Results of greywater and black water recycling testing of the Forward Osmosis Recycling System (FORS) at the Stanford University Codiga Resource Recovery Center

Introduction

The Forward Osmosis Recycling System (FORS) is an integrated membrane water recycling system that incorporates a forward osmosis system and a reverse osmosis system working in series. FORS treats wastewater effluents from industrial, commercial, agricultural and residential buildings characterized by a high content of organics, dissolved solids, and suspended solids. A pilot scale test of the FORS was recently completed by Google Inc. at Stanford University. A 150gal/day FORS was installed in a mobile trailer that was placed at the Codiga Resource Recovery Center at Stanford University. This system was tested for eighty-seven days with greywater feed (Phase I) followed by sixty-four days with black water feed (Phase II). All operations and testing were completed by Stanford University faculty and students. This report summarizes the results of this testing.

The objectives of this project were:

- Demonstrate reliable long-term operation.
- Demonstrate that the effluent meets National Sanitation Foundation NSF-350-1 and the City of San Francisco water reuse standards.
- Determine operating and maintenance requirements.
- Use results to produce financial model of larger FORS system operating in an office building.

Experimental Methods

A 150 gal/day WH2O Systems LLC. FORS system was installed in a trailer and placed at the Stanford University Codiga Resource Recovery Center. The system was composed of two forward osmosis PFO-100 membrane elements (7 m^2) and a Katadyn Spectra AF-200-PPS RO Pump (8 gal/hr) watermaker. The FORS flow diagram is shown in Figure 1. The product was monitored using a Ken Grady Co. Q46H/62-1-1-3-1-1-1 chlorine monitor and Ken Grady Co. Q46/76 2-1-1-1-1 turbidity meter. The chlorine system is shown in Figure 2. The FORS was provided with an EZAutomation ladder logic control system that allows continuous unmanned operation and remote monitoring. Membrane cleaning was conducted manually when needed by adding cleaning chemicals to the feed tank. Normal operations and analytical sample collection were conducted by Stanford University students.

Greywater

Greywater is defined here as wastewater generated by hygiene and clothes washing. Greywater was collected from a laundry located on the campus of Stanford University and truck hauled to the Codiga Resource Recovery Center where it was transferred to the FORS feed tank. The greywater consisted of 75 gallons of laundry effluent collected from five residential washing machines mixed with 75 gallons of synthetic wash water solution. The wash water solution was formulated according to National Sanitation Foundation 350-1 guidelines (Table 1; National Sanitation Foundation, 2019).

Table 1. NSF 350-1 Wash Water Formulation.

Wash Water Components	Item used	Amount/100L
Body wash with moisturizer	Dial Spring Water Hydrating Body Wash	30g
Toothpaste	Colgate Fluoride Toothpaste- regular	3g
Deodorant	Secret Powder Fresh antiperspirant	2g
Shampoo	Suave Ocean Breeze Shampoo	19g
Conditioner	Suave Tropical Coconut Conditioner	21g
Lactic acid	85% w/w ACS grade (Fisher)	3mL
Bath cleaner	Lysol Disinfectant Bathroom Cleaner	10g
Liquid hand soap	Dial Gold Antibacterial Hand Soap	23g
Test dust	Collected indoor dust	10g
Secondary municipal wastewater effluent	Effluent from membrane aerated bioreactor	2L

Black Water

Black water is defined here as wastewater generated in student housing that contains pathogens and fecal contamination. Sources of black water include toilets, urinals, sinks, kitchens, showers, baths, and washing machines. The Codiga Resource Recovery Center facility is connected to the Stanford University sewer that services student housing and provides black water feed on-demand. The Codiga feed is pretreated by the facility using a 300-micron prefilter. The FORS provided a two-stage grease trap pretreatment that reduced any remaining floatable and settable solids.

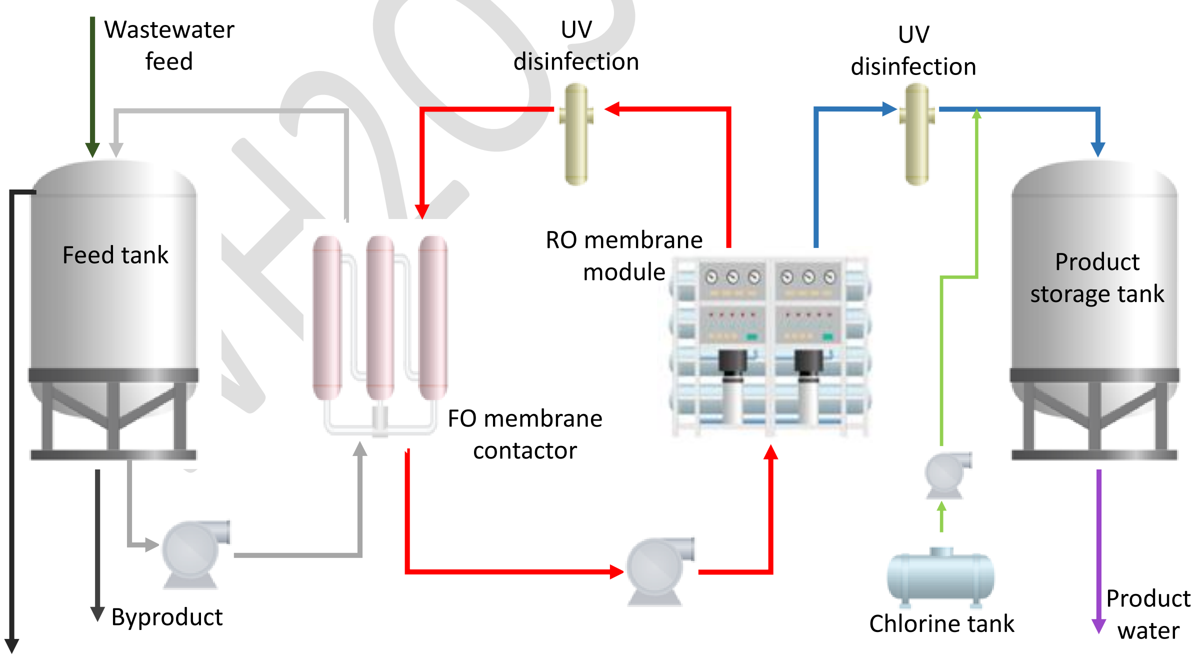

Figure 1. Simplified FORS flow diagram.

Sample collection and spike tests

Samples were collected for analysis of pathogen indicators, organic contaminants, inorganics, disinfection byproducts and contaminates of emerging concern. Samples collected for basic water quality analysis were stored at room temperature and analyzed within two hours of collection. For analysis of coliform and E. coli, samples (100 mL) were collected from the FO feed and RO permeate after chlorination in single use sterile containers (IDEXX), and were analyzed within one hour of collection. MS2 bacteriophage (ATTC 15597-B1) was propagated using lab strain *E. coli* (ATCC 700891) accordingly methods described by *Kohn and Nelson, 2007.* The MS2 stock was spiked into the FO feed tank targeting a concentration of 10^8-10^9 PFU/mL. Samples were collected in sterile containers three times throughout each spike test run from the FO feed, the FO draw solution tank, and the RO permeate before chlorination. MS2 samples were stored on ice, and processed within five hours of collection.

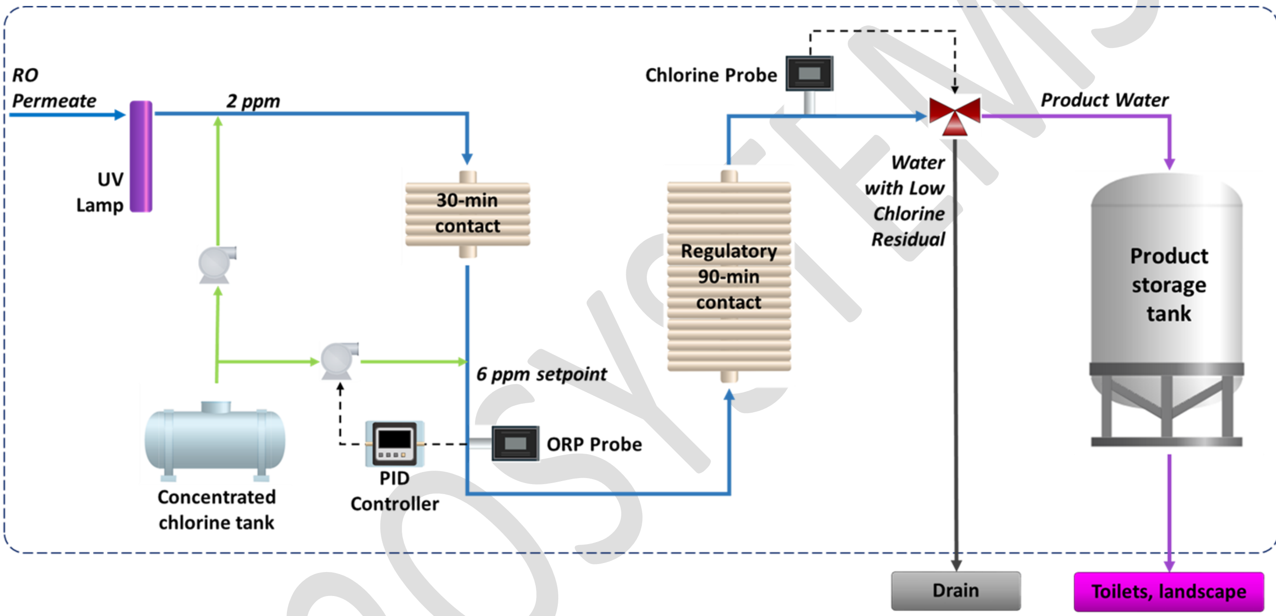

Figure 2. Chlorine control and injection system.

Concentrated organic contaminant of emerging concern stock solutions were spiked into the FO feed tank targeting concentrations of 200-250 nM. Samples (500 mL) were collected from the FO feed, the FO draw solution tank, and the RO permeate, and stored at 4°C prior to analysis. During each spike run, one sample was collected prior to spiking, and three samples were collected throughout the run after at least 160 L of water were processed.

For disinfection byproducts (DBPs), two sets of grab samples were collected from the FO feed, the FO draw solution tank, and the RO permeate. One sample set was treated with 33 mg/L ascorbic acid immediately after collection to quench residual disinfectants in order to measure the DBPs already present in the samples. To measure the levels of DBP precursors, the other sample set was collected without ascorbic acid to enable treatment in the laboratory with chlorine or chloramines. Samples were stored at 4°C prior to analysis.

General Water Quality Analyses

All samples collected for basic water quality analysis, apart from those used for total suspended solids (TSS) and chemical oxygen demand (COD) analyses, were filtered with a 0.7-micron glass fiber filter (Whatman). TSS (Minimum reporting level (MRL) = 0.1 mg/L) were measured using EPA method 160.2.

COD (MRL = 0.7 mg COD/L), ammonia (MRL = 0.015 mg-N/L), nitrate (MRL = 0.2 mg-N/L), and nitrite (MRL = 0.02 mg-N/L), and total phosphorous (MRL = 0.1 mg-P/L) were measured by HACH methods 8000, 10205, 8171, 8507, and 8131 respectively. Dissolved organic carbon (DOC) (MRL = 0.1 mg-C/L) was analyzed using a Shimadzu TOC-VCSH total organic carbon analyzer. The 5-day biological oxygen demand (BOD5) (MRL = 0.1 mg/L) was analyzed using EPA method 405.1. Chloride (MRL = 0.01 mg/L), and bromide (MRL = 0.01 mg/L), were analyzed using a Dionex Integrion HP ion chromatograph (Thermo Scientific). pH was measured using an Accumet pH probe (Fisher Scientific), and verified with pH paper (Hydrion). UV absorbance at 254 nm (MRL = 0.01 cm^{-1}) was measured using an Agilent Cary 60 UV-Vis spectrophotometer. The specific UV absorbance (SUVA254) was calculated by dividing the UV absorbance by the DOC.

Microbial analyses

Total coliform and *E. coli* were analyzed using defined substrate assays (Colilert-18, IDEXX). Samples were diluted with sterile Butterfield phosphate buffer (Hardy Diagnostics) when necessary. MS2 was enumerated using a double agar layer technique according to a modified Standard Method 9224 (Kohn and Nelson, 2007).

Organic contaminant analysis

Eighteen organic contaminants were quantified for the FO-RO treatment of RO concentrate at the centralized potable reuse facility, including benzotriazole, ibuprofen, acyclovir, naproxen, diuron, carbamazepine, sulfamethoxazole, atenolol, hydrochlorothiazide, diclofenac, ranitidine, ciprofloxacin, oryzalin, bezafibrate, fipronil, 1,4-dioxane, sucralose and gemfibrozil were also quantified. 1,4-Dioxane was measured in 40 mL samples by extraction into 3 mL MtBE and analysis by gas chromatography mass spectrometry (GC-MS) *(Zhang et al., 2019).* For analysis of the remaining 17 compounds, samples (250 mL) were passed through 6 mL Oasis HLB cartridges (Waters Corp.), which had been pre-rinsed with 12 mL of methanol and 12 mL of deionized water. The cartridges were then rinsed with 12 mL of deionized water, and eluted with 12 mL of methanol *(McCurry et al., 2014).* The resulting extract was then analyzed by liquid chromatography tandem mass spectrometry (LC-MS/MS).

Disinfection byproducts (DBP) analyses

Samples were treated with 33 mg/L ascorbic acid and measured directly for 43 DBPs belonging to seven classes, including four trihalomethanes (THMs), ten haloacetic acids (HAAs), four haloacetamides (HAMs), four haloacetaldehydes (HALs), six iodinated-THMs, two haloketones (HKs), one halonitromethane (chloropicrin), and eight *N*-nitrosamines. The HAAs and all other halogenated DBPs were quantified using modified EPA Methods 552.3 and 551.1, respectively (Szczuka et al., 2017; 2019). The *N*-nitrosamines were measured using a modified EPA Method 521 with ~2 ng/L reporting limits. Additional details are provided in Text S3.

Weighting DBP concentrations by metrics of toxic potency

The contribution of a DBP to the DBP-associated toxicity of a disinfected water is a function of both DBP concentrations and their toxic potencies *(Li and Mitch, 2018).* Individual DBP concentrations were weighted by metrics of toxic potency; the sums of these toxic potency-weighted DBP concentrations were used to compare the DBP-associated quality of different waters. For halogenated DBPs, the toxic potency metrics were the DBP concentrations associated with a 50% reduction in the growth of Chinese hamster ovary (CHO) cells compared to untreated controls (i.e., cytotoxicity LC_{50} values). For *N*-nitrosamines, the BP concentrations associated with a 50% lifetime excess cancer risk (i.e., $LECR_{50}$ values) were used as toxic potency metrics. This calculation provides only an initial estimate of the relative importance of different DBP classes, since it involves assumptions (e.g., that the toxicity of DBP mixtures is additive) discussed more fully in *Li and Mitch (2018).*

O&M Results

Phase I dealt with the treatment of greywater. During this phase of testing, the FORS system operated for a total 62 days out of a total of 80 days for a 78% operational availability of the system. Phase I was the first phase of the program and was impacted by the normal problems associated with commissioning a new system. Of the 18 days the system was down; 12 were due to critical failures, 3 were due to small failures and 3 were due to planned stoppage.

Phase II dealt with the treatment of black water. During this phase of the testing, the FORS system operated for a total of 60 days out of the 63 total days of operation for a 95% availability. For the 3 Days the system was down 2 were due to small failures and one was for planned stoppage. Figure 3 presents the results of the operations of the FORS for the 2 Phases of the testing program.

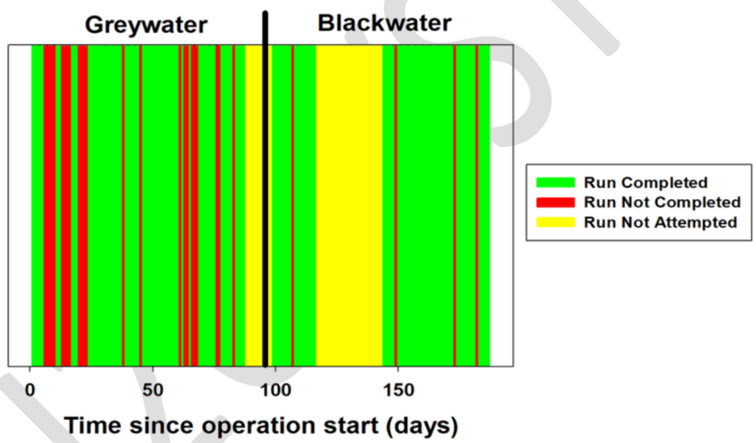

Figure 3. Operational availability of FORS during both phases of testing

The overall volume of product water produced during both phases of testing was about 25,000 gallons. The consumables used during the operations of the system included:

- Filter cartridges: The FO filter was replaced twice. The time for installing the filter is 5 minutes;
- Sodium chloride (NaCl): 1.3 grams of NaCl/gallon of feed.
- Sodium metabisulfite (SMBS): 0.1mg/gal of feed.
- Concentrated bleach: 0.6ml bleach/gallon of feed.
- Baking soda: 0.46 g/gallon
- Membrane back flushing: 45 minutes/week.
- Labor: chlorine tank: 10 minutes every other day; salt tank: 5 minutes twice a week; pH control tank with product water and baking soda: 10 minutes twice a week
- Power consumption: 11 watt-hr/liter of feed

Analytical Results

Table 2 presents the analytical results of the greywater and sewage testing. Data reported are averages of daily testing over the 80 days of gray water testing and 63 days of sewage testing. The column labeled “FORS Product” is the product from the FORS system prior to chlorination. The column labeled “Chlorinated pH Adjusted Product” is the FORS product after addition of chlorine.

Table 2. Results of grey water and sewage testing at Codiga Resource Recovery Center.

	Gray Water			Sewage		
Water Quality Parameter	Feed	FORS Product	Chlorinated pH Adjusted Product	Feed	FORS Product	Chlorinated pH Adjusted Product
Chemical Oxygen Demand (mg/L)	1290	5.8	-	1040	6.5	-
Dissolved Organic Carbon (mg-C/L)	160	0.3	-	84	0.2	-
Biological Oxygen Demand (mg/L)	1210	4.5	-	1030	0.1	-
Total Suspended Solids (mg/L)	48	<0.1	-	67	0.1	-
Total Phosphorous (mg-P/L)	3	<0.1	-	16	<0.1	-
Ammonia (mg-N/L)	14	1.1	0	66	4.3	0
Nitrate (mg-N/L)	2.8	<0.2	-	1.3	0.3	-
Nitrite (mg-N/L)	0.85	0.02	-	0.24	0.02	-
Bromide (mg/L)	0.4	<0.1	-	0.1	<0.1	-
Chloride (mg/L)	160	25	-	110	49	-
pH	6.7	4.4	7	7.2	5.8	7
UV 254 (cm-1)	0.53	<0.01	-	0.54	<0.01	-
SUVA (L mg-1 m-1)	3.2	N/A	-	6.7	N/A	-
Virus as Bacteriophage MS2 (log removal)		6.75	9.75		7.0	10
E. coli (log removal)		5.4	8.5		7.4	10.4
Total coliform (log removal)		5.4	8.5		7.9	10.9
Disinfection Byproducts (mg/L)	0.13	0.039	0.085	0.04	0.005	0.020

For comparison purposes, Table 3 presents again the results of the testing along with water quality standards for NSF-350-1 and the City of San Francisco’s standards for greywater and Black water. As shown, FORS treated greywater and black water meet these standards.

Testing was also completed to evaluate the FORS ability to remove contaminates of emerging concern. These are contaminates such as pharmaceuticals that are not yet regulated by water quality standards but represent potential health concerns. Testing for these compounds was completed by Stanford personnel spiking the feed with known levels of each compound than then analyzing for them in the product water. Table 3 presents the results of this testing.

Table 3. Comparison of applicable standards to FORS product water quality.

Parameter	Unit	San Francisco: Greywater	San Francisco: Blackwater	National Sanitation Foundation NSF-350-1	FORS Graywater	FORS Blackwater
BOD 5	mg/L	10	10	10	4.5	0.1
TOC	mg/L	None	None	Must be measured	0.3	0.2
TSS	mg/L	10	10	10	<0.1	0.1
Turbidity	NTU	2	2	2	<0.2	<0.2
E. coli	CFU/100 mL (SF) MPN/100 mL (NSF)	2.2	None	2.2	<1	<1
Total coliform	CFU/100 mL	None	2	None	None	None
pH	-	6.0-9.0	6.0-9.0	6.0-9.0	7	7
Residual chlorine	mg/L as Cl_2	0.5-2.5	0.5-2.5	0.5-2.5	5	5
Temperature	°C	None	None	Must be measured	ambient	ambient
COD	mg/L	None	None	Must be measured	5.8	6.5
Odor	-	No offensive odors	No offensive odors	None	None	None
Ammonia/ nitrite/nitrate	mg-N/L	None	None	Must be measured	1.1/<0.2/0.02	4.3/0.3/0.02
Phosphorous	mg-P/L	None	None	Must be measured	<0.1	<0.1
Enteric virus	log removal	6.0	8.5	None	9.75	10
Parasitic protozoa	log removal	4.5	7	None	8.5	10.9
Enteric bacteria	log removal	3.5	None	None	8.5	10.4

Table 4. Percent reduction of contaminates of emerging concern in FORS product water.

Chemical Species	Percent Reduction
Benzotriazole	91%
1,4-dixane	>96%
Acyclovir	>99%
Sulfamethoxazole	>99%
Hydrochlorothiazide	>99%
Diuron	>99%
Naproxen	>99%
Carbamazepine	>99%
Ibuprofen	>99%
Diclofenac	92%
Ciproflxacin	>96%
Fipronil	>99%
Sucralos	>99%
Atenolol	>99%
Gemfibrozil	>99%
Oryzalin	>99%
Ranitidine	>99%
Benzafibrate	>99%
Chloroform	>99%

Testing was completed for all compounds, except chloroform, by spiking in the feed to 250 nM with each compound.

Chloroform and 1,4-dixane were present in low levels for the graywater feed.

Concentrations of all species were below reportable levels.

1,4-dixane was at the highest concentration of 0.010 mg/L in the treated graywater.

Disinfection Byproducts (DBPs)

Figure 4 shows the concentrations of (A) total DBPs, (B) chloroform (TCM), and (C) NDMA detected in the FO feed (Feed), FO draw solution (post FO), and RO permeate (post RO) after chlorination during treatment of greywater and sewage. Box plots are based on 4 separate sampling events.

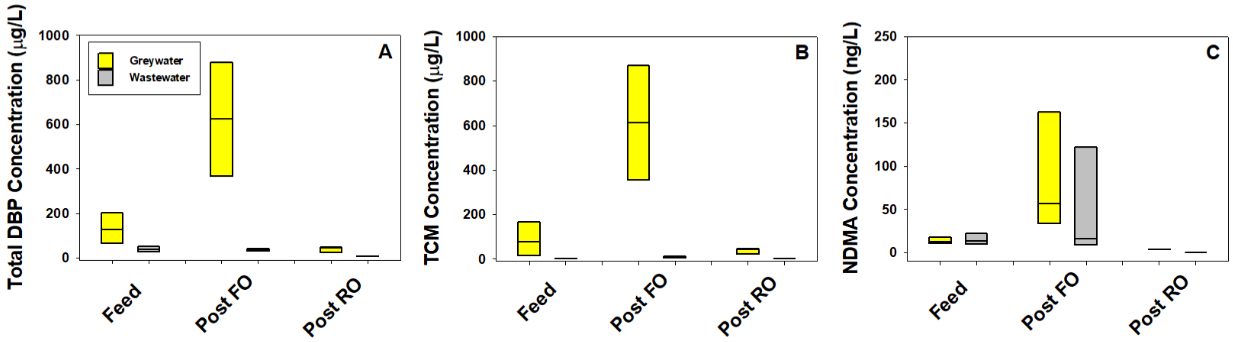

Figure 4. Concentrations of (A) total DBPs, (B) chloroform (TCM), and (C) NDMA

Figure 5 shows DBP concentrations in FO-RO permeate on a (A) mass or (B) toxic potency-weighted basis. Plots show the average (± standard deviation) of total DBP concentrations over 4 sampling events. The bars show the concentrations of individual DBP classes during the third sampling event.

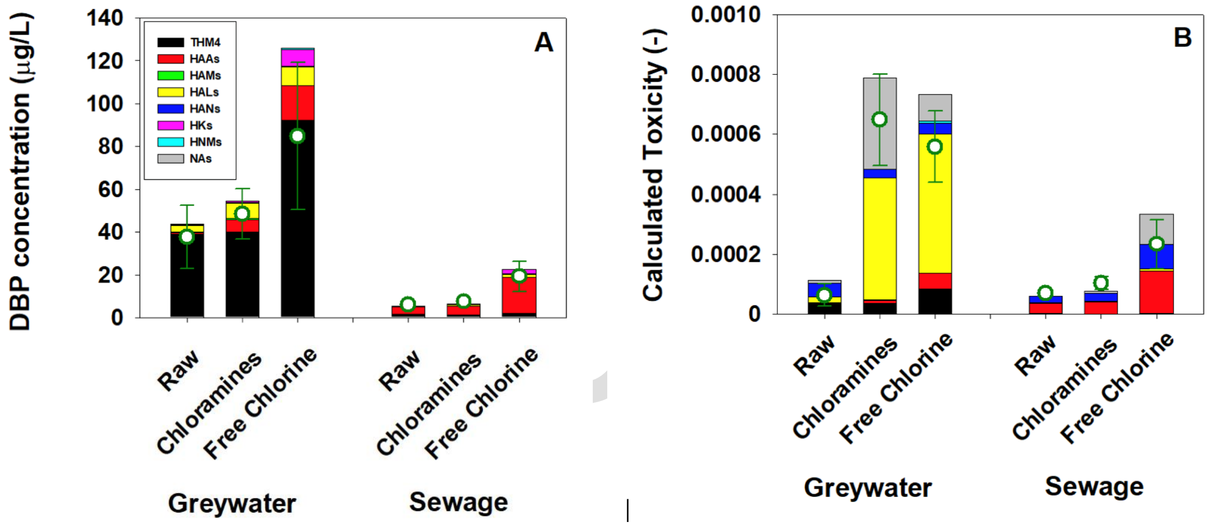

Figure 5. DBP concentrations in FO-RO permeate on a (A) mass or (B) toxic potency-weighted basis. THM4 = four chlorinated and brominated trihalomethanes, HAAs = nine brominated and chlorinated haloacetic acids and iodoacetic acid, HAMs = haloacetamides, HALs = haloacetaldehydes, HANs = haloacetonitriles, HKs = haloketones, HNMs = chloropicrin, NAs = nitrosamines, I-THMs = iodinated trihalomethanes.

Biological Data

FORS product water was analyzed for E. coli and coliform on a regular bases during Phase I and Phase II of the testing program. Results of this testing are shown in Figure 6 for E. coli and Figure 7 for coliform. Data is provided for the influent and effluent of the FO/RO portion of the FORS and the chlorinated effluent of the complete FORS system. Data is provided for both greywater and blackwater.

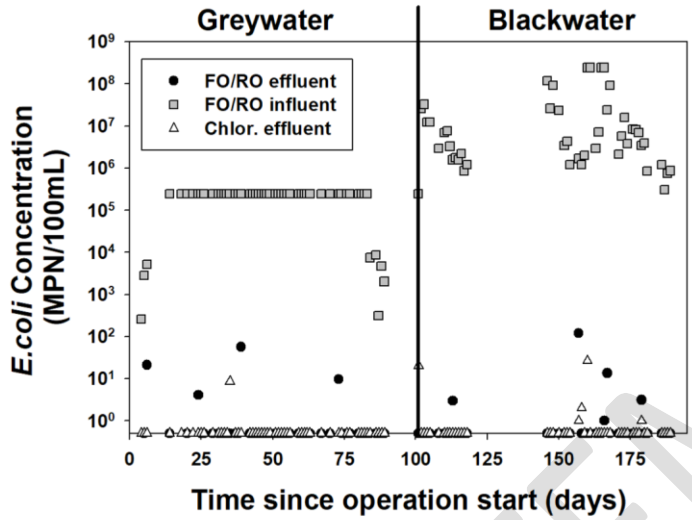

Figure 6. Results of E. coli sampling.

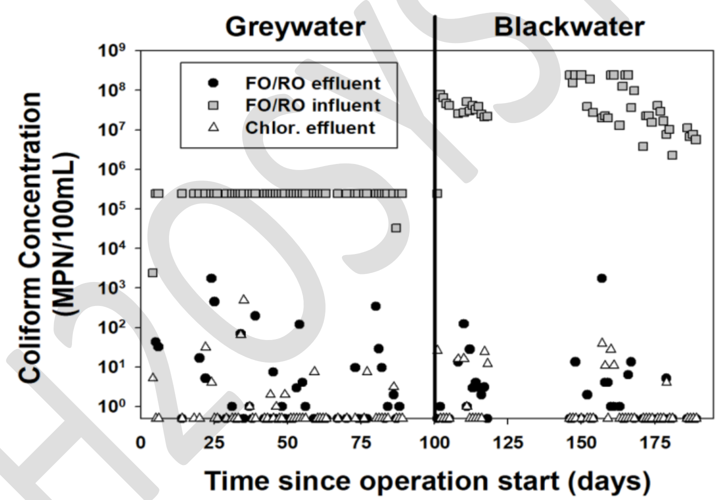

Figure 7. Results of coliform testing.

The maximum detectable limit for the greywater portion of the testing was not high enough to measure E. coli in the influent. This is why it appears as a flat line in the greywater portions of Figure 6 and 7. During the black water testing, the procedure was modified to increase the maximum detectable limit of the influent. As shown in Figure 6 and 7, there are times when the FORS product does not adequately remove bacteria. Figure 8 shows that these events are associated with times that the chlorination system is not working properly. Figure 8 shows that the chlorinated effluent of the FORS regularly achieves the standard of 2.2 colony forming units (CFU)/100ml when the chlorination system is functioning. When the chlorination system is not functioning, the E. coli levels can exceed the 2.2

CFU/100ml standard. The chlorination system is key component of the FORS systems performance and accounts for about 3 logs removal.

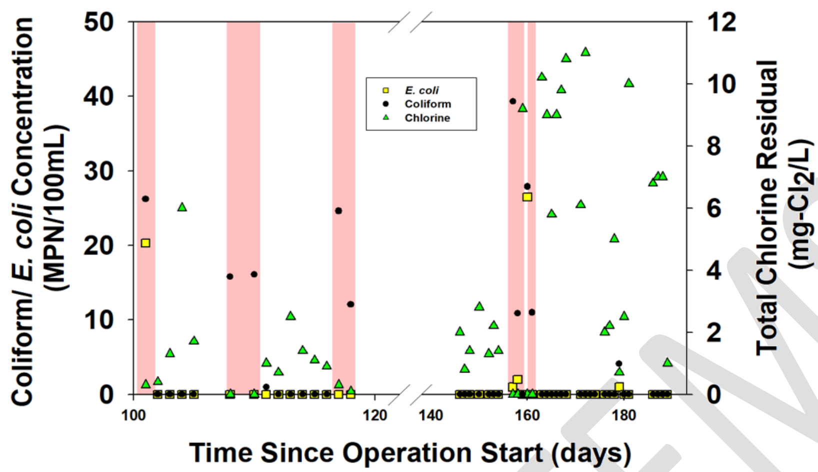

Figure 8. Impact of chlorination system on coliform and E. coli concentration.

Table 5 shows the results of enteric virus spike tests with MS2. Samples were collected after the FO membrane from the draw solution and after the FO and RO membranes from the product but before chlorination of the product. Results show that for graywater an average of 6.25 log reduction across the FO membrane alone and 6.75 log reduction across the combined FO/RO membranes. For black water, there was 5.5 log reductions across the FO membrane alone and 7 log reductions across the combined FO/RO membranes. When the product is chlorinated, an additional 3 additional log reduction can be expected, at 2 ppm chlorine with a 90 min contact time.

Table 5. Log reduction of MS2 spiked into FORS feed.

	Greywater		Blackwater	
	FO only	FO and RO	FO only	FO and RO
Test 1	5.1 ± 0.4	6.7 ± 0.2	8.2 ± 0.9	8.5 ± 0.4
Test 2	6.7 ± 0.4	6.6 ± 0.5	4.9 ± 0.3	6.5 ± 0.2
Test 3	7.0 ± 0.4	7.0 ± 0.4	4.2 ± 0.6	6.6 ± 0.8
Test 4	6.2 ± 0.1	6.7 ± 0.3	4.7 ± 0.1	6.5 ± 0.1

Operations

As shown in Table 6, the operation of the FORS improved from Phase I to Phase II. The systems availability increased from 78% in Phase I to 95% in Phase II. Labor also improved from 2 hrs/day in Phase I to 20 min/day in phase II, the majority of which at the end was Stanford's daily sample collection. We expect that for a commercial system, where less sample collection is required, the system would require about 1.5 min/day in support labor.

Table 6. Summary of Phase I and Phase II testing

Phase I - Graywater	**Phase II – Blackwater**
• Produced about 6842 gallons of produc water	• Produced about 6578 gallons of product water
• Power consumption range, 11 to 13 watt-hr/liter of product	• Power consumption ranged from 11 to 14 watt-hr/liter of product
• System availability, 78%	• System availability was 95%
• FO membranes required a backwash once every 6 weeks	• FO membranes required a backwash once a week
• Cost of chemicals required for continuous operation, $0.002/gal	• Cost of chemicals required for continuous operation, $0.005/gal
• Labor for nominal operations, 2 hr/day	• Labor for nominal operations was 20 min/day
• During nominal operations, product water meets applicable standards	• During nominal operations, product water meets applicable standards

Another key finding of this study was that FORS met all applicable water purity standards when used with a chlorination post-treatment. A two-step chlorination system was required to accurately control product levels. In addition, for black water testing, a two-step grease trap was required to prevent premature feed filter fouling. Regular membrane chemical cleaning was required for blackwater treatment. Graywater required regular back flushing and occasional chemical cleaning.

Economics

In order to evaluate the economics of operation of a full sized FORS the results of the Codiga testing were sized up and used to evaluate a case study for an 87533 SF building at 1100 Gundy LN, San Bruno California. The economic analysis of the San Bruno site shows a positive internal rate of return (IRR) of 2.7% for 16 years and 6.6% for 32 years. This estimate compares the cost of purchasing water from the city in comparison to the cost of recycling water using Forward Osmosis Recycling System (FORS). This model was used to calculate the IRR, and net present cost for the FORS versus municipal water and sewer. The results are shown in Table 7 for both 32 and 16 year terms. Figure 9 shows a comparison of San Bruno water and sewer rates compared to recycling water using FORS. As shown in this Figure, FORS cost less than municipal water in San Bruno, CA and the difference is predicted to increases with time. The assumptions for this model are provided in Table 8 and 9.

Table 7. Economic Analysis of FORS at 1100 Gundy, San Bruno

	32 Years	16 Years
Internal Rate of Return	6.6%	2.7%
Net Present Cost FORS	$1,149,015	$563,171
Net Present Cost Municipal	$1,591,522	$602,659

Table 8. FORS economic model assumptions:

- Includes all consumables as defined by Stanford testing at 1.8% inflation.
- Labor based on janitorial level labor at 20 min/day, from Stanford testing, at $35/hr with 2.8% inflation.
- Maintenance is based on quoted Wh2O Systems maintenance agreement.
- Energy based on 14 cents/kWhr with 2.9% inflation and Stanford testing.
- Byproduct can be discharged down sewer.
- Depreciation of FORS and building upgrades taken form IRS Form A-1.
- Includes installation and permitting costs.

Table 9. San Bruno water and sewer assumptions:

- Assumes C-2 zoning for water and sewer rates.
- Includes both per gallon and meter size fixed costs.
- Meter costs savings calculated by going from a 3” to 1.3” size.
- Water sewer inflation of 5% based on City of San Bruno 10-year plan.
- For FORS, discharge costs for disposing of concentrate down sewer are included.

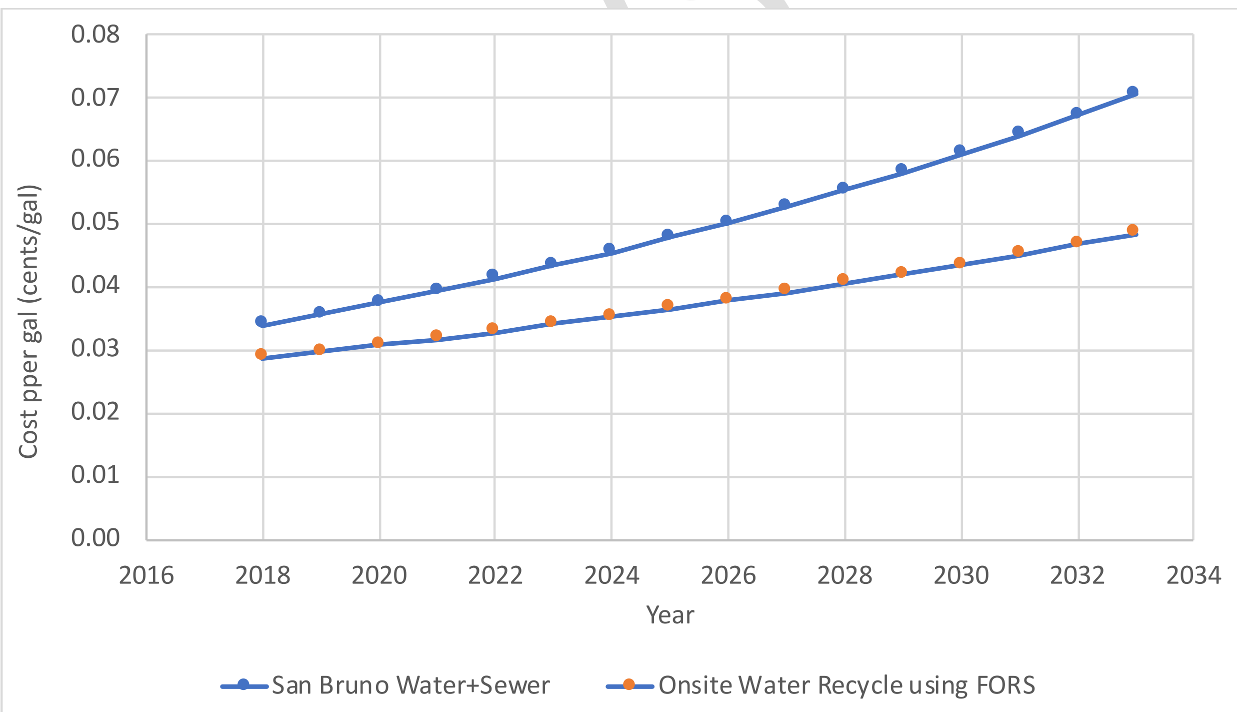

Figure 9. Comparison of San Bruno water and sewer rates compared to recycling water using FORS.

Conclusions

The results of the testing of FORS demonstrated that the system can treat greywater and black water to standards appropriate for reuse as defined by the National Sanitation Foundation NSF-350-1 and the City of San Francisco water reuse standards. Product water quality was shown to meet all applicable standards for reuse within a building as toilet flush, cooling tower, irrigation or other industrial reuse applications. Organic and inorganic rejection standards were met by the base system, and bacterial and viral standards were meet by the combined function of the FOST and product chlorination system. The concentrations of DBPs that formed when chlorine was applied to the product met regulatory limits. Contaminates of emerging concern were under the reporting levels.

The system demonstrated reliable operation with a 95% availability in Phase II of the testing. The testing also helped to quantify labor requirements, consumables, and power consumption. This data was scaled to a system that is sixteen times larger and an economic model was developed that included capital costs, site improvements, operational costs, labor, and depreciation. The proposed system was sized for 80,000 SF office building located in San Bruno CA. The economic model estimates that for this 2,427 GPD system the per gallon cost is around 2.8 cents/gal. The IRR when compared to purchasing water and sewer from the City of San Bruno is 2.7% for 16 years, and 6.6%, for 32 years.