ENERGY RECOVERY DEVICES IN MEMBRANE DESALINATION OPERATIONS

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ABSTRACT:

Most high-pressure membrane desalination plants being designed and built today for seawater applications save energy by utilizing isobaric energy recovery devices (ERDs) such as the ERI PX Pressure Exchanger device. Isobaric ERDs seal the high-pressure portion of a reverse osmosis process and make the high-pressure pump flow rate and the membrane recovery rate independent. As a result, the operation and control of a reverse osmosis process equipped with an isobaric ERD differs substantially from one with either no ERD or a centrifugal ERD such as a Pelton wheel. Reverse osmosis plant designers and operators need to have a thorough knowledge of how an ERD works in a desalination process to be able to optimize capital costs and operational costs and thereby minimize the total cost of ownership of the plant.

The author presents an overview of reverse osmosis with isobaric ERDs including considerations relevant to mining water applications. Key design and operational differences between SWRO with isobaric ERDs and centrifugal ERDs are discussed. Specific energy consumption projections with a number of available energy recovery devices are compared. Case studies drawn from several successful SWRO process retrofits are presented. Issues of potential concern including reliability, maintenance, downtime, and cost of ownership are addressed.

INTRODUCTION

Reverse osmosis is a water desalination process widely used around the world. The osmotic pressure of a salt water solution is overcome with hydraulic pressure, forcing nearly pure water through a semipermeable membrane and leaving concentrated brine behind. In seawater reverse osmosis (SWRO) systems, an operating pressure of between 60 and 70 bar is required. Even at these pressures, a maximum of approximately 50% of the available pure water can be extracted before the osmotic pressure becomes so high that additional extraction is not economically viable. The rejected concentrate leaves the process at nearly the membrane feed pressure. The combination of the high required membrane feed pressure and the high-volume reject stream have historically limited the deployment of large-scale SWRO to regions where power is inexpensive and abundant.

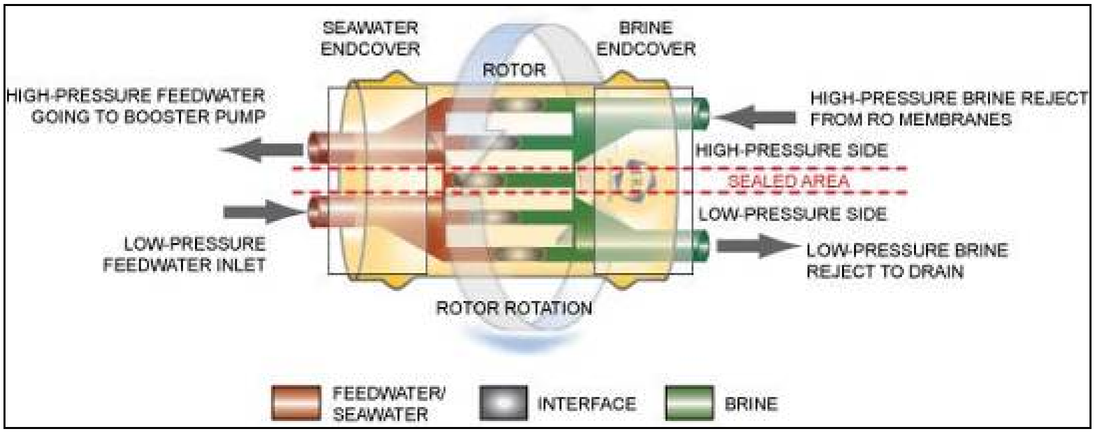
However, SWRO technology consumes far less energy today than it did just a few years ago. Improved membranes, increased pump efficiencies and the implementation of isobaric energy recovery devices (ERDs) have dramatically increased the energy efficiency of these processes. The energy requirement for SWRO can be as low as 1.6 kWh/m^3, making the process energy-competitive with many traditional fresh water supply sources [1, 2].

ERDs have been employed in SWRO applications since the early 1980s to recover pressure energy from the concentrate reject stream of the SWRO membranes and return it to the membrane feed stream. Early ERDs were centrifugal devices, such as Francis turbines, Pelton turbines or turbochargers, which were limited in capacity and had a maximum net transfer efficiency of typically less than 70% at their best efficiency point [3]. More recently, isobaric ERDs, including piston-type work exchangers and the rotary PX Pressure Exchanger® device, have been developed to provide unlimited capacity and an operating efficiency of up to 98% [4]. The positive displacement pressure transfer mechanism used in these devices is similar to that in reciprocating pumps, assuring high efficiency despite flow and pressure variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs including the three largest SWRO plants currently in operation [5]. Many plants built with centrifugal ERDs have been retrofit or their operators are considering converting to isobaric devices to reduce energy consumption and increase production capacity [6].

ISOBARIC ENERGY RECOVERY DEVICES

Isobaric ERDs transfer pressure from the high-pressure brine reject to a portion of feed water by putting them in direct contact in pressure-equilibrating chambers. In a PX® energy recovery device, bores through a rotor serve as the isobaric chambers. The rotor is fit into a ceramic sleeve between two ceramic endcovers. The narrow clearances between the ceramic components fill with seawater, creating an almost frictionless, continuously-regenerating hydrodynamic bearing. A schematic representation of the ceramic components of a PX device is given in Figure 1.

Figure 1 – PX Device Ceramic Components



The speed of the PX rotor is set by the combined flow rate of the high- and low-pressure streams. There are no shafts, motors, or electronic controls on a PX unit. The PX rotor contains no pistons or barriers. When the rotor is not spinning, flow passes directly through the device making startup and shutdown easy. The high- and low-pressure streams are separated at all times, even when the rotor is not spinning, by the seal formed by the tight fit between the rotor and the surrounding ceramic components. In this regard, the PX ceramic components function as a mechanical seal for the high-pressure portion of the SWRO process.

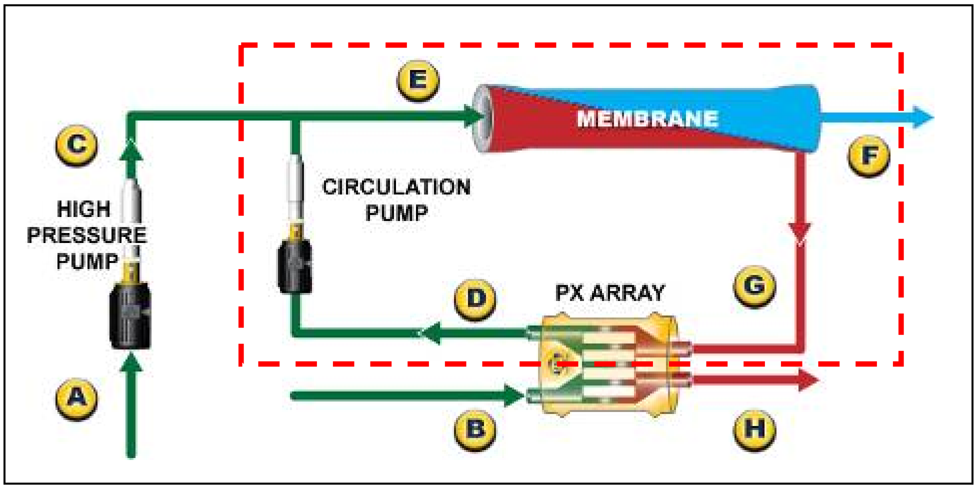
The positive-displacement mechanisms employed by all isobaric ERDs provide high hydraulic-transfer efficiency but also allow some mixing of the concentrate and feedwater. The degree of mixing is a characteristic of the particular ERD and a function of the ratio of concentrate and feedwater flow rates to the ERD. Mixing between the brine and seawater streams in a PX device is limited by the aspect ratio of the rotor ducts which are long and narrow. The PX rotor is designed so that the interface between the brine and seawater never reaches the end of the rotor before the duct is sealed.

SWRO WITH ISOBARIC ERDS

Isobaric ERDs, including PX devices, are now employed in hundreds of desalination plants worldwide. A typical process configuration for an SWRO system equipped with an array of PX devices is illustrated in Figure 2 below. Concentrate, rejected by the membranes, flows to the PX array, driven by a circulation (booster) pump. The ERDs replace the concentrate with seawater. This flow merges with the discharge of the high-pressure pump to feed the membranes. Water leaves the system as membrane permeate or as spent low-pressure concentrate from the ERDs.

Isobaric ERDs separate the high- and low-pressure streams and seal the high-pressure portion of the process. To illustrate how this affects SWRO system operation, a dashed-line box is drawn around the high-pressure portion of the process and through the ERD in Figure 2. Nearly all the water that enters the box from the high-pressure pump leaves as permeate. A small amount – about 1% of the permeate volume – passes through the seals of the ERD as lubrication flow or leakage. High-pressure pump flow and permeate flow are always nearly equal regardless of membrane pressure or circulation pump flow rate.

Figure 2 – Schematic of SWRO System with Isobaric ERDs (PX Array)



Operation and control of a PX unit in an SWRO system can be understood with reference to Figure 2 by considering two parallel pipes; one of high-pressure water and one of low-pressure water flowing in opposite directions. The high-pressure water flows in a circuit through the membrane elements, the PX unit or PX array, the circulation pump, and back to the membranes at a flow rate controlled by the circulation pump. The low-pressure water from the seawater pretreatment system flows through the PX units to the system discharge at a rate controlled by a throttle valve in the brine discharge from the PX array. The function of the PX rotor is to continuously exchange volumes of pressurized brine from the SWRO membrane elements for equal volumes of filtered seawater from the pretreatment system.

Although most engineers understand the performance of individual pumps, membranes, valves and energy recovery devices, the performance of complete SWRO systems can be complex and counter-intuitive. A change in the output of one system component changes the input to other components, and the feedback can alter the outputs of all the components until a new equilibrium condition is reached. To minimize the total cost of ownership, SWRO designers and operators need to have a thorough knowledge of the dynamics of these processes. To illustrate the dynamics of SWRO systems, Energy Recovery, Inc. (ERI®) developed the ERI SIM^{TM} program [7,8]. ERI SIM is an instructional computer program that simulates the pressures, flows and salinities of a SWRO process equipped with ERI's PX Pressure Exchanger technology. The ERI SIM program integrates PX device performance, typical pump and valve characteristics and projected membrane responses into an interactive, dynamic model. It is the first program in the public domain that treats an SWRO process as a complete, coupled system.

SWRO SYSTEM PERFORMANCE

Table 1 presents flow, pressure, salinity and power data for a typical 10,000 cubic meters per day (m^3/day) SWRO train. The data illustrate several points which are generally applicable to SWRO processes equipped with isobaric ERDs.

1. The high-pressure pump and permeate flow rates are nearly equal. The high-pressure pump is sized to the permeate the permeate flow rate, not the membrane feed flow rate.
2. PX devices are deployed in arrays and operated in parallel to fit the brine flow rate.
3. The high-pressure pump consumes about 97% of the energy required by an SWRO while the circulation pump consumes about 3%.

4. PX devices typically operate at over 97% net transfer efficiency, reducing the energy required by the SWRO process to less than half that required with no energy recovery.
5. The membrane feed salinity is less than 3% higher than the salinity of the system feed.
6. The high-pressure pump and the PX devices can be fed with different supply streams. Net positive suction head requirements for the pump may require a feed pressure greater than 3 bar. However, the minimum discharge pressure requirement for the PX devices (1 bar) allows a PX supply pressure of less than 2 bar.

Table 1 – Typical Performance Data for a 10,000 m^3/day SWRO System

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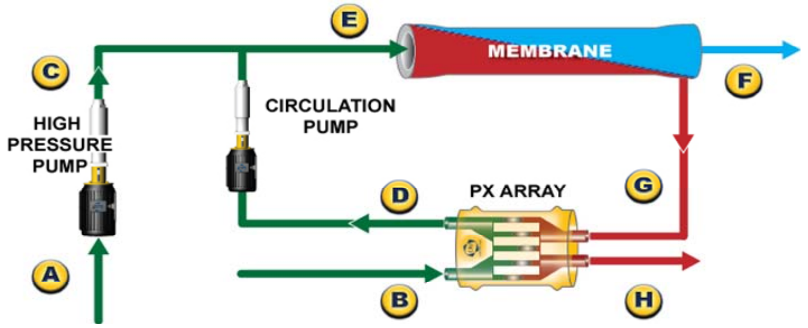


INPUTS IN RED		A	B	C	D	E	F	G	H
FLOW	m^3/hr	420	506	420	506	926	417	509	509
PRESSURE	bar	**3.0**	**1.7**	66.0	64.3	**66.0**	0.0	65.0	1.0
SALINITY	mg/l	**40,000**	40,000	40,000	42,078	41,135	**200**	74,628	72,564

SYSTEM PARAMETERS

Permeate Flow	m^3/day	**10,000**
Recovery	%	**45%**

PRESSURE EXCHANGERS

PX-260 Units/Array	quantity	**9**
Unit Flow	m^3/hr	56.6
Lead Flow	%	**0%**
Lubrication Flow/Array	m^3/hr	3.3
Differential HP side	bar	0.7
Differential LP side	bar	0.7
Salinity Increase @ membranes		2.8%
PX Overall Efficiency	%	97.4%
PX Power Savings	kW	1,131

HIGH PRESSURE PUMP

Pump Efficiency	%	**84%**
Motor Efficiency	%	**93%**
Power	kW	943

CIRCULATION / BOOSTER PUMP

Pump Efficiency	%	**84%**
Motor Efficiency	%	**93%**
VFD Efficiency	%	**97%**
Power	kW	31

OVERALL POWER CONSUMPTION

Total	**kW**	**974**
Specific Energy	**kWh/m^3**	**2.34**

SWRO FOR MINING APPLICATIONS

SWRO with isobaric ERDs is well suited for water supply for mining. For these applications, conventional freshwater sources can be non-existent or unreliable. The temperature and quality of the SWRO feedwater can vary significantly. Trains may be designed with capacities exceeding 10,000 m^3/day to accommodate large, high-efficiency centrifugal pumps [9, 10]. SWRO processes with isobaric ERDs meet these challenges with high reliability, low energy consumption, unlimited capacity and operational flexibility.

The reliability of SWRO technology has been proven in hundreds of desalination installations worldwide. Energy consumption can be lower than the energy required to pump water from conventional freshwater sources [2]. Essentially infinite capacity can be achieved by arraying membranes and ERDs in parallel. But perhaps the greatest benefit provided by isobaric ERD-equipped SWRO processes is the flexibility provided by variable recovery operation.

Isobaric ERDs provide high constant energy transfer efficiency over a wide range of flows and pressures. As a result, the membrane water recovery rate can be varied without increasing the energy required to produce a unit of permeate. This flexibility allows a process operator to optimize membrane performance as seasonal variations in the seawater occur or as the membrane elements age by adjusting the speed of the circulation pump and the position of the concentrate throttle valve. Numerous best-efficiency operating points can be found which is a tremendous advantage for low-cost SWRO operation.

The significance of variable recovery is illustrated with reference to Figure 2 above. If the flow rate of the circulation pump is set with a variable frequency drive to be equal to the flow rate of the high-pressure pump, the system will operate at 50% recovery. If the flow rate of the circulation pump is increased to double the flow rate of the high-pressure pump, the system will operate at 33% recovery. As recovery rate is reduced, membrane pressure reduces and the load on the high-pressure-pump motor reduces. As recovery rate is increased, membrane pressure increases but the SWRO system requires less feedwater. Such adjustments can significantly change membrane performance but have negligible affect on isobaric ERD performance which provides high efficiency regardless of flow rate or pressure. Although the maximum flow rate through each energy recovery device is limited, additional units can be added or removed as necessary to accommodate a wide range of recovery rate variation.

For instance, if heavy fouling conditions occur, the recovery rate can be lowered, increasing membrane cross flow and reducing contaminant deposition and biological growth on membrane surfaces. Alternately, recovery can be increased when feedwater temperatures are high to minimize permeate salinity. In this way, an operator can manipulate and optimize SWRO system performance to achieve low energy consumption throughout the year. Flexible recovery and low-recovery operation are tremendous advantages for low-cost SWRO operation provided by isobaric ERD technology [11].

RETROFITTING WITH ISOBARIC ERDS

Retrofitting existing SWRO processes with isobaric ERDs makes it is possible to reduce the power consumption of existing systems by as much as 60%. Alternately, the capacity of existing systems can be increased with little or no additional power requirements and with minimal additional equipment [6]. For these reasons, owners of many currently-operating SWRO plants have retrofitted or are considering retrofitting with isobaric ERDs. Direct comparisons of the performance of various ERDs are provided below using data from SWRO plants that were originally built with Pelton turbines and then retrofit with PX devices.

Full Retrofit

In a full retrofit of an SWRO train with a Pelton turbine, the turbine is removed. The original high-pressure pump is utilized and an array of PX energy recovery devices and circulation pump are added. The process configuration is the same as that illustrated in Figure 2 above. The number of membrane elements are approximately doubled, resulting in nearly double the permeate flow for the same size high-pressure pump. Or, if two existing trains are combined, one of the high-pressure pumps is removed. The capacity of pretreatment, post-treatment and product water conveyance systems must be increased in proportion to the increase in permeate production. In addition, because the turbine is removed, the high-pressure pump motor be of sufficient capacity to supply all the power necessary to turn the high-pressure pump. This requirement is met in most existing Pelton installations where the high-pressure pump motors have been sized to operate without the turbine if necessary.

Several trains of an SWRO plant in Mazarron, Spain that had been operating with Pelton turbines were retrofit with PX devices and circulation pumps. In each case, two trains were combined and one high-pressure pump was removed from service. A photograph of the 7,200 m^3/day PX installation is given as Figure 4. Data for a train before and after the retrofit are given in Table 2.

Figure 4 – 7,200 m^3/day PX Device Installation in Mazarron, Spain

Table 2 – Process Data for Mazarron Retrofit

Parameter	Units	With Pelton Turbine	After PX Retrofit
Membrane Feed Pressure	bar	59.6	60.6
Membrane Feed Flow Rate	m^3/hr	553	559
Permeate Flow Rate	m^3/day	6,506	6,506
Membrane Recovery Rate	%	49.0	48.5
Power Consumption	kW	826	642
Power Fed to ERD	kW	461	478
Power Recovered by ERD	kW	392	459
ERD Efficiency	%	63.9	96.0
Specific Energy Consumption	**kWh/m^3**	**3.05**	**2.37**

Slightly more membrane feed flow and slightly higher membrane feed pressure were required to produce the same amount of permeate after the PX retrofit, but 22% less energy per unit of permeate produced was consumed by the SWRO process.

Another example of a full retrofit is a Caribbean SWRO train that had been running with a Pelton turbine [12]. It was fully retrofit with PX devices, a circulation pump and additional membrane elements without changing the high-pressure pump or motor. Performance data before and after the retrofit are given in Table 3.

Table 3 – Process Data for Caribbean Expansion Retrofit

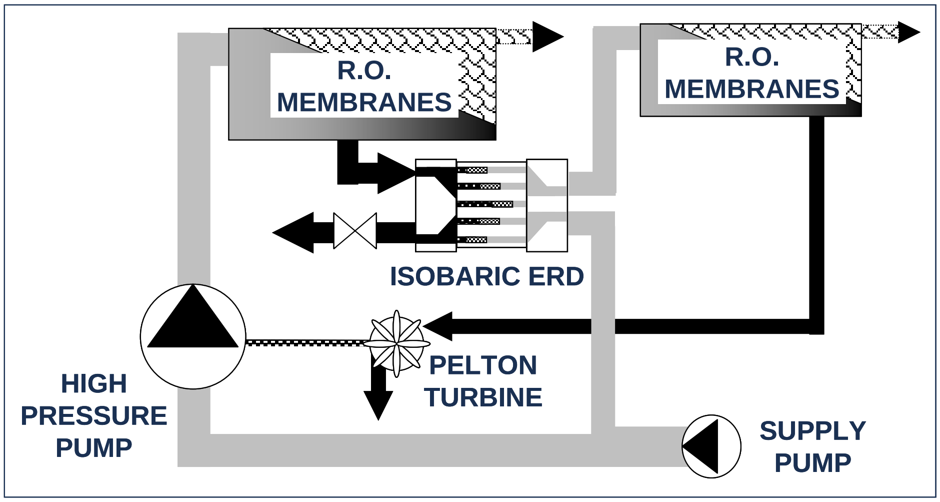
Parameter	Units	Pelton Turbine	After PX Retrofit
Membrane Feed Pressure	bar	67.6	57.2
Membrane Feed Flow Rate	m^3/hr	35	94
Permeate Flow Rate	m^3/day	271	622
Membrane Recovery Rate	%	32.5	27.6
Power Consumption	kW	45	56
Power Fed to ERD	kW	43	105
Power Recovered by ERD	kW	34	101
ERD Efficiency	%	66.2	96.0
Specific Energy Consumption	**kWh/m^3**	**3.94**	**2.15**

As a result of the retrofit, the plant was able to operate at lower recovery and lower pressure but at more than double the production rate. Specific energy consumption reduced by 45%.

Cascade Retrofit

A cascade retrofit uses the original high-pressure pump, a modified Pelton turbine, isobaric ERD(s) and a second set of membranes as illustrated in Figure 5. No circulation pump is required in a cascade scheme. The high-pressure pump motor must be of sufficient capacity to operate with reduced power from the Pelton turbine.

Figure 5 – SWRO Process with Cascade Configuration



A Pelton system was converted to a cascade system at the GEBE plant in Dutch St. Maarten. A photograph of the plant after the retrofit is given as Figure 6. Process data from the original system and from the system after the cascade retrofit are presented in Table 4 below. Included in Table 4 are projected performance data for the St. Maarten system if the Pelton wheel had been removed and the system fully retrofit with isobaric ERDs, a circulation pump and additional membranes.

Figure 6 – SWRO Process with Cascade Retrofit in St. Maarten

Table 4 – Process Data for St. Maarten Cascade Retrofit

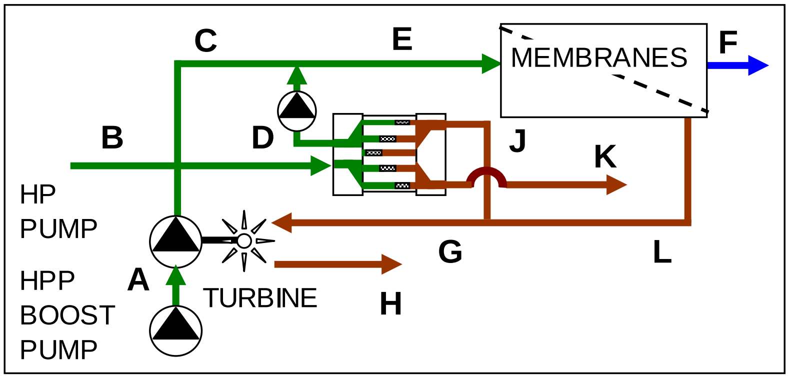
Parameter	**Units**	**Pelton Turbine**	**After Cascade Retrofit**	**After Full Retrofit (Projected)**
Membrane Feed Pressure	bar	71	61	62
Membrane Feed Flow Rate	m^3/hr	216	346	528
Permeate Flow Rate	m^3/day	2,176	2,768	5,299
Membrane Recovery Rate	%	42.0	33.4	41.8
Power Consumption	kW	533	471	513
Power Fed to Isobaric ERD	kW	--	211	527
Power Recovered by Isobaric	kW	--	202	505
Isobaric ERD Efficiency	%	--	96.0	96.0
Power Recovered by Pelton		143	96	--
Pelton Efficiency		60	60	--
Specific Energy Consumption	**kWh/m^3**	**5.87**	**4.08**	**2.32**

The data in Table 4 show that the cascade retrofit resulted in a reduction in feed pressure, an increase in permeate production and a 30% reduction in the amount of energy consumed to produce each cubic meter of permeate. Had the St. Maarten system been fully retrofit, the production rate could have been increased to more than double the original flow rate and a 60% reduction in specific energy consumption achieved.

Partial Retrofit

A partial retrofit scheme has been proposed for a process equipped with a Pelton turbine [13]. This design is illustrated in Figure 7. Additional membranes, an array of PX devices and a circulation pump are added to the existing system. No changes are made to the high-pressure pump or Pelton turbine. The amount of water diverted from the Pelton turbine to the PX devices depends upon the capacity of the high-pressure pump motor, which must operate with reduced power from the Pelton turbine.

Figure 7 – Partial Retrofit



A partial Pelton retrofit is relatively inexpensive to implement but can increase production capacity by 20% and reduce specific energy consumption by 10%.

Other Retrofit Considerations

The importance of reducing SWRO process energy consumption depends strongly upon the cost and availability of power at the installation. This must be balanced with the capital cost of the device(s), the design and cost of any necessary peripheral equipment and life-cycle cost issues such as operation, reliability, maintenance and equipment longevity.

Ease of Operation **–** Pelton turbines and the PX isobaric device are both easy to operate. Both are flow-driven and self-adjusting to changes in flow rates.

Reliability – Pelton turbines and PX devices both have a strong track record for reliability in SWRO applications. Close to 100% uptime can be expected. In the unlikely event of device failure, however, PX devices offer several advantages over Pelton turbines including fail-safe operation and redundancy. In medium and large SWRO trains where several PX devices are arrayed in parallel, one rotor out of service has minimal impact on SWRO membrane performance. If additional capacity is needed, additional PX devices can be added to operate in parallel with existing units.

Maintenance – ERD maintenance must be considered in SWRO system operation because of the direct costs and the associated system downtime. Pelton turbines require periodic changes to seals and bearings. PX devices require no periodic maintenance and no service of seals or bearings.

Device Life – Factors that adversely affect the longevity of SWRO equipment include corrosion, vibration and abrasion (wear). Pelton turbines are typically made with stainless steel alloys which offer resilience against damage by debris, however, all metal eventually corrodes, wears and fatigues in the harsh conditions of SWRO plants. Pressure transfer in the PX device occurs in a ceramic rotor enclosed in ceramic components. This material is more brittle than most metals, but three times harder than stainless steel and never corrodes in seawater.

CONCLUSIONS

Most high-pressure membrane desalination plants being designed and built today save energy by utilizing isobaric energy recovery devices such as the ERI PX Pressure Exchanger device. In addition, the owners and operators of many SWRO processes equipped with centrifugal ERDs such as Pelton turbines have retrofit or are considering retrofitting with isobaric ERDs to increase permeate production and reduce energy consumption. SWRO with isobaric ERDs provide many operating advantages over other system designs, including ease of operation and the flexibility of variable recovery operation. However, reverse osmosis plant designers and operators need to have a thorough knowledge of how an SWRO process works with an ERD to be able to optimize capital and operating costs and thereby minimize the total cost of ownership of the plant.

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