Process Optimization During the First Year of Operation of a 40-mgd Nanofiltration Plant

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1.0 Introduction

In May 1999, the City of Boca Raton and the CDM design team began design of a 40 million gallon per day (mgd) capacity nanofiltration process addition to the City's existing 70 mgd conventional lime softening process at the Glades Road Water Treatment Plant. The primary objective of the project was to maintain continued compliance with the disinfectant/disinfection by-product (D/DBP) rule (i.e., reduce total trihalomethanes, TTHMs and haloacetic acids, HAAs), and improve the level of service to the Boca Raton customers by significantly improving the color in the blended finished water. The construction contract was awarded to the Poole & Kent Company (P&K). The Membrane System Supplier (MSS), as a subcontractor to P&K, was Advanced Environmental Water Technologies, Inc. (AEWT). The membrane elements were procured by the City directly from Hydranautics, who is referred to as the Membrane Element Manufacturer (MEM) in the Contract Documents.

The start-up phase for the nanofiltration process was initiated in August 2004. Due to the large size of this facility, and the fact that it was starting up without chemical pretreatment, the construction contract provided for a cautious, phased start-up program. Start-up of the process was planned to take place one unit at a time over a six-month period. The full 40-mgd capacity was scheduled to come on line with the start-up of the twelfth and last skid.

During start-up and the first year of plant operation, membrane performance was fine-tuned, and several other process optimization efforts were undertaken. This paper discusses the start-up experience relative to these topics.

2.0 Background

The City's existing raw water supply is from three shallow (100 to 200 feet in depth) Biscayne aquifer wellfields. Table 1 presents a representative analysis of the raw water supply.

Table 1. Raw Water Analysis

Constituent/Parameter	Value
Total Hardness	250 mg/L as $CaCO_3$
Alkalinity	214 mg/L as $CaCO_3$
Total Dissolved Solids (TDS)	450 mg/L
Color	50 color units
Total Organic Carbon (TOC)	12 mg/L
Humic Acid	10 mg/L
pH	7.2

As noted above, the overall goal for the project is to maintain continued compliance with the D/DBP rule, and significantly improve the color in the blended finished water. Table 2 summarizes the key blended finished water quality goals, as the basis for the membrane process design.

Table 2. Blended Finished Water Quality Goals

Constituent/Parameter	Value
Total THMs	$<$0.064 mg/L
Five HAAs	$<$0.048 mg/L
Color	$<$6 CU
Total Hardness	70 to 90 mg/L as $CaCO_3$

Other major design objectives included:

- Provide separate third stage units to increase the process recovery rate above the "traditional" rate of 85% to approximately 92%. This objective was a result of a hydraulic capacity limitation during periods of peak wastewater flows on the City's existing wastewater effluent ocean outfall, which is used for concentrate disposal.
- Reduce or eliminate the use of acid for raw water pretreatment. This goal was established due to cost considerations as well as the logistical and safety concerns associated with handling the quantities of acid that would be needed for a plant of this size. In design-phase pilot testing, it was demonstrated that the selected membranes could be successfully operated for extended periods (in excess of 90 days) with no chemical pretreatment (acid or antiscalant), without significant fouling. During pilot testing, the most stable operating characteristics without chemical pretreatment were exhibited by a new low-fouling membrane developed by Hydranautics in cooperation with the design team. Accordingly, although the facility design includes acid and antiscalant feed systems, the full-scale process was started up and is now operating with no chemical pretreatment.
- Provide a permeate quality meeting a relatively narrow hardness "window" of 50 to 80 mg/L as $CaCO_3$. Hardness in this range is considered optimum, resulting in moderately soft water while maintaining sufficient hardness to avoid corrosion control concerns. This range of hardness also avoided concentrating the hardness

and other foulants in the feed water as much as "tighter" conventional nanofilters. This helped the plant operate without chemical pretreatment. Several standard nanofiltration membrane models from various manufacturers were evaluated and tested side by side on the City's raw water supply. All but one of these membranes resulted in permeate hardness that was significantly higher or lower than the specified range. Only one manufacturer provided membrane elements which met the treatment objectives and produced permeate in the required hardness window. During design-phase pilot testing, the membrane element manufacturer worked closely with the design team to "customize" the rejection characteristics to meet the treatment objective.

3.0 Process Description

The new nanofiltration process operates in parallel with an existing 30 mgd lime softening plant, with the product water from the two facilities blended at a 2:1 permeate:lime softened water blending rate. Figure 1 presents a schematic of the lime softening and nanofiltration processes.

Figure 1. Glades Road Water Treatment Plant Process Schematic

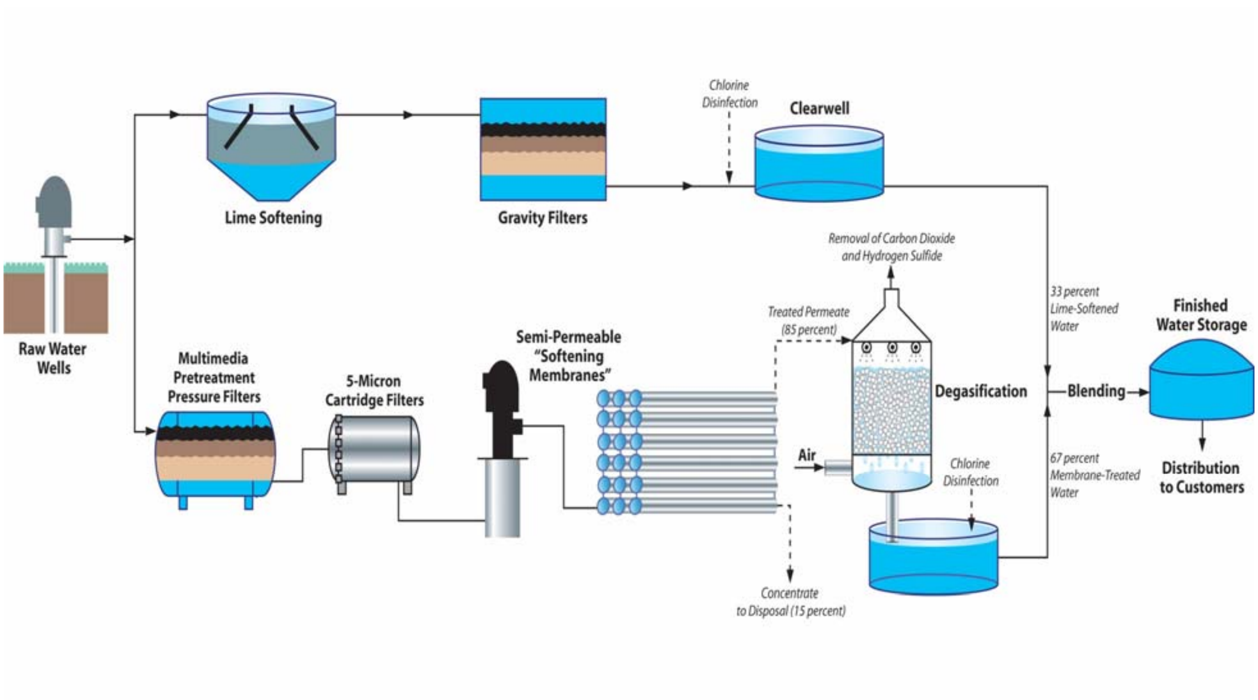


Table 3 presents the general design parameters for the membrane treatment process.

Table 3. General Design Parameters for Full-Scale Nanofiltration Process

Design Paramter	**Stage 1&2 Units (Units 1 through 10)**	**Convertible Units (Units 11 and 12) 3rd Stage/Two-Stage Mode**
Capacity	36.76 mgd	3.24 mgd
Recovery Rate	85 %	50 % / 85 %
Raw Water Feed	43.2 mgd	6.48 mgd / 3.81 mgd
No. of Skids	10 x 3.676 mgd	2 x 1.62 mgd
Array	72:36	54 / 36:18
No. Elements per Vessel	7	7
Flux Rate	12.2 gfd	10.7 gfd / 10.7 gfd
Transmembrane Pressure	80 psi	100 psi / 80 psi

The membrane process design consists of the following:

- Six constant speed, horizontal split case raw water booster pumps
- A multimedia pretreatment pressure filter system
- Twelve cartridge filters
- Ten 3.676 mgd capacity stage 1&2 membrane units
- Two 1.62 mgd capacity convertible membrane units. These units can be operated either as two-stage, 85% recovery units using raw feedwater from the wellfield, or as third-stage "concentrator" units, operating at 50% recovery using concentrate from the other ten membrane units as feedwater.
- Two independent membrane cleaning systems
- A permeate flush system to displace the concentrated feedwater in the membrane unit with permeate upon shut-down of the unit
- Sulfuric acid, antiscalant, and caustic storage and feed systems.
- Six 6.67 mgd capacity degasifiers.
- Two packed tower odor control scrubbers

The degasified permeate drops from the degasifiers into a clearwell below. Sodium hypochlorite, ammonia, corrosion inhibitor, and caustic soda are fed to this clearwell for disinfection, pH adjustment, and corrosion control. Three new transfer pumps are installed at the end of the clearwell to pump the membrane permeate to the on-site finished water storage tanks. Blending of the membrane permeate and lime softened water takes place in the common transfer line from the existing transfer pumps, to the on-site finished water storage.

4.0 Start-Up Experience

4.1 Specified Start-Up Plan and Performance Requirements

The membrane procurement contract provided for the direct purchase of the selected membranes from the Membrane Element Manufacturer (MEM) by the City. This contract required a separate 30-day full-scale performance test of each of the twelve membrane units, concurrent with a 30-day functional performance test of the process equipment (i.e., feed pump, control programming and instrumentation, automatic valves, etc.) specified under the general plant construction contract. The roles and responsibilities of the General Contractor, Membrane System Supplier (MSS), and MEM were defined in both contracts. The key permeate quality and quantity parameters required in the membrane procurement documents are summarized in Table 4. In general, the requirements for each performance test included continuous operation for 30 days, producing permeate meeting the specified permeate quantity and quality, without exceeding the specified maximum transmembrane pressure of 80 psi, and without malfunction of the process equipment. For each performance test, operating data were collected either continuously or on a daily basis and water quality analytical data were collected weekly over the 30-day test period for each unit. At the conclusion of each performance test, a report was submitted to the engineer.

Table 4. Specified Permeate Quality

Constituent/Parameter	Unit	Projected Raw Water Quality	Stage 1&2 Permeate Quality
Bicarbonate	mg/L	265	<175
Color	CU	50	<2.0
Sum of Ions	mg/L	450 to 500	<300
Total Hardness	mg/L as $CaCO_3$	250	50 to 80
Total Organic Carbon	mg/L as C	12.0	<1.0
TTHM Formation Potential	mg/L	0.60	<0.042
HAA Formation Potential	mg/L	0.40	<0.030

Under the general plant construction and membrane element procurement contracts, the start-up phase was extended over a 6-month period by design, with each of twelve units started up individually, in sequence, and tested independently. Since the performance of the membranes was customized for this application, this approach provided time to confirm proper performance of the membranes and process equipment, and to make any necessary adjustments in a systematic manner. The phased start-up plan was devised to minimize the risk of irreversible fouling of the membranes during start-up on this high fouling potential raw water without the use of pretreatment chemicals. Phased start-up also minimized the risk of damage to the membranes associated with long-term storage and/or standby periods.

Figure 2. Specified Start-Up Schedule

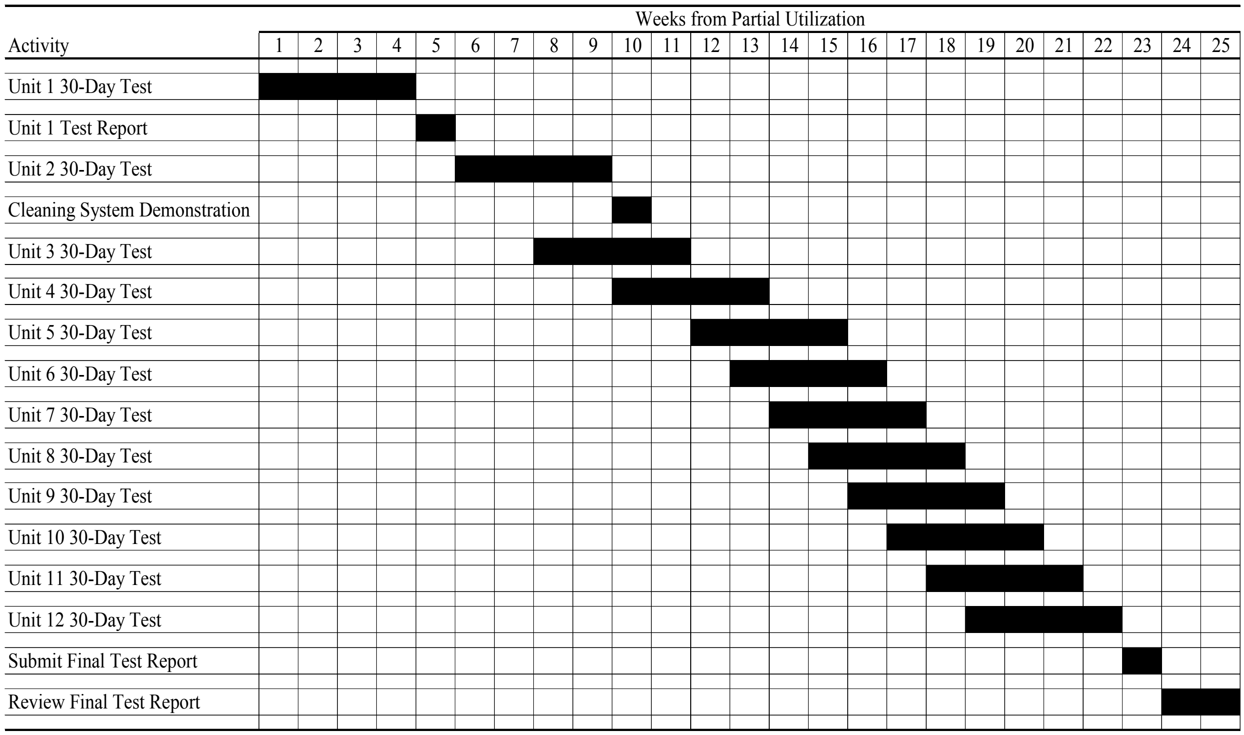


Figure 2 presents the specified overall schedule for start-up of the plant beginning at loading of elements in the first membrane unit, and including loading, start-up, performance testing, reporting, and approval for each membrane unit. As can be seen in the schedule, each membrane unit was to be started up and operated for a 30-day performance test, with the start-up and testing of the units to occur in a planned sequence. The 30-day performance test for the first unit must be completed and approved prior to proceeding with the second unit. Since it was considered likely that any major problems requiring adjustment would be identified in testing of the first unit(s), start-up of the following units were overlapped such that the remaining units could be started up within the six-month period.

4.2 Start-Up Testing

Membrane Unit No. 1 was started up on August 11, 2004. Contractual Partial Utilization, which occurred upon bacteriological clearance of Unit No. 1, was achieved on August 16, 2004, initiating the six-month start-up schedule. Start-up and operation of Units No. 1, 2, and 3 proceeded generally according to the start-up schedule, with the permeate quality and membrane performance meeting the specifications.

Membrane Unit No. 4 was started in November 2004. While it exhibited stable operation with no indication of fouling, the composite permeate hardness, which averaged approximately 100 to 110 mg/L as $CaCO_3$, exceeded the specified maximum of 80 mg/L. The noncompliance was noted, and corrective action was requested of the MEM.

Unit No. 5 had been loaded with membranes from the same manufacturing run as those in Unit No. 4, before the project team received any of the performance data from Unit No. 4. Hydranautics notified CDM and the City that they expected the performance of Unit No. 5 to be similar to Unit No. 4. Hydranautics requested that start-up of Unit No. 5 be deferred until the corrective action, or membrane customization, was proven successful in the remaining units. Therefore, following start-up of Unit No. 4, the membrane elements in Unit No. 5 were pickled in place with a sodium bisulfite solution for long-term storage.

Hydranautics then made adjustments in the manufacture and/or selection of membrane elements for the remaining units. Membrane Unit No. 6 was loaded and started in December 2004. Following start-up, Unit No. 6 exhibited stable operation, with the permeate quality and membrane performance meeting the specifications. Start-up of Units No. 7, 8, and 9 followed with all three units meeting water quality and performance specifications.

After approximately 50 to 60 days of operation, membrane Unit No. 1 began showing a slight declining trend in mass transfer coefficient which appeared to indicate the beginning of some degree of fouling. While the degree of fouling was not alarming at that time, CDM, Hydranautics, and the City began closely monitoring the trend. Periodic flushing of the membrane units with permeate, using the in-place permeate flush system, was highly effective in controlling the fouling. A regimen of regular permeate flushing/soaking was implemented for all the membrane units, which has successfully controlled fouling during the remainder of start-up and to this date. This is discussed in greater detail in Section 5.2.

During the last week of January 2005, an increase in transmembrane pressure was noted on several of the membrane units. The problem was found to be a breach in the cartridge filters which allowed a small amount of sand to pass through to the membrane units. This sand was not apparent from SDI or turbidity readings. The membrane units were shut down temporarily to allow repairs to the cartridge filters. Early detection of the sand problem resulted in the exposure to sand being limited to the lead elements in the units that were on line at the time. Concurrently with the cartridge filter repairs, the lead membrane elements in the exposed membrane units were removed and replaced with non-lead elements from Membrane Unit No. 1. The removed lead elements were cleaned by backflushing and vibration in a special apparatus provided by Poole & Kent and AEWT. Several elements were autopsied to confirm that the sand exposure was limited to the lead elements. There was no indication that any elements other than the lead elements were exposed to sand.

After cleaning, the exposed lead elements were loaded into Membrane Unit No. 1 such that all of the potentially impacted elements were confined to one membrane unit. The plant was gradually brought back on line during the third and fourth weeks of February. Following restarting of the plant, no significant degradation of performance was detected in any of the membrane units, including Unit No. 1 which contained all of the lead elements from the other exposed units.

In February 2005, Hydranautics advised the City that Membrane Unit No. 5 was ready to be started. Unit No. 5 was started during the third week of February. Following start-up, the permeate quality and membrane performance met the specifications, operating at a transmembrane pressure of approximately 67 psi and producing a composite permeate hardness of 80 mg/L.

Membrane Unit No. 10 was started up during the first week in March 2005, with the permeate quality and membrane performance meeting the specifications. Membrane Units No. 11 and 12 (the convertible units) were started up during the first week of April in the two-stage mode. Both units met permeate quality and membrane performance specifications.

4.3 Performance Test Results

Operating Performance Results

Performance testing of the membranes units commenced on August 11, 2004 with start-up of Unit No. 1. During the test period, the membrane units were operated under control of the City's staff, and permeate from the membrane units was degasified, pH adjusted, blended with water from the lime softening plant, and disinfected prior to being introduced into the distribution system. Corrosion inhibitor was also added to the finished water. Performance data that was measured during the start-up, performance test, and initial commercial operation is presented in Figures 3 through 8 for Units No. 1, 3, and 7. These data are generally representative of performance of the other units.

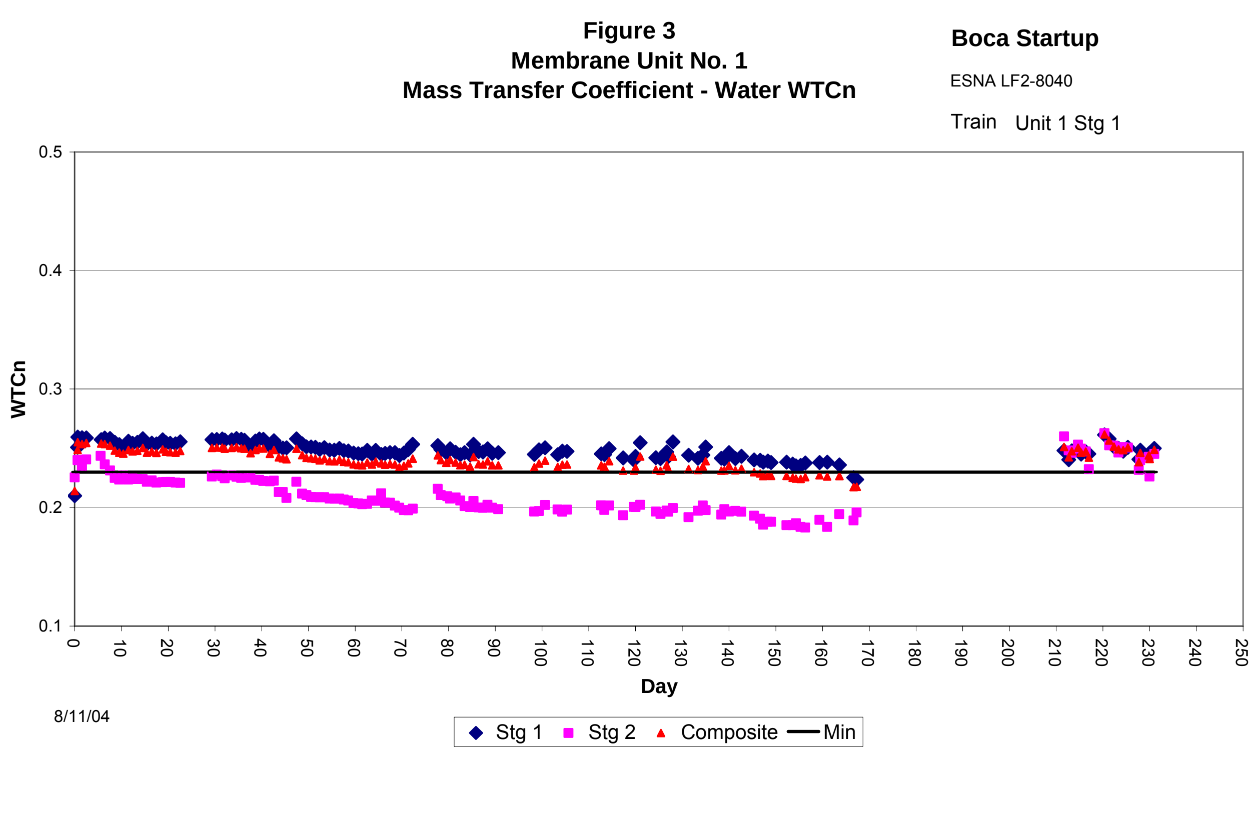


Figure 4
Membrane Unit No. 1
Permeate Hardness

Boca Startup

ESNA LF2-8040

Train Unit 1 Stg 1

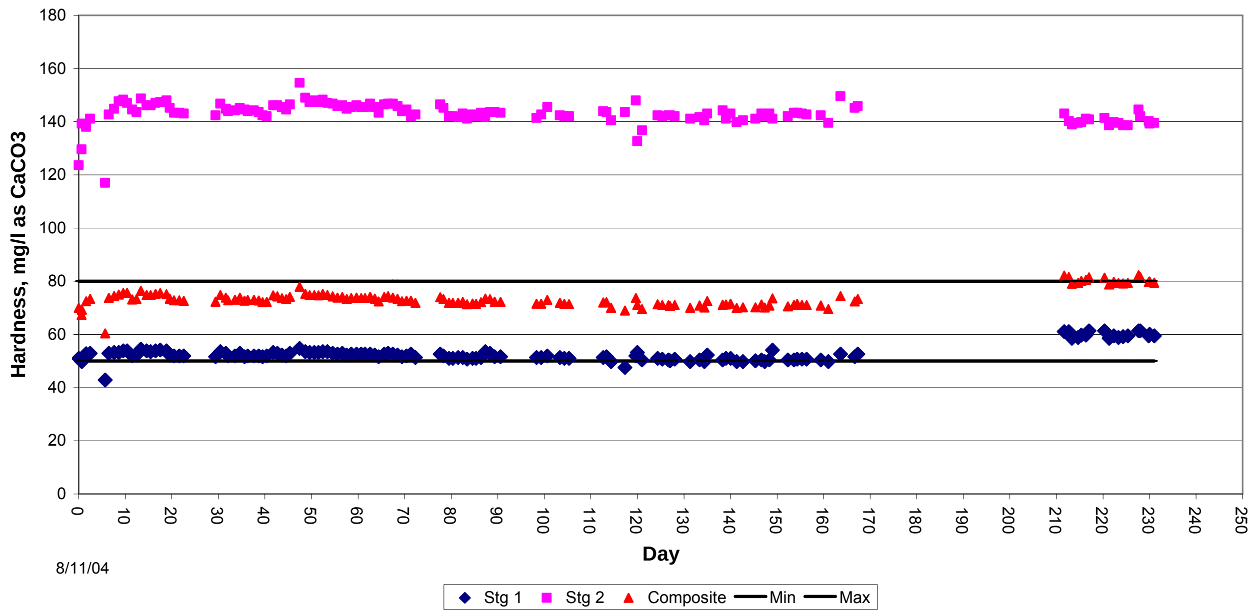
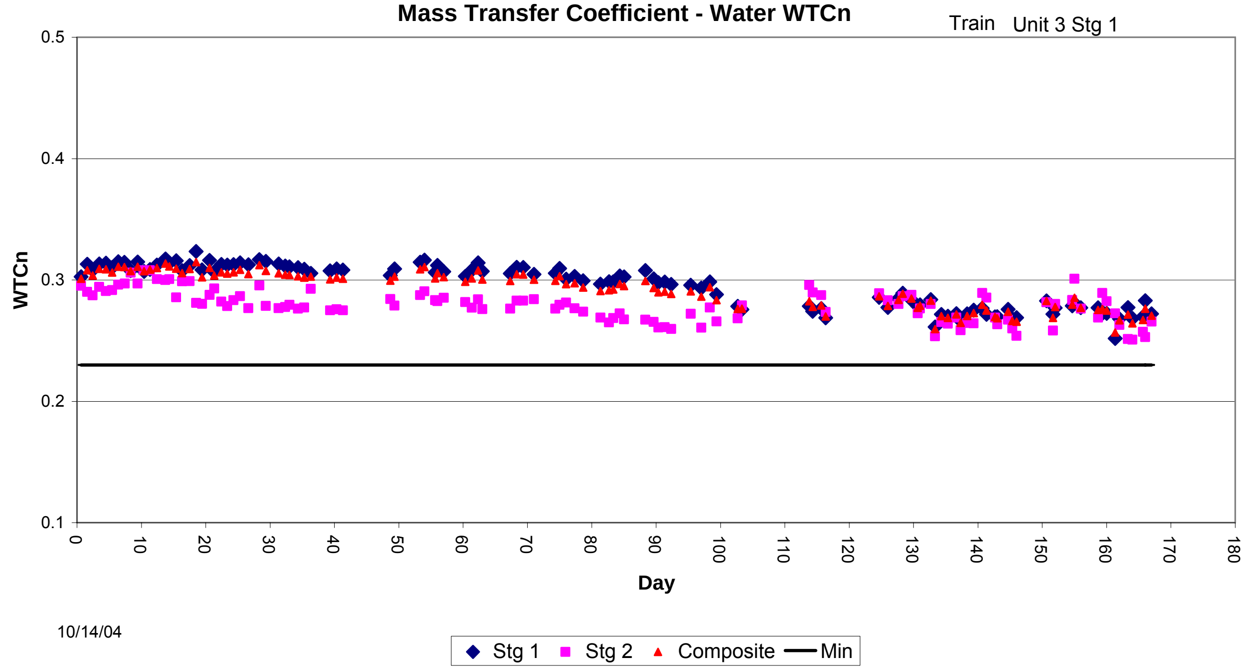


Figure 5
Membrane Unit No. 3
Mass Transfer Coefficient - Water WTCn

Boca Startup

ESNA LF2-8040

Train Unit 3 Stg 1



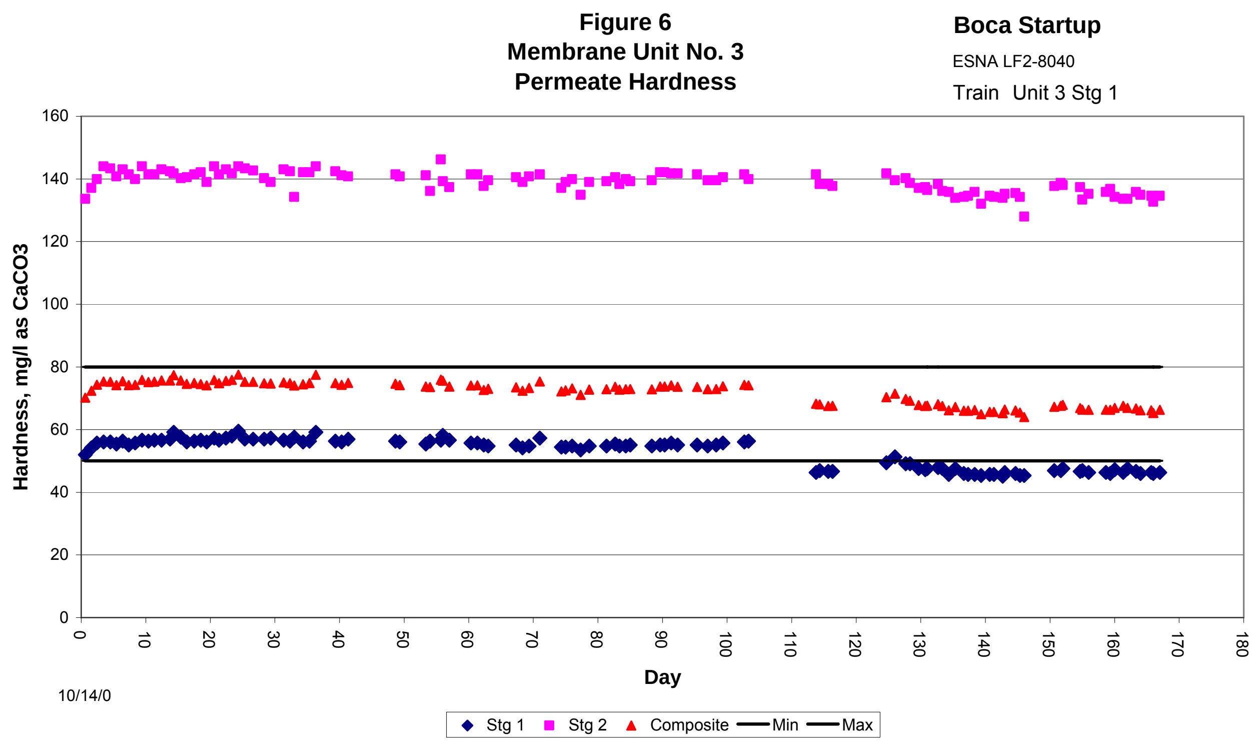


Figure 6
Membrane Unit No. 3
Permeate Hardness
Boca Startup
ESNA LF2-8040
Train Unit 3 Stg 1
Hardness, mg/l as CaCO3
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Day
10/14/0
Stg 1
Stg 2
Composite
Min
Max

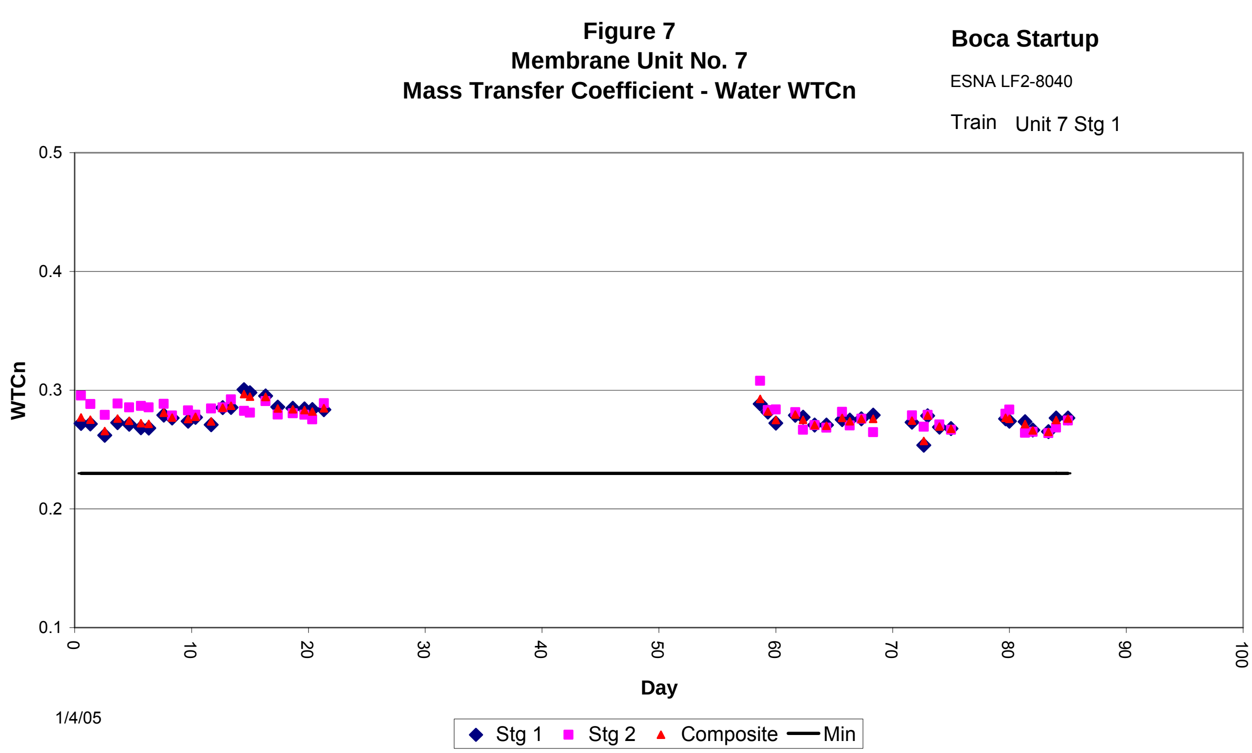
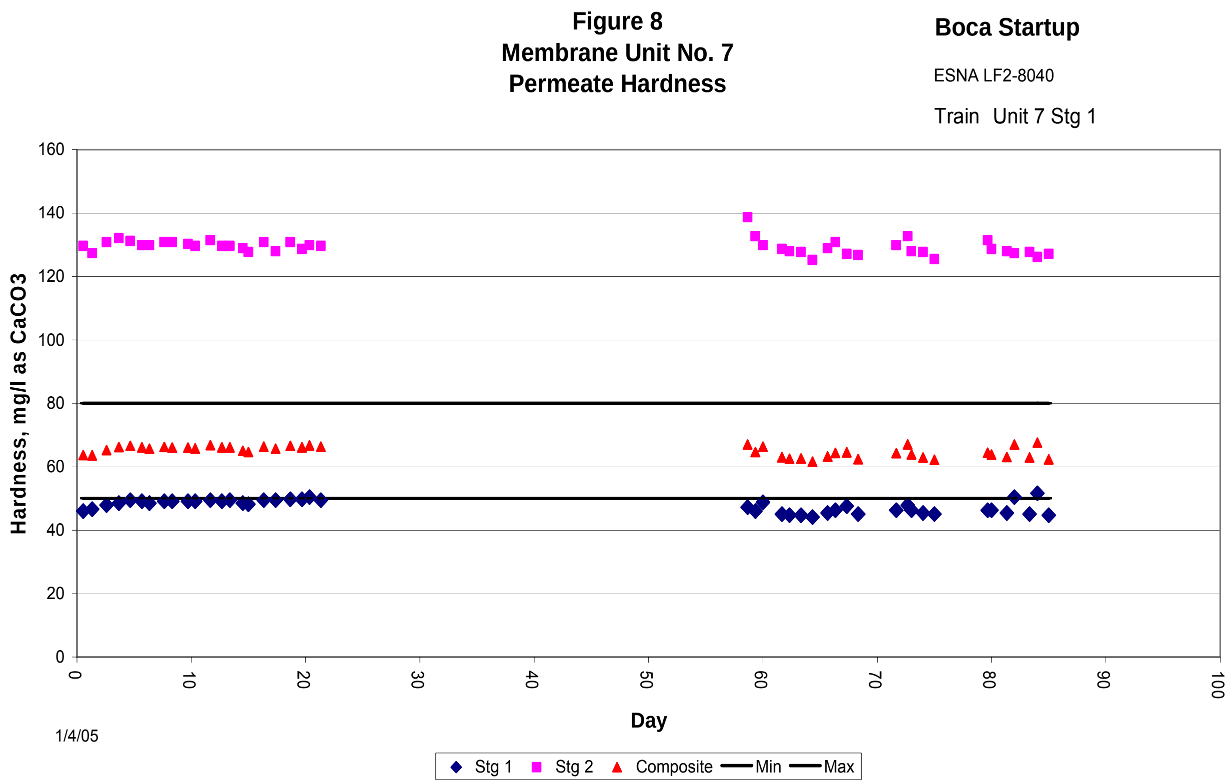


Figure 7
Membrane Unit No. 7
Mass Transfer Coefficient - Water WTCn
Boca Startup
ESNA LF2-8040
Train Unit 7 Stg 1
WTCn
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
80
90
100
Day
1/4/05
Stg 1
Stg 2
Composite
Min



Results of the pilot test program indicated that the membrane units actually operated more reliably without the use of either acid or anitscalant as pretreatment chemicals, as demonstrated by successful test runs of over 90 days. Based on performance demonstrated during the pilot testing, it was decided that the full-scale membrane units would be commissioned and performance tested without pretreatment chemical addition.

Figure 3 shows the mass transfer coefficient for the first stage, second stage, and overall composite performance for Unit No. 1 during the performance test period and the first six months of operation. This graph indicates a settling-in period of approximately one week after start-up. During this period, the mass transfer coefficient of the second stage decreased by five to seven percent. Performance then stabilized through the remainder of the performance test period and through the first 50 days of operation. Another overall small decline in performance of about 2 percent was observed between days 50 and 70. A program of periodic flushing and soaking in permeate on shut-down was initiated. With this flushing program, the performance of the membrane system remainder fairly stable over the next 100 days of operation with only a 2.5 percent decrease in performance over this period. Operation of this unit and other units after the flushing program was initiated indicates very satisfactory performance without the addition of acid and/or antiscalant.

After 150 days of operation, the composite mass transfer coefficient had decreased by slightly over 10 percent since start-up and membrane system cleaning was being considered. At that time, the sand incident described in Section 4.2 was experienced. As discussed in that section, membrane elements which were exposed to sand in other units were cleaned and then consolidated in Unit No. 1. As shown in Figure 3, the mass transfer coefficient for Unit No. 1 actually improved as a result of the rearrangement with elements from other units. This graph also indicates that the performance of the membranes was not impaired by their brief exposure to sand.

As shown in Figure 3 and Table 5, the composite mass transfer coefficient of Unit No. 1 initially was in the range of 0.249 gfd/psi. As shown in Table 5, this translates to a required trans-membrane pressure (TMP) of 73.3 psi, which is comfortably below the maximum specified trans-membrane pressure of 80 psi. This maximum specified TMP corresponds to a mass transfer coefficient of 0.23 psi/gfd and is shown as a solid reference line in Figure 3. On the graph, if the mass transfer coefficient is above 0.23 gfd/psi, the TMP should be below the specified maximum. Figure 3 indicates that Unit No. 1 had a MTC of 0.25 gfd/psi at start-up which gradually decreased to 0.23 gfd/psi over 120 to 160 days of operations, at which time cleaning was considered. The MTC went back up to 0.25 gfd/psi when the unit was restarted with cleaned membranes after the sand incident.

Analytical test results were correlated with conductivity measurements to produce the graph in Figure 4 of permeate hardness for Unit No. 1 over the same time period. The specified hardness window of 50 to 80 mg/L as $CaCO_3$ is indicated by two solid lines on the graph. Hardness measurements for the first and second stages were 50 and 145 mg/L respectively, which resulted in a composite hardness of 73 mg/L. This is comfortably within the required range. After the membrane elements in the first stage were rearranged as a result of the sand incident, the permeate hardness increased to approximately 80 mg/L as a result of relocation of some lower rejection membranes from other units into Unit No.1.

Test results for all ten of the primary 3.676 mgd treatment units are summarized in Table 5. These results indicate that the mass transfer coefficients for all units are above the target value of 0.231 gfd/psi with an average value of 0.278 gfd/psi. Similarly, the trans-membrane pressures for all units were below the specified maximum value of 80 psi with the average value being approximately 15 percent lower at 68.6 psi.

The average combined permeate hardness of all ten of the primary units is 74.7 mg/L, which is within the specified hardness window of 50 to 80 mg/L as $CaCO_3$. All of the primary membrane units, with the exception of Units No. 4, had permeate hardness values which substantially complied with the specified hardness window. The permeate hardness of Unit No. 5 is just marginally above the upper limit at 81.1 mg/L as $CaCO_3$. Unit No. 4 has a permeate hardness of over 95 mg/L as $CaCO_3$. Hydranautics has agreed to take corrective action to bring the total permeate hardness of Unit No. 4 into the required hardness window between 50 and 80 mg/L.

TABLE 5 CITY OF BOCA RATON MEMBRANE UNIT START-UP PERFORMANCE							
	Mass Transfer Coef. (MTCw)			TMP	Permeate Hardness (mg/L as $CaCO_3$)		
	Stage 1	Stage 2	Composite	(psi)	Stage 1	Stage 2	Composite
Unit 1	0.256	0.227	0.249	73.3	52.4	143.3	73.1
Unit 2	0.262	0.229	0.255	71.3	54.8	155.8	76.2
Unit 3	0.313	0.291	0.308	61.0	56.6	141.7	75.1
Unit 4	0.280	0.293	0.283	66.2	70.7	176.8	95.9
Unit 5	0.280	0.252	0.274	67.4	54.1	166.2	81.1
Unit 6	0.335	0.290	0.326	65.9	57.5	143.3	75.9
Unit 7	0.277	0.279	0.277	67.2	47.6	129.4	65.0
Unit 8	0.281	0.278	0.281	69.0	49.7	140.3	68.7
Unit 9	0.257	0.268	0.259	72.7	47.4	138.9	67.7
Unit 10	0.276	0.203	0.263	72.7	51.1	144.7	68.1
Average:			**0.278**	**68.6**			**74.7**
Spec:			>0.23	<80			50 - 80

Analytical Test Results

Analytical test results for the primary membrane units are summarized in Table 6. The primary parameters of interest are hardness, color, and THM and HAA formation potential. Hardness testing was performed by an outside laboratory as well as the City's State certified laboratory. Analytical test results for hardness were correlated with conductivity readings, and permeate hardness plots versus time, similar to the one shown in Figure 4, were developed for each membrane unit. The data in Table 5 summarize daily hardness values calculated from permeate conductivity readings averaged over the 30-day performance test for each membrane unit. The hardness data in Table 6 is the average of all hardness values for each sampling event for each unit as reported by the outside laboratory averaged with the analyses provided by the City for each membrane unit. Although on a case-by-case basis there are some variations between the hardness values in Table 5 and Table 6, the average hardness values for all membrane units is 75.4 mg/L in Table 6 as compared to 74.7 mg/L by the conductivity method (Table 5), which are in relatively good agreement. The hardness data in Table 6 indicates that eight of the ten primary membrane units produced permeate with hardness in the specified 50 to 80 mg/L window. Although the reported hardness results for Unit 5 in Table 6 are somewhat higher, hardness results reported by the City and calculated by the conductivity method in Table 5 indicate that the hardness is only slightly over the 80 mg/L at 81 to 82 mg/L, so this unit is close to compliance. Only Unit No. 4 has permeate hardness which exceeds the 80 mg/l maximum limit by an appreciable amount.

Table 6. Projected Raw Water Quality, Required Permeate Quality, and Performance Test Analytical Results

Parameter	Unit	Projected Raw Water	Required Permeate	Combined Feed	Unit No. 1	Unit No. 2	Unit No. 3	Unit No. 4	Unit No. 5	Unit No. 6	Unit No. 7	Unit No. 8	Unit No. 9	Unit No. 10	Average
Bicarbonate Ion	$CaCO_3$	265	<175	209	73	72	80	95	82	76	65	65	66	64	74
Barium	mg/L	0.02		0.020	0.0055	0.0066	0.0066	0.0084	0.0095	0.0064	0.0058	0.0064		0.0056	0.0067
Calcium	mg/L	100		88.4	26.5	29.3	22.7	38.5	33.0	28.8	24.3	26.0		27.0	28.4
Chloride	mg/L	40		50.7	22.5	28.0	34.5	30.0	27.0	27.5	29.5	24.0		20.0	27.0
Color	PCU	50	<2.0	35	1	1	3	1	1	1	1	1	0	1	1.1
Fluoride	mg/L	0.3		0.31	<0.12	0.14	0.20	0.16	0.16	0.22	0.16	0.14		0.11	0.16
Hydrogen Sulfide	mg/L	0.25		1.92	<0.58	0.51	0.64	0.58	2.02	0.74	3.15	3.80		3.80	1.90
Iron (Dissolved)	mg/L	0.3		0.06	0.11	0.01	<0.0055	<0.0055	<0.0055	<0.0055	<0.0055	0.0064		<0.0055	0.04
Magnesium	mg/L	3.8		4.40	2.21	1.35	1.33	1.90	1.60	1.45	1.15	1.20		1.40	1.51
Nitrate	mg/L as N	<0.10		0.0225	0.01	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018		<0.018	0.01
pH	Units	7		7.0	7.5	6.8	6.9	7.0	7.2	7.0	7.1	7.2		7.0	7.1
Potassium	mg/L	3.1		4.6	2.7	2.6	2.8	3.5	3.4	4.8	3.1	2.7		3.4	3.2
Silica	mg/L as SiO	10		10.0	6.9	6.8	7.2	7.7	7.1	6.3	5.8	6.3		7.0	6.8
Sodium	mg/L	25		27.6	16.0	16.3	13.4	20.3	19.0	26.3	17.3	16.3		21.0	18.4
Strontium	mg/L	0.6		0.39	0.14	0.13	0.12	0.16	0.14	0.13	0.10	0.11		0.10	0.12
Sulfate	mg/L	17		21.36	0.92	1.65	4.53	13.75	5.65	7.10	5.50	5.30		5.70	5.57
Temperature	°C - Field	25^o		24.6	26.1	26.3	26.0	24.5	23.4	24.6	24.9	24.5		24.1	24.9
TDS	mg/L	450-500	<300	387	147	130	154	171	138	118	116	127	151	117	137
Total Hardness	$CaCO_3$	250	50-80	239	71.7	74.3	77.3	107.0	85.5	76.0	63.6	65.9	64.0	68.5	75.4
TOC	mg/L as C	12	<1.0	11.7	1.0	0.9	0.9	0.7	<0.50	0.7	<0.50	<0.50		<0.50	0.8
Total THMFP	microgms/L	600	42		11.3	15.2	20.6	18.6	24.0	16.3	12.8	11.0		16.0	16.2
Total HAAFP	microgms/L	400	30		2.0	14.7	20.3	22.3	29.0	9.6	7.9	13.5		12.0	14.6

Another parameter of primary importance to the City is color. With the lime softening process, the City typically produces water with color in the 12 to 15 CU range, which is marginally below the state secondary standard for color of 15 CU. Since color analysis from the outside lab only had a minimum detection limit of 5 CU for color, more accurate test results from the City's analytical lab were used in Table 6. These results indicate that permeate color was very low, averaging just over 1 CU for all units. All of the membrane units except for Unit No. 3 had reported color values of 1 CU or less. Since color readings are primarily associated with dissolved organics, the fact that the TOC value of 0.9 mg/L is less than 1.0 mg/L similar to all the other membrane units, it would be anticipated that Unit No. 3 should have a similar color reading to the other units, and that there may be some reporting error for color for Unit No. 3.

Results of THMFP and HAAFP, as reported by the outside laboratory and averaged with the City's analytical results, are summarized in Table 6. The THMFP values for all units were well within the required maximum concentration of 42 microgram/l. The HAAFP values in Table 6 are also below the maximum specified limit of 30 microgram/l.

Based on these results and verified by the City, it was concluded that all the primary units met the quality requirements for hardness, color, THMFP, and HAAFP with the exception of Unit No. 4 which did not meet the required permeate hardness. Hydranautics has agreed to take corrective action on Unit No. 4 to bring the permeate hardness into compliance.

5.0 Start-Up Points of Interest

5.1 Operation Without Chemical Pretreatment

Start-up of the process is considered to be a huge success, primarily because it demonstrates the possibility of avoiding the use of pretreatment chemicals, both acid and polymer antiscalants, whenever the feedwater contains naturally occurring antiscalants, "NOA". The naturally occurring antiscalants are characterized by high humic acid content. The small amount of foulant noticed in the slowly occurring fouling appears to be a calcium humate complex, a soft material that can be washed off with a high-velocity permeate flush. The use of a low rejection nanofilter avoids concentrating the mineral scale formers, thus allowing the NOA to perform. There appears to be a threshold above which the NOA will not work, and CDM is doing research to determine those limits. Piloting at other sites has demonstrated stable operation at recovery rates as high as 90%.

5.2 Benefits of Permeate Flushing/Soaking

As noted above, after approximately 50 to 60 days of operation, Membrane Unit No. 1 began showing signs of slight fouling, exhibiting a noticeable declining trend in the water transfer coefficient (refer to Section 4.3). While the degree of fouling did not warrant immediate cleaning at that time, CDM, Hydranautics, and the City began closely monitoring the trend and discussing options for mitigating the potential fouling. Since Membrane Unit No. 1 was the first unit started and had been running the longest, it was considered to be indicative of possible future trends in operation of the remaining units.

In monitoring plant performance data during the first few months of the start-up phase, it was noted that there was an improvement in performance of a unit when it was restarted following a shut-down, during which time the unit was flushed and soaked in permeate. This effect can be seen in Figure No. 3. This improvement was more apparent in units that had been operating longer, but appeared to be consistent over all of the units that were in service. Regular permeate flushing/soaking was very effective in managing the fouling potential.

The plant design includes a permeate flush system consisting of a 3,800 gallon permeate storage tank, a 1,440 gpm capacity permeate flush pump, interconnecting piping to each membrane unit, and control valves on each membrane unit. The permeate tank is automatically filled from head provided in the permeate risers feeding the degasifiers. Permeate from the tank is pumped to the feed side of each membrane unit with the flush pump that is sized to provide a flushing flow of 40 gpm per second-stage vessel. The basic function of the system is to displace the concentrated feedwater left in a unit on shut-down with permeate. The automatic shut-down sequence on each membrane unit includes a permeate flush for an operator-settable time duration as the final step. Since the tank is automatically filled, there is no limit on the flush duration as long as there is another membrane unit in operation during the flush cycle to fill the tank. The plant control system also allows the operator to manually initiate a permeate flush at any time (without having to go through a start-up/shut-down sequence). Therefore, the operators can periodically flush membrane units that have been shut down for longer periods to prevent biological growth in the membrane elements.

A stage one permeate control valve is normally used to apply about 10 psi backpressure to the first stage of membranes during normal operation in order to control the flux rate in that stage. During permeate flushing, this valve was set to close more to apply approximately 50 psi backpressure to the first stage permeate, which diverts more of the flush water into the second stage. Since the organics and inorganic salts are most concentrated in the tail end of stage 2, forcing more water through the second stage increases the effectiveness of the permeate flush. Without the increased back pressure, most of the permeate flush would have permeated away in the first stage, leaving insufficient flow in the second stage for a good flush. In addition, the hardness of the flushing water would be increased as it is concentrated in the first stage by unwanted permeate production. Even at flushing pressures, there is a considerable amount of permeate produced during flushing unless it is inhibited by backpressure. There are plans to experiment with the periodic addition of caustic soda to the permeate flush to determine whether it improves the effectiveness of the flush cycle. This would be a manually initiated chemical flush, and no cross connection exists for inadvertent addition of caustic to the flush water.

There were several factors that appeared to enhance the effectiveness of the permeate flushing/soaking cycle in minimizing fouling. The first was implementing the flushing/soaking program before any significant fouling occurred. The flushing/soaking regimen that was ultimately implemented for all of the membrane units consisted of shutting down the unit, flushing for approximately 10 minutes, and soaking the unit for at least 24 hours before restarting. Since the normal daily water demands require about 30 mgd (eight membrane units) of permeate at the design blend rate, this flushing schedule could easily be implemented by putting the 12 units on a rotation schedule where several of the units are undergoing a soak cycle at any given time.

Another factor that appeared to enhance the effectiveness of the permeate flushing/soaking in controlling fouling was the soak duration. The degree of performance recovery appeared to be significantly greater if the units were soaked for longer than 24 hours. Considering that Unit No. 1 had showed the highest reduction in water transfer coefficient, the City began planning the shut-down/flushing rotation schedule referred to above so that Unit No. 1 would soak several days at a time (e.g., over the weekend). This practice appears to have significantly contributed to the effectiveness of the flushing program in Unit No. 1, as well as the other units.

5.3 Cost Ramifications of Elimination of Chemical Pretreatment

As discussed in Section 2.0, one of the primary design objectives for the project was to reduce or eliminate the need for acid pretreatment due to the costs, operational complications, and potential hazards associated with handling the large amounts of acid necessary for a plant of this size. A great deal of effort was expended to develop this concept, demonstrate the full-scale feasibility, and optimize membrane performance with respect to the City's water quality goals on the high fouling potential raw water supply. These efforts included acrylamide gel electrophoresis investigations in the laboratory conducted by Dr. Harvey Winters of Fairleigh Dickenson University on various antiscalants and membranes using the City's raw water, as well as over three years of pilot testing during the design and construction phases. Ultimately, it was found that operation was actually more stable without any chemical pretreatment than with any of the chemical pretreatment protocols that were evaluated. Consequently, the plant was started up and is now successfully operating with no chemical pretreatment. This finding has substantial cost and operating benefits that are now being realized in the full-scale operation.

The original basis of design during the preliminary design called for feedwater pH adjustment from the raw water pH of 7.2 to a feed pH of 6.2, which is typical of nanofiltration plants treating Biscayne Aquifer raw water in the South Florida area. This would require a dosage rate of approximately 110 mg/L of sulfuric acid. At the City's total average daily demand (ADD) of 45 mgd and the design blend rate of 2:1 permeate:lime softened water, the total permeate production would be 30 mgd, which would require a feed flow of approximately 35.3 mgd. This would result in an average acid usage rate of approximately 34,820 pounds per day of 93% sulfuric acid. Based on a unit price of $0.045 per pound, this translates to an annual cost of approximately $572,000.

In addition to the acid-related cost savings, there is also a substantial cost savings due to the reduced need for caustic for post-treatment pH adjustment. Post-treatment pH adjustment consistent with the above-described pretreatment pH adjustment, to a final permeate pH of 8.3, assuming a unit price of $0.15 per pound for 50% sodium hydroxide, would result in an annual cost increase of approximately $97,000 over the current caustic usage rates at the plant.

There is also a chemical cost savings due to the elimination of pretreatment antiscalant. The original preliminary design basis called for an antiscalant pretreatment dosing of 3 mg/L. Assuming a unit price of $0.80 per pound, this would result in an annual cost of approximately $258,000.

The total direct cost savings resulting from the elimination of chemical pretreatment for this facility can be conservatively estimated at approximately $927,000 per year. This does not consider indirect costs associated with operation and maintenance of the chemical storage and feed systems, training, cleaning, etc. In addition, a substantial source of day-to-day safety risk to the operations staff has been completely avoided at the facility.

5.4 Cost Ramifications of Optimized Membrane Performance (Transmembrane Pressure)

As noted in Section 4.1, the specified maximum transmembrane pressure for the full scale units was 80 psi. The actual average transmembrane pressure demonstrated during performance testing was approximately 69 psi. Under the ADD condition feed flow rate of approximately 35.3 mgd, and assuming a unit power cost of $0.045 per kilowatt-hour, this feed pressure differential results in an annual savings of approximately $48,000 per year.

6.0 Conclusion

The Glades Road Water Treatment Plant is now the largest nanofiltration facility in the world. However, it is a landmark plant in more ways than one. It is the first large plant of its kind to operate with no chemical pretreatment, resulting in substantial operating cost savings as well as reduced safety risks to the operators. The plant also utilizes a new generation of low-fouling membranes which were developed specifically for this project. The extended start-up and performance testing program specified for the project allowed the membrane manufacturer to optimize the performance of the membranes based on full-scale operating data. For this application, the low-fouling membranes operate at lower pressure and require less frequent cleaning than typical membranes. The result is lower energy and operating and maintenance labor costs. Most importantly, all of the water quality and capacity goals established by the City at the onset of the project have been achieved. Stable operation during the first year appears to indicate that this success will be long-term.