ENERGY RECOVERY TECHNOLOGY
OPENS DOORS TO NEW SWRO PLANT DESIGNS

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1.0 INTRODUCTION

Seawater Reverse Osmosis has been around for over 20 years. There are dozens of excellent engineers worldwide who can obtain very good SWRO plant designs using conventional technology. However, there is a new type of commercial energy recovery device on the market, which uses the "isobaric chamber" approach. This new technology changes many conventional SWRO system design beliefs and conventions.

The new pressure exchanger (PX) device transfers the energy from the concentrate stream directly to the feed stream. This direct, positive displacement approach results in a net transfer efficiency of over 95%. Although the application of PX technology is simple in both theory and practice, in order to get the most benefit from the technology it is important to reconsider some basic principles about the SWRO design and operational approach. This paper explores several new types of SWRO plant designs. Much of the data provided in this paper has been verified and derived from operating plants that are now using these devices. It will also be shown that the design and operation of these systems are, to some extent, counter-intuitive and may possibly reverse some fixed standards that have been developed over the past 20 years of SWRO evolution.

There has been a recent proliferation of commercially available energy recovery devices based on the positive displacement, direct pressure exchange approach. This increased interest is driven by the fact that the technology can reduce the energy consumption of an SWRO system by as much as 60%. Since energy costs are rising and can comprise as much as 75% of the total operating costs of an SWRO plant, it is important that the technology be encouraged and disseminated throughout the industry. Although the author of this paper is directly associated with Energy Recovery, Inc., a leading company in pressure exchanger technology, many of the principles and theories presented in this paper will be applicable to all devices that are based on the positive displacement, isobaric chamber approach.

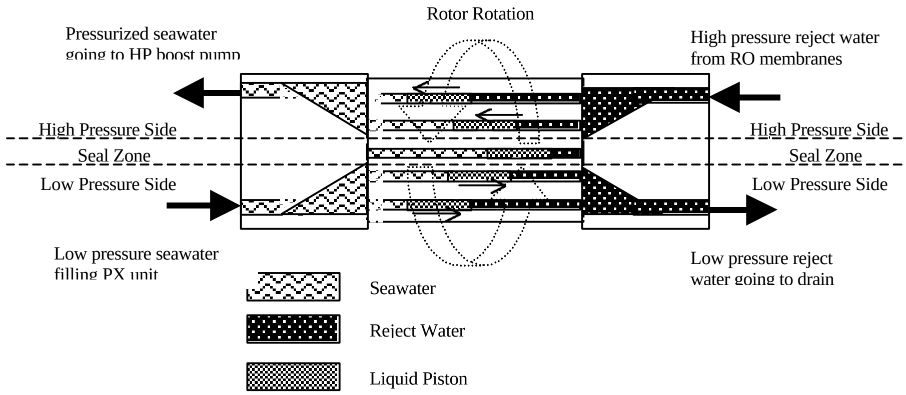
2.0 PRINCIPLE OF OPERATION

The PX unit utilizes the principle of positive displacement to transfer the energy in the reject stream directly to the membrane feed stream. It is interesting to note that the reject stream is continuously in direct hydraulic connection to the feed stream. This direct connection allows a real net transfer efficiency of energy from the reject stream to the feed stream of over 95%. The PX device uses a cylindrical rotor with longitudinal ducts parallel to its rotational axis to transfer the pressure energy from the concentrate/reject stream to the feed stream.

The rotor spins inside a sleeve between two end covers with port openings for low and high pressure (HP). The low-pressure side of the rotor fills with seawater while the high-pressure side discharges seawater. The rotation simply facilitates the valving mechanism, which is to transport the ducts from the low pressure (LP) fill cycle to the high-pressure discharge cycle.

By rotation the ducts are exposed to the low pressure feed water, which fills the duct and displaces the reject water. The rotor continues to rotate and is then exposed to the high-pressure concentrate, which fills the duct from the opposite direction, and displaces the feed water at high pressure. This rotational action is similar to a Gatling machine gun firing high-pressure bullets and being refilled with new seawater cartridges from the muzzle. A liquid piston moves back and forth inside each duct creating a barrier that inhibits mixing between the concentrated reject and new seawater streams. At 1500 rpm, one revolution is completed every 1/25 second. Due to this short cycle time, membrane feed water concentrations typically increase only 1%-2%. See Figure 4-1 below.

Figure 1. Pressure Exchanger Flow Path



Applying PX pressure exchanger technology to SWRO is different from conventional energy recovery device system design, but in practice it is quite simple. The reject brine from the SWRO membranes is passed into the PX unit, where its pressure energy is transferred directly to a portion of the incoming raw seawater at up to 97% efficiency. This seawater stream, nearly equal in volume and pressure to the reject stream, then passes through a high-pressure circulation pump, not the main high-pressure pump. This circulation pump is making up the pressure losses across the RO membrane (approx. 2 bar), PX unit(s) (approx. 1 bar) and piping losses (approx. 0.5 bar). The total differential pressure provided by the circulation pump is typically around 3.5 bar. See figure 4-2 and table 4-1 below.

Figure 2. Typical System Flow Path

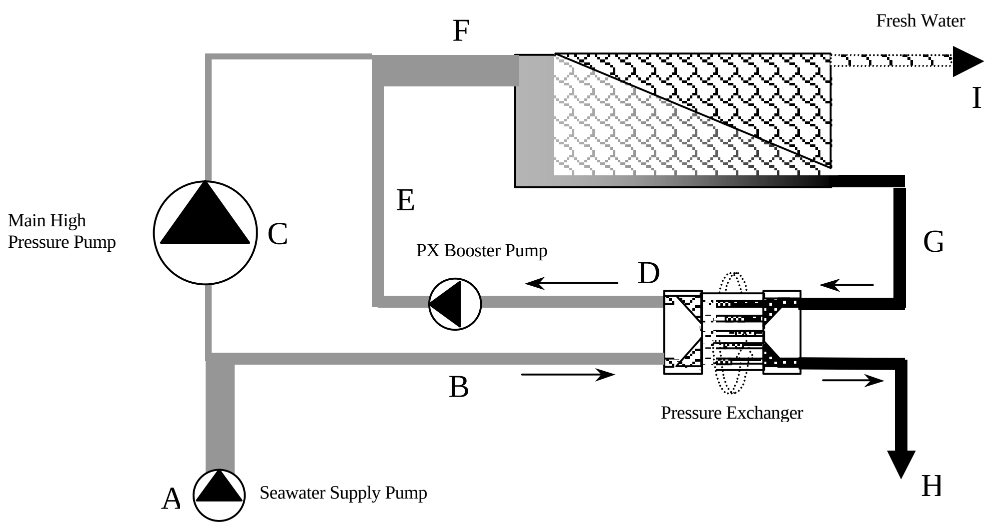


Table 1. Example Flow Rates and Pressures

STREAM	DESCRIPTION	FLOW RATE*	PRESSURE BAR
A	Seawater supply	100	2
B	PX LP Inlet/ Seawater	58.8	2
C	Main HP Pump Flow	41.2	69
D	PX HP Outlet/ Seawater	58.8	66
E	Booster Pump Outlet/ Seawater	58.8	69
F	RO Feed Stream	100	69
G	PX HP Inlet/ Reject	60.0	67
H	PX LP Outlet/ Reject	60.0	1
I	RO Product Water	40.0	0.3

*40% conversion rate RO system independent of units.

In order to determine the specific power consumption of this system we simply sum up the power consumption of each component and divide by the permeate produced by the system as follows:

System KW = Kw Seawater Supply Pump + Kw Main High-Pressure Pump + Kw PX Booster Pump

$$\text{Pump KW} = \frac{\text{Flow} * \text{ÄP Pump.}}{36.0 * \text{pump efficiency.} * \text{motor efficiency}}$$ (Note: Flow in m3/hr and pressure in bar)

$$\text{SW Pump} = \frac{100 * 2}{36.0 * 0.75 * 0.92} = 8.0 \text{ KW}$$

$$\text{Main HP Pump} = \frac{41.2 * 67}{36.0 * 0.90 * 0.93} = 91.6 \text{ KW}$$

$$\text{PX Boost Pump} = \frac{58.8 * 3}{36.0 * 0.70 * 0.92} = 7.6 \text{ KW}$$

$$\text{System Specific Power Consumption (KWh/m3)} = \frac{\text{System KW}}{\text{System Permeate Flow (m3/hr)}} = \frac{107.2 \text{ KW}}{40 \text{ m3/hr}} = 2.68 \text{ KWh/m3}$$

There are several significant points to draw from the flow diagram above when applied to traditional SWRO designs. First is that the product flow and reject flow are being provided by two separate pumping systems and can be controlled independently. Since the PX unit is providing nearly 100% of the reject flow at 95% efficiency there is very little energy penalty associated with increasing this flow and thereby lowering the conversion rate of the RO system. The main HP pump flow can remain relatively constant at varying recoveries. The designer and operator now have direct control of the reject flow and its portion of the feed flow. Putting it simply, the conversion rate of the RO plant is now an independent variable.

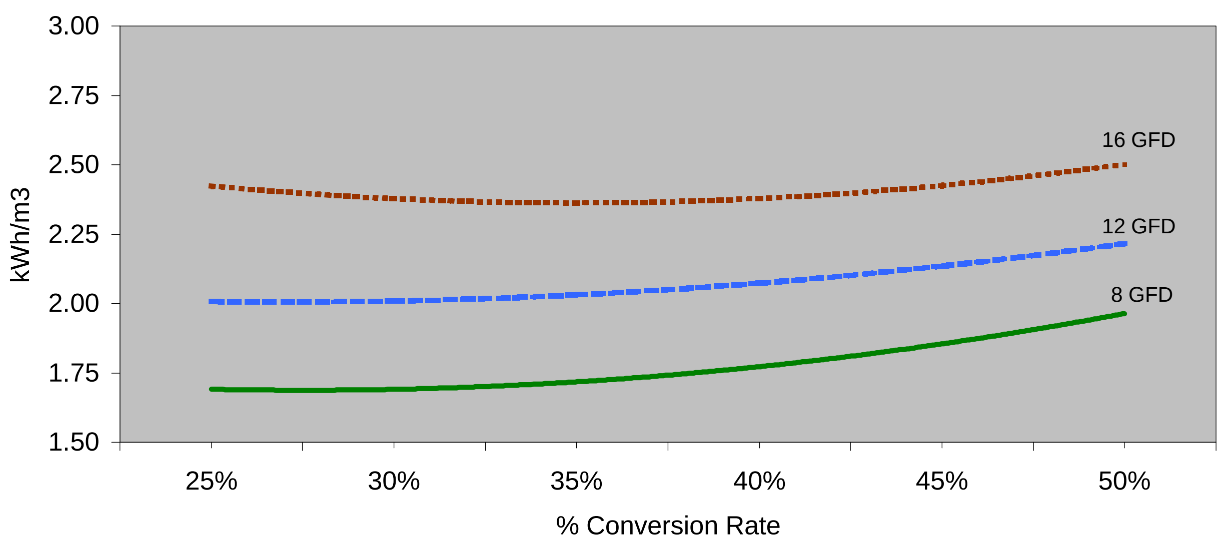
Second is that there is no longer a physical connection between the main high-pressure pump and the actual energy recovery device. This fact allows another new degree of freedom when considering the size that the main HP pump can be and the number of trains that it can service. At any given brine pressure and motor RPM, traditional Pelton technology has flow limits in order operate at maximum efficiency. For larger plants, eliminating the Pelton wheel allows us to go to larger pump sizes and presents several interesting choices that we will discuss later in this paper.

3.0 CONVERSION RATE AND FLUX OPTIMIZATION

There are many factors that affect RO conversion optimization but none has been more influential than energy consumption. This is because energy costs can be as much as 75% of the entire operating cost of an SWRO plant. In the past, the seawater to freshwater conversion rate has had a major and direct impact on the energy consumption of an RO plant. This is because of the inherent shortcomings of the energy recovery and pumping devices that have been used such as Pelton wheels, turbines, and pumps. These technologies have real/overall net transfer efficiencies of 40-79 percent and are designed to pump the entire feed flow of an RO plant. Therefore, at lower conversion rates these inefficient devices are pumping more water. The only way to make these devices pump less water and thereby consume less energy is to increase the conversion rate of the RO system. This is all very logical, and with rising energy costs it is natural that SWRO systems are now being designed at the membrane inefficient (1) conversion rates of 50-60%.

System designs with the PX device are different. This is because the PX, a 95% efficient device, is pumping the reject water independently of the product water being produced. The overall unit energy consumption of an SWRO plant using the PX device has a low point at a conversion rate typically between 30-40%. Outside this range unit energy consumption increases slightly. See Figure 3 below.

Figure 3. SWRO PX kWh/m3 Vs Conversion Rate @ various GFD's (2)



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(1) Efficiency Considerations of Typical Seawater Reverse Osmosis Membranes, Dr. William T. Andrews, Mr. Victor Verbeek, Bahrain IDA Conference Oral Presentation 2002.

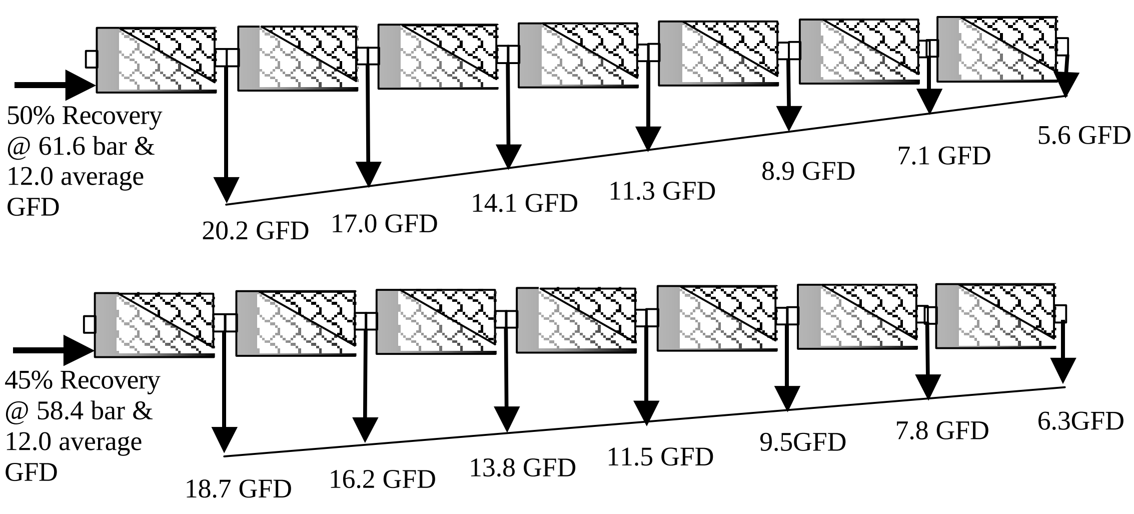
(2) PX curves generated using Hydranautics RODESIGN32, 32,070 TDS ASTM seawater feed @ 25°C, SWC3 membranes, 7 elements per vessel, 0 years. Both feed pressure and membrane differential pressure were considered for each case. 89% and 96% efficient main high-pressure pump and motor. 88% and 95% efficient PX booster pump and motor. Power allowance for 88% and 95% efficient seawater supply pump and motor was also included. Piping and other parasitic losses were neglected and should be avoided.

It is important to remember that with the PX device the main high pressure pump flow approximately equals the product water flow. At lower conversion rates it requires lower pressure to produce the same amount of product water. Therefore, the main high-pressure pump will consume less power by pumping against less pressure at the lower conversion rates. This is also true at lower flux rates. These effects are not isolated to pressure exchanger technology, but it is PX technology that can uniquely take advantage of the lower flux/energy profiles.

The combined effects of recovery and flux yield the family of curves shown in Figure 3. We can see in Figure 3 that the difference in power consumption versus recovery rate is more pronounced at the lower flux rate of 8 gfd where the savings is 14% from high to low compared to the higher flux 16 gfd system where the difference is only about 2% over the total curve. Looking at flux rate directly we see an even more dramatic effect, where the net energy consumption drops an average of about 28% from 16 GFD to 8 GFD. Combining these savings and selecting a reasonable operating point can yield significant reductions in SWRO power consumption. Looking at the curves, we see that the power savings from operating at 50% conversion rate and 16 gfd to 45% conversion rate and 8 gfd is approximately 0.64 kWh/m3 or 26%. In a 100,000 m3/day plant, at $0.05/kWh, this savings totals over US$ 1,168,000.00 per year.

Of course water quality suffers at lower flux rates, but operating at a lower conversion rate can counteract these effects. There are also additional benefits associated with lower conversion rate designs such as lower Boron levels, ease of operation, fewer cleaning cycles, longer membrane life and a better balance of flux from the lead element to the end element in the RO pressure vessel. Figure 4 below shows how element flux is balanced at lower system conversion rates (3).

Figure 4. Element By Element Flux at Various Conversion Rates



Decreasing the system conversion and flux rates does have its disadvantages, mainly by increasing the size of the pretreatment system and membrane stacks. This effect is less significant in smaller systems under 1000 m3/day because of the less expensive piping materials, pressure media filtration systems and

(3) Flux profiles were generated using Hydranautics RODESIGN32, 32,070 TDS ASTM seawater feed @ 25°C, SWC3 membranes, 7 elements per vessel, 0 years.

other components typically employed in these systems. However, conversion rates greater than 45% may be more practical on larger plants using open seawater intakes with large-scale gravity feed media filtration systems or micro-filtration systems, and when the chemical additions associated with coagulation are a significant operating cost. It should be the subject of another paper to consider the capital costs and return on investment of operating at the lower conversion and flux rates.

However, from the analysis above it is clear that lower conversion and flux rates are technically superior when using pressure exchanger energy recovery technologies and membrane manufacturers might be wise to concentrate their development efforts towards high flux low pressure seawater membranes. Ultra-high rejection is no longer so important since lower recoveries can be used to improve water quality.

4.0 INDEPENDENT HIGH-PRESSURE PUMP

In larger SWRO designs the main HP pump has been traditionally connected to a centrifugal energy recovery device such as a Pelton wheel or Francis turbine. In recent years the Pelton wheel has been the most popular choice between these two devices because of its higher achievable efficiencies. Looking at equations for specific speed of pumps and impulse turbines (4) we can see that flow (Q), pressure (m), RPM and efficiency (n_t) are related creating a host of restrictions, conflicts and competition for an optimum operating point.

$$\text{Impulse turbine runner specific speed (SI units)} = N_s = \frac{\text{rpm} \times Q^{1/2}}{m^{5/4}}$$

$$\text{Universal specific speed (SI units)} = \frac{N_s}{16.54\,(n_t \times \text{sp.gr.})}$$

These conflicts make it difficult to control large systems at their optimum operating points. In an SWRO system using standard RPM motors the Pelton device is also limited to maximum allowable flow rate in order to maintain high efficiencies. This limits the size of the main HP pump thereby fixing many aspects of plant design including the maximum pump and train size and the number of pumps that must be used to service mega installations.

Figure 5 below shows how mega trains can now utilize higher flow, higher efficiency pumps while taking advantage of economies of scale to further reduce the cost of producing fresh water from the sea. The 6ea 53,000 m3/day trains would provide 319,000 m3/day (84,000,000 mgd) of permeate operating at 51 bar feed pressure while consuming 1.7 kWh/m3 when considering the RO process portion of the system only.

(4)Pump Handbood, Third Edition, McGraw-Hill, Section 6.4.1Hydrualic Turbines.

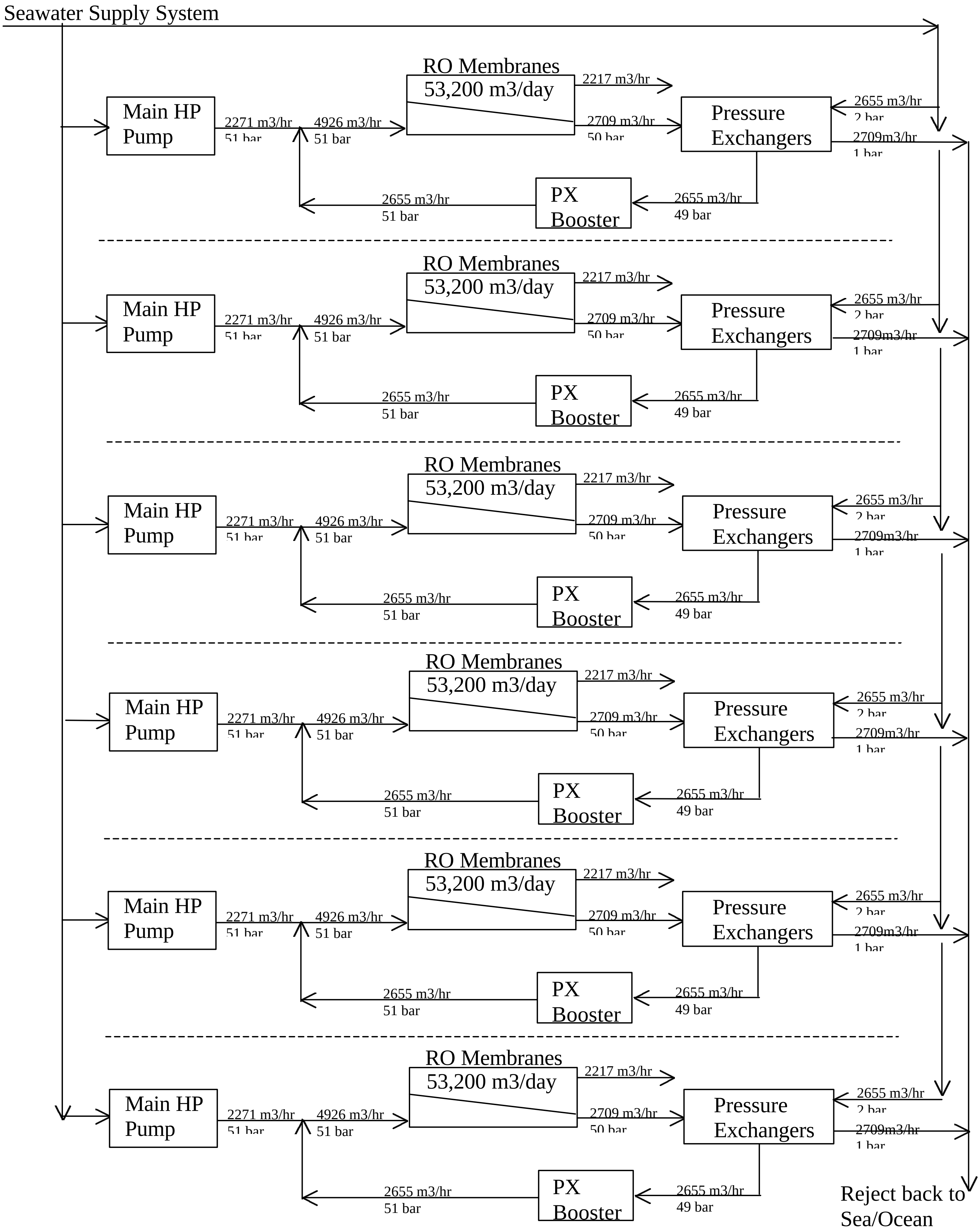


Figure 5. 319,000 m3/day System in 6x50,000 m3/day Trains.

Table 2. 53,200 m3/day Train Parameters and Power Consumption (5)

Temp °C	Feed Press (bar)	Product Flow (m3/hr)	HP Pump Flow (m3/hr)	HP Pump ÄP (bar)	HP Pump KW	PX Booster Flow (m3/hr)	PX Booster ÄP (bar)	PX Booster KW	RO System Kwh/m3
25	51.2	2217	2271	49.2	3624	2655	2 / 4	182 / 365	1.72 / 1.80
22	52.0	2217	2271	50.0	3683	2655	2 / 4	182 / 365	1.74 / 1.83
18	53.2	2217	2271	51.2	3771	2655	2 / 4	182 / 365	1.78 / 1.87

Looking at Table 2 and Figure 5, we can see how pressure exchanger technologies can simplify the control of these large SWRO trains as the inlet conditions and membrane performance vary. This is because the permeate flow and reject flow are independent. The reject flow and corresponding portion of the feed flow are being supplied by the PX system. The only significant variable in this PX circuit is the differential pressure across the RO membranes. The ambient pressure inside the RO membranes is not influential. Therefore this portion of the RO high pressure feed flow is very stable and can be easily maintained with a relatively small VFD and the PX booster pump. Furthermore, since pressure exchangers are positive displacement devices their efficiencies remain stable around 95% regardless of variations in flow and ambient conditions. The control of the main HP pump is also somewhat simplified because it is approximately equal/connected to the product water flow rate and the membranes now act as the system's pressure regulating device. The permeate flow and main HP pump flow can be kept constant and the outlet pressure at the main HP pump can vary depending on inlet conditions and membrane requirements. Control of this pressure can be achieved by means of several efficient methods including a VFD, or varying the main HP pump inlet pressure with the use of a smaller supply pump and VFD. Throttling valves are wasteful and are not recommended. Since the main HP pump is only pumping approximately 45-50% of the feed flow and the other 50-55% is very stable and requires only a low power control solution many of the traditional control challenges are minimized or eliminated.

Another possibility for mega plant design is shown in Figure 6 below, where a few very large HP pumps feed multiple membrane and energy recovery arrays. Trains can be isolated for maintenance and put back on line with fewer HP pumps to operate and maintain. This design allows the operator to use the larger more efficient pumps while still maintaining traditional flow and piping size requirements for the majority of the high-pressure system.

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(5) System parameters were generated using Hydranautics RODESIGN32, 32,070 TDS ASTM seawater feed @ 25°C, SWC3 membranes, 7 elements per vessel, 0 years. 8 gfd and 45% recovery design point. 89% and 96% efficient main high-pressure pump and motor. 88% and 95% efficient PX booster pump and motor. kWh/m3 power figures are for the RO process portion of the system only and do not include an allowance for the seawater supply pump. David Brown Union Pump, main HP pump model 14x14x19C - 2stage DB34D, contact Rick Hammond for more details. Piping and other parasitic losses were neglected and should be avoided.

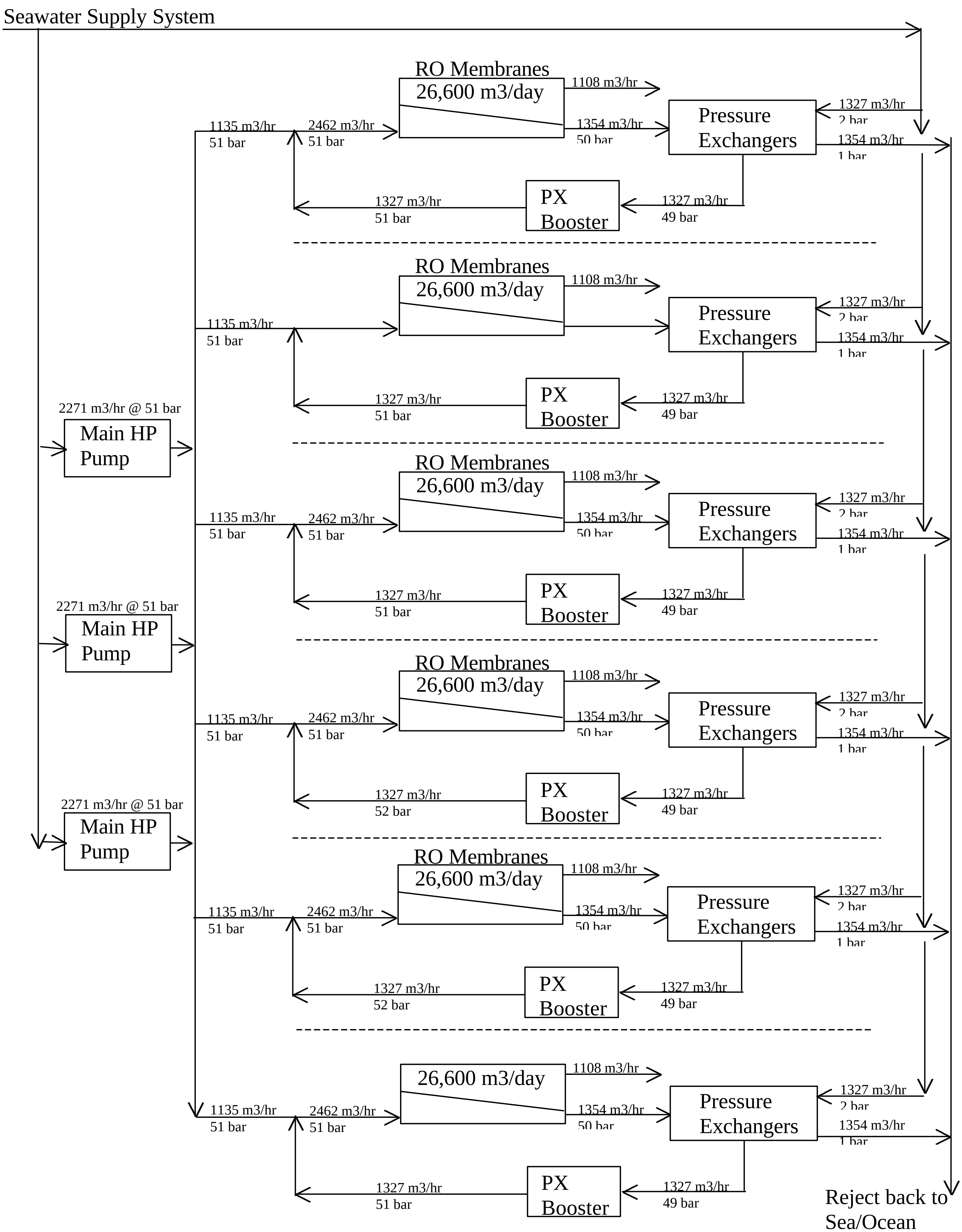

Figure 6. 159,600 m3/day System in 6ea 26,600 m3/day Trains.

Table 3. 26,600,000 m3/day Train Parameters and Power Consumption Table (6)

Temp °C	Feed Press (bar)	Product Flow (m3/hr)	HP Pump Flow (m3/hr)	HP Pump ÄP (bar)	HP Pump KW	PX Booster Flow (m3/hr)	PX Booster ÄP (bar)	PX Booster KW	RO System Kwh/m3
25	51.2	1108	1135	49.2	1811	1327	2 / 4	92 / 184	1.72 / 1.80
22	52.0	1108	1135	50.0	1840	1327	2 / 4	92 / 184	1.74 / 1.83
18	53.2	1108	1135	51.2	1885	1327	2 / 4	92 / 184	1.78 / 1.87

This system also exhibits all of the benefits of pressure exchanger technology, including stable and easy to control reject flows and high efficiencies immune to changes in ambient conditions. Once again we see that the high-pressure pump flow is approximately equal to the permeate flow making the amount of membrane surface the only pressure regulating valve within the system.

5.0 CONCLUSION

Pressure exchanger technologies now give RO designers several new degrees of freedom, which have previously been the significant design barriers of the older centrifugal energy recovery devices. One is that, he/she now has specific control over the conversion rate of the RO system without the previous struggle between higher energy consumption and lower conversion rate designs. This now allows for the possibility for lower flux designs that have significantly lower power consumption profiles while still producing high quality permeate and systems that are easier to operate and maintain. It also opens the door for membrane manufactures to develop even higher flux low-pressure membranes with out being constrained by the requirement for ultra-high rejection values.

The other major difference is that the connection between the high-pressure pump and energy recovery device has been broken. This eliminates many of the struggles between control and efficiency optimization that were present with the centrifugal technologies. It also allows the designers to look at new plant designs that incorporate larger more efficient pumps.

The pressure exchanger technologies are shattering SWRO design barriers yielding seawater power consumption figures that were previously unthinkable. The combination of designing at lower flux and conversion rates and using high flow, higher efficient main high pressure pumps makes it possible today to produce fresh water from the sea at around 1.7 kWh/m3. This represents a 15% reduction from just one year ago, when it was published for the first time that water could be produced for 2.0 kWh/m3 (7). If we can develop membranes that can produce good quality water at 45 bar and 45% conversion rates these systems will be able to reach 1.5 kWh/m3.

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(6) System parameters were generated using Hydranautics RODESIGN32, 32,070 TDS ASTM seawater feed @ 25°C, SWC3 membranes, 7 elements per vessel, 0 years. 8 gfd and 45% recovery design point. 89% and 96% efficient main high-pressure pump and motor. 87% and 95% efficient PX booster pump and motor. kWh/m3 power figures are for the RO process portion of the system only and do not include an allowance for the seawater supply pump. David Brown Union Pump, main HP pump model 14x14x19C - 2stage DB34D, contact Rick Hammond for more details. Piping and other parasitic losses were neglected and should be avoided.

(7) D&WR May/June-01, Volume 11/1, Exchanger Test Verifies 2.0 kWh/m3 SWRO Energy Recovery Use.