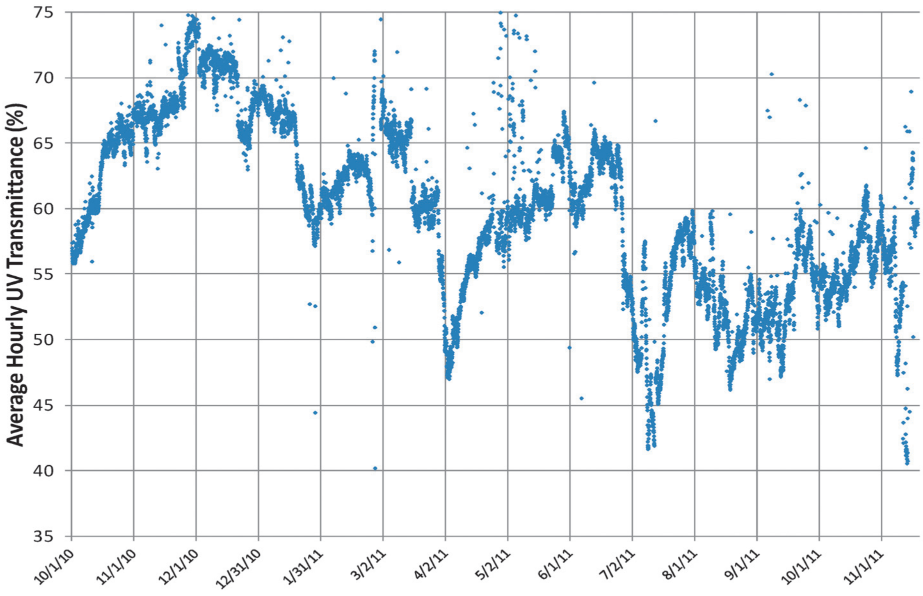

Figure 1. Average Hourly UVT Value

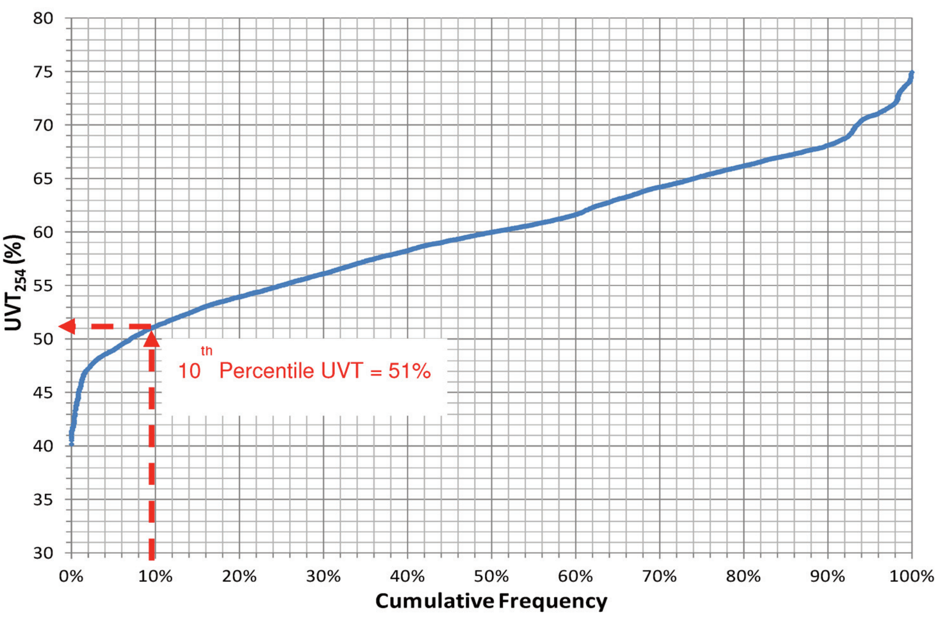

Figure 2. Cumulative Frequency of UVT – Average Hourly Data

Establishing the Design Ultraviolet Transmittance

For a UV system, the design UV dose is an indicator of the amount of pathogen reduction that this system will achieve under the most challenging design conditions. During validation testing, specific UV doses are determined, which represent the UV dose distribution of a specific UV system and account for the inherent variability of UV intensity and hydraulics. The National Water Research Institute (NWRI) has developed guidelines to establish the ability of commercial UV systems to deliver specific UV doses in a standardized way (Second Edition of the NWRI Guidelines for Drinking Water and Reuse, or 2003 NWRI Guidelines). Most UV equipment manufacturers validate their UV systems in general accordance with these guidelines.

The UVT is by far the most important water quality parameter used for sizing UV systems. The UVT is a measurement of the UV light's ability to penetrate the water, which is necessary to inactivate pathogens. Lower UVT values signify that UV light will travel shorter distances before attenuation; this means that more UV light will be required in order to achieve a given design UV dose. As such, selection of a UVT design value is critical due to its impact on disinfection efficacy, system size, footprint, capital costs, and operation and maintenance (O&M) costs.

Regarding reuse applications that require high-level UV disinfection, the FDEP has adopted by reference the 2003 NWRI guidelines. For high-level disinfection of granular media filtration effluent, these guidelines recommend the use of a minimum design dose of 100 mJ/cm^2 and UVT_{254} value of 55 percent, or alternatively, a design UVT_{254} value corresponding to the 10th percentile of a set of data collected at least three times a day over a minimum period of six months.

In accordance with these guidelines, the SCBWRF installed an on-line UVT analyzer and started collecting real-time UVT data in the fall of 2010. Each hourly value was averaged by the plant supervisory control and data acquisition (SCADA) system logic from the on-line UVT analyzer continuous output signal; 24 hourly average UVT_{254} values were thus generated each day. Figure 1 shows a chronological graph of the average hourly UVT_{254} values. As seen since the start of the UVT_{254} collection program, there has been a general downward trend, with occasional prolonged

UVT dips, followed by recoveries. The UVT values have ranged between 40 and 75 percent throughout the monitoring period.

This data set was subsequently used to determine a design UVT_{254} value based on the 10th percentile approach as outlined in the 2003 NWRI guidelines. The data set of average hourly UVT_{254} values from Oct. 1, 2010, to Nov. 18, 2011, was ranked in ascending order relative to the entire data set range, creating a cumulative frequency graph. Figure 2 is the result of this analysis. As seen in the figure, the 10th percentile value recommended for design by the 2003 NWRI guidelines was 51 percent. This design UVT is lower than what would be anticipated from a facility with tertiary treatment and lower than the minimum 55 percent UVT that has been prevalidated for any high-level UV disinfection system.

A detailed review of operating data found correlations between the low UVT_{254} values and rainfall, plant flow, and effluent total organic carbon (TOC). The general relationship among these parameters is that rainfall causes high flows to enter the plant, in turn inducing an increase in TOC, with an associated decrease in UVT_{254}. Only a slight correlation between lower UVT_{254} and higher effluent nitrate was observed. The levels of TOC and nitrate may be a direct consequence of an upset within the plant process at times of high flow.

A broad-level process review and operational shadowing of the SCBWRF was subsequently completed to identify potential opportunities to enhance the UVT through basic process changes within the existing treatment scheme. The process review and operational shadowing identified a number of process changes that may help improve treatment performance and increase UVT. However, identified changes were not used to change the design UVT of 51 percent, but instead were recommended for implementation as a long-term strategy to optimize system performance, increase UVT, and reduce operating costs of the UV system when operational.

To assure the FDEP and Pinellas County that the UV system can meet disinfection requirements at a low design UVT of 51 percent, the selected UV manufacturer was required as part of its contract agreement to:

- Provide a performance guarantee based on permitted effluent limits.
- Complete site-specific computational fluid dynamics (CFD) modeling of the systems and providing detailed calculations and backup documentation demonstrating how the UV system would be sized to meet the design UVT of 51 percent based on validation data at 55 percent (there is a systematic, validated

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relationship between UVT and UV dose).

- Maintain conservative safety factors throughout design (validate with MS2, a conservative challenge organism; design for worst-case scenario, such as lamp aging and fouling factors; and provide a redundant UV bank in each channel).
- Successfully complete 21-day performance testing at startup. Performance testing will include checkpoint bioassay testing and fecal coliform reduction testing to confirm that the correct UV dose is applied and disinfection requirements are met. Flow-split testing will also be required to verify that an even flow-split is achieved among UV channels.

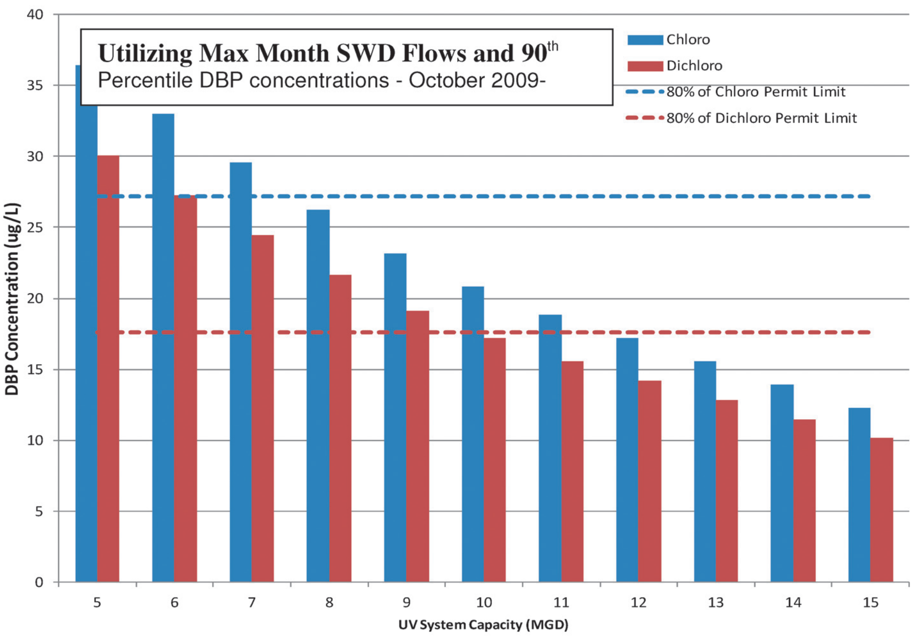

Figure 3. Year-Round UV System Operation DBP Concentrations Versus UV System Capacity

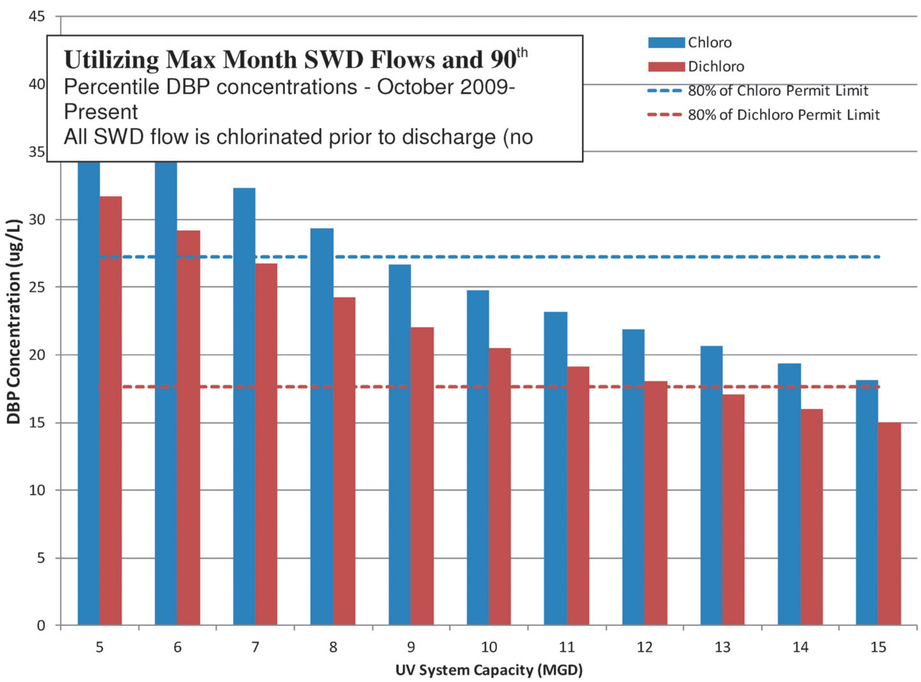

Figure 4. Seasonal UV System Operation DBP Concentrations Versus UV System Capacity

Determining the Required Ultraviolet System Capacity

The required UV system capacity for the SCBWRF was evaluated based on several factors:

- DBP effluent limits.
- Historical DBP concentrations (October 2009 through 2011), which best represent operational conditions for the future UV system. The DBP data prior to this was not included due to plant improvements made in mid-2009, which successfully reduced and consistently maintained DBP levels.
- Historical surface water discharge (SWD) flows (October 2010 through November 2011).
- Historical rainfall and reclaimed system demand (seasonal).
- System cost.

As previously indicated, the UV system was not sized to handle the entire permitted surface water discharge flow (20 mgd). To minimize costs, a split stream treatment approach was used, where the UV system would only treat a portion of the surface water discharge flow. The tertiary-treated effluent would be split into two streams: one would be chlorinated/dechlorinated, while the other stream would be disinfected using UV. The UV-disinfected effluent would have a DBP concentration of 0 mg/L and would be blended with the chlorinated/dechlorinated tertiary effluent stream downstream of dechlorination before discharge to Joe's Creek. To determine the optimal UV system capacity, a range of flows were evaluated that would meet the annual average DBP limits upon blending prior to surface water discharge. The following two overall operational protocols were evaluated:

1. *Year-round operation.* Operating the UV system year round for a selected UV system capacity. Flows within the UV system capacity will be discharged to Joe's Creek with zero DBPs.
2. *Seasonal operation.* Operating the UV system on a seasonal basis for a selected UV system capacity. For this scenario, the UV system would operate during periods of the year when the UVT is at or above a selected UVT value. During periods when the UVT is below the set point, the UV system would not operate and the entire SWD flow would be disinfected by chlorination prior to discharge. To determine the period where the UV system would not be operational, the data set was assessed for months that showed the UVT below the design value. For

the data set of October 2010 through November 2011, it was determined that the UV system would not be operational during the months of July, August, and September.

Due to the overall variability and limited amount of data available, future flows were estimated by assuming maximum monthly surface water flows based on historical data. The DBP concentrations were estimated by assuming the 90th percentile historical concentrations. The target concentrations for each permitted DBP are 80 percent of the current permit limits. Thus, for the various UV system capacities presented in the analysis, and for surface water discharge (SWD) flows greater than the UV system size, the blended DBP concentration was determined using following equation:

90th Percentile DBP Concentrations (µg/L):

Chlorinated Flow (mgd) * Average 90th percentile DBP concentration for data set (µg/L) SWD (mgd)

The resulting capacity analysis for both the year-round operation and seasonal operation based on the analysis described are shown in Figure 3 and Figure 4.

In order to stay below 80 percent of the annual average DBP permit limits, a capacity of 10 mgd is required for year-round treatment. For seasonal treatment, a capacity of 13 mgd is required. The increase for seasonal treatment is due to the higher influent and lower reclaimed flows at this time. It should be

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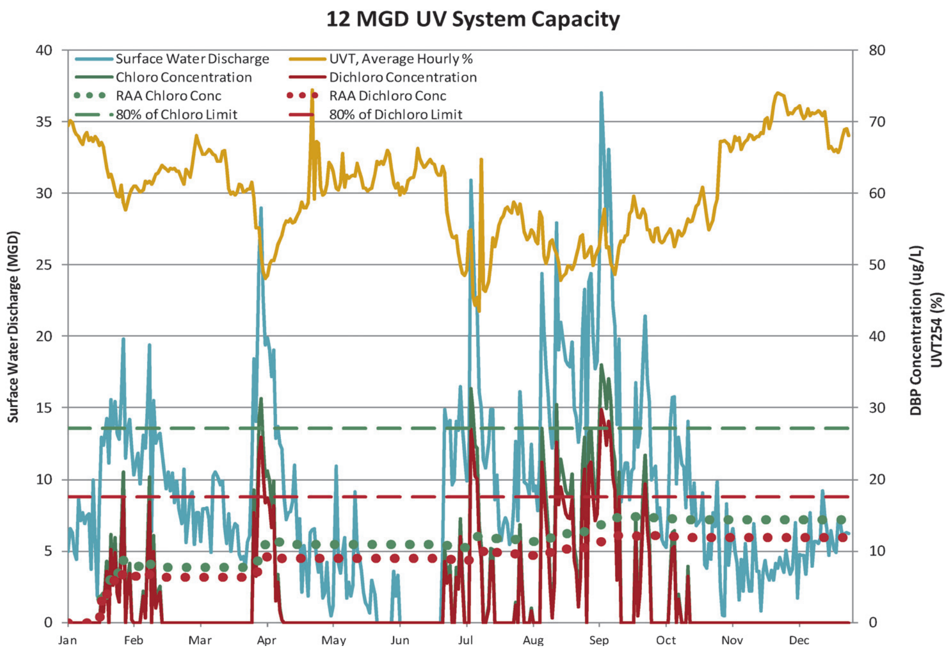

Figure 5. Estimated DBP Concentrations for an 8 mgd UV System

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noted that this particular seasonal treatment analysis had high rainfall and corresponding high SWD for the months of July through September, but could vary considerably depending on the weather (rainfall) in southwest Florida. In addition, DBP formation is influenced by temperature, and during the summer, when the UV system is not operational, the potential for DBP formation is the highest due to the high temperatures. Therefore, year-round treatment may not always be more effective than seasonal operation. A UV system size of 10 mgd would provide the flexibility to utilize either operational option to meet the DBP regulatory effluent limits, depending on the rainfall and amount of time the UV system is not operational. There is potential that operating on a seasonal basis may result in DBPs closer to the permitted limits.

To better illustrate the seasonal variation and implications throughout the entire year for the various system capacities, graphs were prepared to show the estimated daily surface water discharge DBP concentrations, the running annual DBP concentrations, SWD, and UVT based on the calculations and assumptions outlined . Figures 5 through 7 show the modeled DBP concentrations (based on the information and assumptions presented above) for year-long operation for UV system capacities of 8, 10, and 12 mgd.

As shown in the graphs, the number of days with DBP concentrations above 80 percent of the limits increases as the system size decreases. The RAA for the estimated DBP concentrations are below the permit target for the entire year for the 10- and 12-mgd capacities. This analysis shows that a UV system capacity above 10 mgd may be too conservative, since only a few days per year are projected above the limits. The results also show that a UV system capacity of 8 mgd will result in projected DCBM and RAA concentrations above the target limit during the high flow period. Based on these results, the UV system was designed for a capacity of 10 mgd, which should provide sufficient treatment capacity to ensure that effluent DBP concentrations of the blended flow stay within the DBP effluent limits. The UV system design also provides the flexibility necessary to increase system capacity in the future, if needed or desired by the County, by providing room for additional UV channels and required equipment.

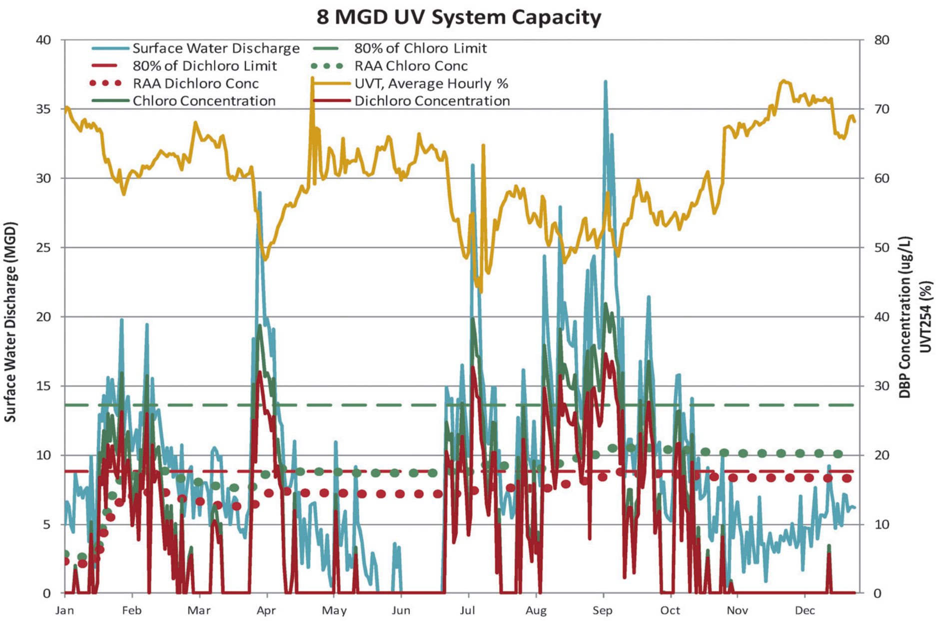

Figure 6. Estimated DBP Concentrations for a 10 mgd UV System

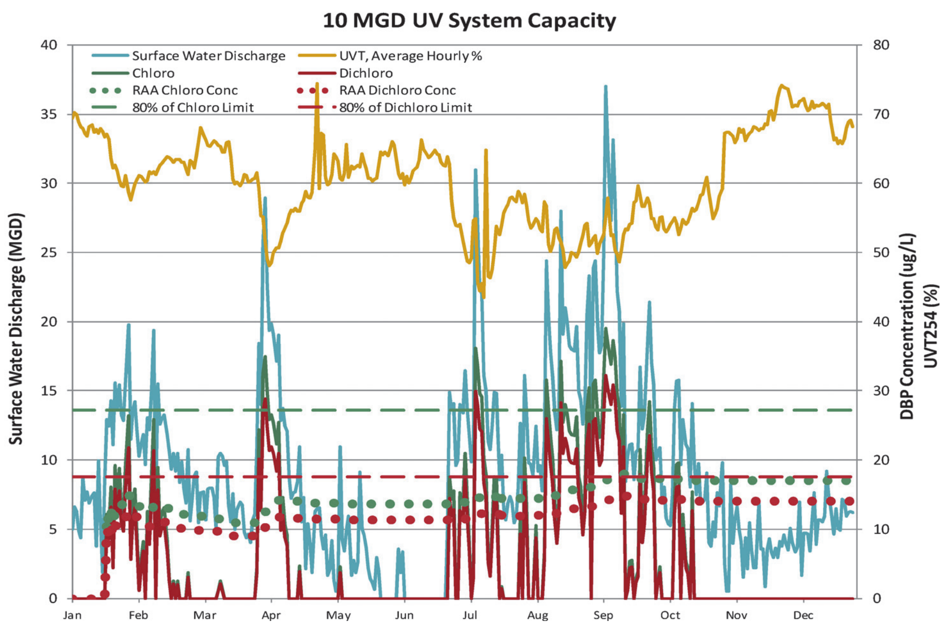

Figure 7. Estimated DBP Concentrations for an 12 mgd UV System

Comparison of Prevalidated Ultraviolet Systems

A detailed review of the major prevalidated UV systems available for high-level disinfection of the SWD at the SCBWRF was conducted to identify and compare the main system characteristics, design criteria, and estimated capital and O&M costs for each of the UV systems. The UV systems evaluated include systems from Trojan, Ozonia, and WEDECO, all of which have been accepted by the California Department of Public Health (CDPH) and FDEP for high-level disinfection applications. Calgon, another major UV manufacturer, did not participate in this initial assessment. The lamp orientation of the UV system (i.e., vertical, Ozonia versus horizontal, Trojan, and WEDECO) was an important consideration in evaluating the UV systems, since it has a significant impact on the required structural modifications to retrofit the modules within the existing filters, maintenance requirements, and overall capital and O&M costs.

Table 1 summarizes and compares the key design criteria, features, and maintenance requirements of the Trojan, Ozonia, and WEDECO UV systems evaluated. Table 2 compares the capital, annual O&M, and pres-

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Table 1. Comparison of Ultraviolet Systems

	PARAMETER	Evaluated UV Systems		
		Trojan 3000Plus	Ozonia 40 HO	WEDECO TAK
PRELIMINARY DESIGN CRITERIA	**UV System Design**			
	Peak design capacity (MGD)	10	10	10
	Average flow (MGD)	7.5	7.5	7.5
	Design UVT	51%	51%	51%
	UV dosage (mJ/cm^2)	100	100	100
	Lamp type	High output amalgam	High output mercury vapor	High output amalgam
	Lamp configuration	Horizontal, parallel flow	Vertical, perpendicular flow	Horizontal, parallel flow
	Number of banks per channel	5	10	5
	Number of modules per bank	14	2	7
	Number of lamps per module	8	40	16
	Number of lamps per bank	112	80	112
	Total number of lamps	1,120	1,600	1,120
	Number of ballasts	560	800	560
	UV Channel Design Requirements			
	Number of channels	2	2	2
	Channel width (in)	56	48.5	60.4
	Channel depth (in)	75	103	77
	Average Water depth (in)	32	60	34.3
	Allowable water level change within channel (in)	1.5	4.5	1.5
	Lamp Design Factors			
	End of lamp life (EOLL) factor	0.98	0.90	0.90
	Fouling factor	0.95	0.80	0.90
COMPARISON OF KEY SYSTEM FEATURES	**System Characteristics**			
	UV dosage control	Based on UVT and flow	Based on UVT and flow	Closed loop sensor based control
	Time to reach max output (cold start)	3 minutes	30 to 45 seconds	4 minutes
	Time to reach max output (hot start)	3 minutes	30 to 45 seconds	2-3 minutes
	Level control device options	Fixed weir, motorized weir gate, ALC	Fixed weir, motorized weir gate, ALC	Fixed weir, motorized weir gate
	Avg. power consumption (kW @7.5 MGD)	60.5	153.1	98.3
	Avg. power consumption per year (MWhr @7.5 MGD)	530	1,341	861
	Guaranteed lamp life	12,000 hours	10,000 hours	12,000 hours
	Module removal from channel required for lamp replacement?	Yes	No	Yes
	Ballast Configuration			
	Ballast type	Electronic, variable output (60 to 100% power)	Electronic, constant output (100% power)	Electronic, variable output (50 to 100% power)
	Ballast number	2 ballasts per lamp	2 ballasts per lamp	2 ballasts per lamp
	Ballast location	Integrated to UV module mounted inside UV channel	Integrated to UV module mounted slightly above channel	Remote ballast cabinet inside air conditioned building
	Ballast cooling method	Convection; no AC/forced air	Forced air in each module	Forced air in cabinet and climate controlled room
	Module removal from channel required for ballast replacement?	Yes	No	No
	Cleaning System			
	Cleaning system	Automatic in-place lamp mechanical/chemical cleaning	> Automatic in-place lamp mechanical cleaning. > Chemical dip tank (optional) > In-channel air scrub (optional)	> Automatic in-place lamp mechanical cleaning system > Chemical dip tank (optional)
	Module removal from channel required for cleaning?	No*	Yes (for chemical cleaning only)	Yes (for chemical cleaning only)
	System Validation for Reuse			
	Validated UVT per NWRI guidelines	55%	55%	55%

Table 2. Ultraviolet System Cost Comparison Matrix

DESCRIPTION	UV SYSTEM COST COMPARISON MATRIX		
	Trojan 3000Plus	Ozonia Aquaray 40 HO	Wedeco TAK 55
Peak Design Flow (MGD)	*10*	*10*	*10*
UV Transmittance (%)	*51%*	*51%*	*51%*
UV Dosage (mJ/cm2)	*100*	*100*	*100*
Capital Costs			
UV Equipment	$ 2,589,500	$ 1,560,000	$ 2,402,400
Miscellaneous Piping and Ancillary Equipment	$ 1,120,000	$ 1,090,000	$ 1,120,000
Structural Systems	$ 1,438,000	$ 1,755,000	$ 1,613,000
Electrical and I&C	$ 862,600	$ 862,600	$ 862,600
Sitework	$ 70,000	$ 70,000	$ 70,000
SUBTOTAL	*$ 6,080,100*	*$ 5,337,600*	*$ 6,068,000*
Contingency (18%)	*$ 1,094,500*	*$ 960,800*	*$ 1,092,300*
Subtotal Construction Cost	***$ 7,174,600***	***$ 6,298,400***	***$ 7,160,300***
Engineering & Administration (25%)	*$ 1,793,700*	*$ 1,574,600*	*$ 1,790,100*
Mobilization, Bonds, Insurance, etc. (5%)	*$ 358,800*	*$ 315,000*	*$ 358,100*
TOTAL CAPITAL COSTS	**$ 9,330,000**	**$ 8,190,000**	**$ 9,310,000**
Annual Operations and Maintenance Costs			
Avg Flow Power - UV System	$ 63,600	$ 161,000	$ 103,300
Lamp Replacement	$ 147,000	$ 30,000	$ 113,400
Quartz Sleeve Replacement	$ 1,500	$ 4,000	$ -
Ballast Replacement	$ 4,600	$ 11,600	$ 11,600
Wiper Replacement	$ 6,800	$ 2,700	$ 5,700
Cleaning Chemicals	$ 5,000	$ 4,000	$ 4,000
Average Labor	$ 36,700	$ 16,800	$ 40,900
Annual O&M Costs	*$ 265,200*	*$ 230,100*	*$ 270,000*
PRESENT WORTH O&M COSTS	**$ 4,360,000**	**$ 3,780,000**	**$ 4,440,000**
TOTAL PRESENT WORTH COSTS	**$ 13,690,000**	**$ 11,970,000**	**$ 13,750,000**

NOTES:

[1] Opinion of probable costs presented as present worth values with a 5% annual discount rate over a 20-year period (i.e. i = 5%, n = 20 years).

[2] Operations and Maintenance costs estimated based on a 7.5 MGD average flow.

[3] Power costs estimated based on electrical unit cost of $0.12/kWh.

[4] O&M cost escalation rate assumed to be 3%.

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ent-worth costs for each of the UV system alternatives.

Selected Ultraviolet System

Based on the technical, maintenance, and cost evaluation of the various UV systems, discussions with Pinellas County technical and maintenance staff, and site visits to various operating UV disinfection systems run by other municipalities in Florida; the selected UV system for the SCBWRF was the vertical array UV system Aquaray 40HO, manufactured by Ozonia. This system was selected due to the following distinguishing characteristics:

- Greater ability to manage fluctuations in liquid level due to the vertical lamp array configuration.
- Faster lamp startup time due to the type of lamp used.
- Ease of lamp replacement since modules do not need to be removed to replace lamps.
- Ease of downturn and flexibility of operation because of the ability of the system to turn off individual rows of lamps within a module and provide faster ramp up capabilities.
- Lower life cycle costs.