THE FIRST U.S. INSTALLATION OF A BWRO PRESSURE EXCHANGER

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Abstract

Energy recovery technologies such as the pressure exchanger (PX), have previously focused on seawater RO applications due to the rather quick payback. This leaves brackish water RO (BWRO) facilities to turbochargers that yield less efficient transfer of energy than their PX counterparts. Recently, the first municipal BRWO application of a PX energy recovery device was designed for the City of North Port, Florida's Southwest Water Treatment Plant and will be started up in 2nd quarter 2022.

This greenfield facility currently has a raw water TDS of about 3,500 mg/L and is anticipated to experience raw water quality degradation based on predictive groundwater modeling. The City's vision for facility includes long-term resiliency and longevity which drove the team to design a wide range of TDS from the aquifer supply including future TDS levels of nearly 13,000 mg/L. This anticipated increase in TDS levels drives careful design, operations, and equipment considerations. More specifically, the energy load for the facility jumps dramatically over the degradation of water quality. The design team sought out opportunities to reduce overall operation expense through PX integration in the high salinities and the first of its kind, low TDS early stages of the facility. These complexities will be identified in the paper as well as a large focus on the PX integration at both low brackish water and into seawater salinities. With feed pressures ranging from 200 psi to 520 psi, the PX offered a significant energy saving opportunity.

An overview of the PX operation will be included to orient the audience with the benefits and drawbacks identified for both seawater and this brackish water application. The integration into a BWRO process varies significantly from the seawater application. Accordingly, the paper will describe the challenges of implementing PX devices into brackish systems and functionality required to ensure the system will achieve the proper operation. A detailed dive into the instrumentation, connectivity of the hydraulics and water quality relationship will be discussed as it varies dramatically from the traditional seawater application. Once the hydraulics and instrumentation items are addressed, the paper will tackle the major benefits of integrating the PX into a BWRO system including:

- Approximately 20% (or more) reduction in membrane feed pump flow, resulting in reduced feed pump horsepower and total dynamic head
- Reduced energy requirements
- Reduced capital and operating costs

This will be the first Brackish Water municipal installation of the Brackish pressure exchanger within the U.S. This paper will present and discuss the design considerations and key parameters including impacts to RO system operation and water quality, energy saving considerations, and data from the facility startup in 2^{nd} quarter 2022. Municipalities with brackish-water supplies will be shown the way to reduce operating costs and maintain water quality from their RO treatment facility.

Introduction

City of North Port, Florida's Southwest Water Treatment Plant is a designed 2.0 MGD Reverse Osmosis (RO) greenfield facility that is under construction and will be started up in the 2^{nd} quarter of 2022. The facility was designed with a total of two RO skids each with a 2:1 array capable of producing 1.0 MGD at 80% recovery and housing brackish water elements. To account for future demands, the skids were designed with the capability to expand the number of vessels within the first and second stage to a total production capacity of 2.5 MGD of permeate each. Post treatment is comprised of degasification, carbonization and pH adjustment for alkalinity addition, calcium chloride injection, and disinfection.

The facility will be serviced by raw water wells with TDS levels of about 3,500 mg/L at the initial startup condition. Due to nearby located well degradation, these wells are anticipated to experience raw water quality degradation from saltwater intrusion based on predictive groundwater modeling. The City's vision for the facility includes long-term resiliency and longevity which drove the design team to provide flexibility with a wide range of raw water TDS from the aquifer supply including future TDS levels of nearly 13,000 mg/L. This anticipated increase in TDS levels drives careful design, operations, and equipment considerations due to a wide range of operating conditions. More specifically, the energy load for the facility jumps dramatically with the degraded water quality requiring increased operational pressures and overall operational costs. As a result, the design team sought out opportunities to reduce overall operation expense through the integration of an energy recovery pressure exchanger (PX), that will integrate anticipated future pressures from high salinities, while meeting the expected pressures of the low TDS levels in early stages of facility operation. The implementation of this PX unit will be first Brackish reverse osmosis application installed within a United States municipality.

Overview of Energy Recovery Devices for BWRO

Traditional energy recovery devices used within brackish RO facilities are typical pelton wheel style recovery turbos. However, based upon anticipated increases in feed pressures and, several operational conditions a traditional turbocharger was not capable of providing the full boost pressure necessary to feed the second stage in future conditions. In coordination with Energy Recovery, Inc. (ERI) the equipment provider, it was determined that a PX would best suit future operations as well as provide a significant energy reduction during the early operations of the facility. ERI supplies the pressure exchangers (PX) and turbochargers that are further discussed in this paper.

Pressure Exchanger:

The Pressure Exchanger (PX) energy recovery device facilitates pressure transfer from the high-pressure brine reject stream to a low-pressure seawater feed stream. It does this by putting the streams in direct, momentary contact within the ducts of a rotor. The rotor is fit into a ceramic sleeve between two ceramic end covers with precise clearances that, when filled with high-pressure water, create an almost frictionless hydrodynamic bearing. The rotor spinning inside the hydrodynamic bearing is the only moving part in the PX device.

At any given instant, half of the rotor ducts are exposed to the high-pressure stream and half to the low-pressure stream. As the rotor turns, the ducts pass a sealing area that separates high and low pressure. Thus, the ducts that contain high pressure are separated from the adjacent ducts containing low pressure by the seal that is formed with the rotor's ribs and the ceramic end covers.

Figure 1 illustrates the typical flow path of a PX energy recovery device in a brackish RO system. The booster pump will boost the pressure of the first stage concentrate flow to increase the flux of the second stage and endure that the second stage concentrate pressure is higher than the pressure at location (K) by 15-20 psi. The reject brine from the brackish RO membranes (J) passes through the PX unit, where its pressure is transferred directly to a portion of the incoming raw feedwater at up to 97% efficiency. This pressurized feedwater stream (K), flows to the first stage membrane feed, and the associated piping.

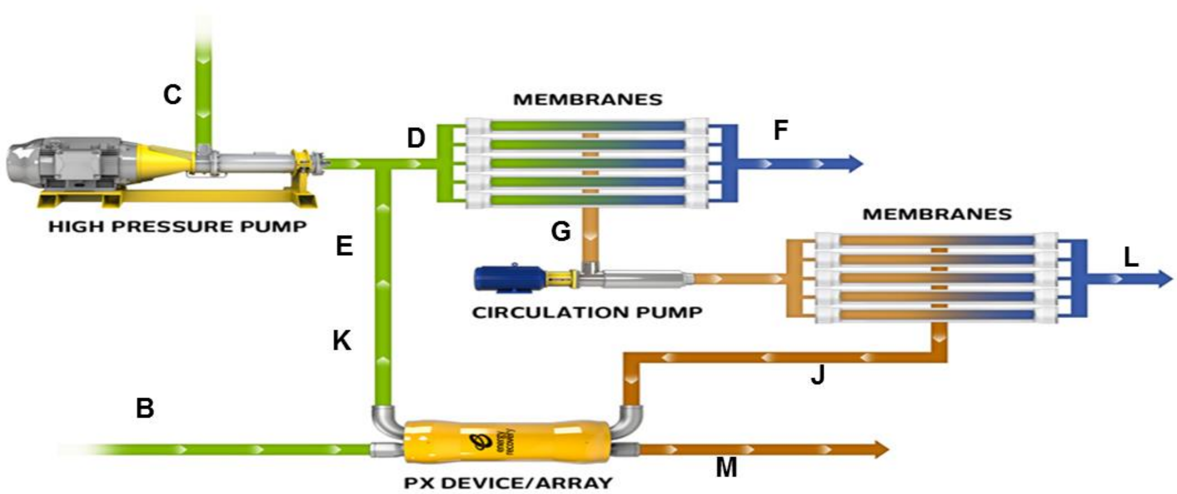

Figure 1. Typical PX device Installation for 2-stage BWRO

The majority of two stage brackish RO conventional designs require permeate backpressure, hybrid membrane designs or an insterstage booster pump to balance the flux in each stage. For this specific project, the best solution was to use an interstage booster pump in addition to an energy recovery device. The engineering team was required to design the brackish RO system to operate in a large operational envelope (3000 – 13000 ppm); one of the largest challenges is to find equipment that can operate inside the entire operational envelope.

Turbochargers:

The turbocharger device recovers hydraulic energy from the high-pressure concentrate (brine) stream in the reverse osmosis (RO) process and transfers that energy to a feed stream. That feed stream may be seawater going into a single stage RO membrane block, or it may be first stage brine stream being boosted in pressure for a second stage membrane block for further recovery of permeate or flux balancing.

The turbocharger device consists of a pump section and a turbine section shown in **Figure 2**. Both pump and turbine sections each contain a single stage impeller. The turbine impeller extracts hydraulic energy from the brine stream and converts it to mechanical energy. The pump impeller converts the mechanical energy produced by the turbine impeller back to pressure energy in the feed stream. Thus, the turbocharger is entirely energized by the brine stream. It has no electrical requirements, external lubrication, or pneumatic requirements.

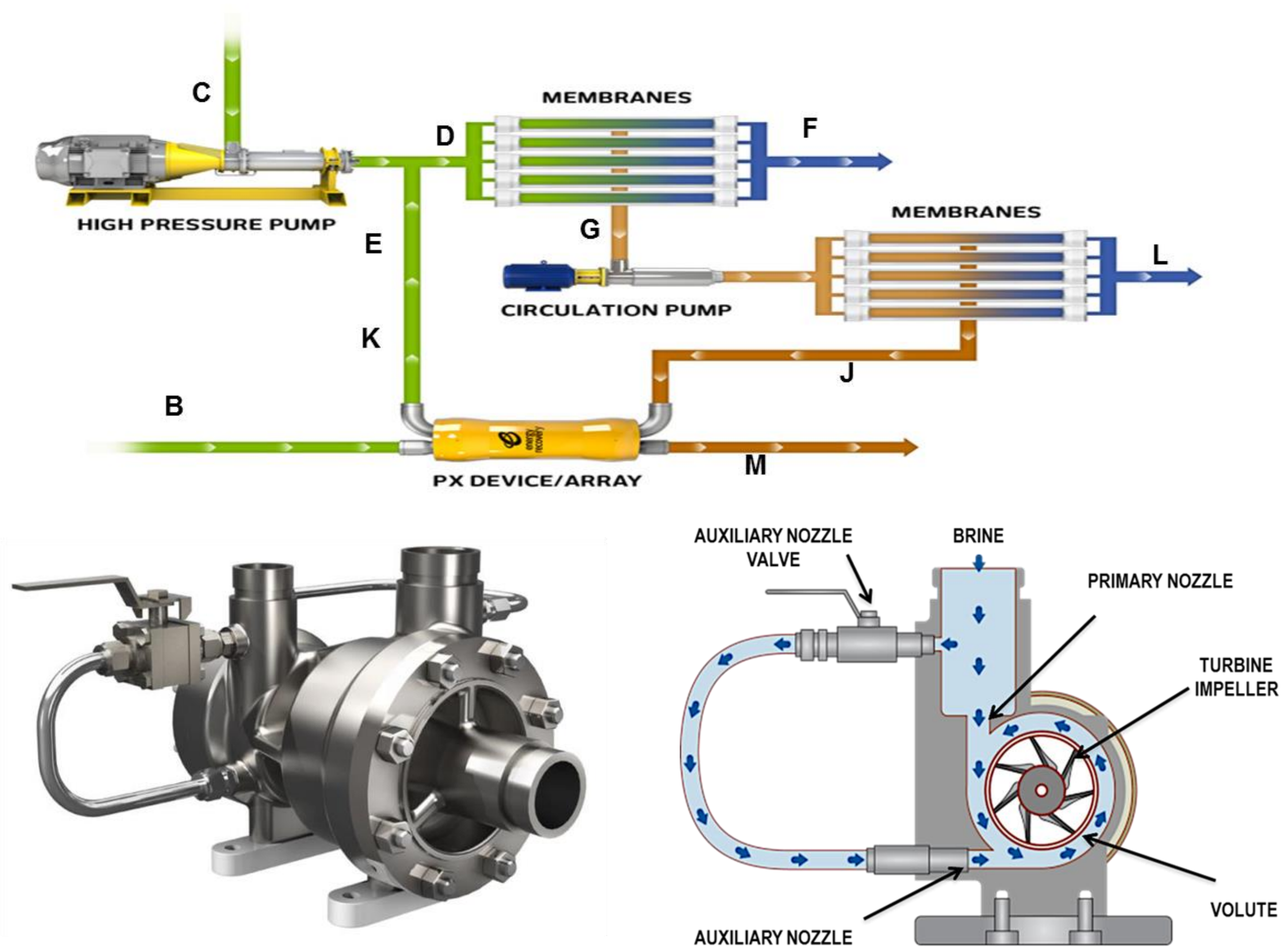

Figure 2. Turbocharger Depiction

Figure 3 illustrates how the turbocharger works as an interstage pressure booster in a 2-stage RO system. The turbocharger device is designed to produce a pressure boost in the RO feed stream (3 & 4) using the hydraulic energy available in the brine stream (5). The brine water from the 1st Stage passes through the turbocharger which provides the required interstage pressure boost (3-4). The water then enters the 2nd stage membrane pressure vessels (4). A percentage of the 2nd stage feed water exits the membrane as permeate. The rest exits as high-pressure brine (5). The 2nd stage brine passes through the turbocharger which extracts the pressure energy (5-6). The 2nd stage brine leaves the turbocharger at low pressure for disposal (6).

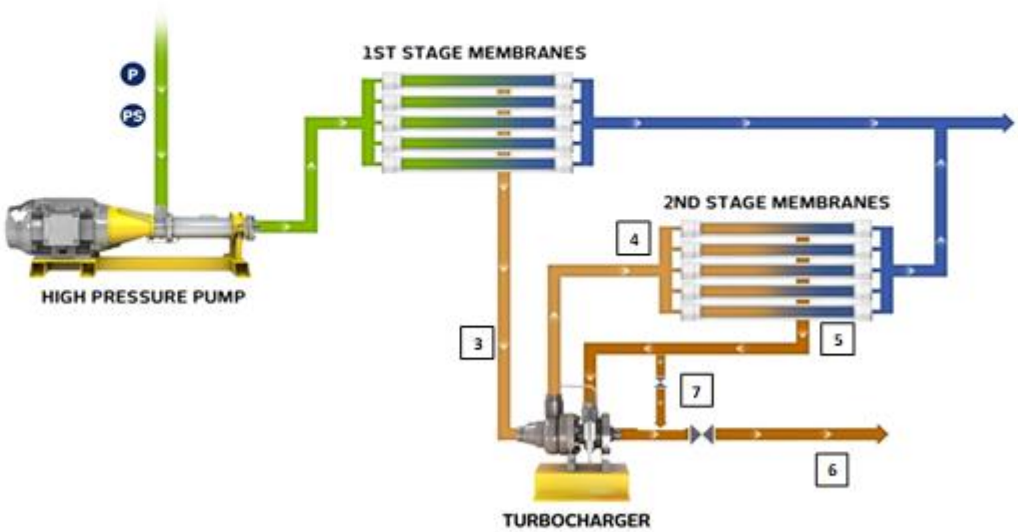

Figure 3. Typical turbocharger Installation for 2-stage BWRO

The main challenge is to select equipment with the capacity to operate at all conditions.

Operational Challenges with Energy Recovery Devices

The BWRO system have been designed to operate for four operational points.

- Fist stage membrane feed pressure between 207 psi to 520 psi
- Second stage feed pressure between 256 psi to 650 psi
- Second stage feed flow between 338 gpm to 998 gpm
- Second stage brine flow between 174 gpm to 580 gpm.

Turbochargers:

- Efficiency: Efficiency peaks at a specific flow and pressure (Commonly known as Best Efficiency Point) ; any variations decrease efficiency significantly.
- Performance: Looking at the turbo performance curves, it can be inferred that changes in Flow or pressure in the turbine side will change the boost
- RPM: The turbocharger is a high-speed centrifugal device that requires to operate a high RPM (Over 10,000 RPM) to keep high efficiency.
- Boost control: It is not possible to control the boost because it depends on operational conditions. It can be reduced by using a control valve or it can be increased by using a external booster pump.
- Multiple operational points: The turbocharger device bypass valve shown in **Figure 3** (Stream 7) is typically installed when a wide operating range of system pressures are expected, such as in brackish water applications. As the system operating pressure varies, the available brine pressure may not be enough to drive the required amount of brine flow through the primary turbine inlet nozzle, shown in **Figure 2**. The auxiliary nozzle valve acts as a variable orifice but in some cases may not be sufficient in obtaining the desired flow. The bypass valve is then used to obtain the desired flow by diverting a small amount of the main flow from the Turbocharger device turbine inlet (7) to the brine exhaust (H). The bypass valve (I) can also be used to facilitate the fresh water flush sequence, which is typically conducted at lower pressures. The bypass implies that some of the high pressure concentrate energy will be lost. Furthermore, with a bypass extra instrumentation and equipment is required to control the system.

PX devices:

- Efficiency: Efficiency is less affected by pressure, but if anything tends to increase as pressure increases. Device can be run at any point on their curve without efficiency loss. Pressure losses in the PX don't depend on the operating pressure and pressure losses are constant for a given flow rate.
- Performance: Looking at the performance curves, as the PX device is a positive displacement device the flow and pressure are not directly related. The PX can operate a constant flow for variable pressure conditions.
- RPM: The PX device operates RPM over 1000 RPM
- Boost Control: Using the interstage booster pump with a VFD
- Multiple operational points: Because the PX device operational flexibility, the Efficiency curve is almost flat and the PX can easily accommodate several operational points within the operational envelope of the PX devices without extra auxiliar equipment or instrumentation.

Hydraulics, Instrumentation, and Water Quality

In order to meet desired operational recoveries, RO facilities are operated around flow set points for production with pressure usually adjusting to meet the flow conditions. This is traditionally, done with monitoring second stage and total permeate flow, and final concentrate flow. In addition, first and second stage feed pressures, first and second stage concentrate pressures, and final permeate and concentrate pressures are monitored. With the installation of a PX device these same parameters are monitored and controlled. Since the PX unit utilizes high pressure concentrate water to hydraulically boost low pressure raw water, the boosted raw water is the same pressure as the second stage concentrate which is higher than what is supplied by the membrane feed pump. To hydraulically balance the system, a throttling valve and flow monitoring element is needed downstream of the PX raw water outlet to throttle pressures and control flow to match that of the membrane feed pump discharge. To automatically adjust throttling based upon variations in pressures integration of this valve into SCADA is required. As previously mentioned with the installation of turbocharger devices, the addition of a bypass valve upstream of the turbocharger is needed to tailor boost operations and extra instrumentation incorporated into SCADA for monitoring and control. With the use of a PX unit an additional bypass valve is not needed.

Facility Impacts

At the onset of design for this facility, it was determined that water quality degradation of the raw water wells would increase similar to the degradation curve for nearby water supply wells. Data collected from the historical water quality predicts a nearly 370% increase in salinity within the first 10 years of operations as shown in **Figure 4**. The historical well data shows a 20% rate of decline per year which was utilized to project the salinity degradation of the Southwest WTP water quality. As anticipated, the higher salinity impacts the design and operating considerations for multiple components of the facility. Major facility impacts include, but are not limited to:

- Increased membrane feed pressures over time
- Increased capital costs to account for larger horsepower requirements for membrane feed pumps
- Increased operational expenses from energy demands at higher feed pressures
- More complex materials selection matrices for wetted metal components

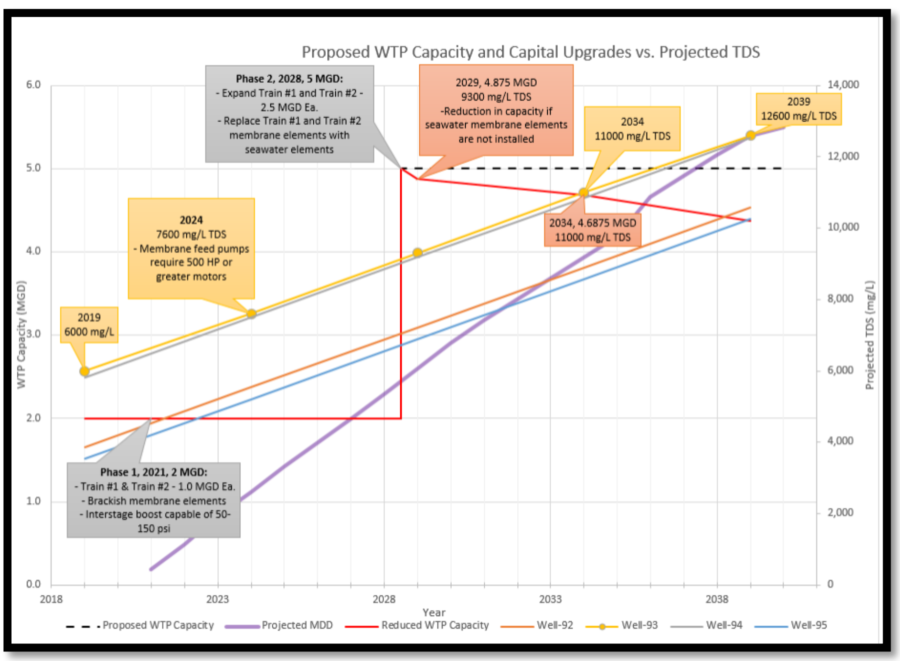

Figure 4. Raw Water Quality Degradation

Tailoring these anticipated improvements, workshopping options with the equipment provider to find the most efficient energy recovery device, and aligning all operating conditions has identified a significant energy savings to the Facility operation. Moreover, a reduction in water supply withdrawal for the same production capacity, reduced pump horsepower, and decreases in overall capital and operational costs have and will be realized by the owner. Specific impacts on the design are identified by the following:

- Approximately 20% reduction in membrane feed pump flow, resulting in a minimum reduced horsepower of 33 HP
- Reduced energy requirements providing minimum operating expense savings of $11,680 per year
- Estimated $95,000 reduced capital savings for pump motor, conduit, switch gear and additional components

Feed Flow Reduction and Pump Requirements

An advantage to PX units is the reduction in membrane feed pump size required to operate the RO system. Transferring hydraulic energy from the second stage concentrate, to raw water within the first stage feed enables flow to be boosted at or above the first stage feed pressure. This ~20% reduction in feed pump flow required to be pumped reduces the overall size of the pump by a minimum of 33 horsepower. Membrane and energy recovery projections were produced throughout the project with the following the minimum and maximum flows and TDS levels in the following cases:

1) 1.0 MGD permeate production at 3,500 mg/L TDS
2) 1.0 MGD permeate production at 13,000 mg/L TDS
3) 2.5 MGD permeate production at 6,250 mg/L TDS
4) 2.5 MGD permeate production at 13,000 mg/L TDS

The membrane projection pressures and flows are shown in **Table 1**, which were used as the starting point for the PX/RO integration design iterations.

Table 1. Membrane Projection Pressures and Flows

Cases	TDS (mg/L)	1st Stage (psi)	Boost (psi)	2nd Stage (psi)	Total Raw Water Feed Flow (gpm)	Membrane Feed Pump Flow (gpm)	PX Boosted Flow (gpm)	% Reduction of Membrane Feed Pump Flow
1	3,500	207	52	247	868	695	173	20
2	13,000	277	107	373	868	695	173	20
3	6,250	278	117	384	2170	1739	431	20
4	13,000	520	147	649	2,315	1743	572	24

As shown in the table, startup projections indicate a 20% reduction in membrane feed pump flow due to the PX's capability to boost 173 gpm of raw feed. With a feed pressure of 207 psi, this reduces the required membrane feed pump motor demands by approximately 33 HP at startup. A reduction of membrane feed pump flow in Case 2 (13,000 mg/L TDS with 1 MGD permeate production) leads to a HP reduction of 108. In future Case 3, a 120 HP reduction is achieved. At the highest TDS value and permeate production in future year projections a 24% reduction in membrane feed pump flow is achieved with the PX boosting 572 gpm of raw water. This results in a 270 HP feed pump motor demand reduction. A summary of HP reduction for each case is provided within **Table 2**.

Table 2. Feed Pump HP Reduction

Cases	TDS (mg/L)	Feed Pump HP Reduction
1	3,500	33
2	13,000	108
3	6,250	110
4	13,000	270

Reduced Energy for Operation

An advantage to PX units is the reduction in energy requirements needed to operate the RO membrane feed pump. Energy requirements for both the startup 1.0 MGD configuration and future 2.5 MGD configuration were calculated based upon the feed pump size reduction for the four sets of projections outlined above. Since the PX unit is augmenting pressurized feed flow to the first stage of the skid, an interstage booster pump was required for the project to achieve product flow through the Second Stage. Therefore, the total reduction in energy saved from the PX unit was calculated from the difference of energy reduced by the PX minus the energy needed for the interstage booster pump. This corresponds to an estimated 1.7 KW/KGal energy reduction during the first year of operations and a 4.2 KW/KGal energy reduction is estimated at future operations with a TDS of 13,000 mg/L.

Table 3. Operational Energy Reduction

Cases	TDS (mg/L)	Feed Pump HP Reduction	Feed Pump Energy Reduction (KW/KGal)	Total Operational Energy Reduction (KW/KGal)
1	3,500	33	2.3	1.7
2	13,000	108	5.84	4.6
3	6,250	110	3.17	1.8
4	13,000	270	5.9	4.2

Capital and Operational Costs

Reduction in both feed pump sizing and operational energy requirements provide capital and operational savings. Reduction in feed pump size by 20% provides an overall capital savings of

$95,000. This savings includes estimate equipment/material cost reductions for motor, conduit, motor switch gear, and motor control centers sizing. Additional savings due to wire size reduction, labor and other soft costs were not considered for this analysis. Total operational savings are provided within **Table 4**. Estimated costs were calculated assuming plant operations for 24 hours with energy costs of $0.12 per KWh. The savings values shown in the table reflect subtracting the interstage booster pump energy demands and assuming a 24-hour operations period.

Table 4. Operational Savings

Cases	TDS (mg/L)	Feed Pump HP Reduction	Savings Per Day	Savings Per Year
1	3,500	33	$32	$11,680
2	13,000	108	$140	$52,195
3	6,250	110	$36	$13,140
4	13,000	270	$290	$105,850

Design Considerations and Key Parameters

Degradation of feed water quality provides design and operational challenges for both current and future water quality conditions requiring a wholistic analysis of facility design. The flexible operating conditions impact key parameters of design that are required to meet the utility's current and future needs. These key parameters include consideration for the following:

- Membrane feed pressures – 1st and 2nd stage
    - Feed pump sizing
    - Overall operational recovery
    - Energy recovery efficiencies
    - Interstage feed pump sizing
- Energy recovery device selection
- Membrane element selection
- Reduced Permeate Water Quality
- Material selection for equipment, piping, and appurtenances
- Pressure vessel ratings

In order to capture the City's vision of long-term resiliency and longevity for the facility, a heavy emphasis in design was placed upon RO feed pumps and pressure vessels, energy recovery devices, membrane elements, and material selection of corrosion resistant alloys. In addition, a capacity and capital upgrades plan was created to assess trigger points on equipment upgrades or needed replacement. This enables the City to track the rate of raw water quality degradation against capital improvements to budget for necessary upgrades when needed. Resulting triggers where:

- Start up 2022 – install brackish membrane elements
- 3-4 years or TDS of approximately 7,600 mg/L – upsize membrane feed pump motor

- 6-7 Years or TDS of approximately 12,000 mg/L – replace brackish membrane elements with seawater elements and increase skid array with additional vessels

RO Pumps and Pressure Vessels

Membrane projections were run for various raw water quality scenarios resulting in wide range of feed pressures expected for the facility. Feed pressures ranged from 150 psi to above 500 psi, requiring corresponding pumps with 120 – 1,000 HP. This wide range in motor requirements incurs substantial capital costs and over design for the current facility's needs. Therefore, the resulting design incorporated the PX unit to provide an overall HP reduction and an appropriately sized motor that met pressure conditions for the first several years of operations. Once TDS values reach and exceed 7,600 mg/L, which is anticipated between 3-5 years of operation, the membrane feed pump motor will need to be upsized. Variations in feed pressures also impacted pressure vessel ratings for both the first and second stage. Current TDS levels provided feed pressures for both stages below 300 psi, however, due to water quality degradation first and second stage pressures exceed 300 and 600 psi respectively at TDS 13,000 mg/L values. To mitigate future capital expenses of purchasing higher rated pressure vessels, first stage pressure vessels were rated for 600 psi and second stage vessels were rated for 1,000 psi.

Membrane Elements

Based upon current raw water TDS levels and membrane projections, brackish water membrane elements were determined sufficient to meet the City's finished water quality goals. Should water quality degrade as predicted, the City will have to modify operational recoveries to 75% to adjust for increases in membrane feed pressures, or replace the brackish membrane elements with sea water elements. Based upon water quality degradation modeling the decline in recovery will occur around the six or seventh year of operation, which is typically the recommended time period to replace membrane elements. Therefore, switching to sea water elements after seven years of operation, provide the degradation occurs, will allow the facility to maintain permeate production while improving water quality. These membrane change outs are scheduled after a good portion of the useful life has been consumed. As for the equipment, vessels, piping, and valves are all designed for future conditions requiring no additional capital investment.

Material Selection

Water quality degradation has significant impacts on material selection which also drives facility capital costs. This is of significant importance on raw water feed piping, interstage piping, concentrate piping, and corresponding appurtenances due to the elevated chloride levels increasing the potential for corrosion such as pitting in metals including 316 or 316L stainless steel. There is a high potential for corrosion in 316L stainless steel at chloride concentrations above 1,000 ppm according to the 2017 Journal AWWA study done *Guidelines for Using Stainless Steel in the Water and Desalination Industries* by Mackey and Seacord. Higher grades of stainless steel, such as Duplex (2205) and Super Duplex (2507) have superior corrosion resistance but can be significantly more costly than 316L stainless steel. Therefore, the capital cost impacts of potential material replacements of 316L stainless steel with higher grades of stainless-steel alloys in future phases were evaluated for consideration. In alignment with City's goals for long term resiliency, Duplex (2205) was selected for the high-pressure feed and Super Duplex 2507 was utilized for the interstage and concentrate piping on the RO skids. Downstream wetted components such as concentrate disposal pumps, valves, fittings, and other wetted appurtenances were also aligned with the corrosion resistant properties and are constructed using the Super Duplex 2507 for all wetted components. HDPE was selected for raw water feed, and low pressure concentrate piping.

Conclusion

In conclusion, the design of North Port's Southwest RO Water Treatment Plant provided challenges due to anticipated degradation of raw water wells suppling the plant. Raw water degradation affects multiple design and operating parameter of the plant and should be analyzed on a wholistic approach. As discussed throughout the paper, integration of the PX devices are more than applicable to brackish RO facilities and offer a significant cost savings on the capital and operational expenses. The unit is anticipated to provide overall reductions in membrane feed pump flow and size, reduced operational energies, and cost savings to utilities and brackish applications ahead.

Acknowledgments

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References

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