Retro-Fitting Existing SWRO Systems with a New Energy Recovery Device

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ABSTRACT

A 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%. This efficiency advantage makes it possible to dramatically improve the performance of existing SWRO plants by reducing their energy consumption by as much as 75% or by expanding their capacity as much as 300%. Detailed system designs, parameters, and recommendations are provided this paper for several retro-fit configurations and will be accompanied with case data from operating plants that have been retro-fitted using these new devices.

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 significantly reduce the energy consumption of new and existing SWRO systems. Since energy costs are rising and can consume 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 supplier of Pressure Exchanger technology, the principles and theories presented in this paper will be applicable to all devices that are based on the positive displacement, isobaric chamber approach.

Key Words: energy recovery, retro-fit, SWRO system, pressure exchanger, cost savings, reverse osmosis.

1.0 INTRODUCTION

A new pressure exchanger (PX) device transfers the energy from the concentrate stream directly to the feed stream using a cylindrical rotor with longitudinal ducts. The rotor spins inside a sleeve between two end covers that divide the rotor into high and low pressure halves. This direct, positive displacement approach results in a net transfer efficiency of over 95%. This efficiency advantage makes it possible to dramatically improve the performance of existing SWRO plants by reducing their energy consumption by as much as 75% or by expanding their capacity as much as 300%. Detailed system designs, parameters, and recommendations will be provided for several retro-fit configurations and are accompanied with case data from operating plants that have been retro-fitted using these new devices.

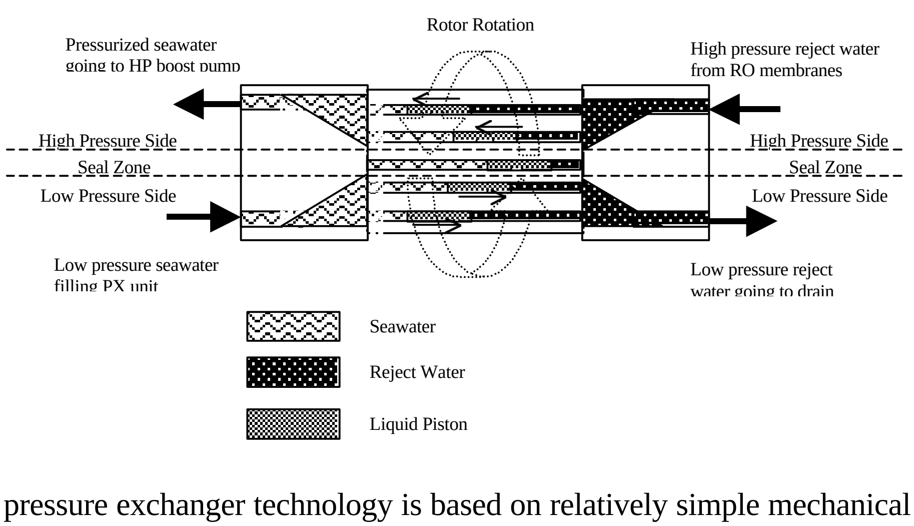
2.0 PRINCIPLE OF OPERATION

The PX unit utilizes the principle of positive displacement to transfer the energy in the reject stream directly to the incoming seawater feed stream. It is interesting to note that the reject stream is continuously and directly connected to the new seawater stream. This direct connection allows a real net transfer efficiency of energy from the reject stream to the feed stream of over 95%.

The rotor spins inside a sleeve between two end covers with port openings for low and high pressure. The low-pressure side of the rotor fills with seawater and ejects brine water while the high-pressure side fills with brine water and discharges seawater. The rotation simply facilitates the valving mechanism, which is to transport the ducts from one side to the other.

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 seawater stream out at high pressure. This rotational action is similar to a Gatling machine gun firing high-pressure bullets and being refilled with new seawater cartridges. A virtual liquid piston moves back and forth inside each duct creating a barrier zone 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 1)

Figure 1. Pressure Exchanger Flow Path



Although PX pressure exchanger technology is based on relatively simple mechanical concepts its application to existing systems can take on many forms.

3.0 GENERAL APPLICATIONS

The pressure exchanger makes it is possible to significantly increase the capacity of existing systems by adding little or no additional power and/or reduce the power consumption of existing systems by as much as 75%. There are several proven approaches to retro-fitting existing SWRO system with pressure exchanger technology. They fall into three classes with numerous variations within each type of retro-fit. There are the simple power reductions, the expansions, and the multiple train power reductions. We are going to provide real case examples with before and after diagrams and results. Each approach comes with its own unique advantages and disadvantages, which must be compared and studied for each individual system. Furthermore, this technology is relatively new, and unique ways of applying it are still being created as the market tries to maximize system efficiency and reduce the costs of every application.

3.1 POWER REDUCTION RETRO-FITS

Using the PX to reduce the power of existing systems is the most widely used method of applying this technology. Systems were retro-fitted this way as long as 5 years ago and have been running continuously since that time. Almost every kind of seawater RO system has been retro-fitted effectively to reduce power, including standard RO's with no energy recovery at all, systems that use turbo charger technology, reverse running pumps and Pelton units.

3.1.0 Simple Power Reduction Scheme

Figure 2 shows a simple SWRO plant operating with a 40% conversion rate and 62 bar feed pressure with no energy recovery technology in place. It is atypical for existing small to medium sized SWRO systems (200-1000 m3/day) today to have no form of energy recovery device already in place, but this simple example will help us to become familiar with how the PX is applied. Subsequent examples will take on more challenging designs where some form of energy recovery is already in place.

Figure 2. Before Simple Power Reduction Retro-Fit

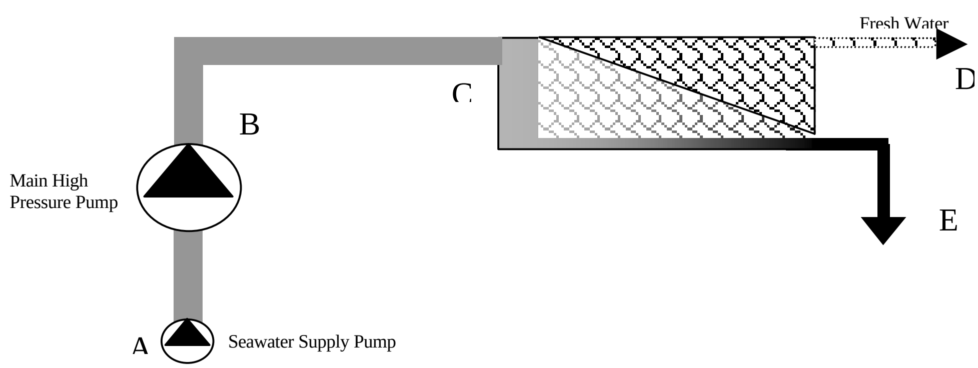
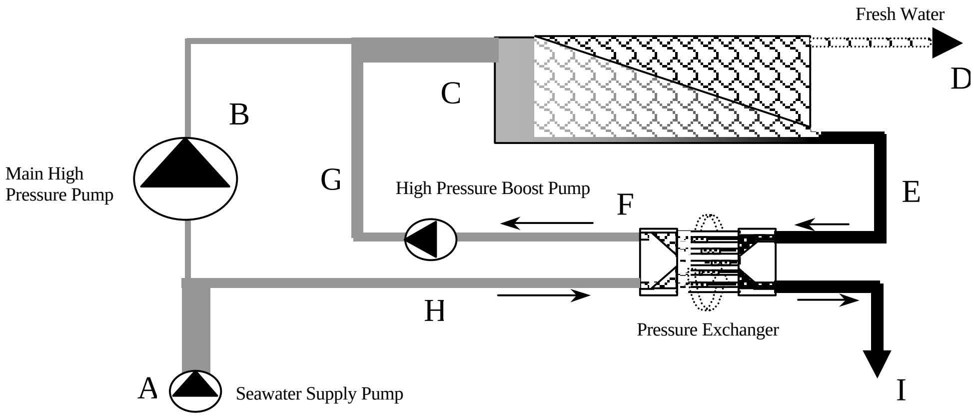


Figure 3 shows the same SWRO system after being retro-fitted with the PX unit. This is the typical configuration for most power reduction retro-fits. It is the simplest and most efficient configuration for the PX, however there are several flow schemes that offer other advantages and

Figure 3. After Simple Power Reduction Retro-Fit



that are just as efficient which we will examine later. Looking at table 1 we can see that the main high pressure (HP) pump flow has been reduced by 13.4 m3/hr down to 9.4 m3/hr at 67 bar. The missing 13.4 m3/hr of seawater required to feed the RO membranes is being supplied by the PX unit and its associated circulation pump, which requires only 2 bar delta pressure. When considering a retro-fit it may be necessary to reconfigure or replace the main high pressure pump to match the new system's reduced flow requirements.

Table 1. Example Flow Rates and Pressures

Stream	Description	Before m3/hr (gpm)	After m3/hr (gpm)	Pressure Bar (psi)
A	Seawater supply	22.7 (100)	22.7 (100)	2 (29)
B	Main HP Pump Flow	22.7 (100)	9.3 (41)	62 (900)
C	RO Feed Stream	22.7 (100)	22.7 (100)	62 (900)
D	RO Product Water	9.1 (40)	9.1 (40)	0.3 (5)
E	PX HP Inlet/ Reject	13.6 (60)	13.6 (60)	60 (870)
F	PX HP Outlet/ Seawater	n/a	13.4 (58.8)	59 (856)
G	Booster Pump Outlet/ Seawater	n/a	13.4 (58.8)	62 (900)
H	PX LP Inlet/ Seawater	n/a	13.4 (58.8)	2 (29)
I	PX LP Outlet/ Reject	n/a	13.6 (60)	1 (14.5)

Table 2 shows us that by retro-fitting an existing system that does not have any existing energy recovery in place with the pressure exchanger, one can achieve tremendous energy savings. These benefits can be increased further in small to medium sized packages such as the example above, where the original main high pressure pump was assumed to have been a centrifugal type and was replaced with a much smaller positive displacement main high pressure pump.

Table 2. Comparative Power Consumption and Production Rates vs No Energy Recovery

DESCRIPTION	Before PX	After PX	% Difference
KW requirement main HP pump*	78.8	18.9	76%
KW requirement PX booster pump*	n/a	4.2	n/a
KWh/m3	8.68	2.31	72%
KWh/1000 gal	32.84	8.76	72%
Permeate Production m3/hr	9.1	9.1	0%

*Figures are for RO process only. They do not include power allowance for seawater supply pump.
**See reference (1) for notes and efficiency figures used to calculated values in table.

Of course most existing systems today do have some form of energy recovery and in the cases to follow we will consider how to retro-fit these more typical applications.

3.1.1 Retro-fitting The Turbo Charger

Figure 4 shows an SWRO plant that was operating at the Club Lanzarote Tourist Complex in the Canary Islands. The plant was using a turbo charger energy recovery device in conjunction with a positive displacement main HP pump. Commercial examples of such energy recovery systems are Grundfos's Pelton based BMET system, FEDCO's Turbo Chargers and PEI's Turbo units. The system below was operating at 35% recover and 64 bar feed pressure with the turbo charger providing approximately 17 bar of boost.

Figure 4. Before Turbo Retro-Fit

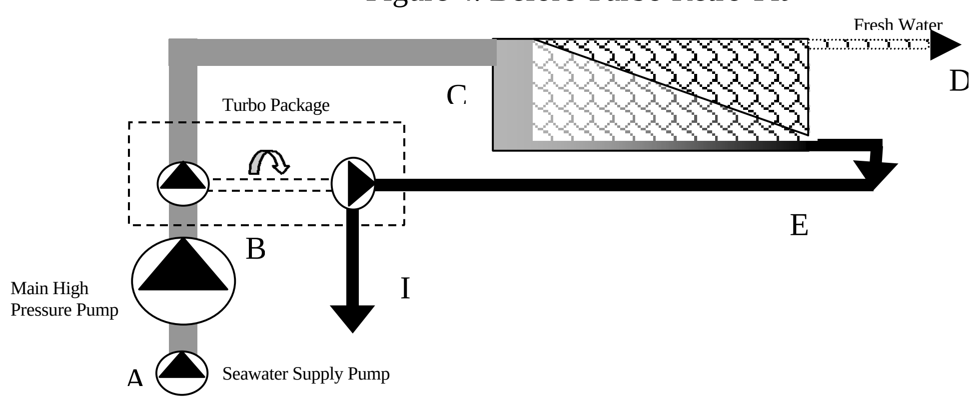


Figure 3 again shows the flow scheme of the plant after retro-fitting it with PX technology. Table 3 shows all the flows and pressures of the plant before and after the retro-fit was completed. Table 4 shows that the energy savings for this application was 45%. 40-50% savings are typical when retro-fitting turbo systems that are operating at or near their optimum design points. These savings can be significantly higher when considering systems that are off their design point and/or when a centrifugal main HP pump can be changed to a PD main HP pump because of the lower required flow rates.

Table 3. Flow Rates and Pressures before and after the Turbo Retro-fit

Stream	Description	Turbo m3/hr (gpm)	PX m3/hr (gpm)	Turbo Bar (psi)	PX Bar (psi)
A	Seawater supply	29.8 (131.1)	29.8 (131.1)	2.0 (29)	2.0 (29)
B	Main HP Pump Flow	29.8 (131.1)	10.7 (47.1)	47.0 (682)	64.0 (928)
C	RO Feed Stream	29.8 (131.1)	29.8 (131.1)	64.0 (928)	64.0 (928)
D	RO Product Water	10.4 (45.9)	10.4 (45.9)	0 (0)	0 (0)
E	PX HP Inlet/ Reject	19.3 (85.2)	19.4 (85.2)	61.9 (898)	61.9 (898)
F	PX HP Outlet/ Seawater	n/a	19.1 (84.0)	n/a	60.9 (883)
G	Booster Pump Outlet/ Seawater	n/a	19.1 (84.0)	n/a	64.0 (928)
H	PX LP Inlet/ Seawater	n/a	19.1 (84.0)	n/a	2.0 (29)
I	PX LP Outlet/ Reject	19.3 (85.2)	19.4 (85.2)	0.3 (5)	0.3 (5)

Table 4. Curacao Comparative Power Consumption and Production Rates vs Turbo Charger Energy Recovery

DESCRIPTION	Before PX	After PX	% Difference
KW requirement main HP pump*	45.9	22.1	52%
KW requirement PX booster pump*	n/a	3.3	n/a
KWh/m3	4.42	2.45	45%
KWh/1000 gal	16.7	9.27	45%
Permeate Production m3/hr	10.4	10.4	0%

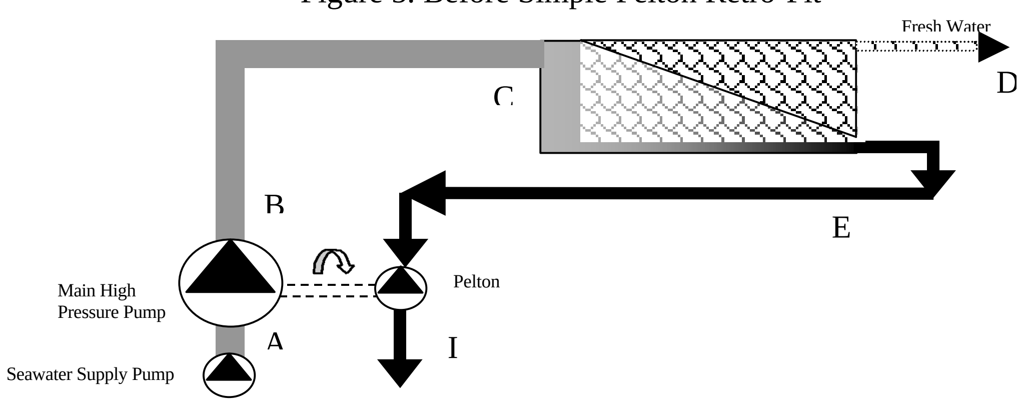
*Figures are for RO process only. They do not include power allowance for seawater supply pump.
**See reference (2) for notes and efficiency figures used to calculated values in table.

When considering a turbo system retro-fit, it will be necessary to reconfigure or replace the main high pressure pump in order to match the new reduced flow rate and increased pressure that the main HP pump must produce in a PX system.

3.1.1 Retro-fitting The Pelton Wheel

Figure 7 shows an SWRO plant producing 2500 m3/day at 40% recovery and 61 bar feed pressure. This plant is very similar to an actual multiple train power reduction retro-fit that we will look at later in this paper.

Figure 5. Before Simple Pelton Retro-Fit



Once again, figure 3 shows the flow scheme of the plant after retro-fitting it with PX technology. Table 5 shows all the flows an pressures of the plant before and after the retro-fit was completed. Table 6 shows that the energy savings for this application was 27%.

Table 5. 2500m3/day Pelton Retro Fit Flows and Pressures (See Figure 3 for F, G and H flows)

Stream	Description	Pelton m3/hr (gpm)	PX m3/hr (gpm)	Pelton Bar (psi)	PX Bar (psi)
A	Seawater supply	260.7 (1147)	260.7 (1147)	1.8 (26)	1.8 (26)
B	Main HP Pump Flow	260.7 (1147)	105.8 (466)	61 (885)	61 (885)
C	RO Feed Stream	260.7 (1147)	260.7 (1147)	61 (885)	61 (885)
D	RO Product Water	104.2 (458)	104.2 (458)	0 (0)	0 (0)
E	PX HP Inlet/ Reject	156.4 (688)	156.3 (688)	59.3 (860)	59.3 (860)
F	PX HP Outlet/ Seawater	n/a	154.6 (681)	n/a	58.3 (845)
G	Booster Pump Outlet/ Seawater	n/a	154.6 (681)	n/a	61 (885)
H	PX LP Inlet/ Seawater	n/a	154.6 (681)	n/a	1.8 (26)
I	PX LP Outlet/ Reject	156.4 (688)	156.3 (688	0 (0)	0.3 (5)

Table 6. Comparative Power Consumption and Production Rates vs Pelton Energy Recovery

DESCRIPTION	Before PX	After PX	% Difference
KW requirement main HP pump*	344.4	236.4	31%
KW requirement PX booster pump*	n/a	16.5	n/a
KWh/m3	3.31	2.43	27%
KWh/1000 gal	12.53	9.19	27%
Permeate Production m3/hr	104.2	104.2	0%

*Figures are for RO process only. They do not include power allowance for seawater supply pump.
**See reference (3) for notes and efficiency figures used to calculated values in table.

Because the main HP pump in a Pelton system operates at full system pressure, many of these retro-fits incorporate expansion strategies that use the existing HP pump to produce more water for the same power or slightly additional power.

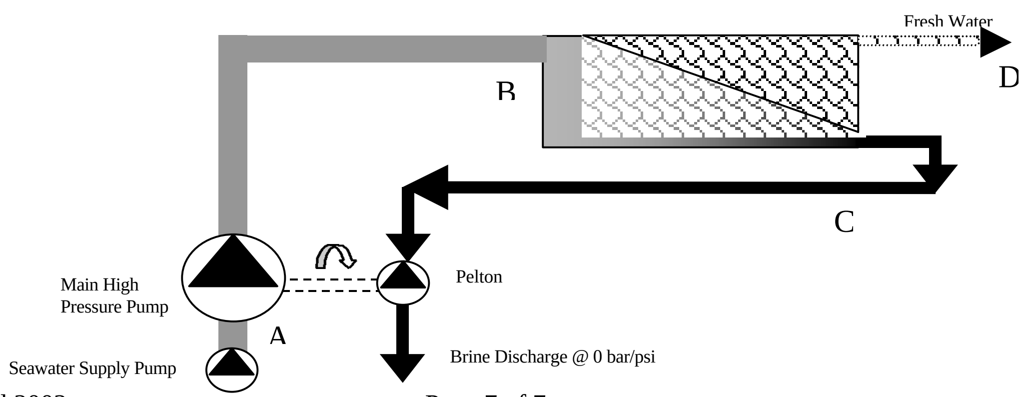
3.2 EXPANSION RETRO-FITS

One of the new design rules associated with using pressure exchanger technology is that the main HP pump flow approximately equals the permeate flow. Notice that in tables 1, 3 and 5 above, after retro-fitting the systems with the PX, the main HP pump flow (B) was approximately equal to the RO product water flow (D). This fact allows many systems to considerably expand permeate capacity while requiring little or no additional power, and in fact, expansions are being commercially applied at a rate of approximately 5 to 1 over simple power reductions.

3.2.0 The Maximum Expansion Retro-Fit

Figure 6 shows a Pelton system that was installed on a Caribbean Island. After retro-fitting the plant with the PX expansion scheme the user was able to increase capacity from approximately 275 m3/day to 800 m3/day while lowering the unit power consumption (kWh/m3) by approximately 36%.

Figure 6. Pelton System Before Expansion Retro-Fit



Notice in Figure 7 how the original plant is nearly intact after the expansion skid is put on line. There is only one necessary connection from the high pressure reject of the original skid to the high pressure reject of the retro-fit skid that needs to be made during final installation and start up. The additional low pressure feed requirements can be part of the expansion package if there is not enough capacity avaliable from the original skid. In many cases the Pelton or other energy recovery devices can be isolated in place (see figure 7) and put back on line during the regular cleaning and maintenance cycles of the retro-fit package.

Figure 7. Pelton System After Expansion Retro-Fit

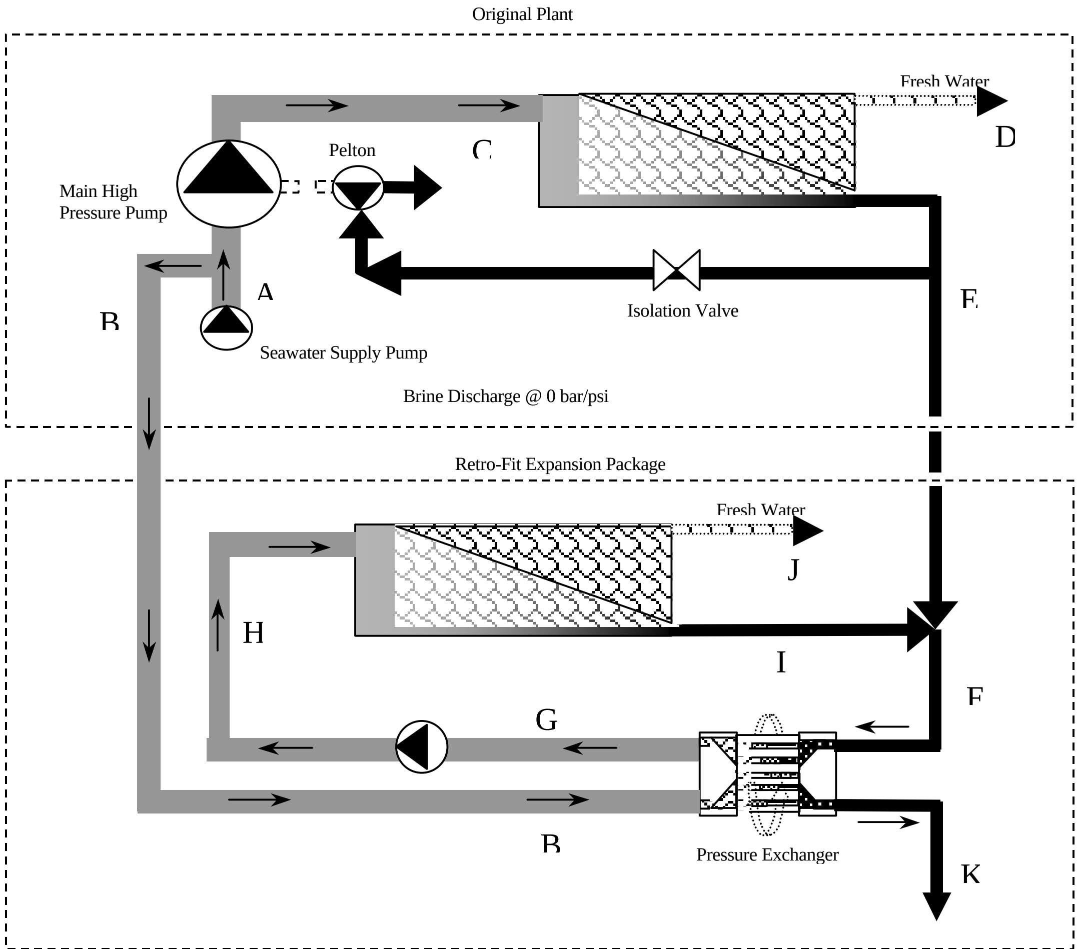


Table 7. Maximum Expansion Scheme Flows and Pressures Before and After

Stream	Description	Before PX m3/hr (gpm)	After PX m3/hr (gpm)	Before PX Bar (psi)	After PX Bar (psi)
A	System Seawater Feed Supply	34.8 (153)	103.9 (457)	2.2 (32)	2.0 (29)
B	PX LP Inlet / Seawater	n/a	63.6 (280)	n/a	2.0 (29)
C	Main HP Pump Flow / Original RO Feed Flow	34.8 (153)	34.8 (153)	67.6 (980)	57.2 (830)
D	Original RO Product Water	11.3 (50)	7.7 (34)	0.3 (5)	0.3 (5)
E	Original Reject Flow	22.7 (100)	27.0 (119)	65.9 (955)	55.5 (805)
F	PX HP Inlet / Reject	n/a	60.2 (265)	n/a	55.5 (805)
G	PX HP Outlet / Seawater	n/a	59.1 (260)	n/a	54.5 (790)
H	Booster Pump Outlet/ Expansion RO Feed	n/a	59.1 (260)	n/a	57.2 (830)
I	Expansion Reject Flow	n/a	33.2 (146)	n/a	55.5 (805)
J	Expansion RO Product Water	n/a	25.9 (114)	n/a	0.3 (5)
K	Expansion Reject Flow	n/a	65.9 (290)	n/a	0.3 (5)

When the PX is running with balanced flows where the PX LP inlet flow rate (B) equals the PX HP outlet flow rate (G) the salinity of the PX outlet water (G) is typically about 3-5% higher than the salinity of the inlet seawater (B). In the standard flow scheme shown in figure 3 this higher salinity feed water combines with the main HP pump flow rate and dilutes this increase. In these schemes where the HP pump flow combines with the PX flow the RO membranes typically see an increase in salinity of less than 2%. This is an acceptable figure that typically does not affect the overall performance of the RO membranes. However, in the case of the maximum expansion scheme one can see that there is no dilution assistance from the main HP and the salinity increase to the RO membranes would be 3-5% if the system were operated with balanced flows. That is why this system is being operated with the PX low pressure inlet flow adjusted about 5-10% higher than the PX high pressure outlet. This helps to flush out the PX unit on the low pressure side and results in about 0-2% increase in salinity at the outlet of the PX unit and inlet of the expansion RO membrane array.

Table 8. Maximum Expansion Comparative Power Consumption and Production Rates Before and After

DESCRIPTION	Before PX	After PX	% Difference
KW requirement main HP pump*	37.5	62.4	67%
KW requirement PX booster pump*	n/a	8.4	n/a
KWh/m3	3.27	2.10	36%
KWh/1000 gal	12.4	7.97	36%
Permeate Production m3/hr	11.3	33.6	200%

*Figures are for RO process only. They do not include power allowance for seawater supply pump.
**See reference (4) for notes and efficiency figures used to calculated values in table.

The advantages of the maximum expansion scheme are that one can produce the most amount of water while operating a plant at the highest possible overall efficiency. The disadvantage is that it requires the largest capital expenditure, as compared with other PX expansion schemes, in order to create an entirely new package that produces typically 2-3 times more water than the original system. In this example, the original motor of the main HP pump had sufficient horsepower to handle the full load of the HP pump without the assistance of the Pelton turbine.

3.2.1 The Simple Cascade Expansion Retro-Fit

Looking at figure 8 we see a simple SWRO system that was operating on St. Croix, in the US Virgin Islands. The system was producing 83 m3/day at 65bar feed pressure and 39% recovery. The system was retro-fitted with the cascade expansion skid, which employs the simple concept of using the new high-pressure seawater stream that the PX produces to directly feed a new array of membranes. The result was that the new cascade expansion skid produced an additional 34 m3/day of “free” product water without the need for an intermediate booster pump or electrical controls and connections. Tables 9 and 10 summarize the results.

Figure 8. Simple Cascade Expansion Diagram

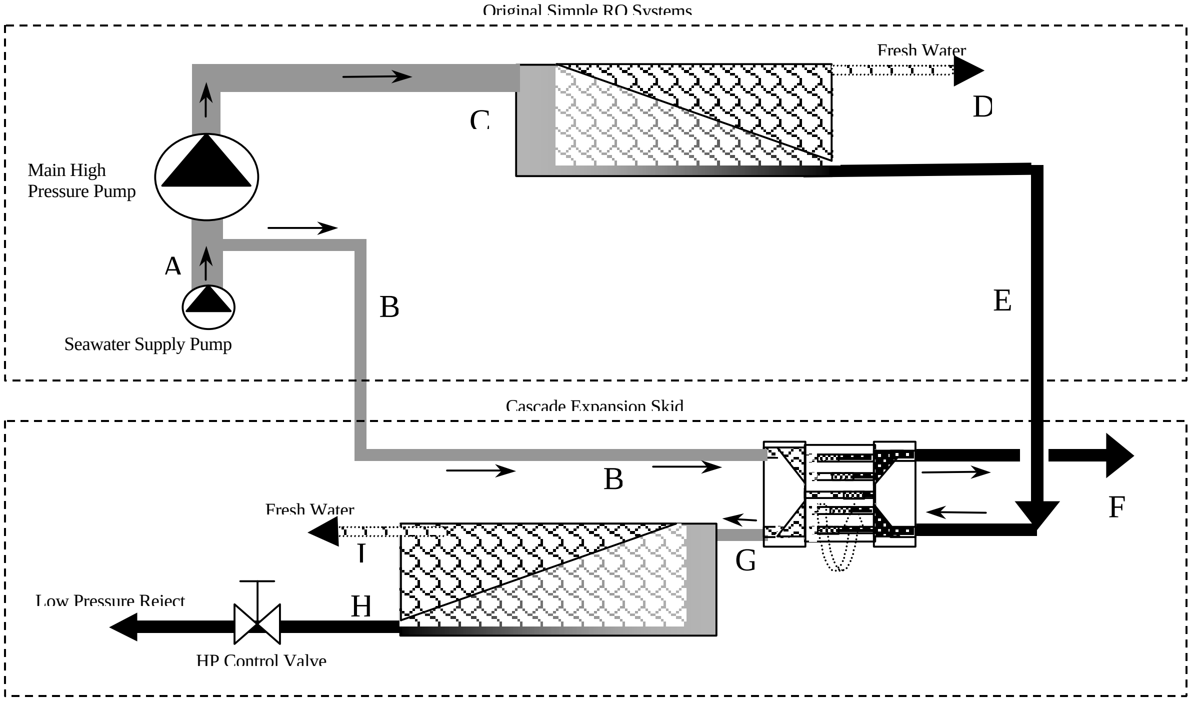


Table 9. Simple Cascade Expansion Retro-fit Flows and Pressures Before and After

Stream	Description	Before PX m3/hr (gpm)	After PX m3/hr (gpm)	Before PX Bar (psi)	After PX Bar (psi)
A	System Seawater Feed Supply	8.9 (39)	8.9 (39)	2.1 (30)	2.1 (30)
B	PX LP Inlet / Seawater	n/a	5.4 (24)	n/a	2.1 (30)
C	HP Pump Flow / Original RO Feed Flow	8.9 (39)	8.9 (39)	64.8 (940)	64.8 (940)
D	Original RO Product Water	3.4 (15)	3.4 (15)	0	0.0 (0)
E	Original Reject Flow	5.4 (24)	5.4 (24)	64.1 (930)	64.1 (930)
F	PX LP outlet Flow / Original Reject	n/a	5.4 (24)	n/a	0.3 (5)
G	PX HP outlet / Expansion RO Feed Flow	n/a	5.2 (23)	n/a	63.8 (925)
H	Expansion Reject Flow	n/a	3.8 (16.8)	n/a	0.3 (5)
I	Expansion Product Flow	n/a	1.4 (6.2)	n/a	0.0 (0)

Table 10. Simple Cascade Expansion Retro-fit Comparative Power Consumption and Production

DESCRIPTION	Before PX	After PX	% Difference
KW requirement main HP pump*	19.5	19.5	0%
KW requirement PX booster pump*	n/a	n/a	n/a
KWh/m3	5.57	4.1	26%
KWh/1000 gal	21.07	15.5	26%
Permeate Production m3/hr	3.4	4.8	41%

*Figures are for RO process only. They do not include power allowance for seawater supply pump.
**See reference (5) for notes and efficiency figures used to calculated values in table.

This expansion can be achieved without any additional electrical requirements or connections. It is also very economical since the PX unit is acting as the main HP pump for the expansion package and is often less expensive than an equivalent standard high pressure pump when considering the frame motor, switch gear, and controls that would be required. The disadvantage to this approach is that at 4.1

kWh/m3, the overall system is not as efficient as a system would be that incorporates the standard flow scheme shown in figure 3.

3.3 THE MULTIPLE TRAIN POWER REDUCTION

The multiple train power reduction takes advantage of the fact that the main HP pump flow equals the permeate flow and combines multiple trains of existing RO systems while eliminating their associated high pressure pumps resulting in significant power savings. The plant in Figure 9 was operating in Murcia Spain with Pelton wheel energy recovery turbines. Each plant was producing approximately 3,200 m3/day at 49% recovery and 60 bar feed pressure.

Figure 9. Mazarron Pelton Train Before PX Retro-Fit

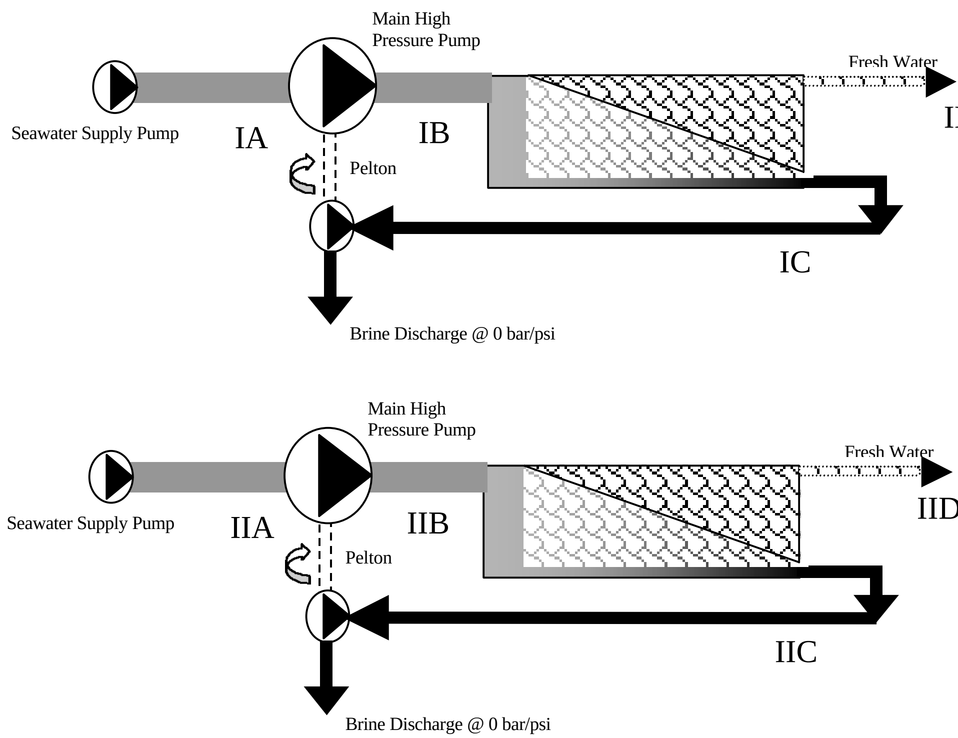
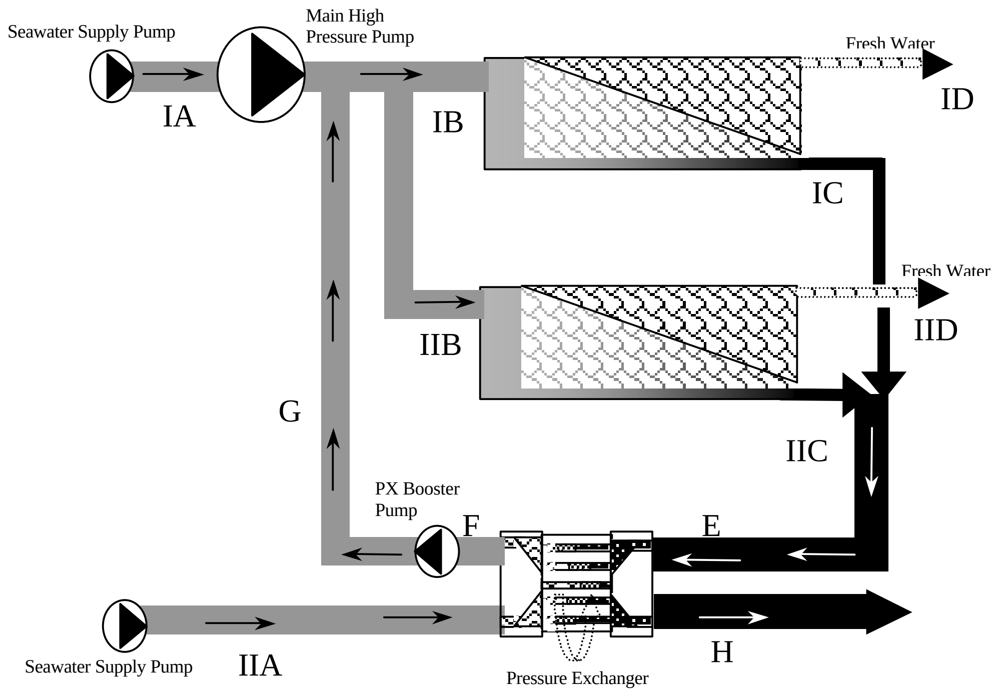


Figure 10. Mazarron Train After PX Retro-Fit



After the retro-fit, the PX system had replaced one of the main HP pumps and both of the Pelton turbines. The original motor of the main HP pump had sufficient horsepower to handle the full load of the HP pump without the assistance of the Pelton turbine. In fact the PX booster pump was installed on the same double shafted motor in place of the Pelton turbine.

Table 11Multiple Train Power Reduction Flows and Pressures Before and After

Stream	Description	Before PX m3/hr (gpm)	After PX m3/hr (gpm)	Before PX Bar (psi)	After PX Bar (psi)
IA	Seawater Feed supply Train I	277.3 (1220)	277.3 (1220)	1.8 (26)	1.8 (26)
IB	RO Feed Stream Train I	277.3 (1220)	309.8 (1363)	59.6 (865)	59.6 (865)
IC	Reject Stream Train I / PX HP Inlet	141.4 (622)	164.3 (723)	58.3 (845)	58.3 (845)
ID	RO Product Flow Train I	135.9 (598)	145.4 (640)	0 (0)	0 (0)
IIA	Seawater Feed Supply Train II	270.4 (1190)	294.1 (1294)	1.6 (24)	1.4 (20)
IIB	RO Feed Stream Train II	270.4 (1190)	261.8 (1152)	60.3 (875)	59.6 (865)
IIC	Reject Stream Train II / PX HP Inlet	135.2 (595)	132.9 (585)	59.3 (860)	58.3 (845)
IID	RO Product Flow Train II	135.2 (595)	128.9 (567)	0 (0)	0 (0)
E	PX HP Inlet / Reject	n/a	297.3 (1308)	n/a	58.3 (845)
F	PX HP Outlet	n/a	294.1 (1294)	n/a	57.2 (830)
G	Booster Pump Outlet / Seawater	n/a	294.1 (1294)	n/a	59.6 (865)
H	PX LP Outlet / Reject	n/a	297.3 (1308)	n/a	0.3 (5)

The Pelton wheel in this system was less than 2 years old and operating at least 85% efficiently. It represented the state of the art in energy recovery technology at the time, before the pressure exchanger was introduced into the market place.

Table 12. Multiple Train Power Reduction Comparative Power Consumption and Production

DESCRIPTION	Before PX	After PX	% Difference
KW requirement main HP pump(s)*	778	590	24%
KW requirement PX booster pump*	n/a	28	n/a
KWh/m3	2.88	2.25	22%
KWh/1000 gal	10.9	8.53	22%
Permeate Production m3/hr	6501	6578	1%

*Figures are for RO process only. They do not include power allowance for seawater supply pump.
**See reference (6) for notes and efficiency figures used to calculated values in table.

The multiple train power reduction takes advantage of the existing equipment at any given installation. In many larger installations where multiple trains typically exist, and the main HP pumps are producing full system pressure, this strategy works very well. This approach can be used in conjunction with expansion schemes in order to optimize the match between the high pressure pump flows and the fresh water production rates while simultanously achieving significant power savings.

4.0 CONCLUSION

The extreme high efficiency of pressure exchanger technology makes it is possible to significantly increase the capacity of existing systems and/or reduce the power consumption of existing systems even when the best of yesterdays energy recovery technologies are already in place. We have shown several approaches to retro-fitting existing SWRO systems with pressure exchanger technology, which include the power reductions, the expansions, and the multiple train power reduction. These real case examples have been applied around the world and many other approaches are possible. As the market tries to maximize system efficiency and reduce costs of operating systems, new designs and unique variations on the above examples are being created at a rapid pace.

References:

(1) Pre-PX data was generated using 70% efficient centrifugal main high-pressure pump and 92% efficient electric motor. Post-PX data was generated using 90% efficient positive displacement main high-pressure pump, 60% efficient PX booster pump and 92% efficient electric motors. Energy losses due to throttling and piping losses were ignored. Good design should minimize HP pump throttling losses in order to maximize system efficiency. Isolation valves on PX arrays are not typically employed.

(2) Pre-PX data was generated using 90% efficient positive displacement (PD) main high-pressure pump and 92% efficient electric motor. Post-PX data was generated using 90% efficient positive displacement main high-pressure pump, 60% efficient PX booster pump and 92% efficient electric motors. All data was actual case data taken from the Club Lanzarote plant in the Canary Islands. Piping and throttling losses (where applicable) were included in the flow and pressure data.

(3) Pre-PX data was generated using 80% efficient centrifugal main high-pressure pump, 92% efficient electric motor and 85% efficient Pelton Wheel. Post-PX data was generated using 78% efficient centrifugal main high-pressure pump, 78% efficient PX booster pump and 94% efficient main motor and 92% efficient booster motor. Energy losses due to throttling and

piping losses were ignored. Good design should minimize HP pump throttling losses in order to maximize system efficiency. Isolation valves on PX arrays are not typically employed.

(4) Pre-PX data was generated using 90% efficient PD main high-pressure pump, 92% efficient electric motor and 80% efficient Pelton wheel. Post-PX data was generated using 92% efficient PD main high-pressure pump, 70% efficient PX booster pump and 92% efficient motors. This was a real case example where piping and throttling losses (where applicable) were included in the flow and pressure data.

(5) All data was generated using 90% efficient PD main high-pressure pump and 92% efficient electric motor. This was a real case example where piping and throttling losses (where applicable) were included in the flow and pressure data.

(6) Pre-PX data was generated using 80% efficient centrifugal main high-pressure pump, 94% efficient electric motor and 87% efficient Pelton wheel. Post-PX data was generated using 80% efficient centrifugal main high-pressure pump, 75% efficient PX booster pump and 94% efficient motors. This was a real case example where piping and throttling losses (when applicable) were included in the flow and pressure data.