OPTIMIZING REPLACEMENT MEMBRANES AT THE 10 MGD CITY OF POMPANO BEACH NANOFILTRATION PLANT

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Introduction and Background

The City of Pompano Beach is located in northeast Broward County, Florida, and provides potable water service to a population of approximately 84,000 in Broward County. Current annual average day demands (ADD) are approximately 13.6 million gallons per day (mgd), while the maximum day demand (MDD) is approximately 17.4 mgd.

The City owns and operates a 50 mgd water treatment plant (WTP) that utilizes a combination of conventional lime softening (LS) and nanofiltration (NF) to treat the raw water supply. The products of the two parallel treatment processes are blended at a rate of approximately 40% to 50% NF:LS, prior to four-log virus treatment disinfection and pumping to distribution. The 40 mgd LS process was constructed in 1985, which incorporated the original filtration and chlorination plant constructed in 1959. The NF plant was constructed and placed on line in 2002. The original NF membrane elements were replaced in 2009 as part of the City's routine, periodic membrane element replacement program. Figure 1 presents a general schematic of the Pompano Beach WTP.

The raw water supply for both the LS process and the NF process is the shallow Biscayne Aquifer, which is relatively high in dissolved organics, including precursors for regulated trihalomethane and haloacetic acids. A major driver for construction of the NF process in 2003 was to maintain continued compliance with the Stage 2 Disinfectants/Disinfection By-Product Rule (D/DBPR) by improving the overall treatment process removal efficiency for DBP precursors, thus reducing DBP levels in the finished water. Table 1 summarizes typical selected raw water quality parameters.

In addition to compliance with all primary and secondary drinking water standards, the City has established stated goals for certain constituents in the blended finished water, as summarized in Table 2.

Figure 1 – City of Pompano Beach WTP Process Schematic

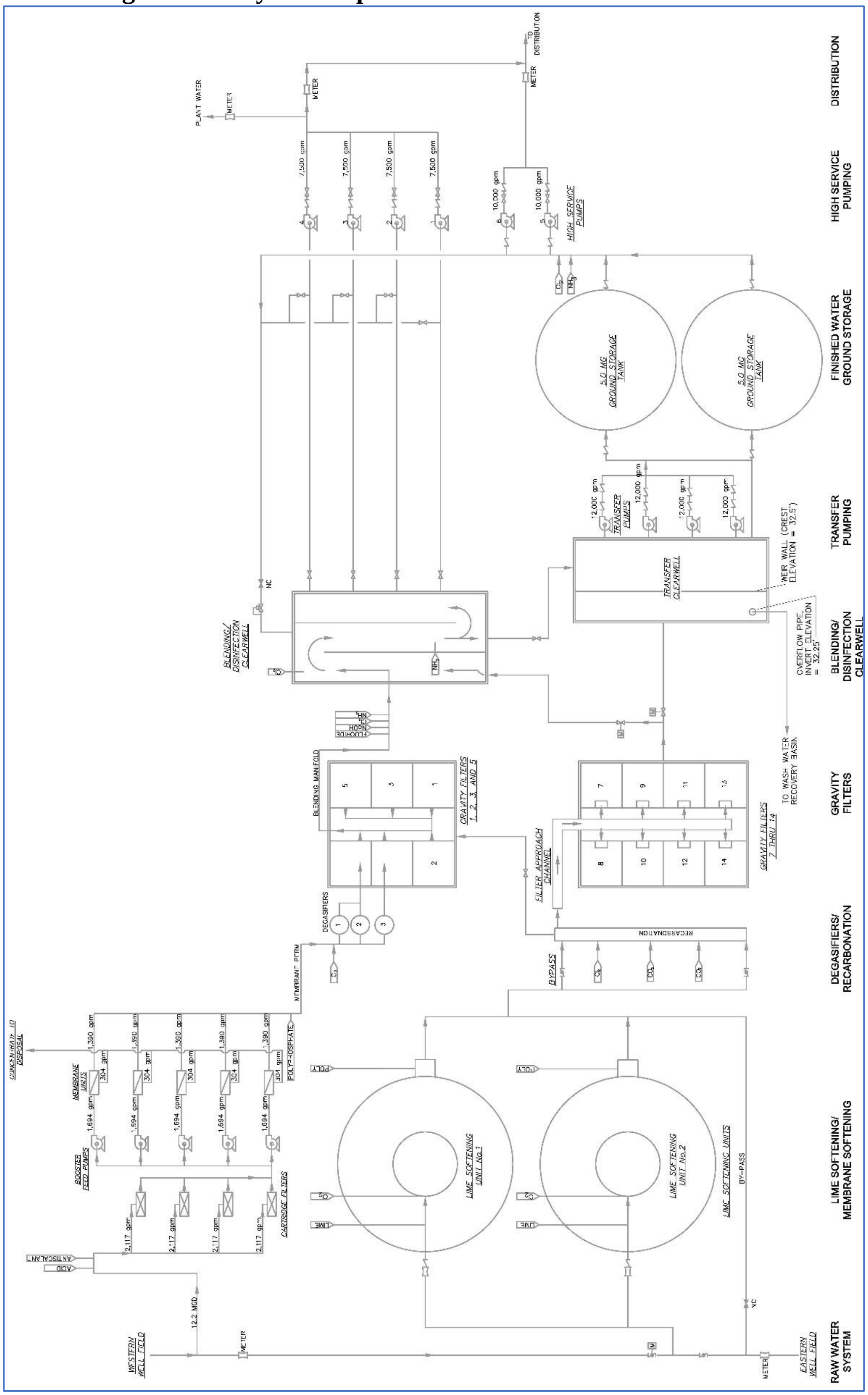


Table 1 – Typical Raw Water Quality

Constituent/Parameter	Value
Total Hardness	247 mg/L as $CaCO_3$
Total Dissolved Solids	495 mg/L
Color	80 Color Units
Total Organic Carbon	20 mg/L
pH	7.2
Iron	1.7 mg/L
TTHMFP	0.40 mg/L
HAA5FP	0.3 mg/L

Table 2 – Blended Finished Water Quality Goals

Constituent/Parameter	Value
Total Hardness	50 to 80 mg/L as $CaCO_3$
Color	< 6 Color Units
Total Trihalomethanes (TTHM)	< 0.064 mg/L
Five Haloacetic Acids (HAA5)	< 0.048 mg/L

Description of NF Process

The NF process includes five 2-mgd NF units. The NF units are two-stage units in a 36:16 array, operating at a recovery rate of 85% and average flux of 13.7 gallons per square foot per day (gfd). As noted above, the raw water supply is relatively high in organics and has an iron level of approximately 1.7 mg/L. Physical pretreatment of the NF feedwater consists of four 5-micron cartridge filters upstream of the NF units, each rated at 2,117 gpm capacity. The City acidifies the feedwater to a pH of 5.8 and feeds Nalco 1850T antiscalant at a dosage rate of 1.0 mg/L. The current cleaning frequency for the NF units is approximately every 12 months, or every 7 months of run time.

The NF units are currently populated with a hybrid of membrane element models (Hydranautics ESNA1-LF and ESNA1-LF2) which were installed in 2009. These membranes were selected to achieve the City's permeate hardness goal of 20 mg/L as $CaCO_3$ (minimum) while achieving the permeate iron goal of 0.25 mg/L (maximum), as well as other water quality goals (e.g., color, TDS, organics). The existing membrane selection has met the City's permeate quality goals throughout their service lives. Table 3 summarizes the general design parameters for the NF process.

Table 3 – Design Parameters for NF Process

Design Parameter	Units 1 through 5
Total Permeate Capacity	10.0 mgd
Recovery Rate	85 percent
Raw Water Feed Flow	11.76 mgd
Number of Units	5 x 2.0 mgd
Array	36:16
Flux Rate	13.7 gfd
Feedwater pH	5.8
Feedwater Antiscalant Dose	1.0 mg/L

Planning for NF Membrane Replacement

In early 2017, the City began planning for replacement of the membrane elements. In addition to continuing to achieve the City's blended finished water quality goals, the City elected to investigate the possibility of reducing the NF process operating costs with the replacement membranes by taking advantage of recent advances in membrane technology to reduce power costs, and by optimizing chemical pretreatment of the NF feedwater.

Achieving a significant reduction in the required operating feed pressures without significantly affecting permeate quality was demonstrated to be feasible at the City of Boca Raton NF plant in 2016 during their recent membrane element replacement. The Boca Raton NF plant uses a Biscayne Aquifer raw water supply of similar quality to the Pompano Beach raw water, and utilizes a comparable (but somewhat different) membrane selection from the same element manufacturer. During Boca Raton's 2016 membrane element replacement, they achieved a reduction in the start-up feed pressure of approximately 20 psi, resulting in a substantial operating power cost savings from their previous membranes. Updated performance projections for the similar Pompano Beach replacement membranes, meeting the City's established permeate quality goals, reflect a potential reduction in required feed pressure of approximately 17 psi. For the Pompano Beach WTP, this equates to a potential operating power cost savings of approximately $27,000 per year (assuming 5.5 mgd permeate ADD and a unit power cost of $0.064 per kilowatt-hour). Table 4 presents a summary of the permeate quality and membrane performance requirements specified in the procurement documents for both the existing (2009) and proposed for the replacement (2018) membrane elements.

During the 2009 membrane replacement, the City identified the trade-off between iron rejection and hardness passage as the primary controlling constraint in optimizing the membrane selection with respect to permeate quality (i.e., meeting the goal for maximum iron 0.25 mg/L as well as the minimum goal for total hardness, refer to Table 4). All other permeate goals were met with little difficulty.

As noted above, the City's current NF process operating protocol includes acidification of the feedwater to a pH of 5.8 and application of an antiscalant at a dosing rate of 1.0 mg/L. Full-scale, long-term operation at the City of Boca Raton, as well as limited pilot testing at several other NF facilities in Southeast Florida that use similar Biscayne Aquifer raw water supplies, have indicated that stable operation without acid or antiscalant pretreatment is feasible, presumably depending on the raw water characteristics and process operating parameters. There are indications that this may be due to the high levels of dissolved organic constituents (e.g., humic acids) in the raw water acting as a "natural antiscalant," and/or boundary-layer interactions between the charged surface of the membrane and charged foulant particles. Also, it is notable that the Boca Raton plant, which is, to our knowledge, the only large NF plant in Southeast Florida that has a long-term history of stable operation without acid or antiscalant pretreatment, operates at a relatively low average flux of 12.2 gfd and an 82 percent recovery rate. Whatever the cause, achieving stable operation without acid or antiscalant chemical pretreatment of the feedwater at the Pompano Beach WTP has the potential of reducing long-term operating cost by up to $218,000 annually based on current water demands, chemical usage rates, and actual chemical unit prices. Due to the substantial potential operating cost savings, as well as potential reduced risks and "headaches" associated with handling large quantities of acid (and antiscalant), the City of Pompano Beach elected to conduct pilot testing to evaluate the possibility of achieving stable operation without acid or antiscalant.

As noted above, the current cleaning frequency for the NF units is approximately every 12 months, or every 7 months of unit run time. The City recognizes that operation without acid or antiscalant may require more frequent cleaning of the membranes, and any savings in pretreatment chemical costs will be offset by the cost of increased cleaning frequency. To gauge the success of the pilot testing without acid or antiscalant, the City established a goal of a minimum of 90 days of operation with no more that 15% loss in specific flux, while meeting all water quality goals. This would correspond to a maximum cleaning frequency of once every three months of run time, which would represent a potential increase in membrane cleaning costs of approximately $6,800 annually (to offset the $218,000 savings in pretreatment chemicals).

Table 4 – Specified Permeate Quality and Membrane Performance

Constituent/Parameter	**Existing Membranes (2009)**	**Replacement Membranes (2018)**
Bicarbonate	25 to 75 mg/L	25 – 75 mg/L
Color	< 3 Color Units	< 3 Color Units
Total Dissolved Solids	< 250 mg/L	< 250 mg/L
Total Hardness	**20 mg/L as $CaCO_3$**	**Min 25 mg/L as $CaCO_3$**
Iron	**0.25 mg/L**	**0.25 mg/L**
Total Organic Carbon	< 1.0 mg/L	< 1.0 mg/L
TTHM Formation Potential	< 0.040 mg/L	< 0.040 mg/L
HAA5 Formation Potential	< 0.030 mg/L	< 0.030 mg/L
Maximum TMP	**90 psi**	**73 psi**

In pursuit of the above-described optimization goals, the City has undertaken an extensive pilot testing program. The City's NF plant is currently equipped with a two-stage pilot unit that uses three, 4-inch diameter, 6-element pressure vessels in a 2:1 array. This pilot unit was constructed and used for testing prior to the original construction of the NF plant in 2002. This pilot unit has been successfully used over the history of the NF plant to evaluate chemical pretreatment protocols, membrane cleaning chemicals and procedures, as well as for performance and proof testing of replacement membrane elements during the 2009 replacement effort. However, there are limitations on the pilot unit's "scalability" to the full-scale membrane units due to the fact that the pressure vessels are six-element vessels.

In preparation for the 2017-2018 membrane replacement, the City designed, permitted, and constructed a 2:1 array pilot test unit consisting of three full-size (8-inch diameter, 7-element) membrane pressure vessels with independent pre-treatment chemical feed systems, cartridge filters, feed pump, and control instrumentation. The pilot unit was permitted to withdraw raw water from the full-scale plant feed water header and discharge concentrate and permeate to the full-scale plant concentrate and permeate headers, respectively. Figure 2 presents a schematic of the 8-inch pilot test unit, and Figure 3 presents an overall schematic of the full-scale NF process including process connections for the 8-inch pilot test unit. As shown in Figure 2, the pilot test unit is equipped with appropriate instrumentation to monitor and control all process operating parameters (e.g., stage-specific feed, permeate, and concentrate flows, average flux rates, recovery rates, pretreatment chemical dosing rates, operating pressures, flow-stream conductivity and other water quality parameters, etc.) that may be relevant to the objectives of the pilot testing effort.

Membrane Pilot Testing

The City's objectives for the pilot testing include:

- Optimize chemical and power operating costs
- Confirm that proposed selections from membrane element manufacturers will meet the City's minimum performance and permeate quality specifications.

Testing with Four-Inch Pilot Unit

The membrane replacement program, which included design, permitting, and construction of the 8-inch pilot test unit, was initiated in early 2017. The availability of the City's existing 4-inch pilot test unit enabled the City to begin preliminary testing immediately and continue testing during design, permitting, and construction of the 8-inch test unit. For preliminary testing with the 4-inch test unit, the City was provided with the latest version of the membrane element models that are currently installed in the full-scale plant. In general, the objective of the preliminary testing with the 4-inch test unit was to collect as much data as possible relative to the overall program objectives, in preparation for the more formal testing program using the 8-inch test unit. Specific objectives of testing with the 4-inch unit included confirmation of the performance of the updated membrane selection from Hydranautics and investigation of various flux and recovery rates relative operation without acid or antiscalant in an effort to identify stable operating conditions to be used in testing with the 8-inch pilot unit. Preliminary testing with the 4-inch test unit commenced May 3, 2017 and continued through present (January 5, 2018). Individual periods of testing with the 4-inch test unit are discussed below. Figures 4 through 7 present plots of selected parameters from the normalized data collected during the study period. Table 5 summarizes the permeate total hardness and iron data collected during the study period.

Figure 2 – 8-inch Pilot Test Unit

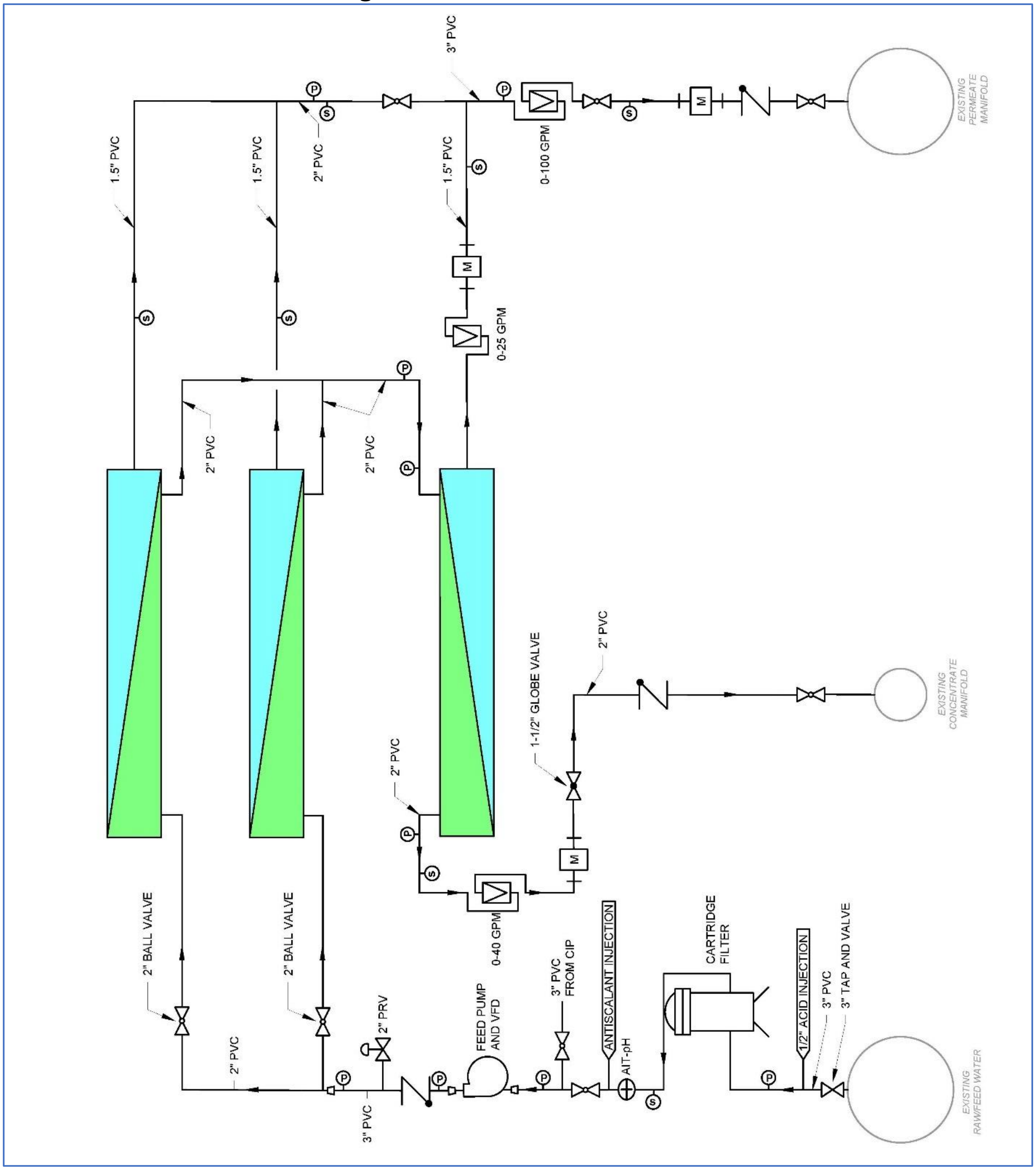
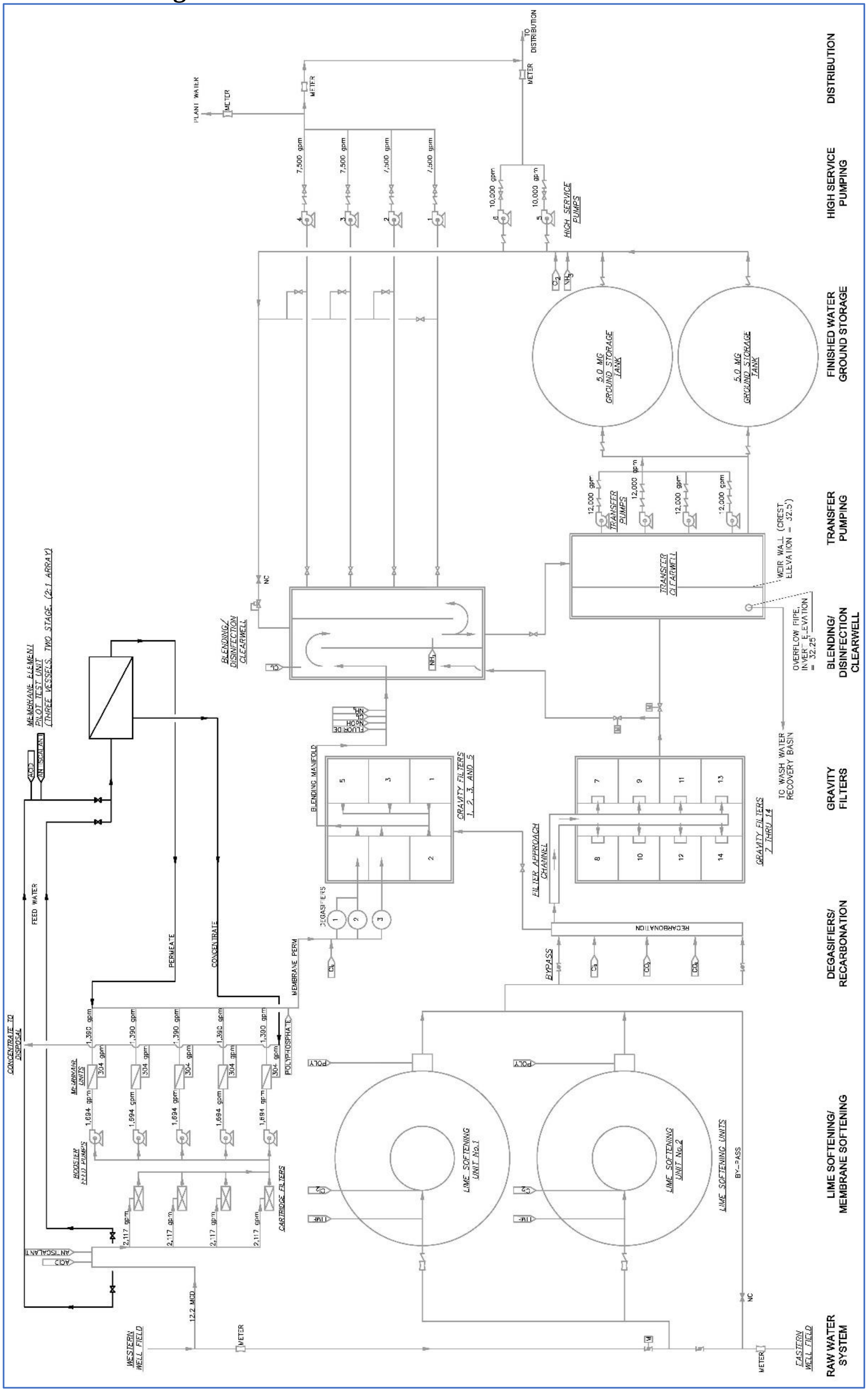


Figure 3 – WTP Process Schematic with Pilot Unit



May 3, 2017 through June 13, 2017. The first phase of the testing was aimed at confirming that the City could still meet the stated water quality goals with the same (updated) membrane element models that are currently installed in the full-scale plant. A secondary objective was to obtain a preliminary indication of the feed pressure that may be expected with the new elements. During this time period, the pilot unit was operated under conditions representative of current operating conditions in the full-scale plant (i.e., using the full-scale plant chemically pre-treated feedwater, and at a recovery rate of 85%). The "scalability" limitations of the 4-inch tested unit (using six-element vessels), make it impossible to accurately represent all relevant process operating parameters of the full-scale NF units. In consultation with the membrane element manufacturer, it was decided that the best representation of operating conditions for the full-scale NF units was to pilot test at 80% recovery and 14.6 gfd flux rate. (This highlights the City's motivation for designing and constructing the 8-inch pilot test unit).

As noted above, the City's total hardness and iron goals are the controlling constraint in optimizing the membrane selection with respect to permeate quality. As shown in Table 5, both the total hardness goal of 25 mg/L minimum, as well as maximum iron goal of 0.25 mg/L, were met during the initial 30-day testing phase. 30 days of testing was considered sufficient to confirm the performance of the membranes with respect to permeate quality. The City also sampled for other water quality parameters during this test phase, all of which were in compliance with the City's stated goals.

Referring to Figure 4, the first-stage feed pressure during the initial phase of testing was between 85 and 90 psi. However, due to the important differences in the design and configuration of the 4-inch pilot unit relative to the full-scale NF units, this can not be considered representative of feed pressures for the full-scale plant.

June 14, 2017 through October 9, 2018. Following the initial phase of confirmation testing, the City elected to begin investigating the feasibility of operating without acid or antiscalant pretreatment. During the 2009 membrane replacement, the City had tested several variations of reduced chemical pretreatment (i.e., acidification with no antiscalant, antiscalant feed without acidification), without success. Experience during design-phase NF pilot testing at Boca Raton in the late 1990s indicated that, under certain conditions, operation without either acid or antiscalant was more stable than any tested variation of chemical pretreatment (e.g., antiscalant only, acid only, or combined acid and antiscalant). (During that testing effort, chemical pretreatment appeared to cause membrane fouling.) Therefore, the City elected to initiate this phase of testing with neither acid nor antiscalant.

The general approach to this phase of testing was to begin testing at a conservative recovery rate and flux rate. The plan was to conduct testing in discreet 90-day phases using different settings for recovery rate and flux. Testing began on June 13, 2017 with the unit operating at an 80% recovery rate and flux rate of 12 gfd.

Figure 6 presents a plot of specific flux. The first- and second-stage specific flux at the start of testing without acid or antiscalant (June 13, 2017) were 0.258 and 0.321 gfd, respectively. The first- and second-stage specific flux at the conclusion of this testing phase (118 calendar days of

Figure 4 – Feed Pressures

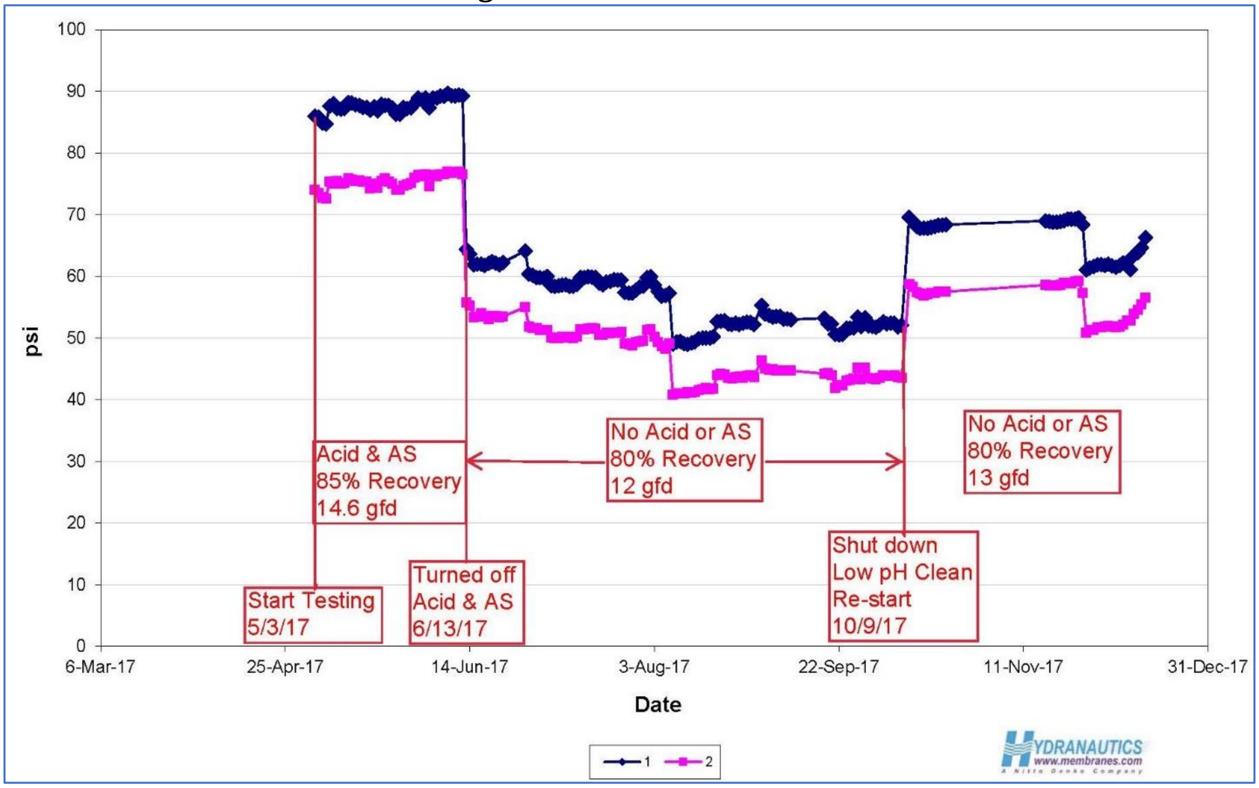


Figure 5 – Permeate Conductivity

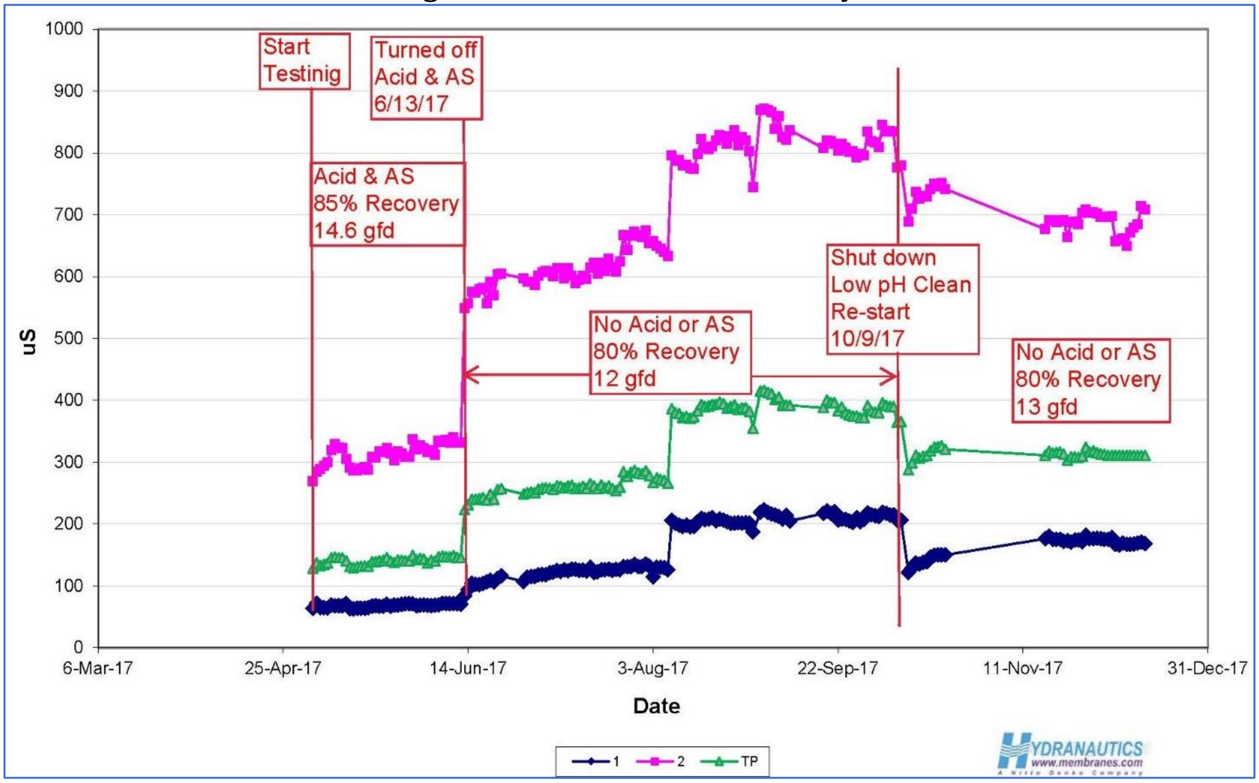


Figure 6 – Specific Flux

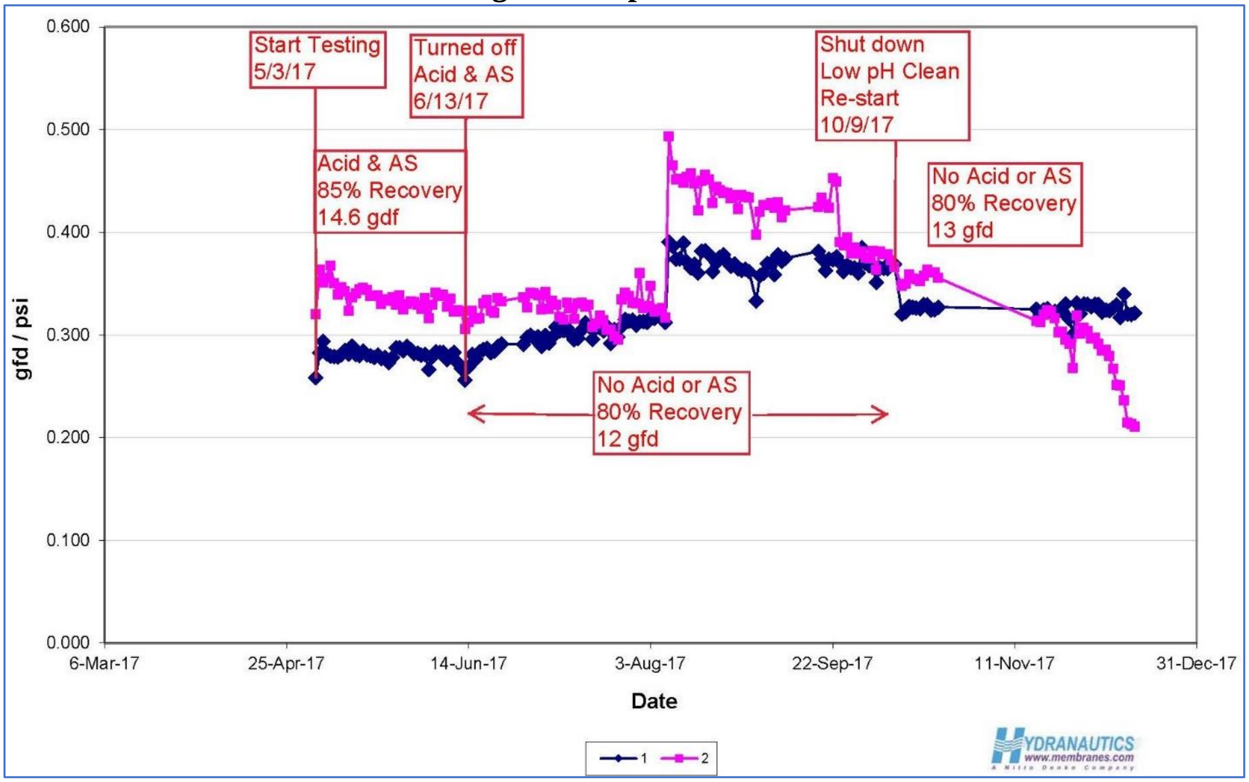


Figure 7 – Salt Passage

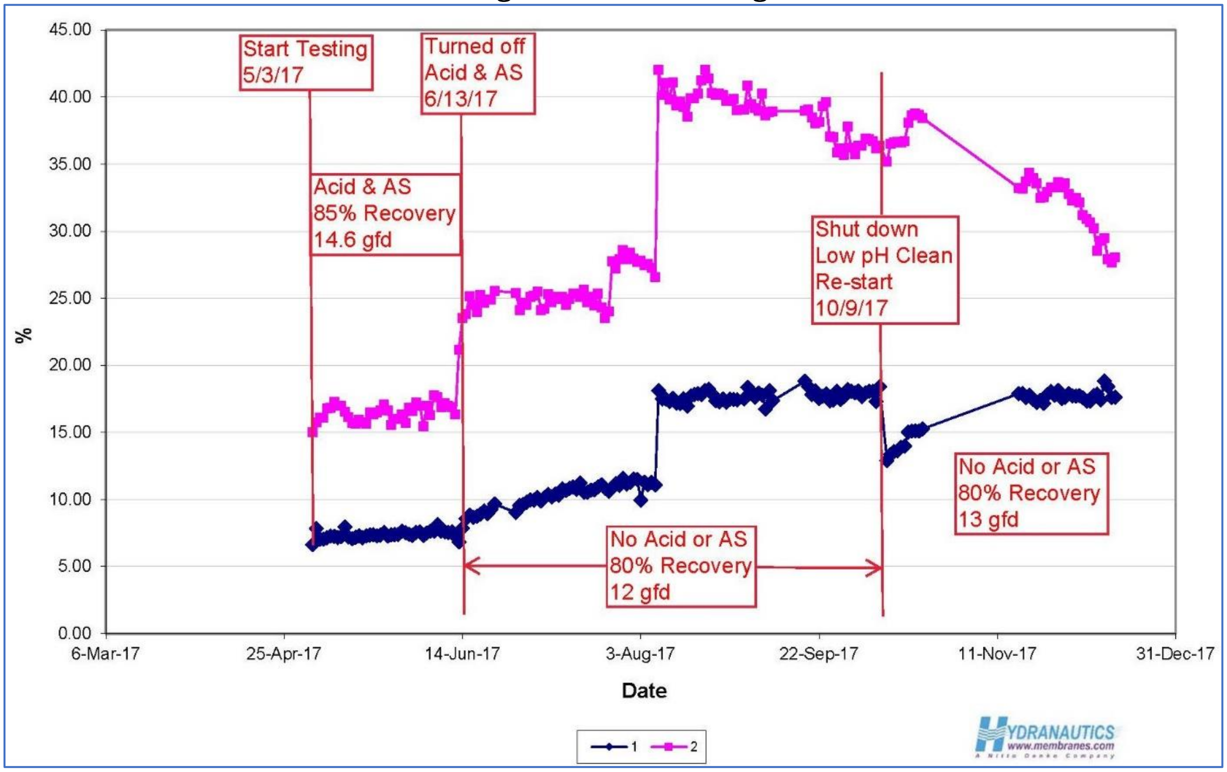


Table 5 – Permeate Hardness and Iron

Date	Total Hardness (mg/L as $CaCO_3$)	Iron (mg/L)
Phase I		
May 9, 2017	25.5	0.12
May 18, 2017	25.9	0.10
May 24, 2017	26.4	0.12
June 6, 2017	26.7	0.08
Average:	**26.1**	**0.11**
Phase II		
June 13, 2017	63.9	0.16
June 23, 2017	76.1	0.48
June 30, 2017	70.5	0.34
July 7, 2017	71.6	0.36
July 14, 2017	77.6	0.33
July 21, 2017	74.1	0.35
July 27, 2017	82.0	0.10
Average:	**73.7**	**0.30**

testing) were 0.369 and 0.366 gfd, respectively. This appears to indicate stable operation and meet the City's established criteria for success. However, there were several events that occurred during this time period that must be considered when drawing any conclusions.

On July 25, 2017, the City performed a permeate flush of the pilot unit in preparation for a short-term shut-down of the unit. This is routine operation for the full-scale NF process and normally could be considered representative of full-scale operations for pilot testing purposes. However, in this case, the permeate used for flushing was from the full-scale plant, which had a pH of approximately 5.8 due to fact that the feedwater to the full-scale plant is acidified. Under the scenario of the full-scale plant operating without acid or antiscalant, permeate used for flushing would have a significantly higher pH. The effect of the low-pH permeate flush on the membrane performance, relative to a non-acidified permeate flush, is not known.

On August 8, 2017, the pilot unit was inadvertently exposed to a small slug of proprietary high-pH cleaning chemical that was left in a section of two-inch piping following cleaning of one of the full-scale NF units. Following this exposure, the City observed a significant increase in permeate conductivity, specific flux, and salt passage, coupled with a drop in feed pressure. Again, the exact impact on membrane performance is difficult to quantify and explain, but the event clearly had a significant, unintended influence on testing. Membrane performance appeared to stabilize for some period of time following the event, but it is questionable whether any meaningful conclusions can be drawn from the data from August 7, 2017 through October 9, 2017.

Notwithstanding the anomalies above, it does appear that stable, uninterrupted operation was observed during the period from June 13, 2017 through July 25, 2017, immediately prior to the permeate flush (42 calendar days). During this time period, the City observed a 7.8% decline in specific flux in the second stage and no decline (increase) in the first stage. During the period from June 13, 2017 through August 7, 2017 (immediately prior to the exposure to cleaning chemical, 55 calendar days), the City observed a negligible (0.4%) decline in specific flux in the second stage and no decline (increase) in the first stage. While these time periods does not meet the City's goal of 90 days of stable operation, the data do appear to indicate that stable operation without acid or antiscalant is feasible. Further testing is needed under better controlled conditions. The City hopes that the new 8-inch pilot test unit will enable more controlled testing conditions to demonstrate long-term stable operation without chemical pretreatment.

October 11, 2017 through January 5, 2018. The first phase of the testing without acid or antiscalant was conducted from June 13 through October 9, 2017 (118 calendar days). On October 11, 2017, the City elected to clean the membranes and initiate the second phase of testing without chemical pretreatment. During the second phase, the flux rate was increased to 13 gfd, and testing continued through January 5, 2018. During this time period, there were several significant interruptions in testing due to shut-downs of the full-scale NF plant for work on the deep injection well, pigging of the raw water main, and high SDI events. A significant decline in specific flux and corresponding increase in feed pressure were observed towards the end of this time period. After an overall review in January 2018, the City concluded that the performance data collected following the August 2017 exposure to high-pH cleaner is questionable due to the possibility of permanent effects on the membranes from the the exposure to cleaning chemicals and the numerous unexpected disruptions from October 2017 to January 2018. However, the City believes that the data set as a whole appear to indicate that a flux rate lower than 13 gfd is more likely to yield long-term stable operation.

Planned Testing with Eight-Inch Pilot Unit

As noted above, preliminary pilot testing with the existing 4-inch test unit was undertaken recognizing the limitations of the unit due to the age and design of the unit. The primary, general purpose of this preliminary testing was to establish a foundation for the 8-inch testing program. The preliminary testing conducted to date appear to indicate that stable operation without acid or antiscalant pretreatment is feasible, likely at a relatively low flux rate and recovery rate in the range of 80% to 82%. As of this date, the 8-inch pilot test unit has been constructed, cleared for service, and is operational. The City is planning to begin pilot testing with the 8-inch unit in February 2018, following completion of pending work on the main raw water main feeding the NF process. The City is planning to test proposed membrane element selections from two manufacturers in preparation for the membrane procurement process. The general objectives of testing will be:

- Finalize and demonstrate baseline conditions for the replacement membranes (i.e., chemical pretreatment, recovery rate, and flux rate).
- Confirm that proposed selections from membrane element manufacturers will meet the City's minimum performance and permeate quality specifications.