Energy Recovery Case Studies for Brackish Water Membrane Treatment Systems

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The use of an interstage boost on brackish reverse osmosis (RO) membrane treatment systems is not only a green approach to reducing operating costs and saving money; it can restore and even increase treatment capacity utilizing existing equipment. Implementation of energy saving devices to provide practical solutions to increasing recovery and capacity, while decreasing operating costs of existing RO systems, is presented. With ever-increasing demands on alternative water supplies using brackish groundwater, degrading raw water quality is becoming apparently common and affecting treatment capacities, as well as operating costs. Several case studies are presented that also provide the cost–benefit of implementing an interstage boost utilizing energy recovery devices.

Interstage Boost on Reverse Osmosis Treatment Systems

It is first important to have a basic understanding of the RO membrane treatment process to fully appreciate the use of interstage boost. Raw water is typically pumped from its source and sent through pretreatment to feedwater pumps that feed the RO trains. The RO train is an array of pressure vessels loaded with membrane elements that reject, or remove, salts and other ions that are too large to pass through the membranes. Water that passes through these membranes is classified as permeate (free of salts and other ions); water that does not pass through the membranes is classified as concentrate (concentrated saltwater). To increase the recovery, typically first-stage concentrate flow is directed to pass through a second stage of elements (second-stage stage feed) producing second-stage permeate and second-stage concentrate. First- and second-stage permeate then flows to post-treatment processes, while concentrate is usually disposed of down deep injection wells.

It is critical to the overall design that the raw water quality is determined and permeate and finished water goals are established. In retrofit applications, it may be found that cases where water quality is high in total dissolved solids (TDS), feedwater pressures may need to be greater to obtain the desired permeate water quality. If the feedwater pump is not capable of meeting these demands, the use of different membranes should be evaluated.

The performance of the membranes contributes to the energy required to produce permeate water. Membrane selection and condition are components that need to be considered when reviewing feed pressure and energy costs. Many times, due to newer membrane technology, performance can be increased (improved permeate water quality and/or reduced feedwater pressures) with proper membrane selection. Membrane selection is key to capturing these advantages.

The energy recovery turbine (ERT) device provides boost to the second-stage feed by capturing the energy (residual pressure) from the final (second-stage) concentrate. The ERT includes a turbine (captures the second-stage concentrate flow) coupled to a pump, which takes the first-stage concentrate and boosts inlet pressure to the second stage. Normally, all of the flow from the final concentrate (same as second-stage concentrate) flows through the ERT and is used to boost pressure to the second stage (Figure 1). A bypass valve (ERT trim valve) allows some of the flow to bypass the ERT, allowing a reduction in boost for optimizing the operation and performance.

The RO trains are typically operated based on set points of total permeate flow and percent recovery. The feedwater pump modulates speed to maintain total permeate flow, whereas the turbine bypass valve (ERT trim valve) modulates to maintain a recovery, or concentrate flow, which is calculated based on the input value of total permeate and recovery. The first-stage permeate flow can be maintained and limited based on the first-stage control valve. It can modulate in order to maintain a desired first-stage permeate, or can be set manually to provide a fixed first-stage backpressure, which reduces first-stage permeate flow. This valve should *never* be closed and should always allow flow. This valve should also remain open when the RO train is off-line.

Energy Recovery Devices

There are four styles of energy recovery devices that can be evaluated as possible interstage boost devices.

Pelton Wheel

The Pelton Wheel (Figure 2) is one of the earliest forms of energy recovery. This device utilizes the force of high-pressure water streams directed at buckets on a wheel that is coupled to a pump. The force of the highly pressurized water pushes the buckets to make the wheel spin on its axis. Since the wheel is coupled to the pump with a shaft, rotational movement of the wheel provides energy for the pump to operate.

Implementation of energy recovery through the use of the Pelton Wheel in brack-

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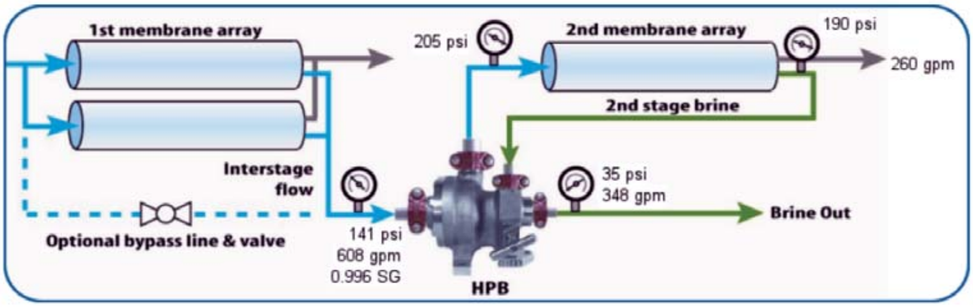

Figure 1. Energy Recovery Turbine Flow Diagram

Continued from page 41

ish RO membrane treatment systems is not practical and cannot be justified. In this application, second-stage concentrate would be utilized as the source of kinetic energy directed at the Pelton Wheel to boost first-stage concentrate through the second stage of membranes. In this application the water jet that provides the force the Pelton Wheel needs to rotate would be exposed to the atmosphere. The highly concentrated water, utilized as the source of energy for the Pelton Wheel, would have to be captured and another pump would be required to push the final concentrate down the injection well. The capital and operating costs of this additional pump would counteract the original intent of implementing energy recovery.

Isobaric Pressure Exchanger

The RO plants treating seawater commonly use an energy recovery device known as the Isobaric Pressure Exchanger, or PX (Figure 3). These devices operate at approximately 100 percent recovery; however, they have not been adapted at this time for brackish water RO since they are only more effective at higher operating pressures.

Energy Recovery Turbine

The ERT has been used for interstage boost since the early 1990s (Figure 4). This device consists of a turbine and a pump on a common shaft. Second-stage concentrate is used to drive the turbine, which drives the pump that elevates pressure in the first-stage concentrate before it becomes feedwater to the second stage. These devices operate at a maximum efficiency of approximately 64 percent, which means approximately 36 percent of the available energy is not recovered.

With ever-increasing demands on alternative water supplies using brackish groundwater, degrading raw water quality is becoming apparently common and affecting treatment capacities, as well as operating costs. An ERT becomes a practical solution in brackish RO treatment systems for utilities that wish to lower feedwater pressures to the RO trains and improve overall permeate water quality. It is also important to analyze the cost savings in operating the feedwater pumps at lower pressures and compare them to the capital cost of purchasing and installing the ERT.

Energy Recovery with Motor

A hybrid of the ERT has been developed that attaches an electric motor to the same shaft as the turbine and pump (Figure 5). This device allows the applied interstage boost to be higher than that which can be achieved only through the energy recovery turbine. For the two facilities discussed in this case study, with the amount of energy available from the final concentrate pressures from the RO plant case studies, no motor-assisted device was necessary. Therefore, no outside energy is required to provide second-stage boost.

The use of interstage boost on brackish RO membrane treatment systems can increase treatment capacity, improve permeate water quality, and save money. Two current case studies are presented that also provide the cost–benefit of implementing interstage boost utilizing energy recovery turbines.

Case Study 1: Palm Beach County Plant #11, Lake Region Water Treatment Plant

Background

The Palm Beach County Water Plant #11, Lake Region Water Treatment Plant (LRWTP) is a 10-mil-gal-per-day (mgd) low-pressure brackish RO treatment plant that utilizes water from the Floridan aquifer through multiple wells. The plant consists of four trains with feedwater pumps that produce permeate from 38 first-stage membranes and 19 second-stage membranes. The plant was placed in service in 2009 and began to experience severe degradation of raw water quality over time, which led to it operating at a reduced capacity with much higher feedwater. With declining raw water quality from one of the Floridan supply wells (RO-3), the membrane system had difficulty meeting the current rated capacity.

In order to address this deficiency and improve operating efficiencies of the RO skids, the existing membranes were cleaned, the RO train array was increased to 40 first-stage pressure vessels and 20 second-stage pressure vessels, and energy recovery using interstage boost was implemented. Implementation of energy recovery utilizing interstage boost was necessary to restore treatment capacity and recovery and help compensate for the increased total dissolved solids this facility has experienced over the past several years (decreasing raw water quality). The following design criteria were used to establish guidelines for the design of these improvements:

Capacity:	2.375-mgd permeate (each RO train)
Recovery:	80 percent (total permeate/raw water)
Operating Pressures:	350 pounds per sq in. (psi) max, first-stage feed; 400 psi max, second-stage feed

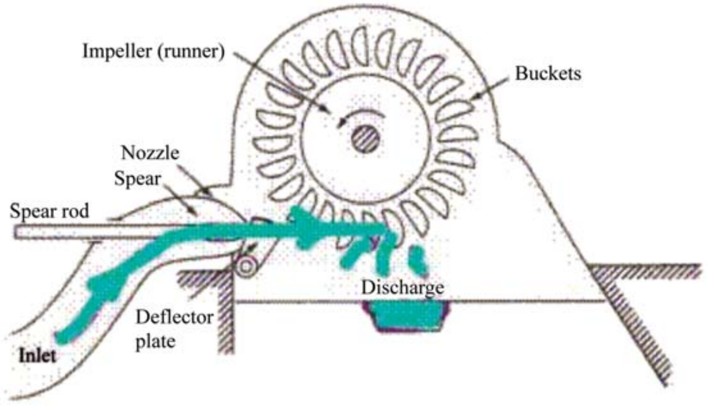

Figure 2. Pelton Wheel

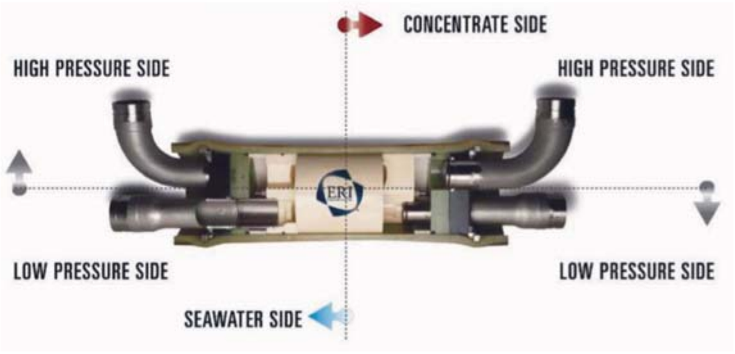

Figure 3. Isobaric Pressure Exchanger

Raw Water Press to Feed Pumps: ....45-60 psi

Deep Injection Backpressure: ....20-35 psi

Permeate Backpressure: ....15 psi

Capacity

The RO trains operated at a reduced capacity and recovery. The design-rated capacity of each of the RO trains is 2.375 mgd, or 1,650 gal per minute (gpm), which stayed true as the desired design capacity. If water quality continues to decline and vary significantly, operating conditions other than 2.375 mgd may be necessary and be more optimal from an operational standpoint. The Interstage ERT sizing had accounted for these potential variations in RO train capacities ranging from 2.0 mgd up to 2.5 mgd.

Reverse Osmosis System Recovery

Given the fact that raw water quantity is limited and predicted raw water quality degradation may continue, it may be advantageous to operate the RO trains at recovery rates other than the design of 80 percent recovery. Recovery rates between 75 and 80 percent, and up to 83 percent, are possible and considered feasible.

The existing membrane elements are low-pressure brackish elements manufactured by DOW Filmtec (model LE-400), are 8 in. in diameter, and include 400 sq ft of membrane surface area per element. Additional pressure vessels were installed under these improvements, which utilized the same type of membranes within the additional pressure vessel locations. Alternative membrane elements (DOW Filmtec LE 440i, HRLE 440i), which have a larger surface area and alternate rejection rates, should be considered for future replacement if performance of the existing ones declines along with declining raw water quality.

Membrane flux, or permeate flow across the membrane surface area in gal per sq ft per day (gfd), will be limited to the published flux limit of 28 gfd for the existing membrane elements in order to maximize membrane capacity and longevity. The original design limited the lead element flux to 24 gfd, which is now not practical with higher TDS in raw water.

Operating Pressures: First and Second Stage

Each of the RO trains has operating pressure limitations, based on pressure ratings of pipe, valves, fittings, feedwater pumps, or pressure vessels. The operating pressure limits for each of the RO trains will be based on a first-stage pressure limit of 350 psi, and second-stage pressure limit of 400 psi. The first-stage pressure limit is based on 8-in. piping, valves, and fittings, whereas the second-stage is limited based on the pressure limits of the pressure vessels, rated for 450 psi, and the valves, each rated for a 450- to 500-lb body test. Therefore, the following alarm pressure set points should be:

	Alarm Set Point	Design Rating
Feed Pressure (first-stage)	320 psi	350 psi
Second-Stage Pressure (after ERT)	350 psi	400 psi

Deep injection well backpressures were important for sizing of the interstage boost ERT, since these pressures directly affect the available energy to power the turbine and resultant second stage feed pressure. Normal increase in injection well pressures must be taken into account when sizing ERTs. Current concentrate backpressures were observed to be 18-20 psi and a long-term concentrate backpressure was assumed to be 35 psi.

Water Quality

The RO system must accommodate variations in raw water TDS, which vary significantly at each of the wells. The following range of water quality TDS levels were evaluated for the operating conditions list above.

Raw Water TDS	Source
4,358 mg/l	Original design, operations and maintenance manual
5,050 mg/l	Current average of operating wells
6,250 mg/l	Design (for this project)
8,620 mg/l	Well #5, elevated level
10,050 mg/l	Worst case, upper limit

Total and First-Stage Permeate Flow

Total permeate flow can range from 1,390 gpm to 1,740 gpm (2.0 to 2.5 mgd) and can be adjusted accordingly. Flows lower than this can contribute to low concentrate flow conditions on the tail-end elements, which can lead to concentration polarization and scaling. If lower permeate flows are necessary, overall recovery of the RO trains should be lowered concurrently (<80 percent).

The first-stage permeate flow should be limited to 1,300 gpm in order to limit the maximum flux, which is the permeate flow at gal per day (gpd)/sq ft-gfd on the lead element of the first stage, which is based on a maximum lead element flux of 28 gfd. Limiting this flow will reduce the potential for long-term fouling on the lead elements and scaling po-

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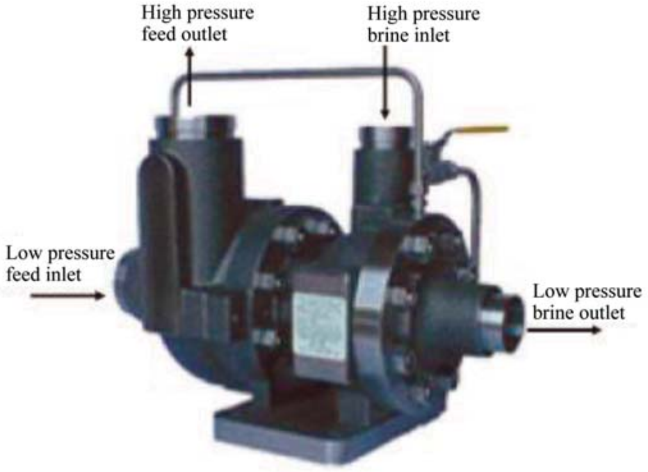

Figure 4. Energy Recovery Turbine

Figure 5. Energy Recovery Turbine with Motor Assist

Continued from page 43

tential on the tail element of the first stage. This is a general guideline and does not require an immediate shutdown of the RO trains. Unless this flow is greater than 1,300 gpm, this first-stage permeate control valve should remain fully open in order to minimize wasted energy. Providing first-stage permeate control directly affects the feed pressure and increases the energy required to produce permeate.

Recovery

The recovery is controlled by the ERT trim valve, which can modulate to control how much concentrate flows to the ERT. As the valve opens, it allows more flow to bypass the ERT, which reduces the overall system recovery. Adversely, as the bypass (trim) valve to the ERT closes, overall recovery of the system increases. Currently, recovery varies between 75 to 80 percent.

Operational Testing

Operational testing was performed for each individual RO train once they were converted with energy recovery. In general, the conversion included the following:

- Increase array from 38x19 to 40x20 and install new membranes to fill new vessels
- Replace all stainless steel piping to improve pressure rating
- Install ERT
- Install ERT trim valve and bypass valve with actuators
- Install additional instrumentation (permeate conductivity and second-stage feed pressure)
- Modify programmable logic controller (PLC) and human machine interface (HMI) programming to accommodate energy recovery
- Update normalization data logger and implement automatic updating of NormPro (a computer program for use with RO equipment)

Testing included several actions to ensure the RO trains were operating within the design ranges, which consisted of the following:

- Witness sequencing of train startup (preflush), presteady state, and postflush (adjust timers for each if needed)
- Calibration of instruments/transmitters (conductivity, pressure, flow; ranges correct)
- Conduct general profile (raw, first- and second-stage permeate, interstage, concentrate conductivity) and verify flow meters with mass balance
- Conduct vessel profile once operating conditions in steady state for minimum of 24 hours
- Record pressures across ERT
- Operate ERT with control valve forced closed (record second-stage flux)
- Collect raw water quality (15 parameters) for raw and permeate water used for membrane projections for steady state design conditions

Due to the significant variation in raw water quality, the following RO skid operating targets were also conducted to test performance at alternative design conditions:

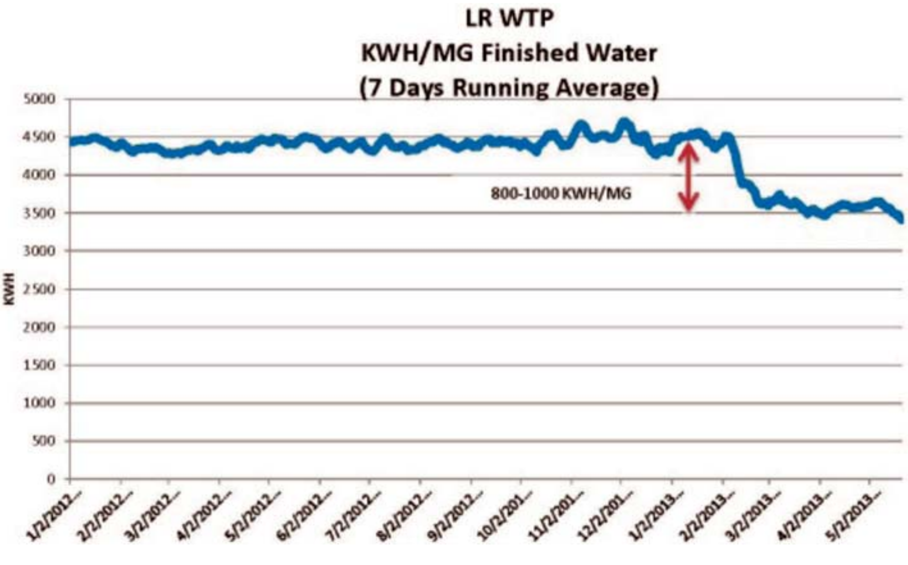

Figure 6. Lake Region Water Treatment Plant Energy Reduction Graph

Recovery	Permeate Flow	Concentrate Flow
75–80%	2.0 mgd (1390 gpm)	0.66 mgd (460 gpm)
75–80%	2.0 mgd (1390 gpm)	0.60 mgd 347 gpm)
75–80%	2.375 mgd (1650 gpm)	0.60 mgd (412 gpm) DESIGN
75–80%	2.5 mgd (1738 gpm)	0.625 mgd (434 gpm)
83%*	2.375 mgd (1650 gpm)	0.486 mgd (338 gpm)
80%*	2.5 mgd (1738 gpm)	0.637 mgd (442 gpm)

* Could not be achieved at the time of testing

As depicted in Figure 6, energy savings ranged from 800 to 1000 kilowatts per hour (kWh) per mil gal (MG) of permeate produced by the RO trains. Assuming electrical costs are around $0.12/kWh, the utility could essentially save around $120 per MG of water produced. Energy recovery implementation at water treatment plant #11 has proven to be a successful project, providing cost savings in permeate production and overall improvement of permeate water quality at the plant.

Case Study 2: North Martin County Reverse Osmosis Water Treatment Plant

Project Background

Martin County's North Jensen Beach RO water treatment plant was constructed in the early 1990s with limited attention to energy recovery at that time. The plant, rated at 5.5 mgd, has low-pressure brackish RO membranes that are more than 10 years old and reaching their useful life. Membrane performance has declined, and in conjunction with declining water quality (increased TDS), the membrane system has had difficulty meeting the current rated capacity. In order to address these problems and improve operating efficiencies of the RO skids, membrane replacement, along with implementation of energy recovery using interstage boost, was recommended. There are three trains at the treatment plant and two of the existing three trains (A and B) operate without energy recovery, while Train C has an ERT.

The membrane replacement and the implementation of the ERTs allowed an increased recovery and capacity at a reduced operating pressure, resulting in lower operating costs at

Continued on page 46

Continued from page 44

greater plant capacity. These two improvements will allow the plant to increase capacity up to 6 mgd without any improvements to the feedwater pumps or other components, which would be very expensive. The return on investment for just the ERT improvement alone is six to 10 years and will save nearly $100,000 per year in operating costs.

Capacity

The RO trains currently operate at reduced capacity and recovery. The existing rated capacity for each of the three RO trains is 1.83 mgd. If water quality continues to decline and vary significantly, operating conditions other than 1.83 mgd may be necessary and be more optimal from an operational standpoint. Interstage ERT sizing had accounted for these potential variations in RO train capacities ranging from 1.83 mgd up to 2 mgd.

Reverse Osmosis System Recovery

Similar to that of Water Treatment Plant #11, raw water quality from well 3 (RO-3) has shown to diminish over the years. Since it is predicted that water quality degradation may continue, it may be advantageous to operate the RO trains at recovery rates other than the design of 80 percent recovery. Recovery rates between 75 and 80 percent are possible and considered feasible.

The existing membrane elements are low-pressure brackish elements, manufactured by Hydranautics, and are energy-saving polyamide (ESPA) membranes. As part of this project, the existing membranes on all trains will be replaced with a newer specified model, and additional pressure vessels will be added to Train A to increase recovery to match that of Train B.

Operating Pressures: First and Second Stage

Each of the RO trains has operating pressure limitations, based on pressure ratings of pipe, valves, fittings, feedwater pumps, or pressure vessels. The existing feedwater pumps are limited to 200 psi due to the pump impellers and motor size.

The existing conditions of the feedwater pumps made it difficult to select several different membranes that would meet permeate water quality specifications. With the limitations on feedwater pressures, it was difficult to find several membranes with a high enough rejection rate to provide the desired permeate water quality.

Deep injection well backpressures were important for sizing of the interstage boost ERT, since these pressures directly affect the available energy to power the turbine and resultant second stage feedpressure. Normal increase in injection well pressures must be taken into account when sizing ERTs. Current concentrate backpressures were observed to be 15-35 psi and a long-term concentrate backpressure was assumed to be 35 psi.

Water Quality

The RO system must accommodate for variations in raw water TDS, which vary significantly at each of the wells. The following range of water quality TDS levels were evaluated for the operating conditions listed:

Raw Water TDS	Source
2,990 mg/l	Standard design from raw water quality
3,980 mg/l	Worst case raw water quality

Given the variation in raw water quality, the pH of the raw water entering the RO system is assumed to be lowered using sulfuric acid, which is consistent with current plant operations. A pH of 7.35 was used in each of the projections in order to minimize scaling potential of the concentrate in the membranes. Since there is post-treatment addition of sulfuric acid (as opposed to pretreatment), the pH of the feedwater is greater than that of Case Study 1.

Total and First-Stage Permeate Flow

Total permeate flow can range from 1,250 gpm to 1,390 gpm (1.8 to 2.0 mgd) and can be adjusted accordingly. Flows lower than this can contribute to low concentrate flow conditions on the tail-end elements, which can lead to concentration polarization and scaling. If lower permeate flows are necessary, overall recovery of the RO trains should be lowered concurrently (<80 percent).

Recovery

As previously noted, the recovery is controlled by the ERT trim valve, which can modulate to control how much concentrate flows to the ERT. As the valve opens, it allows more flow to bypass the ERT, which reduces the overall system recovery. Inversely, as the bypass (trim) valve to the ERT closes, overall recovery of the system increases. Currently, recovery varies from 75 to 80 percent.

Energy Conservation Measures

The existing RO trains (A and B) currently operate with ESPA membranes that operate at higher fluxes (permeate flow) and lower operating pressure. The drawback to this is that the first-stage permeate must operate with induced backpressure to prevent overfluxing of the first-stage membrane elements. This results in higher-than-normal feed pressures. In order to maximize membrane efficiency and balance the first- and second-stage fluxes, an interstage boost is typically implemented to increase the operating pressure to the second stage. The use of an ERT, which captures the energy from the concentrate pressure and provides boost to the second-stage feed, is a common approach and has been recommended.

The key to this project is to provide the lowest energy (kWh) per gal of water produced at the desired permeate water quality through selection of the appropriate membranes and the most efficient ERT. Similar to Case Study 1, minimizing operating costs of the RO plant and providing better permeate water quality are the primary goals of energy recovery implementation. Currently, operating-cost savings are not available without the ERT and membrane replacement. Construction of the recommended improvements will commence in the early part of 2015. Once these items are implemented, immediate operating-cost savings can be experienced.

Modifications of Existing Reverse Osmosis Skids

Skids A and B

In order to improve recovery, efficiency, and lower energy consumption, improvements to RO skids A and B should consist of the following:

- Modification of the existing interstage and concentrate piping
- Replacement of the concentrate control valves
- Removal of first-stage permeate control valves if necessary
- Membrane replacement
- Modification or addition of pressure vessels to provide the most efficient second-stage array
- Installation of energy recovery turbines
- Additional instrumentation (flow, conductivity, pressure)
- Relocation of sample panels

Skid C

Improvements to RO skid C would include the following:

- Membrane replacement

Items That Affect Energy Recovery Turbine Efficiency

Raw water quality has the largest impact on the need for energy recovery and interstage boost. Well water quality has declined slightly over the years, and is most noticeable when membrane performance has declined. With a decline in raw water quality goes an increase in feedwater pressures needed to overcome the osmotic pressures. A target raw water quality should be defined for energy calculations. Raw water conductivity currently ranges from 4,500 umhos to 7,500 umhos.

Water chemistry, such as sparingly soluble salt concentrations in the raw water (i.e., strontium, barium, silica, and calcium) and the feedwater pH can also affect the recovery that can be achieved with the RO system. Current parameter levels should be defined to ensure that the higher membrane recoveries can be achieved. In addition, the recent reduction of acid at the facilities to reduce feedwater pH may need to be readdressed if these sparingly soluble salt levels are higher than original values.

Conclusion

Decreasing water quality of brackish groundwater is becoming more common and is affecting treatment capacities, as well as operating costs. An ERT becomes a practical solution in brackish RO treatment systems to lower operating costs and improve permeate water quality. The function of the ERT is purely hydraulic, and the existing water quality and feedwater pressures in both case studies allow energy recovery to be highly beneficial without the use of additional power. The case studies show that the implementation of energy recovery is highly beneficial to utilities in improving permeate water quality, and equally important, lowering operating costs.

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