START-UP OF THE WORLD'S LARGEST NANOFILTRATION PLANT

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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 design team included CDM, CH2M Hill, Craig A. Smith & Associates, and A. Grant Thornbrough. 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. Construction of the project began in December 2001. Currently, major construction activities are complete, the process equipment has been functionally tested, and the project team is preparing to start up the process. This paper discusses the start-up plan for the plant, the provisions in the construction and procurement contract documents related to performance verification testing of the process and the membrane elements during start-up, as well as the results of that testing.

Description of Pre-Existing Conditions

The City's existing raw water supply is from three Biscayne aquifer wellfields, the Northwest, Eastern, and Southwest Wellfields. The wellfields include 56 shallow (100 to 200 feet in depth) wells. Most of the wells were in generally poor condition with respect to treatability with the membrane process, with silt density index (SDI) values in excess of 6 at times. Fouling issues associated with the raw water included sand and silt production, biofouling, and dissolved organic fouling. Also, the wells were subject to air inleakage from corrosion of the well colunns, draining of the well columns at shut-down, and from excessive drawdown at some of the wells resulting in the pumps entraining air. This air inleakage resulted in oxidation of iron and hydrogen sulfide in the raw water supply. Table 1 presents a representative analysis of the raw water supply. As discussed below, a comprehensive wellfield rehabilitation program was undertaken and completed prior to commissioning of the membrane softening process to address these issues.

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

The existing lime softening plant includes three upflow solids-contact lime softening treatment units, and three filter buildings. The softening treatment unit capacities are 15 mgd, 27.5 mgd, and 27.5 mgd. Each of the three filter buildings has three dual media filters of 10-mgd capacity each, except that filter no. 9 in Filter Building No. 3 has not been equipped with internal components (underdrains, media, launders), and has not been placed into service. The softened, filtered water flows into clearwells under the filters from which the water can be transferred to on-site ground storage tanks using the transfer pumps or pumped directly into the distribution system by the high service pumps. Chemical additions include lime, polymer, sodium hypochlorite, ammonia, and sodium phosphate as a corrosion inhibitor. Short-term free chlorination is used for primary disinfection and reduction of color; however this method of color reduction is limited by the formation of disinfection by-products. A chloramine disinfectant residual is maintained in the distribution system. As with many South Florida utilities, plant operators maintain a balance in complying with the finished water color and DBP standards. The lime softened water average color ranges between 13 and 15 color units (CU), while the average TTHMs historically has ranged between 85 and 100 µg/L. Figure 1 presents the basic treatment process schematic of the existing lime process.

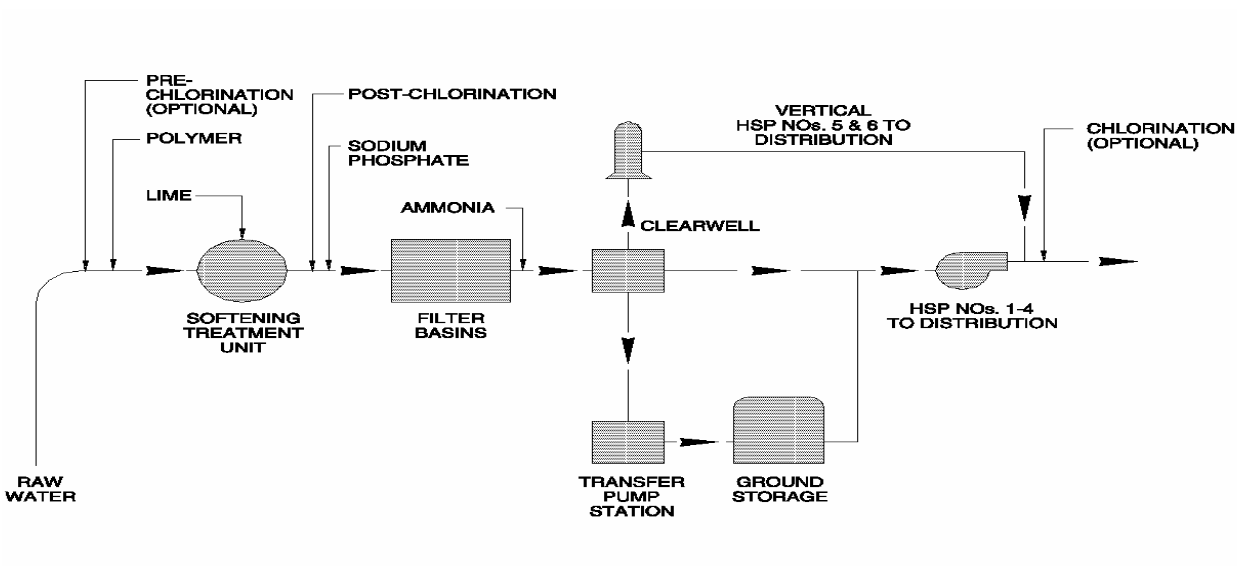

Figure 1. Existing Lime Softening Process Schematic

Process Design

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	<0.040 mg/L
Five HAAs	<0.030 mg/L
Color	<6
Total Hardness	70 to 90 mg/L as $CaCO_3$

Other major design objectives included:

- Provide the ability 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 on the proposed concentrate disposal method, which is through the City’s existing wastewater effluent ocean outfall.
- Reduce or eliminate the use of acid for raw water pretreatment.

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

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

Design Paramter	**Stage 1&2 Membrane Units (Units 1 through 10)**	**Convertible Membrane Units (Units 11 and 12) Concentrator/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 including eight independent filter cells
- Twelve cartridge filters
- Ten 3.676 mgd capacity stage 1&2 membrane units with dedicated variable speed vertical turbine membrane feed pumps

- Two 1.62 mgd capacity convertible membrane units with dedicated variable speed vertical turbine membrane feed pumps. 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 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 located over the existing Filter Building No. 3 clearwell
- Two packed tower odor control scrubbers

The degasified permeate will drop from the degasifiers into the Filter Building No. 3 clearwell directly below the degasifiers. Sodium hypochlorite, ammonia, corrosion inhibitor, and caustic soda is 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 will take place in the common transfer line from the existing transfer pumps, to the on-site finished water storage. Two existing old high service pumps that draw directly from the Filter Building No. 2 clearwell will be decommissioned to ensure that all finished water is thoroughly blended prior to being pumped to distribution (unblended finished water will be pumped from the clearwell directly into the distribution system only under emergency conditions).

Figure 2 depicts a schematic of the membrane process. Figure 3 presents a general plan of the membrane process building.

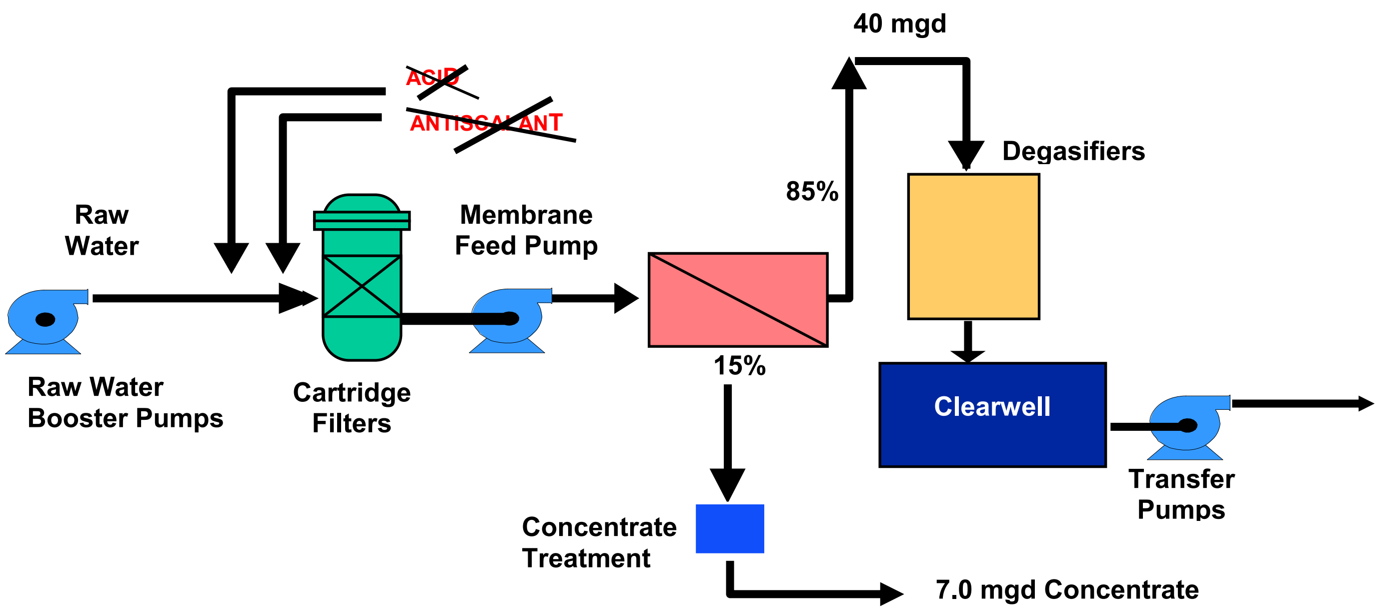

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Figure 2. Nanofiltration Process Schematic

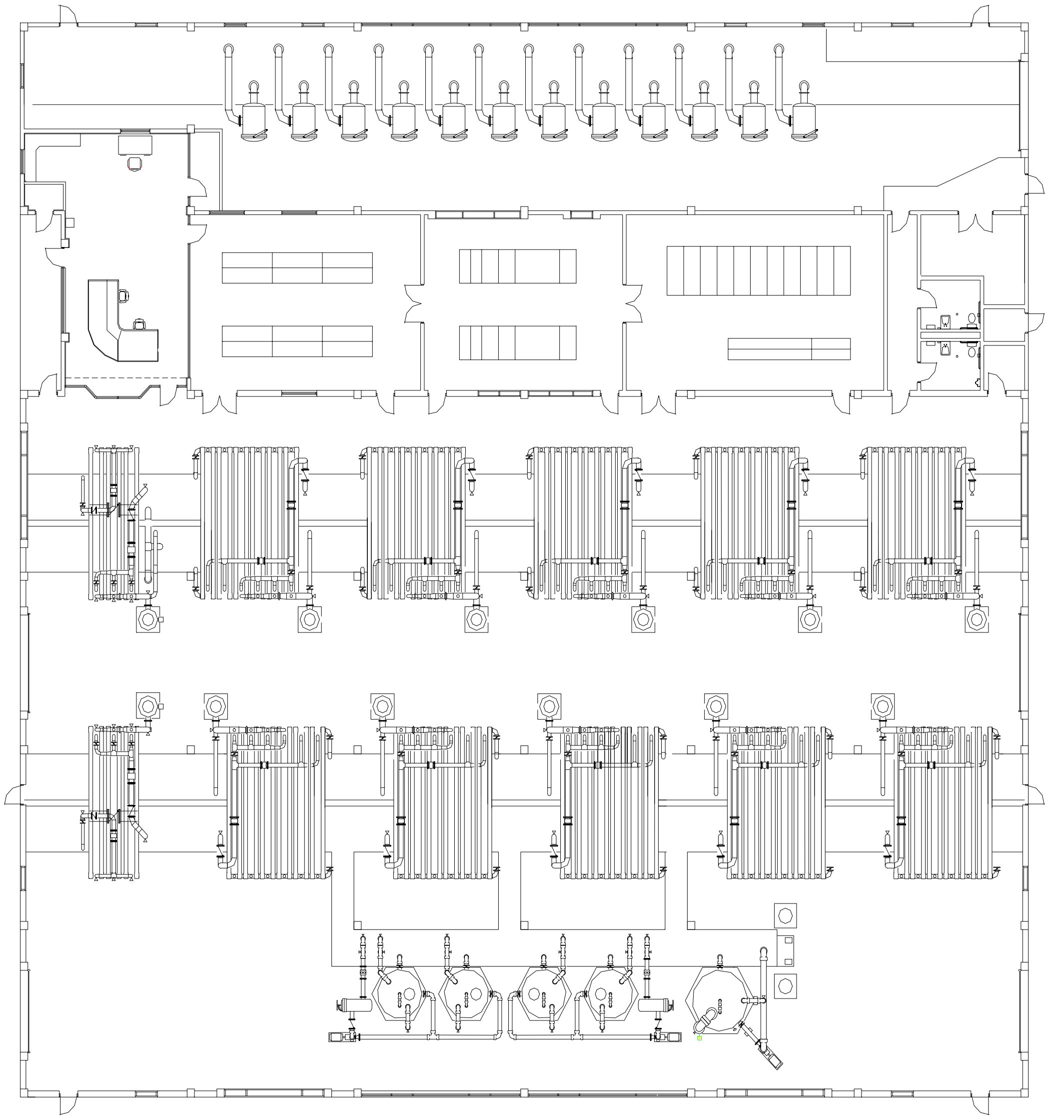

Figure 3. Plan of Membrane Process Building

Structure of Construction Contracts

The Contract Documents for the improvements associated with the project were separated into four separate contracts for the following components: wellfield rehabilitation (completed by a well specialty contractor), off-site wastewater, concentrate, and finished water transmission main improvements (completed by a pipeline general contractor), water treatment plant construction (completed by a heavy mechanical contractor), and membrane procurement.

As noted above, a comprehensive wellfield rehabilitation program was undertaken with the objective of improving the quality of the raw water with respect to treatability with the nanofiltration process. This project targeted both hydrogeological issues as well issues with the mechanical and general condition of the well pump equipment and transmission system. Also, it was determined that the Northwest Wellfield was better suited for the membrane process; although the raw water is high in color and organics, the system is somewhat newer, the wells produce less sand and particulates, there appears to be less biological activity in the wells, and SDI values are lower. Also, the capacity of the Northwest Wellfield is approximately 44 mgd, which nearly meets the raw water supply requirement for the membrane process. Raw water transmission piping improvements were completed on the water treatment plant site such that the primary raw water supply to the membrane process is from the Northwest Wellfield trunk main. Whenever the raw water demand from the membrane process exceeds the capacity of the Northwest Wellfield, raw water will be drawn from the Eastern Wellfield trunk main. The Southwest Wellfield (which was determined to be the worst quality with respect to membrane treatment) is dedicated exclusively to the lime softening process.

The wellfield rehabilitation program was focused on the Northwest Wellfield initially, so that all desired improvements could be completed prior to commissioning the membrane process. The improvements included acid treatment, disinfection, and redeveloping of the wells, replacement of some well packs and well screens, replacement of carbon steel submersible well pump columns with non-metallic (PVC) column pipe, the addition of column pipe to increase the pump setting depth for wells that had a risk of "breaking suction" due to drawdown, installation of foot valves on all wells, installation of flow meters on all wells that were not so equipped, as well as rehabilitation and repair of air valves to eliminate air in the raw water system. Upon completion of the wellfield rehabilitation program, a substantial improvement in both well capacity / drawdown and water quality was realized. SDI values in the raw water supply in the Northwest Wellfield trunk main were reduced to consistently below 3. Membrane optimization pilot testing conducted in parallel with construction of the plant demonstrated stable long-term operation of the selected membranes, meeting the membrane performance requirements, with the rehabilitated raw water supply.

The second construction contract noted above included off-site finished water, concentrate, and wastewater force main improvements. With respect to the membrane process, this project provided the means of concentrate discharge to the wastewater effluent storage tank and the process wastewater discharge to the wastewater treatment plant adjacent to the water treatment plant site. This work was completed in a timely manner with no significant problems.

The two main contracts associated with the membrane process improvements were the plant construction contract and the membrane procurement contract. The plant construction contract includes all on-site civil, structural, architectural, mechanical, electrical, and instrumentation work associated with the new membrane process, including functional testing of the treatment equipment (start-up, shut-down, and operational testing of various operating scenarios for the entire process, with orifice plates installed in the membrane units to mimic the hydraulic characteristics of the membrane elements, before loading the units with membranes). The plant construction contract was awarded to the Poole and Kent Company (the Contractor), and required that the Contractor execute a subcontract with a prequalified Membrane System Supplier (MSS) to provide specialty services associated with shop drawing preparation, fabrication, installation, and start-up of the membrane units. The Contractor for the project selected Advanced Environmental Water Technologies to act as MSS for this project.

The membrane procurement contract provides for the direct purchase of the selected membranes from the Membrane Element Manufacturer (MEM) by the City, and delivery of the membrane elements to the plant general contractor to install. The membrane element procurement contract was awarded to Hydranautics. This contract also requires factory hardness rejection wet bench testing of each membrane element using a mixed ion test solution prior to shipping the membranes to the site, on-site proof testing of pilot-scale (4-inch diameter) membranes using the City's 4:2:1 array membrane pilot plant, on-site single-element hardness rejection testing of full-size (8-inch diameter) elements selected from the supply lot for the full-scale plant, as well as assistance with installation, and full-scale performance testing of each membrane unit. The roles and responsibilities of the Contractor, MSS, and MEM are defined in both contracts. The procedures and results of the testing specified in the membrane procurement documents, prerequisite to membrane loading and start-up of the process, are discussed in greater detail below. The key permeate quality parameters required in the membrane procurement documents are summarized in Table 4.

Table 4. Required Permeate Quality Specified in the Membrane Procurement Contract

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

Membrane Element Delivery and Membrane Unit Start-Up Schedule

The conceptual plan for start-up of the plant, around which the contracts were written, provides for start-up to take place over a six-month period. The objective of this plan is to provide ample time to confirm proper performance of the membranes and process, and make any necessary adjustments in a systematic manner, while minimizing the risk of damage to the membranes during on-site storage, or irreversibly fouling the membranes during start-up process optimization. Figure 4 presents an overall schedule for start-up of the plant beginning at loading of elements in the first membrane unit, and includes loading, start-up, performance testing, reporting, and approval for each membrane unit. As can be seen in the schedule, each membrane unit is 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 is likely that any major problems requiring adjustment will be identified in testing of the first unit(s), start-up of the following units may be overlapped such that the remaining units can be started up within the remaining time.

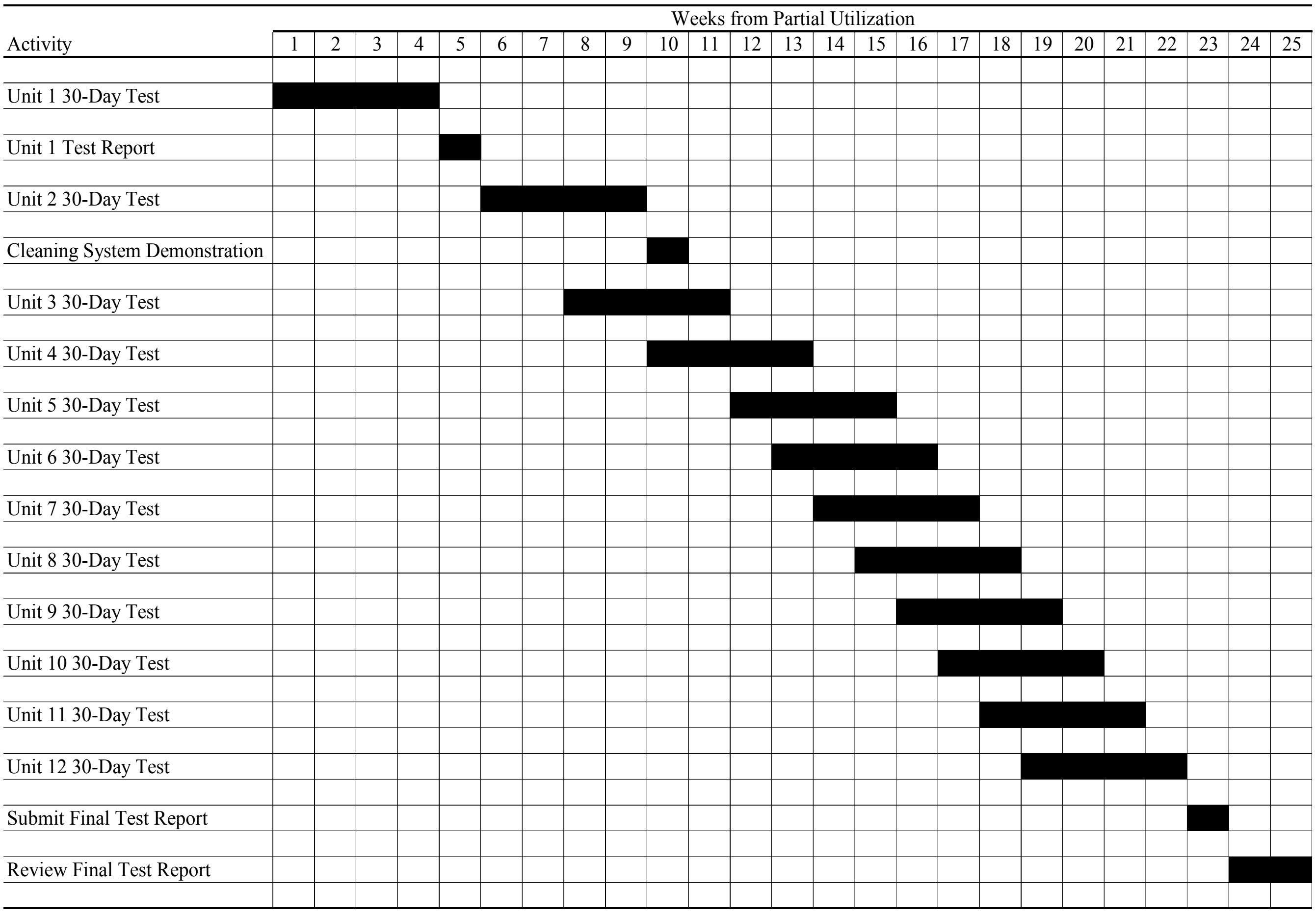

Figure 4. Membrane Process Start-Up Schedule

The contracts require that the general contractor notify the MEM 12 weeks prior to the anticipated loading date for the first membrane unit. The MEM may not ship the membranes prior to receiving written notice from the general contractor.

Proof Testing

As noted above, the membrane procurement documents required that the MEM perform a field proof test using the City's pilot plant and raw water supply to verify that the membrane elements proposed to be furnished will meet the specified permeate quality requirements with the actual raw water supply. The City provided a 4:2:1 array pilot plant for the testing. Proof testing was conducted under the following conditions:

- Operation without acid or antiscalant pretreatment
- Operation at the same flux rates as the full-scale plant
- Operation with a pilot-scale pretreatment pressure filter (which was provided by the manufacturer of the full-scale pretreatment pressure filter under the general plant construction contract
- Operation with existing micron cartridge filters to mimic the full-scale cartridge filters
- Operation at the same or lower transmembrane pressure as the full-size plant
- Use of membranes of the same sheet stock produced for the full-scale plant
- Use of sufficient pressure and flow indicators to determine flux, net driving pressure, transmembrane pressure, and pressure changes, including stage differential pressure.

The specified minimum proof test duration was 60 days, continuous to the greatest degree possible. The MEM was required to submit a test report at the end of the 60-day test summarizing the procedures, operational data collected, and results.

The proof test commenced on August 7, 2003 and continued for 60 days. As noted above, one of the important treatment objectives is to achieve a permeate hardness in the range of 50 to 80 mg/L as $CaCO_3$. This permeate hardness range is necessary to meet the City's blended hardness goal noted above. Analytical test results for hardness were correlated with conductivity readings to develop plots of hardness passage versus time. Figure 5 illustrates the first stage, second stage, and composite hardness results over duration of the proof test. As can be seen in the plot, the product hardness was within the specified range throughout the test. Hardness readings were relatively stable throughout the test, varying from 75 mg/L at start-up to 70 mg/L at the conclusion of the test.

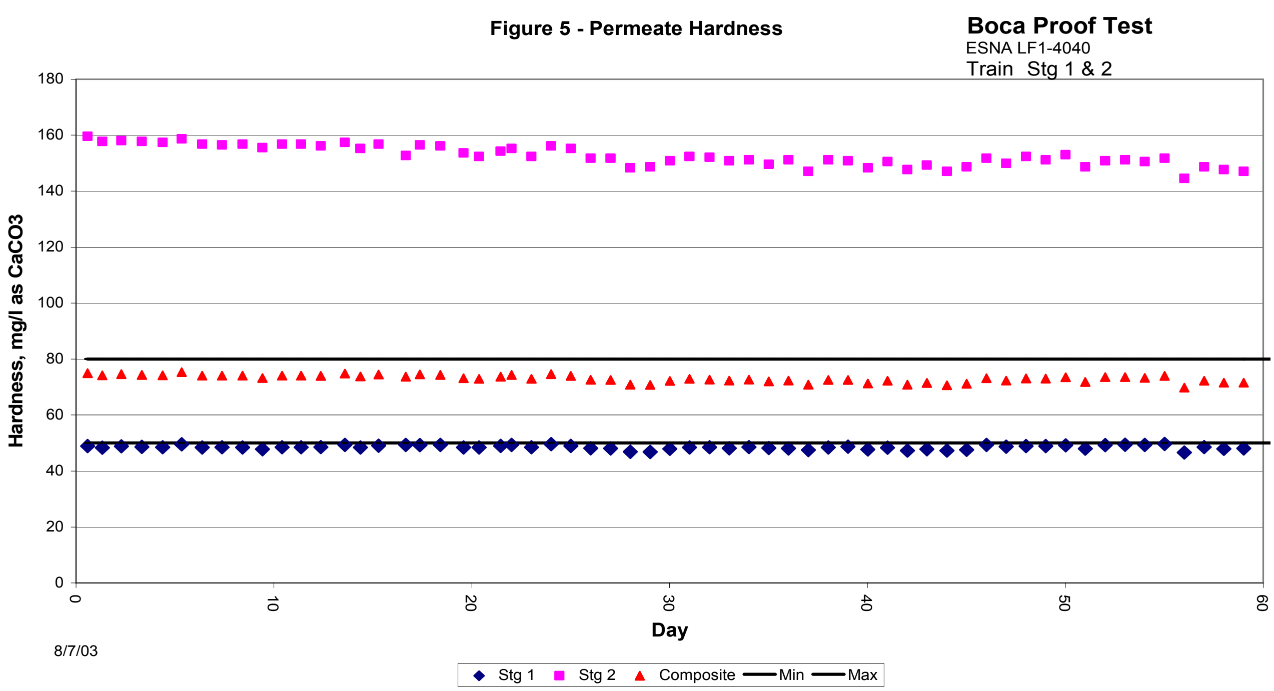

Figure 5. Membrane Element Proof Test Permeate Hardness

The mass transfer coefficient is a measure of how much product water in gallons per day (gpd) is produced per square foot of membrane surface per pound per square inch (psi) of applied pressure. The membrane procurement specifications required that the stage 1&2 membrane units should be capable of producing the specified permeate flow rate at a transmembrane pressure (TMP) of 80 psi or less. As the membrane mass transfer coefficient decreases, the transmembrane pressure must be increased to maintain the same permeate flow. Figure 6 illustrates the variation in mass transfer coefficient over the duration of the proof test. The solid line on the plot represents the membrane mass transfer coefficient corresponding to the maximum transmembrane pressure of 80 psi. If the mass transfer coefficient is above the line, the transmembrane pressure will be below the 80 psi limit (meeting the performance specification). If the mass transfer coefficient falls below this line, the required transmembrane pressure will exceed the specified maximum. As shown in Figure 6, the mass transfer coefficient at start-up was within the acceptable range, but was close to the lower limit. Between days 20 and 30 of the test, the mass transfer coefficient decreased below the lower limit, but appeared to stabilize through the remainder of the test. The composite mass transfer coefficient declined from 0.215 gfd/psi at start-up to 0.198 gfd/psi at the end of the test. This constitutes approximately an 8 percent decrease in performance over the test period. The corresponding transmembrane pressure at the end of the test run, normalized to design conditions, was calculated to be approximately 84 psi, which is 4 psi above the 80 psi specified maximum allowable TMP.

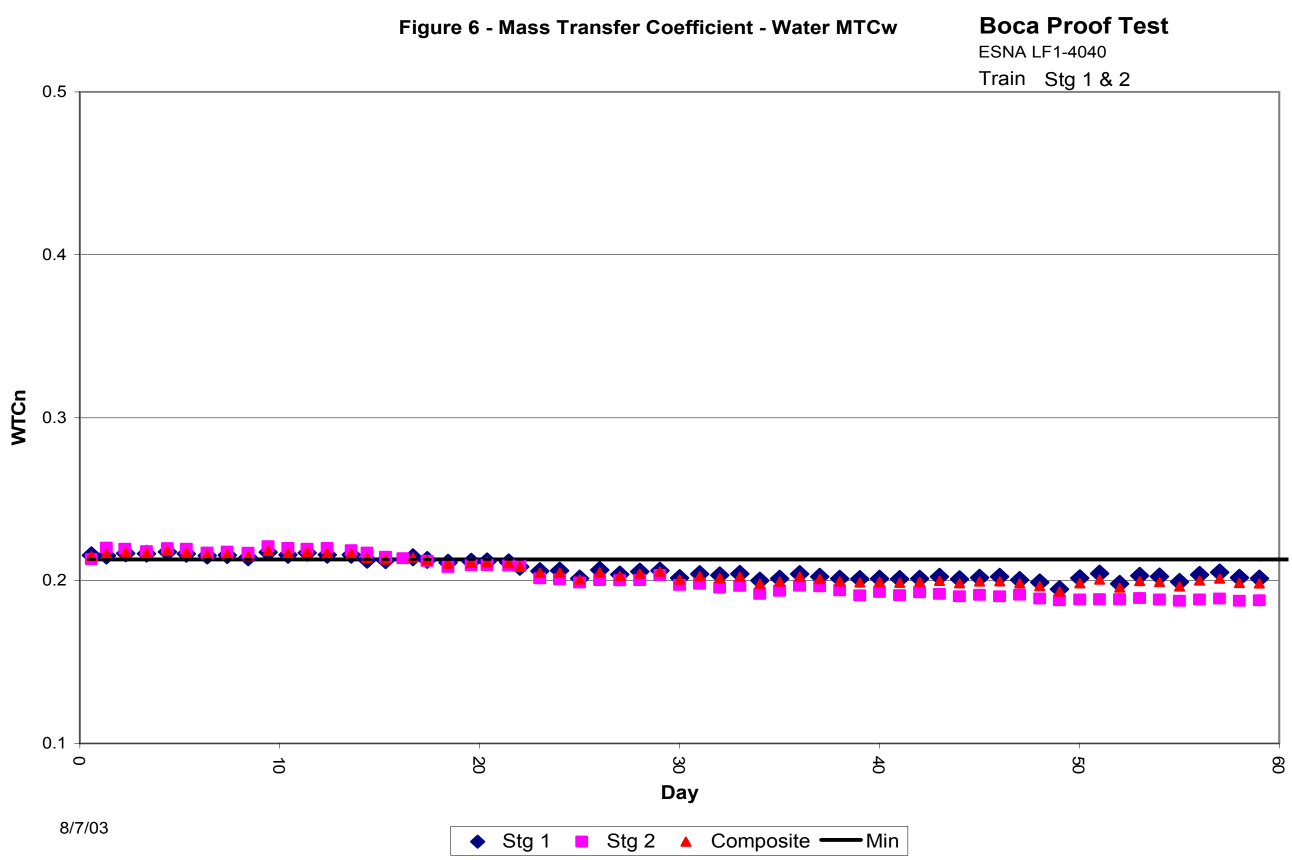

Figure 6. Membrane Element Proof Test Mass Transfer Coefficient

Five analytical sampling events were scheduled during the proof test. The results of some of the key parameters are summarized in Table 5. Table 5 shows that the permeate hardness reported during the test was within the specified range, averaging 70 mg/L as $CaCO_3$. The total trihalomethane formation potential (TTHMFP) and haloacetic acid formation potential (HAAFP) values reported during the proof test met the specification requirement, with average values of 9.4 µg/L and 16.3 µg/L for THMFP and HAAFP, respectively. These values compare to the specified limits of 42 µg/L and 30 µg/L, respectively. Permeate color was found to be less than 1.0 CU, below the specified limit of 2 CU. All permeate samples had TOC values less than the laboratory detection limit of 0.5 mg/L, which is less than the specified limit of 1.0 mg/L.

Table 5. Analytical Results from Membrane Proof Testing

Constituent/Parameter	Unit	Minimum	Maximum	Average
Total Hardness	mg/L as $CaCO_3$	59.0	79.0	70.0
Alkalinity	mg/L	66.0	82.0	71.6
THMFP	µg/L	6.1	13.0	9.4
HAAFP	µg/L	12.0	21.0	16.3

The initial 60-day proof testing effort came close to meeting all the specified performance criteria, but marginally exceeded the specified TMP requirement. The contract provided various alternatives for addressing a failure of the proof test, depending on the specifics of the failure. After some discussion with the MEM, it was agreed to conduct an additional 30 days of testing using 14 new membrane elements installed in the second stage of the pilot plant. In the 30-day retest, all specified water quality and performance parameters were met.

On-Site Single-Element Hardness Rejection Testing

The membrane element procurement documents also require that the MEM provide 50 full-size (8-inch diameter) membrane elements selected from the lot of membranes manufactured for the full-scale two-stage membrane units, and to conduct on-site hardness rejection testing of each element with a MEM-supplied single element test unit and the actual raw water supply for the full-scale plant. The objective of this testing was essentially to verify the results of the factory hardness rejection wet bench test using the City's raw water supply. The membranes selected for single-element testing must have a permeate flow rate within +/- 4 percent and a hardness passage within +/- 4 percent of the median permeate flow and hardness passage of all membranes tested with a mixed ion solution at the factory. Scheduling of the single-element testing was phased to allow adjustments to be made in the manufacturing process, if determined necessary to meet performance requirements, based on the results of the single-element testing.

The test elements for the first two membrane units were to be shipped to the site and tested prior to continuing manufacturing for the subsequent units. Subsequent test sets were to be delivered and tested based on the following schedule:

- Units 3 and 4
- Units 5, 6, and 7
- Units 8, 9, and 10.

On-site hardness testing must be completed on each batch prior to the start of manufacturing of elements for subsequent batches.

There was no minimum duration specified for the single-element testing. Monitored parameters include recovery rate, transmembrane pressure, permeate flow rate, and feedwater and permeate samples were analyzed. A test report is to be submitted for each test.

As of this date, single-element testing for the full-scale membrane units 1 and 2 has been completed. Based on the single-element testing, the projected transmembrane pressures for membrane units 1 and 2 are 67.2 psi and 68.0 psi, respectively. Both values are less than the specified maximum of 80 psi. The projected total permeate hardness values for units 1 and 2 are 78.0 mg/L as $CaCO_3$ and 73.7 mg/L as $CaCO_3$, respectively. Both values are within the specified total permeate hardness range of 50 to 80 mg/L as $CaCO_3$.

Conclusion

As of this date, the Contractor is addressing several process control issues that were identified during functional testing of the process equipment. Preparations are being made for loading of the membrane elements and start-up of the first membrane unit. Following resolution of all issues identified during functional testing, the City will proceed with loading of the membrane elements and full-scale performance testing of each membrane unit, in accordance with the start-up plan and schedule.