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SWRO process simulator

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Abstract

Most large seawater reverse osmosis (SWRO) desalination plants built before 2002 incorporated turbine-type energy recovery devices (ERDs) that were connected with a shaft to the high pressure pump. Both the pump and the ERD had best efficiency points corresponding to specific flow rates and pressures. To obtain the high energy-efficiency necessary for cost-effective operation, SWRO plants were designed and operated at a fixed membrane water recovery rates — typically 45% for Mediterranean Sea waters and 35% for Arabian Sea waters.

Most SWRO plants being designed and built today utilize isobaric ERDs. These designs emancipate the ERD and high-pressure pump making their operation independent. High efficiency can be obtained at range of membrane water recovery rates and can be changed as seasonal variations in the seawater occur or as the membrane elements age. Numerous best-efficiency operating points can be found which is a tremendous advantage for low-cost SWRO operation but can be too complex for manual design calculations. For this reason, Energy Recovery, Inc. (ERI®: ERI SIM is a copyright and trademark of Energy Recovery, Inc. ERI, PX Pressure Exchanger, PX and the PX logo are registered trademarks of Energy Recovery, Inc.) developed the ERI SIM™ program.

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. The author demonstrates the ERI SIM program by using it to compute SWRO-process responses to changes in process variables, typical startup and shutdown conditions, and various possible process upset conditions.

Keywords: SWRO; Desalination; Simulator; Energy recovery device; Pressure exchanger

1. Introduction

Although most system designers 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

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new equilibrium condition is reached. This is especially the case in SWRO systems equipped with isobaric ERDs which seal the high pressure portion of an SWRO process. No such model currently exists in the public domain for computing SWRO process dynamics.

The ERI SIM program was developed by Energy Recovery, Inc. as an instructional tool for SWRO system designers and operators. It integrates PX device performance, typical pump and valve characteristics and projected membrane responses into an interactive, dynamic model. Although it is not a design tool, the ERI SIM program can assist with the design process by giving a quantitative demonstration of system responses for a specific SWRO process.

This paper describes the SWRO process that the ERI SIM program simulates in detail. The performance characteristics of the individual components and the assumptions that were made in the development of the model are listed. ERI SIM program output data are presented for some basic SWRO operations including process startup, shutdown and membrane recovery adjustment. Finally, the affects of several possible process upset conditions are considered.

2. SWRO components

The ERI SIM program is based on the single-feed SWRO process with isobaric energy recovery illustrated in Fig. 1. The model system has a nominal capacity of 10,000 cubic meters per day of permeate. A supply pump feeds both the high pressure pump and the PX array. Membrane pressure and permeate flow are supplied by the high-pressure pump. A booster pump circulates water through the membrane elements and the energy recovery device(s). These components and their performance are described in the following subsections.

2.1. PX pressure exchanger energy recovery devices

A PX device transfers pressure from the high-pressure brine reject to a portion of feed water by putting them in direct, momentary contact in a rotor. The rotor is fit into a ceramic sleeve between two ceramic endcovers with narrow clearances that create an almost frictionless hydrodynamic bearing. As the rotor turns, the ducts pass a sealing area that separates high and low pressure. A schematic representation of the ceramic components of a PX device is given in Fig. 2.

Operation and control of a PX unit in an SWRO system can be understood 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 units or PX array, the booster pump, and back to the membrane elements at a rate controlled by the booster pump. The low-pressure water from the seawater supply flows through the PX units to the system discharge at a rate controlled by the supply pump and a throttle

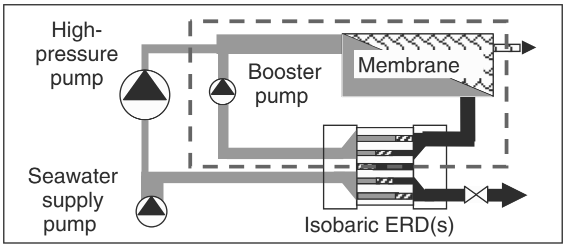


Fig. 1. SWRO system flow schematic.

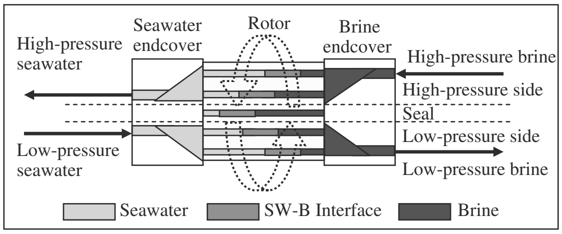


Fig. 2. PX device flow schematic.

valve in the brine discharge from the PX array. The function of the PX rotor is to continuously exchange one volume of pressurized brine from the SWRO membrane elements for one volume of filtered seawater from the cartridge filters.

The speed of the PX rotor is controlled by the combined flow rate of the low and high pressure streams. There are no shafts, motors, or electronic controls on a PX unit or array. The PX rotor contains no pistons or barriers. When the rotor is not spinning, flow passes directly through the device. Mixing between the brine and seawater streams is limited by the aspect ratio of the rotor ducts which are long and narrow. The PX rotor designed so that the interface between the brine and seawater never reaches the end of the rotor before the duct is sealed.

The pressure of the feedwater flowing from the PX is slightly lower than the pressure of the brine fed to the PX. Similarly, the pressure at the brine outlet of the PX is slightly lower than the pressure at the feedwater inlet. These pressure drops or head losses are associated with viscous friction as the water flows through constrictions in the ceramic components and are well characterized as a function of flow rate. High-pressure (HP) and low-pressure (LP) flow-differential pressure curves for the PX-220 are provided in Fig. 3. The PX-220 always operates in accordance with the flow-differential-pressure design curves. These curves are similar to pump curves in that the PX always stays on its curves. Even if a rotor stops spinning, the flow performance adheres to the design curves.

The ERI SIM program utilizes an array of up to 18 PX-220 devices. The maximum capacity of each device is 50 m^3/h. The nominal minimum flow rate is 40 m^3/h, however, operation below the nominal minimum does not typically reduce performance and will not damage the device.

2.2. Seawater supply

In practice, seawater can be supplied to an SWRO system with a number of possible configurations of pumps, filters and break tanks. Seawater supply in the ERI SIM program consists of a single supply pump followed by filters. The pump curve for the supply pump is shown in Fig. 4. The flow rate delivered by the pump varies with downstream pressure. If the filters clog or the control valve downstream from the PX array is closed, the pressure at the supply pump discharge increases and flow decreases according to Fig. 4.

Low-pressure flow through the PX array is delivered by the supply pump at a rate controlled by a control valve located downstream from the PX array. A family of curves that describe the

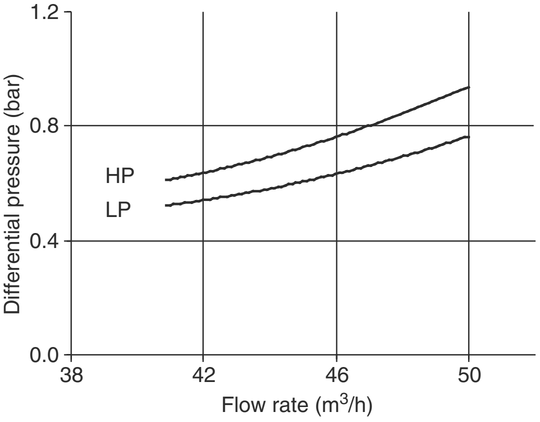


Fig. 3. PX-220 differential pressure.

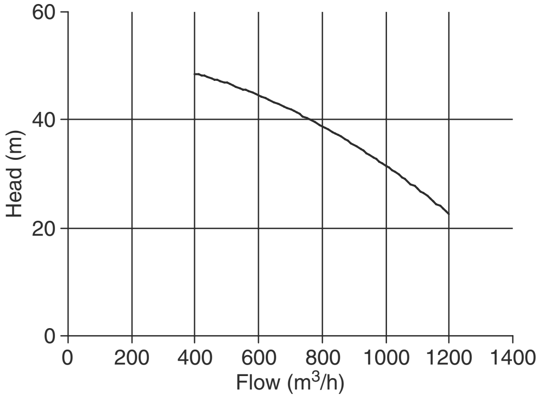


Fig. 4. Supply pump curve.

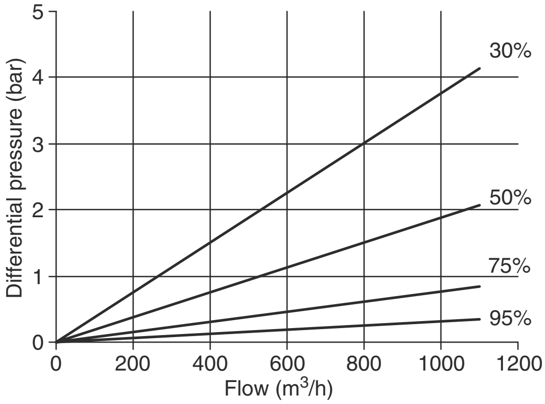


Fig. 5. LP control valve curves.

performance of the control valve at a number of valve positions is illustrated in Fig. 5.

2.3. SWRO pumps

The two pumps that feed the SWRO membranes are the high-pressure pump and the booster pump. The high-pressure pump in the ERI SIM program has a 1200 kW motor. For simplicity, constant (flat) pump and motor efficiencies of 84 and 96% are assumed. The high-pressure pump always stays on its curve, illustrated in Fig. 6. As downstream pressure increases as a result of membrane fouling, scaling or osmotic pressure, high-pressure pump flow decreases according to Fig. 6.

The booster pump in the ERI SIM program is equipped with an inverter or variable frequency driver (VFD). The motor has a nominal capacity of 100 kW, a constant pump efficiency of 85% and a constant motor efficiency of 92%. A family of curves corresponding to a range of VFD settings is given in Fig. 7.

2.4. Membrane elements

Membrane performance was derived using a commercially available membrane projection program. A four-hundred square foot or thirty-seven square-meter seawater membrane element model was selected. The number of elements in the ERI SIM program is adjustable, but for the sake of the analysis presented below, it was set at 700 to provide a nominal flux of 16 L per square meter per hour. Feedwater salinity and temperature are adjustable within the ERI SIM program, but for the sake of this analysis were set at 36,000 parts per million (ppm) total dissolved solids (TDS) and 25 degrees Centigrade (deg C). Membrane age and cleaning frequency can also be altered by the program user. A membrane age of three years and cleaning frequency of four times per year were used in the analysis presented below.

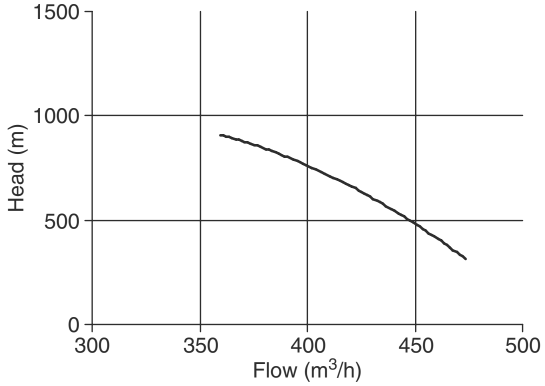


Fig. 6. High pressure pump curve.

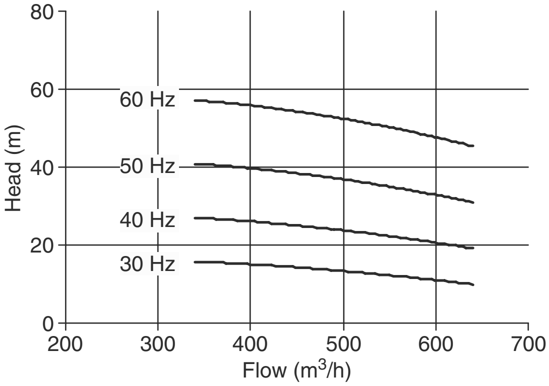


Fig. 7. Booster pump curves.

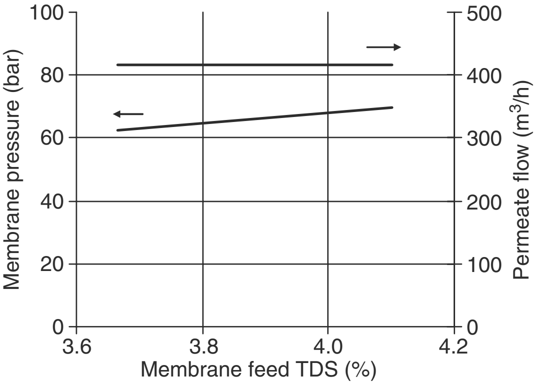


Fig. 8. Membrane pressure and flow versus feed salinity.

Membrane performance data for a wide range of feedwater conditions were computed with the membrane projection program. These data are summarized in Figs. 8–11. These data show that permeate flow rate is relatively independent of feed salinity, membrane recovery and membrane feed pressure. Membrane feed pressure is lower when feed salinity, recovery rate and fouling are low or when feed temperature is high. Membrane differential pressure increases only slightly with fouling but membrane feed pressure increases substantially. The affects of membrane age and cleaning are not illustrated here. Increased membrane age has a similar affect as increased fouling. A higher cleaning frequency reduces the affects of fouling but shortens membrane life and adds costs, and this is taken into account in the operating cost estimate generated by the program.

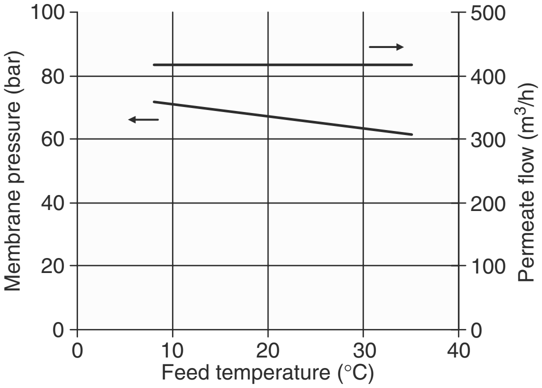


Fig. 10. Membrane pressure and permeate flow versus temperature.

3. ERI SIM program setup

The ERI SIM program integrates the PX device performance, pump and valve characteristics and projected membrane responses described above into an interactive, dynamic computer model. A commercially available spreadsheet is used as the platform for the model. Linear or quadratic equations that were fit to the relationships illustrated above are used to estimate the state of

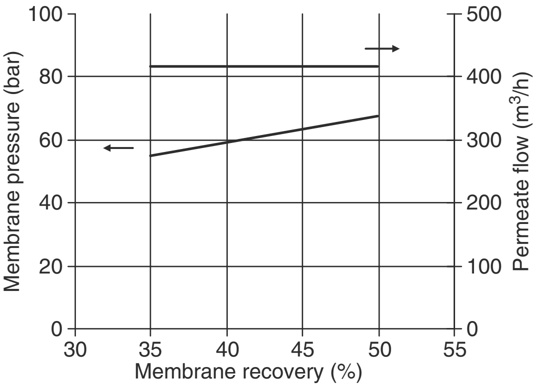


Fig. 9. Membrane pressure and flow versus membrane recovery.

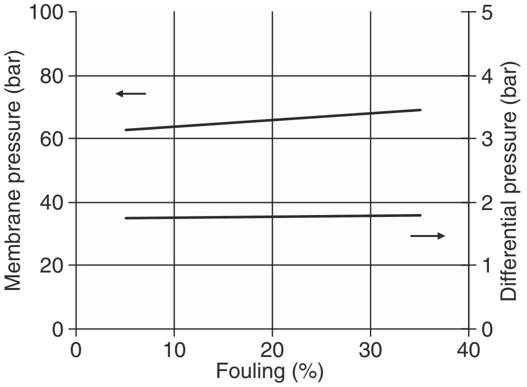


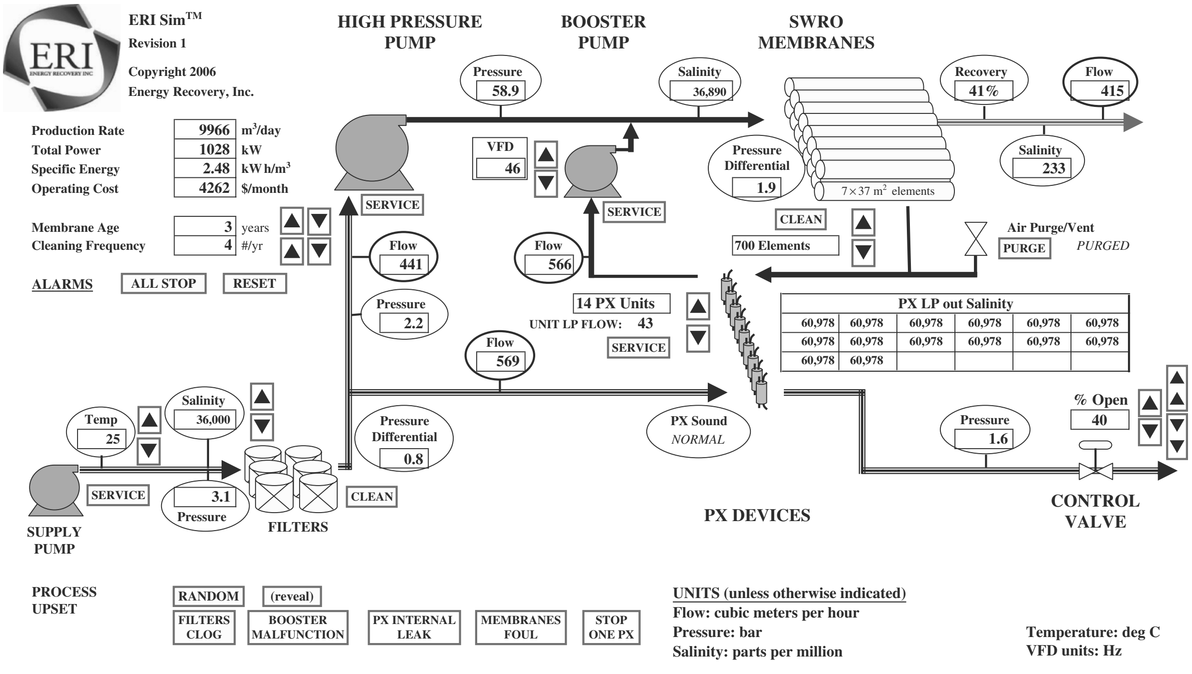
Fig. 11. Membrane pressure and differential pressure versus fouling.

each component. Pressures, flows and salinities at various process locations are derived by mass balance. Because the membrane feed pressure, the booster pump differential pressure and the supply flow rate are inputs and outputs for several system components, they cannot be derived independently or directly and are therefore computed by trial-and-error iteration.

The user interface is illustrated in Fig. 12. Pressures, flows and salinities are indicated with instruments at locations they would typically be found in an SWRO process. The three process pumps are started and stopped with mouse clicks. The low-pressure control valve, booster pump VFD, feed salinity and temperature, membrane age and cleaning frequency are adjusted with up- or down-arrows. The number of membrane elements and number of PX devices can also be adjusted but only when the system is stopped.

A number of process upset conditions can be simulated. These include filter and membrane fouling, pump malfunction and PX device malfunction. Unknown process upsets can be initiated in which the ERI SIM program randomly imposes one of sixteen upset conditions. The random upset can be corrected with appropriate action and/or be revealed to the user upon request. The components can then be serviced to correct the upset in ways that are consistent with real SWRO process operations. For example, the membranes can be cleaned but only after the process is shut down.

The ERI SIM program estimates the power consumption and operating cost of the SWRO process which vary with operating conditions and settings. Power is consumed by the high-pressure pump, booster pump and supply pump. To compute power costs, 0.1 USD/kWh was used. This was combined with an estimate of the filter replacement, membrane replacement, chemical and labor costs to obtain the overall process operating cost.



Production Rate	9966	m³/day
Total Power	1028	kW
Specific Energy	2.48	kW h/m³
Operating Cost	4262	$/month
Membrane Age	3	years
Cleaning Frequency	4	#/yr

Pressure 58.9
VFD 46
Salinity 36,890
Pressure Differential 1.9
7 × 37 m² elements
Recovery 41%
Flow 415
Salinity 233
700 Elements
Flow 441
Pressure 2.2
Flow 566
14 PX Units
UNIT LP FLOW: 43
Flow 569
Temp 25
Salinity 36,000
Pressure 3.1
Pressure Differential 0.8
PX Sound NORMAL
Pressure 1.6
% Open 40

PX LP out Salinity					
60,978	60,978	60,978	60,978	60,978	60,978
60,978	60,978	60,978	60,978	60,978	60,978
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UNITS (unless otherwise indicated)
Flow: cubic meters per hour
Pressure: bar
Salinity: parts per million
Temperature: deg C
VFD units: Hz

Fig. 12. ERI SIM program user interface.

4. ERI SIM program results

Several SWRO operations have been simulated with the ERI SIM program. The results tabulated in the following subsections.

4.1. Startup and shutdown

The normal startup sequence for the SWRO process that the ERI SIM program is based upon is listed as follows. ERI SIM program responses for a system with an array of 16 PX devices are summarized in Table 1 below.

(1) Start the seawater supply pump. Adjust the seawater flow to the desired flow rate. Most of the seawater flows through the PX array and some is forced through the high-pressure pump.

(2) Start the booster pump. Purge air from the system. Seawater circulates through the membranes and the pressure increases slightly. The salinity of the membrane feed is the same as the seawater salinity. Essentially no change in the low-pressure flow through the PX array occurs.

(3) Start the main high-pressure pump. The membrane pressure increases and permeate begins to flow. The high-pressure pump draws down the supply pressure and reduces the low-pressure flow through the PX. Because the low- and high-pressure flows to the PX array are not equal, mixing in the PX devices is relatively high which increases the membrane feedwater salinity by about 8%.

(4) Adjust the low-pressure control valve until the seawater flow to the PX device array approximately equals the booster pump flow rate — a condition referred to as “balanced flow.” The salinity at the membrane feed reduces to less than 3% higher than the seawater salinity and the membrane feed pressure lowers accordingly. High-pressure pump and permeate flow rates increase slightly as the duty point of the high-pressure pump shifts down its curve.

To shut down the process, the startup sequence is carried out in reverse. With a high-pressure pump that shuts off abruptly, the low-pressure flow rate through the PX device array must first be reduced. If the low-pressure flow rate is not reduced before the high-pressure pump is stopped, seawater can overflow the PX array as illustrated in step 1′ in Table 2. In practice, this problem can be avoided with soft-stop control on the high-pressure pump, by supplying the high-pressure pump and PX array with separate pumps or with fast-responding, automated low-pressure flow control.

Pressure remains in the high-pressure portion of the process after the high-pressure pump stops because of osmotic flow through the membrane elements, also known as suck back. This pressure stays in the high-pressure portion of the system until it is vented as illustrated in step 5 in Table 2. In practice, pressure would slowly drain through the PX array, but because the lubrication flow rate through the PX devices is

Table 1
ERI SIM program startup data

Step	Action	PX HP flow	PX LP flow	HP pump flow	Membrane salinity	Membrane pressure	Membrane DP	Membrane recovery (%)	Permeate flow
1	Supply pump start	0	637	10	36,000	4	0.0	0	0
2	Booster pump start	629	640	0	36,000	7	2.1	0	0
3	HP pump start	624	476	434	38,956	64	2.1	40	426
4	Flows balanced	625	625	440	36,914	60	2.1	41	432

Table 2
ERI SIM program shutdown data

Step	Action	PX HP flow	PX LP flow	HP pump flow	Membrane salinity	Membrane pressure	Membrane DP	Membrane recovery (%)	Permeate flow
0	System running	625	625	440	36,914	60	2.1	41	432
1′	HP pump stop	629	851	10	36,000	29	2.1	0	0
1	LP flow reduced	625	572	439	37,290	60	2.1	41	431
2	HP pump stop	629	777	10	36,000	29	2.1	0	0
3	Booster pump stop	0	773	10	36,000	29	0.0	0	0
4	Supply pump stop	0	0	10	36,000	29	0.0	0	0
5	Purge/vent	0	0	10	36,000	0	0.0	0	0

so low, it could take many hours for the pressure to reduce to near atmospheric pressure.

4.2. *Lead flow and lag flow*

As described above, some mixing between the brine and seawater occurs in the PX devices. If the low-pressure flow rate to the PX devices is increased such that it is greater than the high-pressure flow rate from the PX devices, the PX devices are said to be operating in a “lead-flow” condition. Lead flow reduces the mixing affect by flushing the PX devices with seawater. If the low-pressure flow rate is lower than the high-pressure flow rate, the PX devices are said to be operating in a “lag-flow” condition.

ERI SIM program data for these conditions for a system with 12 PX devices is illustrated in Table 3. Applying five percent lead flow slightly reduces membrane pressure, energy consumption and operating cost by lowering membrane salinity, but this requires additional seawater supply capacity. Applying lag flow has the opposite affects.

4.3. *Membrane recovery rate adjustment*

The membrane recovery rate in the ERI SIM program is lowered by reducing flow through the energy recovery devices. In practice, it can also be changed by adjusting the speed of the high-pressure pump, by adjusting the feed pressure or by altering the number of membrane elements. The osmotic pressure in the membrane elements is lower at lower recovery rates; therefore, the membrane pressure and the pressure

Table 3
ERI SIM program lead- and lag-flow data

Action	PX HP flow	PX LP flow	HP pump flow	Membrane salinity	Membrane pressure	Membrane DP	Membrane recovery (%)	Permeate flow	Specific energy	Operating cost ($)
System running	519	519	434	37,019	64.2	1.8	45	426	2.53	4577
5% lead flow	519	545	435	37,009	63.7	1.8	45	427	2.52	4569
5% lag flow	519	493	434	37,054	64.5	1.8	45	426	2.54	4582

Table 4
ERI SIM program membrane recovery rate data

Membrane recovery (%)	Membrane salinity	Membrane pressure	Permeate flow rate	Permeate salinity	Membrane DP	Number of PX units	Specific energy	Operating cost ($)
36.9	36,815	56.3	437	193	2.5	18	2.35	4050
37.4	36,843	56.8	437	194	2.4	16	2.37	4093
38.8	36,857	58.0	435	202	2.3	16	2.39	4169
40.6	36,919	59.7	432	211	2.1	16	2.42	4274
40.9	36,902	60.0	433	211	2.1	13	2.44	4316
42.7	36,943	61.8	430	220	2.0	13	2.48	4424
44.9	36,976	64.2	425	233	1.8	13	2.53	4576
46.5	37,017	66.3	424	241	1.7	10	2.60	4717
48.9	37,069	69.7	416	256	1.5	10	2.68	4902
50.5	37,137	72.4	411	268	1.5	10	2.76	5039
51.5	37,128	74.3	407	275	1.4	10	2.82	5130

duty of the high-pressure pump are lower and the permeate flow rate is higher. Generally, SWRO system energy consumption follows the same trend — with lower energy consumption at lower recoveries — because the high-pressure pump is the greatest energy consumer in the process. In addition, membrane scaling and the need for membrane cleaning are reduced at lower recoveries, which can increase membrane life. However, in the limit of very low recovery, supply pump and booster pump energy consumption exceed high-pressure pump energy consumption. These trends are illustrated in the ERI SIM program data presented in Table 4 and in Fig. 13.

4.4. Process upsets

One advantage of using a simulator for training is that failure modes can be examined without risk of damage to expensive equipment. There are 16 possible process upsets incorporated into the ERI SIM program including five conditions that can be specified by the operator. System responses to four of the upset conditions are described below and the data is presented in Table 5.

- Baseline condition — The baseline condition is 36,000 ppm TDS seawater salinity, 25°C water temperature and 45% membrane recovery rate. The system includes 700 membrane elements and 12 PX units.
- Booster pump stop — If the booster pump stops while the high-pressure pump is running, the salinity of the seawater in the membrane elements builds very rapidly, typically triggering a high-pressure shutdown of the process. If the high-pressure pump stops suddenly and the supply pump does not stop, the low-pressure flow to the PX devices can exceed their maximum flow limit.

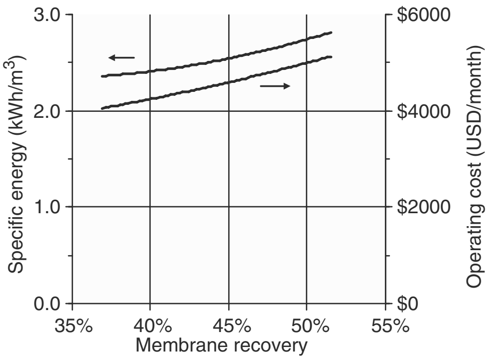

Fig. 13. Membrane recovery rate energy and cost trends.

Table 5
ERI SIM program process upset data

Event	PX HP flow	PX LP flow	HP pump flow	Membrane recovery (%)	Membrane salinity	Membrane pressure	Permeate flow rate	Membrane DP	Specific energy	Operating cost ($)
Baseline condition	519	519	432	45	37,019	64.2	426	1.8	2.53	4577
Booster pump stop	0	677	–	100	90,000	100	–	0.0	–	–
Membranes foul	507	523	421	45	36,865	69.8	415	1.9	2.74	4710
PX Internal leak	514	520	437	44	36,988	61.5	414	1.8	2.53	4433
One PX rotor stop	517	521	427	45	38,252	66.8	421	1.8	2.63	4630

- Membrane fouling — Membrane fouling causes a significant increase in membrane pressure and a corresponding reduction in permeate flow as the high-pressure pump is pushed up its curve. Membrane differential pressure increases only slightly, but enough to reduce booster pump flow.
- PX Internal leak — As long as the SWRO process is pressurized, lubrication flow through the hydrodynamic bearing of the PX devices occurs. This flow can be measured as the difference between the high-pressure pump flow rate and the permeate flow rate. For the baseline condition, the lubrication flow rate is 6 m^3/h. An internal leak in a PX device could occur if, for example, a unit was serviced and reassembled incorrectly. An internal leak in a PX device would increase the difference between the high-pressure pump and permeate flow rates. ERI SIM program data with a relatively large internal leak of 21 m^3/h in the PX array are shown in Table 5. Such a leak has little affect on PX flow rates or upon membrane feed salinity. However, permeate production decreases.
- PX Rotor stop — If a PX rotor stops for any reason, flow passes through the rotor but the seal between high- and low-pressure inside the PX device remains intact. As illustrated in Table 5, a stopped rotor causes a 3% increase in membrane feed salinity and a 4% increase in membrane pressure and energy consumption compared to the baseline condition. However, there is very little reduction in permeate flow.

5. Summary

The ERI SIM program 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. This paper has demonstrated the ERI SIM program by using it to compute SWRO-process responses to changes in process variables, typical startup and shutdown conditions, and various possible process upset conditions. Copies of the ERI SIM program and detailed instructions on operating the program are available from Energy Recovery, Inc. at sales@energy-recovery.com, www.energyrecovery.com or +1-510-483-7370.