OPTIMIZING CHEMICAL PRETREMENT FOR A 10 MGD NANOFILTRATION PLANT

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Background

The City of Pompano Beach (City) is located in northeast Broward County, Florida and provides potable water service to a population of approximately 84,000. The City's current potable water annual average day demand (ADD) is approximately 13.6 million gallons per day (mgd), and the maximum day demand (MDD) is approximately 17.4 mgd. The City owns and operates a 50 mgd water treatment plant (WTP) that utilizes conventional lime softening (LS) and nanofiltration (NF) to treat the raw water. These processes run in parallel and are blended at approximately 40% to 50% NF:LS ratio in a blending clearwell prior to four-log virus treatment disinfection and distribution. Both process streams treat raw water from the shallow Biscayne Aquifer, which is high in dissolved organics including precursors for regulated trihalomethanes and haloacetic acids. Typical raw water quality is summarized in Table 1.

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	1.70 mg/L
TTHMFP	0.40 mg/L
HAA5FP	0.30 mg/L

The NF process was constructed and placed into service in 2002 and includes five 2-mgd NF units. This process was added to improve the removal of dissolved organics to maintain compliance with the Stage 2 Disinfectant/Disinfection By-Product Rule (D/DBPR) and all primary and secondary drinking water standards. Each NF unit is two-staged in a 36:16 array, and the system was designed to operate at an 85% recovery rate with an average flux of 13.7 gallons per square foot per day (gfd). Physical pretreatment of the NF feedwater consists of four 5-micron cartridge filters, each rated at a 2,117 gpm capacity. Currently, in addition to physical pretreatment, the City pretreats the NF feedwater with acid to lower the pH to 5.8 and Nalco 1850T antiscalant at a dosage rate of 1.0 mg/L. The NF units are currently populated with a hybrid of membrane element models (Hydranautics ESNA1-LF and ESNA1-LF2) which were

installed in 2009. The current membrane cleaning frequency is approximately once every twelve months, or every seven months of runtime.

As presented in Table 1, the raw water is relatively high in organics and has an average iron concentration of approximately 1.7 mg/L. In order to remain in compliance with the D/DBPR and primary and secondary drinking water regulations, the City has established goals for concentrations of certain constituents in the finished blended water. To achieve these goals, the City has set NF permeate quality and membrane performance criteria for the existing membrane elements that were installed in 2009, as presented in Table 2.

Table 2 – Specified Permeate Quality and Membrane Performance

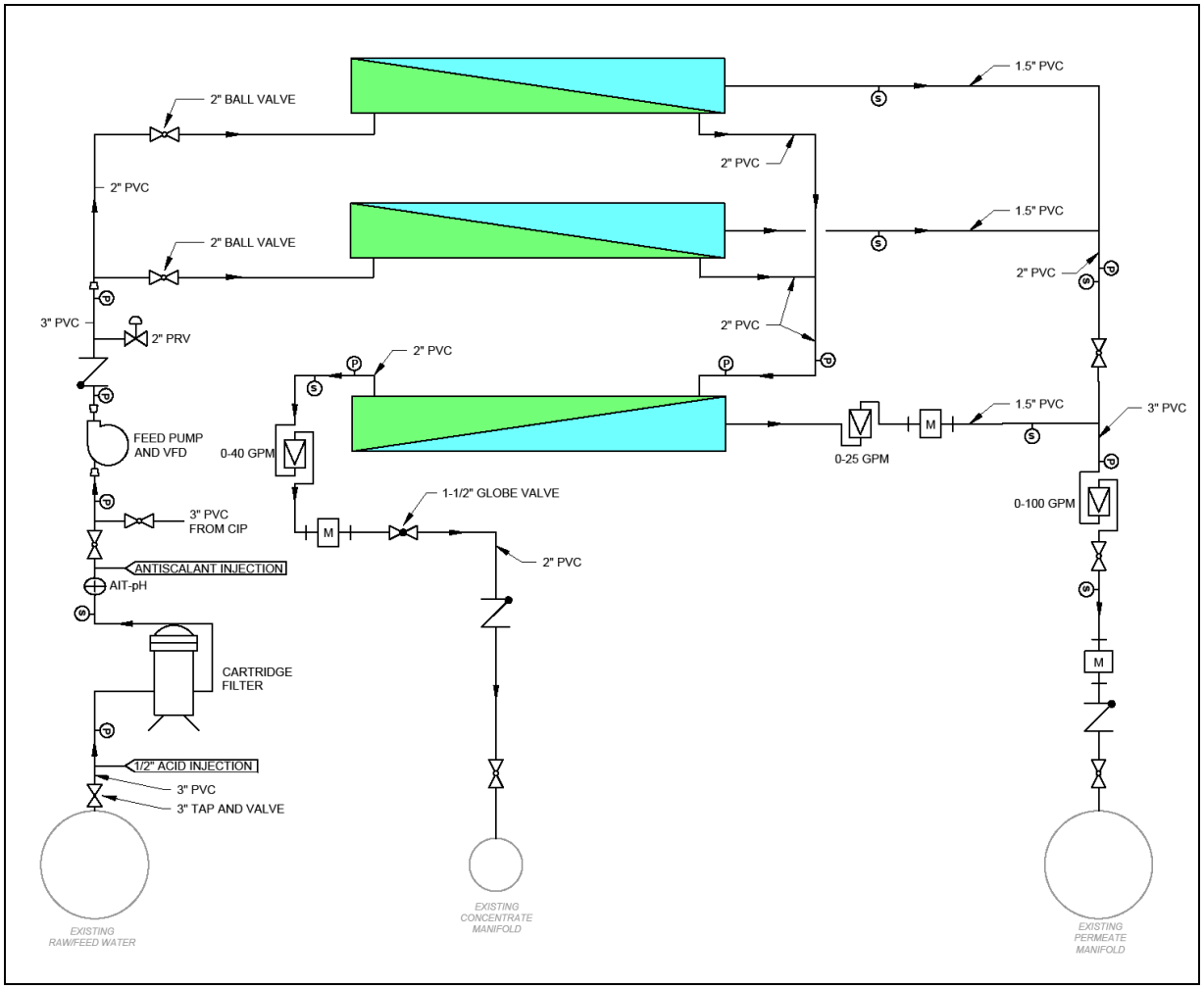
Constituent/Parameter	Existing Membranes (2009)	Replacement Membranes (2018)
Bicarbonate	25 to 75 mg/L	25 to 75 mg/L
Color	< 3 Color Units	< 3 Color Units
Total Dissolved Solids	< 250 mg/L	< 250 mg/L
Total Hardness	20 mg/L as $CaCO_3$	Min 25 mg/L as $CaCO_3$
Iron	0.25 mg/L	0.25 mg/L
Total Organic Carbon	< 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 2016, the City began planning to replace the membrane elements and were interested in investigating the possibility of reducing operating costs by taking advantage of advances in membrane technology to reduce power costs and eliminate chemical pretreatment of feedwater. As part of the City's membrane replacement plan, the City requested letters of interest (LOI) from three leading nanofiltration membrane element manufactures (MEM); Hydranautics, Dow Water and Process Solutions, Inc. (Dow), and Koch Membrane Systems, Inc. The City received responses from Hydranautics and Dow.

These LOI's requested membrane selections from the MEM's, in preparation for prequalification pilot testing of the proposed membrane selections from each manufacturer to verify that the membrane selections meet the City's specified permeate quality and membrane performance requirements, as presented in Table 2. Meeting these permeate quality and membrane performance requirements during pilot testing allowed the MEM's proposed membrane element selections to prequalify for installation in the City's full-scale NF process skids under the Nanofiltration Membrane Element Replacement Project.

To facilitate pilot testing the City designed, permitted, and constructed a pilot unit with full-size pressure vessels (8-inch diameter, 7-element) in a 2:1 array with independent cartridge filters and pre-treatment chemical feed systems. The pilot unit was permitted to withdraw feedwater from the NF process raw water header and discharge permeate and concentrate to the plant's respective headers. Figure 1 presents a schematic of the pilot test unit.

Figure 1 – Pilot Test Unit Schematic



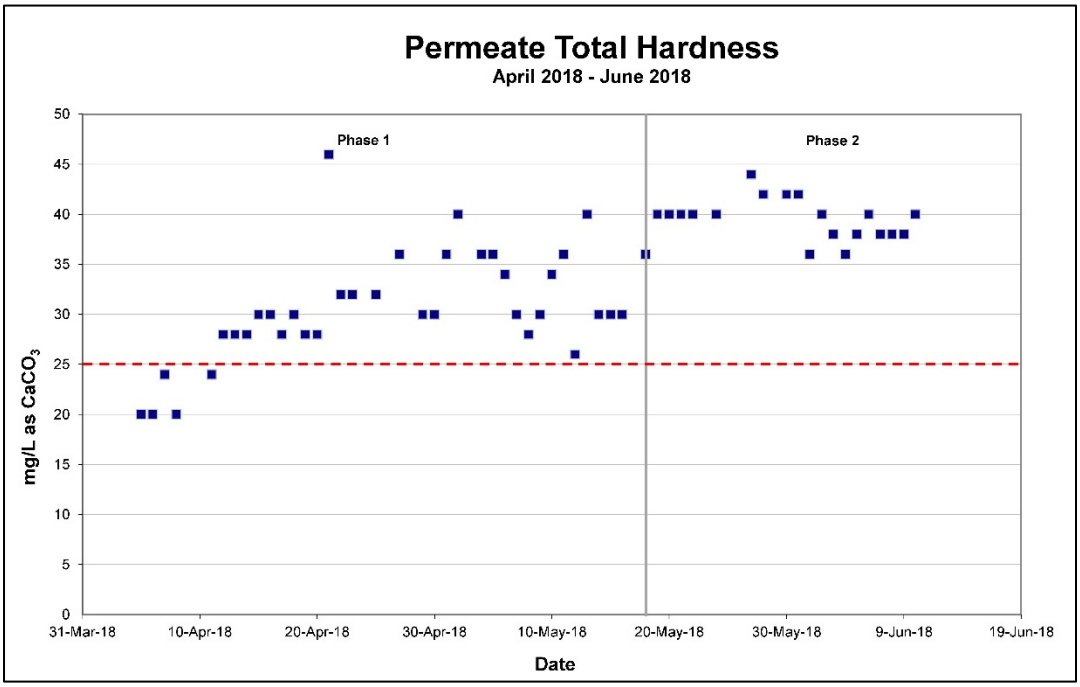
NF Membrane Pilot Testing

Pilot testing with the pilot unit was conducted in two phases. Phase 1 was aimed at confirming that the City could meet the specified permeate quality and membrane performance requirements with the replacement membrane elements under the current operating conditions of full-scale NF process (acid and antiscalant chemical pretreatment, 85% recovery rate, and 13.7 gfd average flux). The objective of Phase 2 was to evaluate the performance of the membrane selection and potential fouling tendencies under modified operating conditions (no chemical pretreatment, an 82% recovery rate, and a 12.2 gfd average flux). In general, the objective of Phase 2 of pilot testing was to evaluate the potential for stable operation without acid or antiscalant pretreatment under the subject modified operating conditions (i.e. essentially to reproduce the operating conditions of the nearby Boca Raton NF plant which has operated without acid or antiscalant pretreatment since 2005 under similar recovery rate and flux conditions).

Dow Testing

The initial loading configuration to start Phase 1 included all model NF90 elements in the first stage and three NF 270 elements followed by four NF90 elements in the second stage. As shown in Figure 2, this membrane element selection resulted in permeate hardness that was below the specified minimum of 25 mg/L as $CaCO_3$. All other parameters were within specification. As allowed under the Testing Protocol, Dow provided two additional NF 270 membrane elements (one spare) to adjust the loading schedule in the second stage to four NF270 element in the lead position followed by three NF 90 elements. The pilot plant was re-started on April 12, 2018. Phase 1 testing continued through the end of Phase 1 on May 17, 2018. During the remainder of the Phase 1 testing, all water quality and performance parameters were within compliance with the specifications, with the exception of the iron sample result on May 3, 2018 (0.26 mg/L). It should be noted, from April 12, 2018 through May 17, 2018, the second-stage specific flux, presented in Figure 3, showed a decline from 0.441 gfd to 0.375 gfd (approximately 15%), indicating some fouling in the second stage.

Figure 2 – Dow Permeate Total Hardness



Phase 2 testing commenced on May 19, 2018 with the following loading configuration: all model NF90 elements in the first stage and two NF 270 elements followed by five NF90 elements in the second stage. The pilot plant was re-started on May 19, 2018 under the new Phase 2 operating conditions. Phase 2 testing continued until June 10, 2018, throughout Phase 2 of testing, all water quality and performance parameters were within compliance with the specifications, with the exception of the iron sample results on May 18, 2018 (0.23 mg/L) and May 19, 2018 (0.21 mg/L). During the Phase 2 testing, permeate iron averaged 0.16 mg/L. Differential pressure and specific flux (Figures 4 and 5, respectively) remained stable throughout Phase 2 testing.

Figure 3 – Dow Permeate Iron

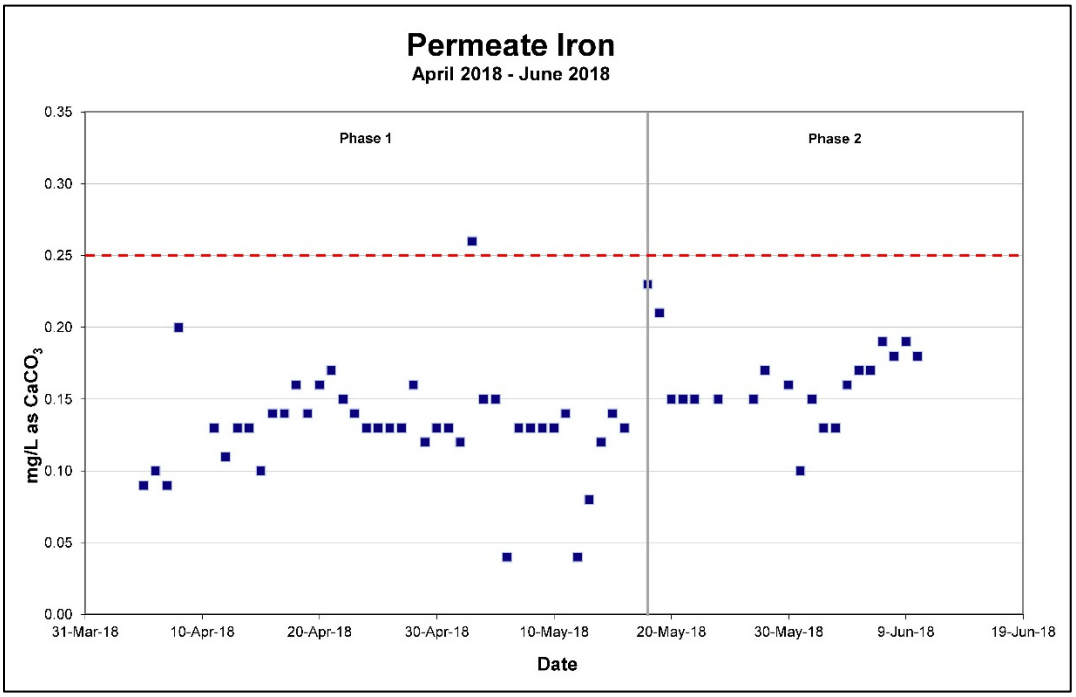


Figure 4 – Dow Differential Pressure

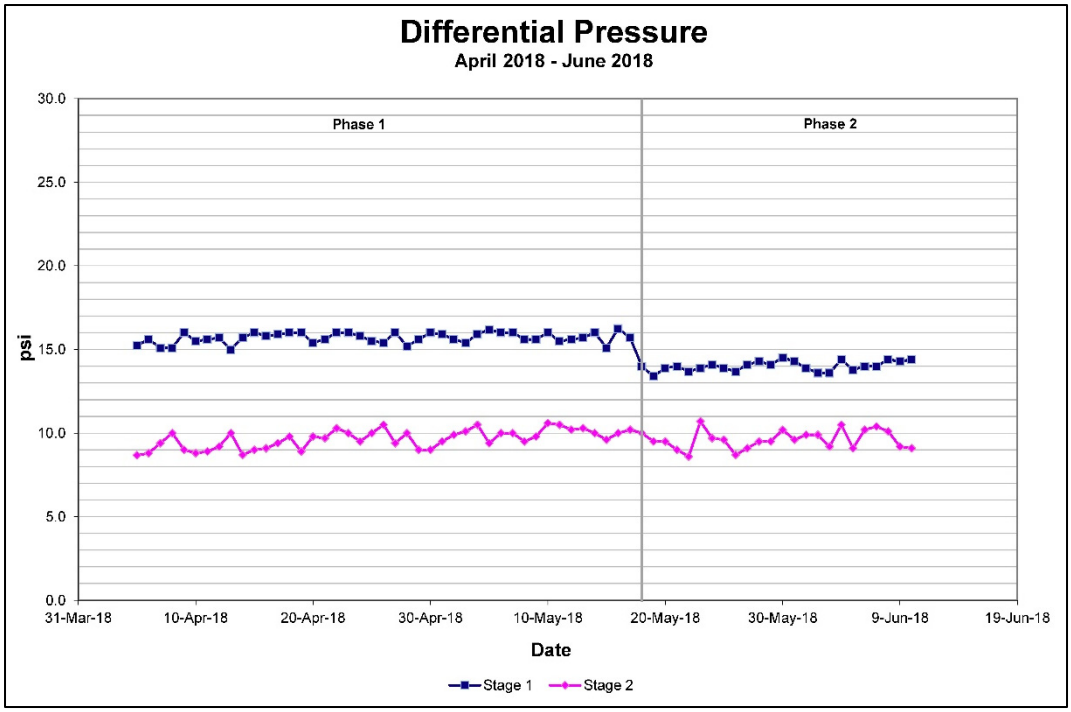
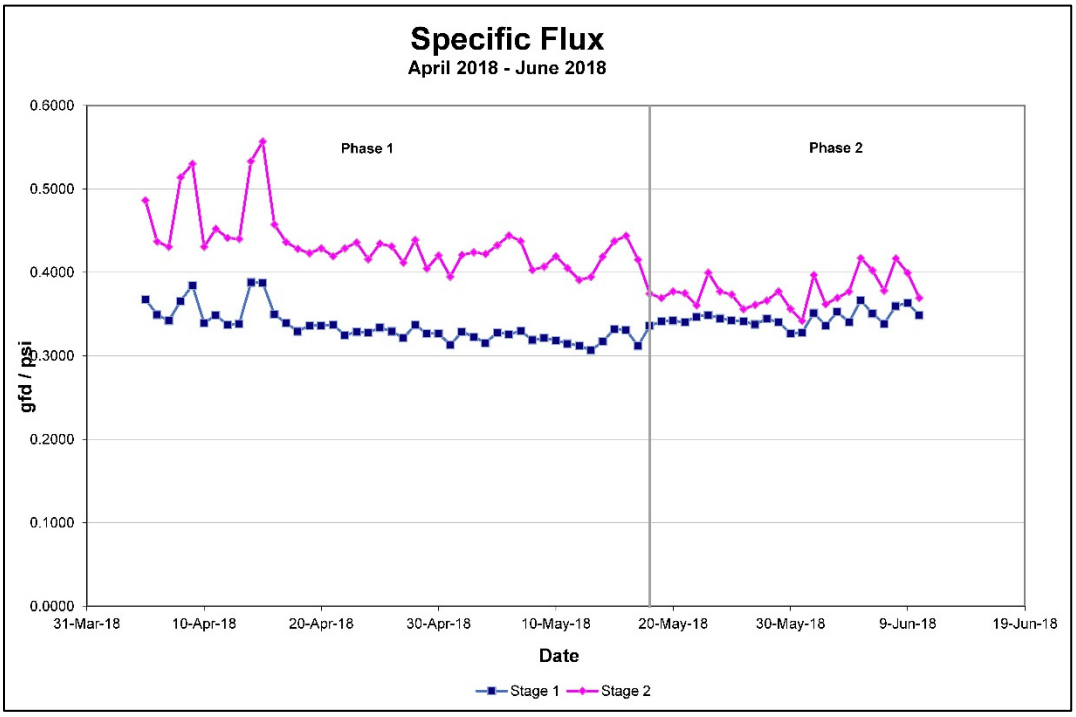


Figure 5 – Dow Specific Flux



Hydranautics Testing

Phase 1 pilot testing was performed from October 22, 2018 through November 27, 2018. During Phase 1 the pilot unit was populated with all model ESNA1-LF2-LD Hydranautics membrane elements in the first and second stages of the pilot unit. Throughout Phase 1 of pilot testing, all water quality and performance parameters were within compliance of the specified criteria, except for a total hardness sample on October 23, 2018 (24 mg/L as $CaCO_3$) and an iron sample on November 12, 2018 (0.20 mg/L). During Phase 1 testing the feed pressure, differential pressure, and specific flux (Figures 6, 7, 8, respectively) reflected stable operation.

Phase 2 of pilot testing began on December 5, 2018 and ended on January 25, 2019. During this phase (Phase 2A) the pilot unit was populated with Hydranautics membrane elements in the following configuration: six ESPA4-LD elements and one ESNA1-LF2-LD tail element in the first stage and all ESNA-LF2-LD elements in the second stage. Following the initial stabilization period (December 5 through December 10), throughout Phase 2 testing, all water quality and performance parameters were within compliance with the specifications and the feed pressure, differential pressure, and specific flux (Figures 6, 7, 8, respectively) continued to reflect stable operation.

Following Phase 2A, and with direction from the City, Hydranautics was authorized to continue pilot testing with the same membrane configuration and modified operating conditions (Phase 2B). The pilot unit performed under these conditions between January 26, 2019 and August 14, 2019. Over this eight-month period the pilot unit met all specified permeate quality and performance parameters with the exception of total hardness on six days and iron samples on three days (Figures 9 and 10, respectively).

Figure 6 – Hydranautics Feed Pressure

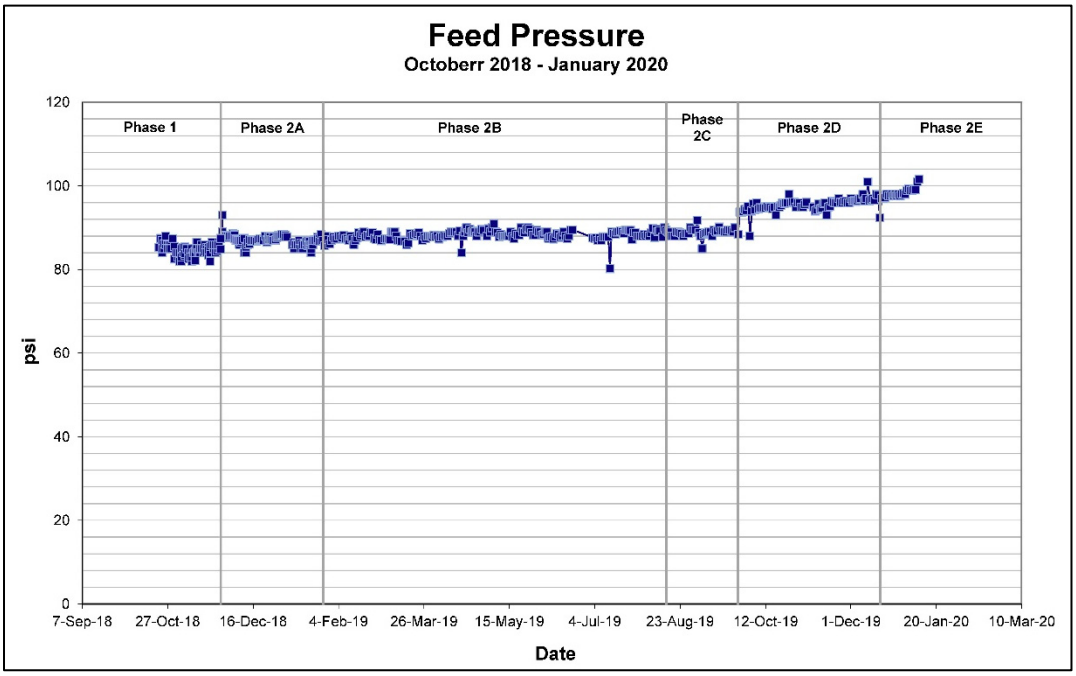


Figure 7 – Hydranautics Differential Pressure

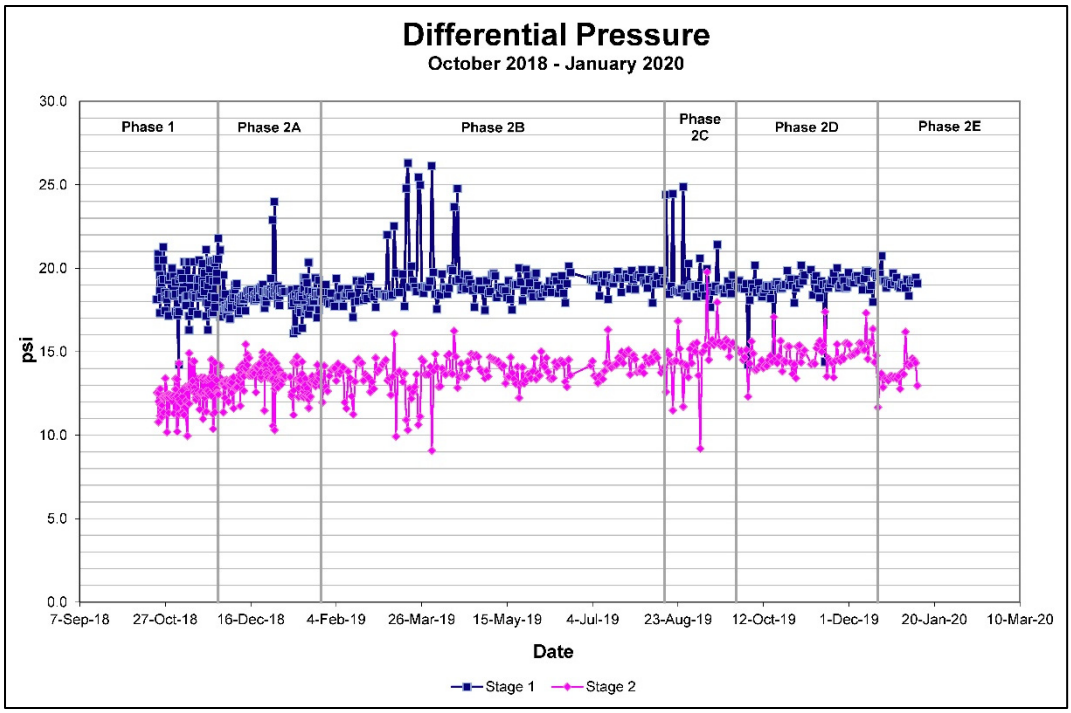


Figure 8 – Hydranautics Specific Flux

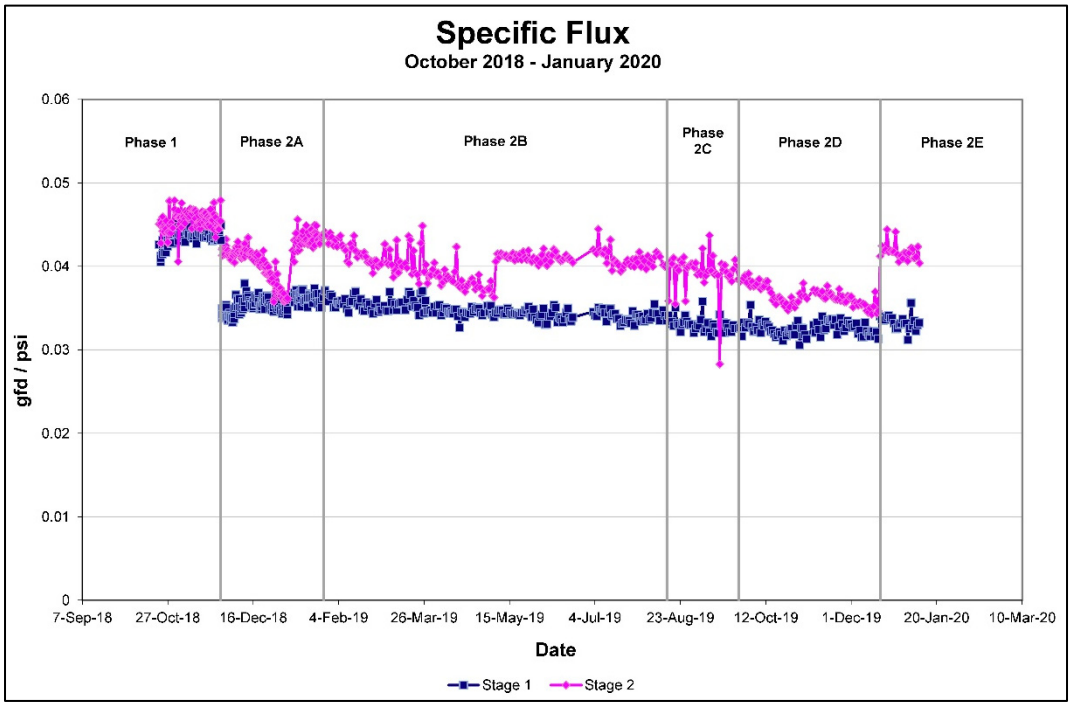


Figure 9 – Hydranautics Permeate Total Hardness

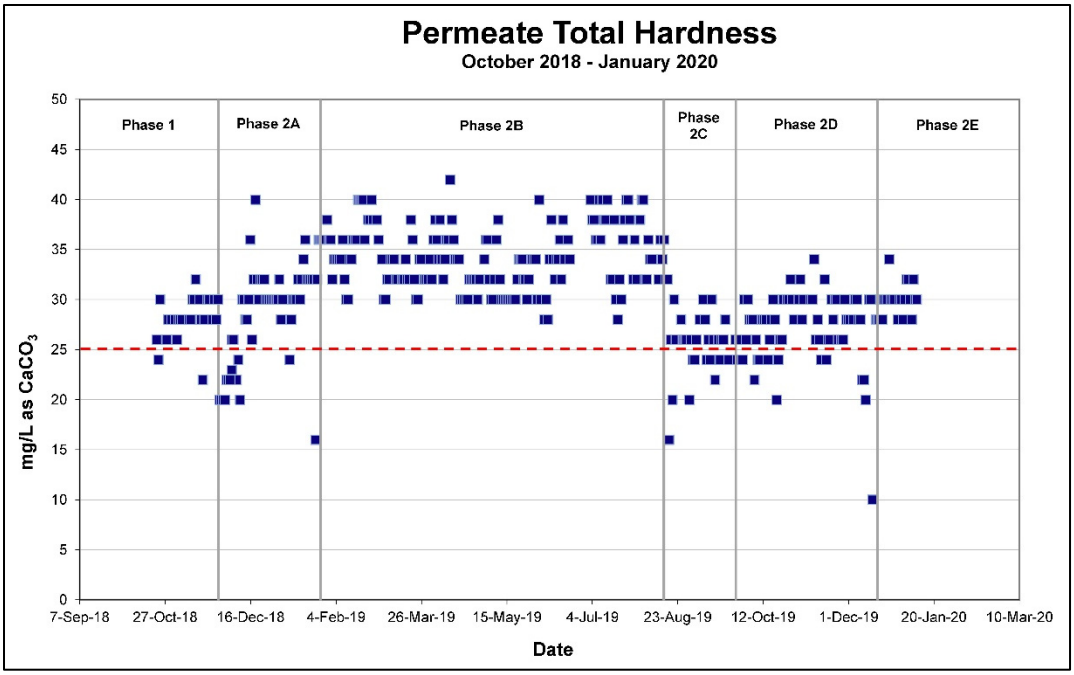
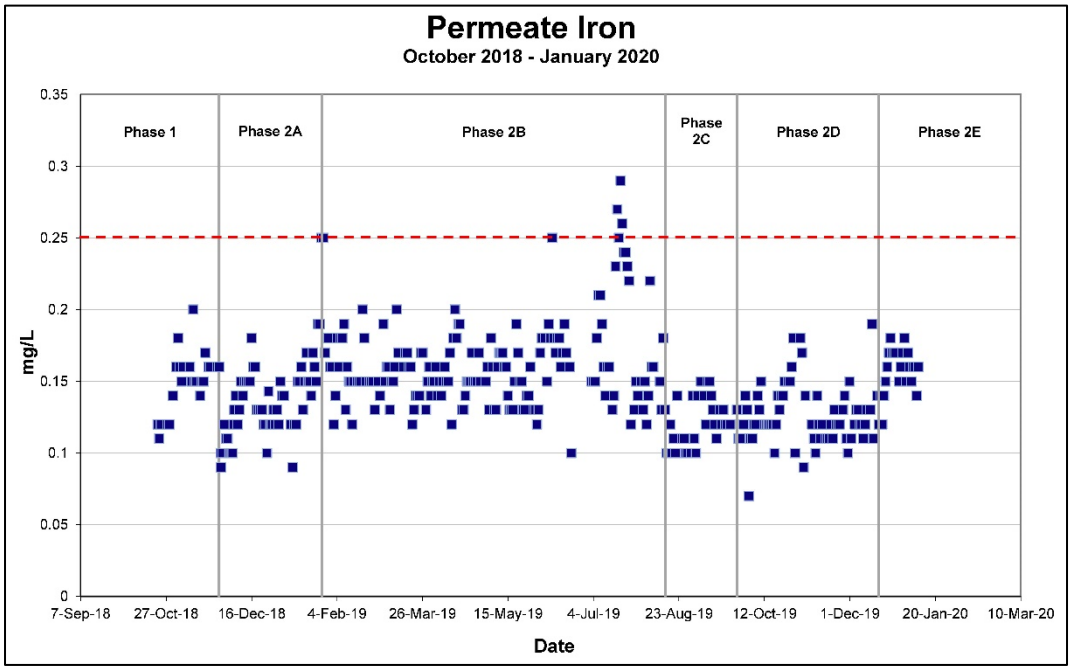


Figure 10 – Hydranautics Permeate Iron



With the exception of the marginally increased permeate total hardness and iron concentrations over the last few weeks of testing, the proposed Hydranautics membrane elements operating at the modified operating conditions met all permeate quality goals and reflected stable operation without chemical pretreatment. Comparing the Phase 2A start-up conditions to the averages over the last week of Phase 2B operation, the first stage feed pressure increased by 1%, the first and second stage differential pressure increased by 8% and 11% respectively, second stage specific flux decreased by 1%, and there was no change observed in the first stage specific flux since start-up without chemical pretreatment. It should be noted that during this eight-month period of runtime no cleanings were performed on the elements populating the pilot unit, exceeding the City's existing membrane elements with respect to runtime between cleanings (seven months).

Following the completion of Phase 2B, the City continued pilot testing to attempt to further optimize the permeate quality by modifying the element selection. On August 15, 2019, with assistance from Hydranautics, the configuration of the pilot unit's first stage was modified (Phase 2C) to be all ESPA4-LD membrane elements (in-lieu of six ESPA4-LD followed by one ESNA1-LF2-LD tail element), the membrane element configuration in the second stage remained the same (all ESNA-LF2-LD elements). This configuration performed at the modified operating conditions (no chemical pretreatment, 82% recovery rate, and 12.2 gfd average flux) until September 26, 2019 and appears to have typically met the permeate quality and membrane performance criteria, except for permeate total hardness which failed to exceed the minimum specified concentration on ten of the forty-two days of testing, or 24% of the test period. This indicates that the new ESPA4-LD first stage tail element increased hardness rejection from the first stage of the pilot unit, as evidenced by the sharp decrease in first stage permeate conductivity and salt passage (Figures 11 and 12, respectively) that occurred immediately after the new membrane element was installed. It is expected that over time the membrane

performance will continue to stabilize and the permeate conductivity, hardness, and iron concentration will consistently meet the specified requirements.

Figure 11 – Hydranautics Permeate Conductivity

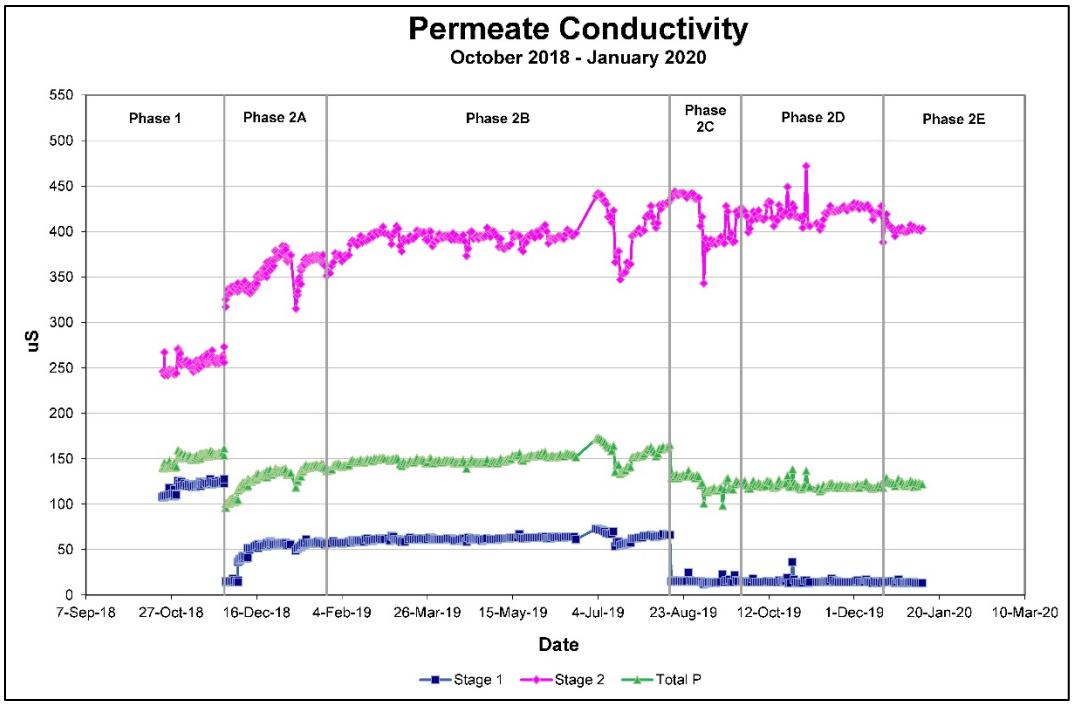
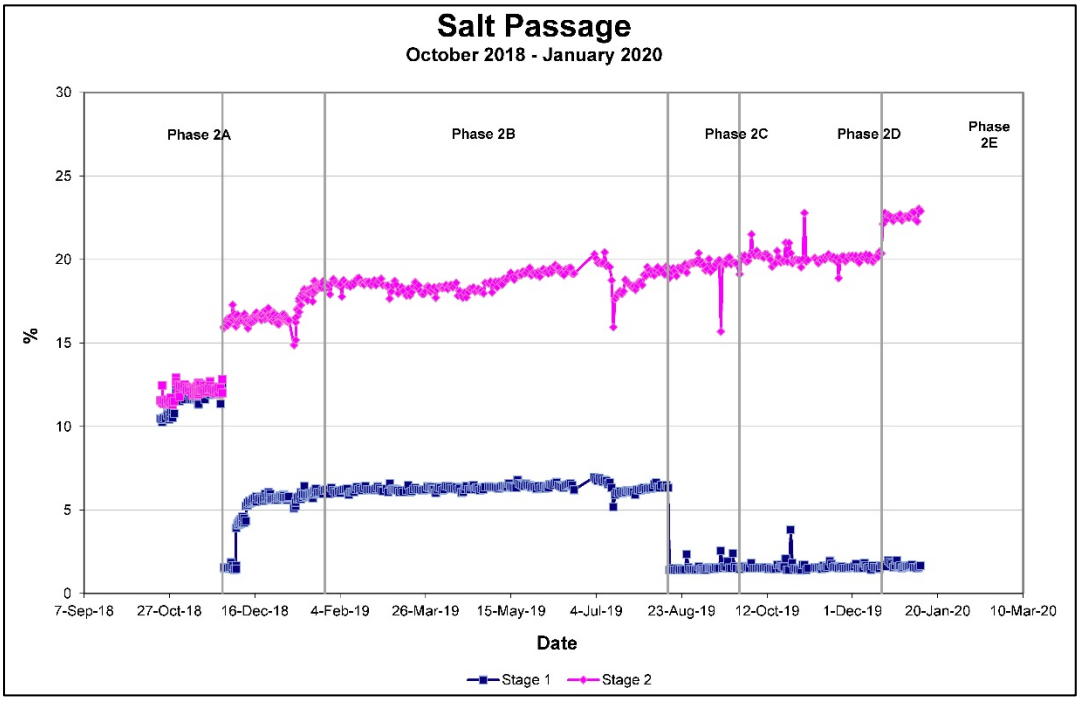


Figure 12 – Hydranautics Salt Passage



Comparing the Phase 2A start-up conditions to the averages over the last week of Phase 2C operation (42 days), the feed pressure increased by 1%, the first and second differential pressure increased by 7% and 18% respectively, and the first and second stage specific flux both decreased by 5%. The City was satisfied with the pilot unit's performance and permeate quality under the previously outlined modified operating conditions and directed Hydranautics to continue pilot testing without chemical pretreatment while incrementally increasing average flux and recovery rates to ultimately determine if the new membrane elements could meet specified permeate quality and membrane performance requirements at the current operating conditions of full-scale NF process stream (85% recovery and 13.7 gfd average flux) without chemical pretreatment.

Between September 27, 2019 and December 18, 2019, the pilot unit was operated at an 82% recovery rate with an average specific flux of 13.0 gfd (Phase 2D). It should be noted that during this time no cleanings had occurred and that the membrane element configuration in the pilot unit had remained unchanged since Phase 2B. As evidenced in Figures 8 and 9, the pilot unit appears to be producing permeate with similar quality as the last phase of testing. The permeate total hardness did not exceed the minimum specified concentration on thirteen of the eighty-two days of testing, or 16% of the test period. Comparing the Phase 2A start-up conditions to the averages over the last week of Phase 2D operation, the feed pressure increased by 11%, the first and second stage differential pressure increased by 9% and 16% respectively, and the first and second stage specific flux decreased by 7% and 9% respectively. The data indicates the membrane elements will continue to meet the specified permeate quality and membrane performance requirements as fouling occurs.

Based on the performance parameters of the pilot unit at the end of Phase 2D the City, with assistance from Hydranautics, elected to perform a cleaning on the membrane elements populating the pilot unit. On December 17, 2019 the pilot unit was cleaned with a sodium chloride, sodium hydroxide, and detergent solution at a pH of 11.0, flushed with permeate, and then filled with permeate and left to soak overnight. The next day it was cleaned with hydrochloric acid, flushed with permeate, and then placed back into service under Phase 2D operating conditions temporarily until the pilot unit's recovery rate was increased to 83% with an average flux rate 13.7 gfd (Phase 2E).

Phase 2E of pilot testing formally began on December 19, 2019 and is currently underway. The data presented herein is through January 10, 2020. When comparing the Phase 2A start-up conditions to the averages over the most recent week of Phase 2E operation the feed pressure increased by 13%, the first and second stage differential pressure increased by 7% and 9% respectively, the first stage specific flux decreased by 3%, and the second stage specific flux increased by 1%. Considering the improvements to the performance parameters associated with the recent cleaning event and the short window of testing, it is too early to determine if the Phase 2E operating parameters are feasible for implementing long term on the full-scale NF process stream. However, the pilot unit appears to be performing relatively well. So far both the permeate iron and total hardness concentration have consistently conformed to the specified permeate quality requirements. The City will continue to monitor the pilot unit's performance and modify its operating conditions to further optimize the performance of the membrane elements without the use of chemical treatment.

It should be noted that, based on the data provided, the most significant change in the membrane performance parameters occurred when the average flux rate was increased from 12.2 gfd to 13.0 gfd during Phase 2D of pilot testing and again when it was increased to 13.7 gfd during Phase 2E, as evidenced in Figures 6 through 8. The more prominent increases and decreases in differential pressure and specific flux, respectively, during both Phase 2D and 2E of pilot testing indicate that both flux and recovery rate are critical factors affecting the stability of operation without chemical pretreatment with this this raw water supply.

NF Membrane Element Replacement

Based on the results of pilot testing, the membrane elements provided by both MEM's met the specified permeate quality and membrane performance requirements which prequalified the proposed membrane element selections for installation in the City's full-scale NF process skids under the Nanofiltration Membrane Element Replacement Project. In May 2019 the City advertised bid documents for this project and following evaluation of bid packages, Hydranautics was identified as the low bidder.

The City issued the Notice to Proceed to Hydranautics in December 2019 to commence work on the Nanofiltration Membrane Element Replacement Project. Under this project Hydranautics will furnish and install 1,827 membrane elements in the same configuration and operating conditions as Phase 2C of pilot testing. Upon completion of this project the first stage pressure vessels of the full-scale NF process will be populated entirely with ESPA 4-LD membrane elements, the second stage vessels will be populated with all ESNA-LF2-LD elements. The City intends to operate the full-scale NF process at an average flux of 12.2 gpd, a recovery rate of 82%, and without any chemical pretreatment. Future adjustments to these operating parameters may be made based on the findings of ongoing pilot testing.