Seawater Reverse Osmosis Plants in the Caribbean Recover Energy and Brine and Reduce Costs

Authors: Shawn Meyer-Steele, Antonia von Gottberg and Jose Luis Talavera

Introduction

With continued population growth and an overall expansion in tourism over the last few decades, a heavy burden has been placed upon the natural resources of the Caribbean. Water, essential for life itself, is one of the resources most drastically affected, whether by over-pumping of the natural source that has sustained island nations for centuries, or the inadvertent contamination of sources through development. One of the challenges for the people of the Caribbean and their governments has been to manage and sustain this natural resource. Most of the Caribbean, built over the millennia through the natural growth of coral reefs or volcanic eruption, does not typically have sufficient natural reservoirs, aquifers, and rain recharge that larger landmasses enjoy.

The Caribbean—and the rest of the world—faces the unmistakable irony that, although the world's major surface component is made up principally of water, there is "water, water, everywhere and not a drop to drink." The salinity of human blood is almost equal to that of the oceans, possibly hinting at our humble beginnings, but we would perish more quickly drinking seawater than drinking nothing at all.

So we turn back to the ocean, but this time we do so with a twist. Advances in technology allow us the small miracle, that we mimic from nature, of removing enough of the salt from the seawater to be able to produce clean, safe, drinking water. The supply seemingly inexhaustible at first glance, it might appear that our problems are solved. But to accomplish this remarkable alchemy requires energy, and energy in the Caribbean, primarily imported, is a more dear and precious commodity than the water it is required to produce.

Seawater Desalination Costs

The next challenge comes in applying the technology as efficiently and as cost effectively as possible. The costs in seawater desalination have been reduced greatly over the last twenty years, most notably through the advances in reverse osmosis (RO) as shown in Figure 1. In 1978, the cost to produce 1,000 U.S. gallons (4 m^3) of potable water from seawater in a large desalination facility was over US$20. Today, the cost has decreased by a factor of six, to less than US$3 per 1,000 U.S. gallons (4 m^3) today.

TP1029EN 0601

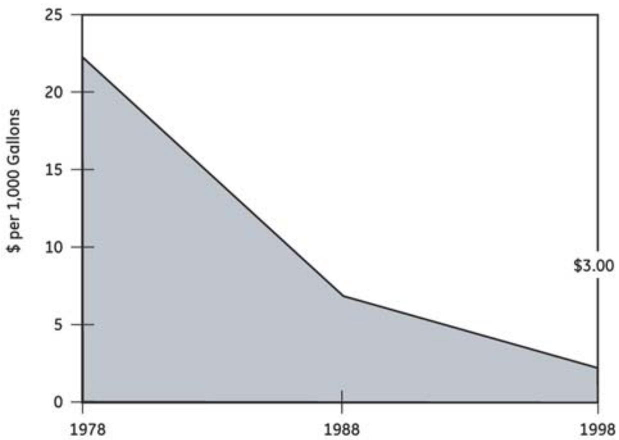

Figure 1: Cost of Water Produced by Seawater RO 1978 - 1998

In the Caribbean, and in most of the world, (except where large amounts of waste heat from true co-generation facilities are available) reverse osmosis has proven to be, by far, the most cost-effective technology for seawater desalination. [1]

RO is a pressure-driven process by which salt can be removed from seawater. If a solution containing salts is placed on one side of a semi-permeable membrane, with a more dilute solution on the other side, water will be forced by natural osmosis through the membrane from the more dilute to the concentrated side in an attempt to reach equilibrium. Reverse osmosis utilizes external pressure to overcome the natural osmotic pressure, and forces water through a semipermeable membrane from the more concentrated to the less concentrated side.

RO is chosen for many desalination applications today because of its proven ability to produce high quality water in an energy efficient manner with the ability to withstand, given appropriate pretreatment, fluctuations in feed water quality. A seawater reverse osmosis (SWRO) plant includes several major blocks, as shown in Figure 2: the site and building; feedwater supply; pretreatment; SWRO unit; post treatment; chemical systems; instrumentation; electrical and control system. The section below discusses each of these areas in more detail.

Site and Building

The site as a whole generally includes:

- The plant building
- Outdoor chemical storage area
- Production reservoir
- Wastewater collection and discharge system
- The site including civil works, paving, fencing, and landscaping

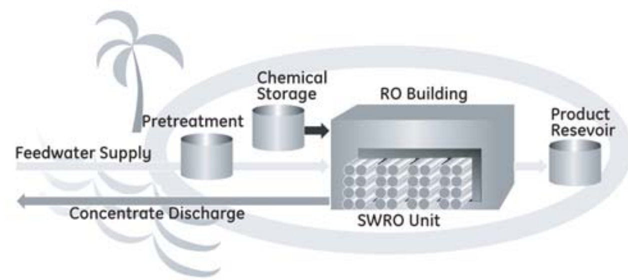

Figure 2: Typical SWRO Plant

Feed Water Supply

Feed water to the desalination system is collected from a seawater intake or beach wells located as near the plant site as is possible. From the intake, a feed pump will convey feed water to the pretreatment system.

Pretreatment

The seawater must be treated before it reaches the RO unit to remove suspended solids. Typically, multimedia filters are used to effectively remove solids. The filters are designed to operate at a loading rate consistent with the overall plant design.

The suspended solids are removed from the water into the filtering media by a combination of mechanisms including straining, interception, impaction, sedimentation, flocculation, and adsorption. A majority of the suspended material in the raw seawater is removed during this first filtration step.

Recently, there has been much interest in the application of back-washable, hollow-fiber ultrafiltration systems (UF) as pretreatment for SWRO systems. Today, the capital cost is higher than with traditional media filters, but the space requirement is smaller and UF provides higher quality feedwater to the RO. Ongoing work in this area may soon provide a reduction in the cost of seawater desalination. Filtered water then flows to the reverse osmosis unit.

Seawater Reverse Osmosis Unit

The core desalination operation is reverse osmosis. The process elements of a typical desalination unit are cartridge filters; an RO feed pump, an energy recovery device, an RO membrane unit, and auxiliary systems for cleaning and chemical addition. Figure 3 shows a photograph of a 3,000m^3/day (792,000 gpd) SWRO plant at Aqualectra, Curaçao, Netherland Antilles before expansion to its present 10,000 m^3/day (2,690,000 gpd) size.

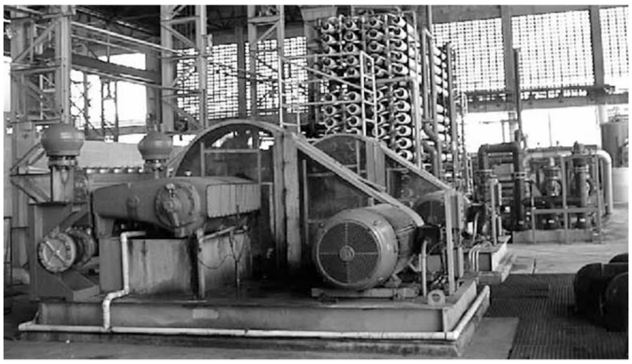

Figure 3: SWRO Unit, Aqualectra, Curaçao, N.A.

Cartridge Filtration

Water is conveyed to the cartridge filters from the media filters. The cartridge filter system is used to remove fine suspended matter from water, typically down to five microns in size. A cartridge filter consists of a filter housing and filter elements mounted to tube supports. Water enters the housing and flows through the filter elements. The suspended solids are trapped in the fine fibers of the filter.

Reverse Osmosis

In reverse osmosis, water under pressure is forced across a membrane element with a portion of the feed permeating the membrane and the balance of the feed water sweeping along the membrane surface and exiting without passing through the membrane. In the case of seawater, the membrane will freely pass water but will reject most of the dissolved minerals as well as any small particles. An illustration of an RO membrane element is shown in Figure 4.

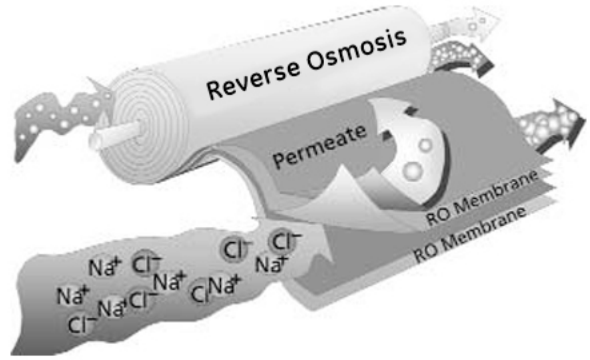

Figure 4: RO Membrane Element

SWRO plants typically employ spiral-wound, thin-film composite polyamide membrane elements to separate dissolved salts from the seawater. In a typical one-stage SWRO system, the process can convert, or "recover" approximately 40% of the incoming seawater as desalted product. The remaining approximately 60% of the incoming water is concentrated by the salts rejected from the product and is returned to the sea. Two-stage SWRO recovers approximately 60% of the incoming seawater as product with 40% returned to the sea.

The high pressure required for RO treatment is provided by a high-pressure pump. The RO system includes a single pass of treatment in one stage.

Permeate from the RO system flows to the post-treatment system. Concentrate (reject) from the RO system flows through the energy recovery device and is then discharged back to the sea.

Energy Recovery

The pressure required for RO treatment is provided by a high-pressure pump. Because of the relatively high energy requirements, most SWRO systems are equipped with an energy recovery device that recovers energy from the pressurized RO concentrate leaving the system. The energy recovery system typically recaptures anywhere from 20 - 50% of the initial pumping energy.

Concentrate Discharge

Concentrate from the RO system is discharged back to the sea through a reject pipeline or through a deep well. This pipe is also used for disposal of wastewater such as filter backwash.

Clean-In-Place System

A membrane cleaning system is normally provided to clean RO membrane elements if suspended solids or precipitates foul them. Cleaning procedures are undertaken when operating pressures or RO permeate production falls outside normal operating limits. The system used to effect this cleaning (referred to as the Clean-In-Place, or CIP procedure) consists of: a chemical tank; a pump to recirculate the cleaning chemicals through the RO membranes; a cartridge filter to remove any solid contaminants or scale which is removed from the vessels and/or piping.

Post Treatment

Post-treatment of the RO permeate is needed to create a potable water that is properly adjusted for storage and distribution. A calcium carbonate filter and/or caustic soda addition systems are typically provided for pH adjustment and remineralization. Sodium hypochlorite and/or UV sterilization are used for disinfection of the final product. After post-treatment, the product water is delivered to a production reservoir.

Chemical Systems

The water treatment plant can require the addition of chemicals at certain points throughout the system, as indicated in the descriptions given in this section. The chemicals used in the plant vary depending on the water source. The chemical systems supplied depend upon the nature of the chemical used but generally consist of a chemical storage tank of suitable capacity and material of construction for the chemical under consideration, two chemical dosing pumps (main and standby) and interconnecting piping. In addition, each system will be supplied with a mixer if necessary.

Instrumentation

Instrumentation characteristically includes: pressure gauges, pressure switches, conductivity indicators and transmitters, temperature indicators and transmitters, level indicators and switches, and flow indicators and transmitters. The system is normally equipped with sample ports so that water samples may be collected at various locations in the process.

Electrical and Control System

The power and control system normally includes:

- power distribution components
- control panels, instrument panels
- programmable control devices

The control system typically provides for complete automatic operation of the desalination system. A central control system will control, monitor performance, and record operating data for all aspects of the desalting plant. It will provide plant-operating status, alarm messages, data collection, protective shutdowns, and automatic regulation of the plant equipment.

Advances in SWRO

The developments that account for most of the advances seen in RO cost reduction over the last 20 years in Figure 1 came about on five different fronts:

1. Through the use of energy recovery devices
2. Through new membrane chemistries that allowed for the same salt rejection with lower feed pressure, which requires less energy and hence lower operating costs
3. Through new membrane elements and pressure vessels that allow operation at higher pressures, and hence higher salinities at similar salt rejection rates
4. Through larger basic RO units (trains) that provide some cost reduction through economies of scale for key components such as pumps, piping, and pressure vessels
5. Through the establishment of relationships with municipalities, whereby each side lends its own expertise and ability to lower the capital and operating costs to the project

While the fourth front is valid, there have been industry-wide "growing pains" resulting from making the basic trains too large. The fifth front is very project specific. In this paper, we will limit our focus to the first three areas.

When designing a SWRO system today, the engineer must decide what kind of energy recovery device to use, and whether or not to use a brine conversion system. By optimizing the system for local conditions, one can minimize the overall life-cycle costs of producing desalted water.

Energy Recovery Devices

There are a number of devices available commercially that are capable of reducing the unit power consumption of reverse osmosis units. This is primarily accomplished by reducing the power consumption of the high-pressure pump by capturing and returning the energy in the concentrate stream (which was waste energy before the development of energy recovery devices). For typical single-pass, single-stage seawater desalination, the concentrate pressure can be from 55 to 65 bar (800-950 psi). Three of the most successful are the turbocharger, the Pelton wheel, and the work or pressure exchanger.

Turbocharger

The turbocharger[5] has been successfully used for SWRO energy recovery since 1989. The turbocharger essentially acts like a reverse running pump, where the RO concentrate is used to turn a turbine that is coupled to a pump section with its impeller on the turbine shaft. The energy transfer from the RO concentrate to the RO feed through the turbo-charger increases the pressure of the RO feed and thus reduces the external energy requirement for the RO feed. Figure 5 illustrates the process flow diagram (PFD) of a typical RO system using a turbocharger for energy recovery.

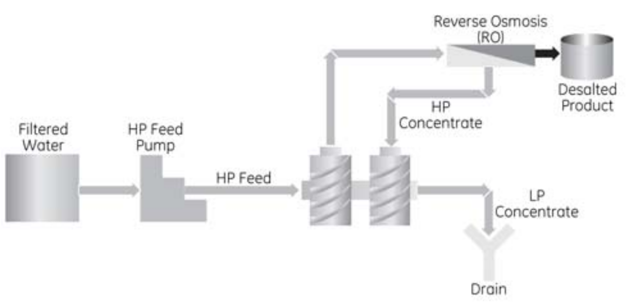

Figure 5: Process Flow Diagram—Turbocharger

Since the turbocharger is a highspeed rotary machine it requires little maintenance. It is compact in size and low weight. The waste stream is pressurized so it can be disposed of without repumping being required. The nominal efficiency of the device is quite low, however, due to high viscous losses in the device. Also, flow deviations with respect to the design point, such as temperature fluctuation or change in water recovery, has a potentially large impact on performance. The turbocharger is generally used on smaller units.

Pelton Wheel

Pelton[2] wheel technology was first evaluated for energy recovery almost 20 years ago. The first prototype machines were based on standard hydroelectric turbine hydraulics. Development of this technology over the past two decades has led to the widespread use of Pelton wheels in SWRO systems, accounting for about 80% of energy recovery devices fitted to SWRO plants over 1 mgd capacity.

A nozzle valve is used to direct a jet of high-pressure RO concentrate onto the bucket type blades of the Pelton wheel[3]. This causes the wheel to turn. The kinetic energy of the jet is converted into rotating mechanical energy. By coupling the shaft of the Pelton wheel to a motor or pump, this energy can be used to reduce the electrical energy that is needed to pump the RO feedwater. Figure 6 illustrates the PFD of a typical RO system using a Pelton wheel for energy recovery.

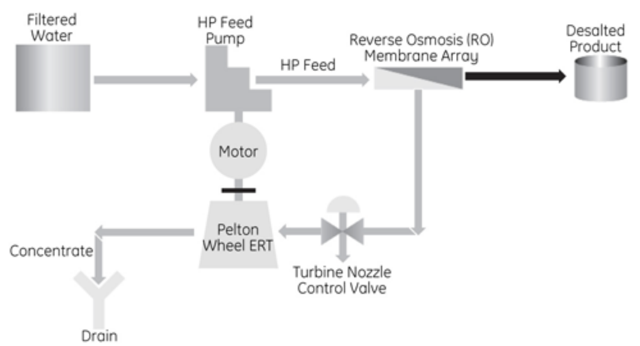

Figure 6: Process Flow Diagram—Pelton Wheel

Pelton[4] wheels are reliable and easy to maintain. Typical device efficiency ranges between 84 and 90%. Since the discharge from a Pelton wheel is at atmospheric pressure, either the waste must be able to drain by gravity, or else it has to be repumped.

Work Exchangers

The original work exchanger was built for the U.S. Government in 1980. There are a number of similar products on the market. The authors' company markets their version of the work exchanger under the name "Dyprex". The work exchanger uses a system of pistons and valves to transfer the pressure of the RO concentrate to part of the RO feed. A high-pressure booster pump then pumps this pre-pressurized feed to the required RO feed pressure. The remaining RO feed is pumped by a high-pressure pump. Figure 7 illustrates the PFD of a typical RO system using a work exchanger for energy recovery. Since the work exchanger directly transfers energy from the concentrate to the feed rather than through rotating machinery, it has higher efficiency in comparison to the Pelton wheel and turbocharger. However, the work exchanger is limited in size, and, although adding units in parallel can increase capacity, the capital cost is high for large plants. Work exchangers also have a large number of moving parts that can be subject to wear. Figure 8 shows a photograph of a work exchanger at a 26,400 m^3/day (360,000 gpd) SWRO plant at Handsome Bay, BVI.

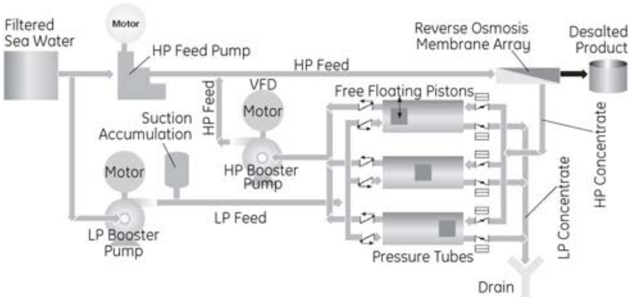

Figure 7: Process Flow Diagram—Work Exchanger

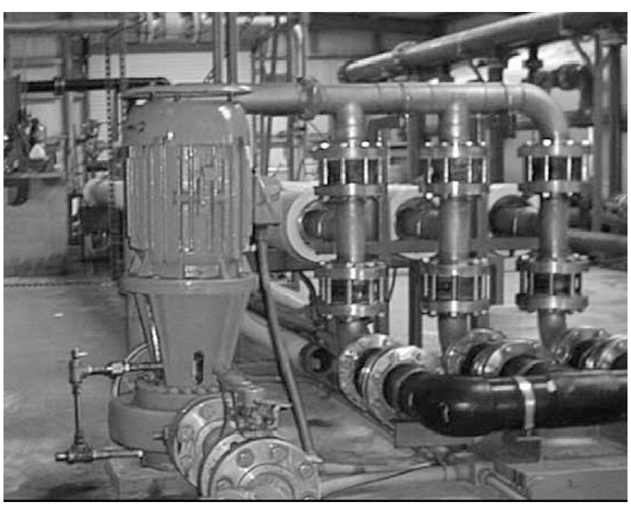

Figure 8: Work Exchanger, Handsome Bay, B.V.I.

PEI has introduced a smaller version of a work exchanger (the Pressure exchanger) built on a principle similar to the Dyprex with fewer moving parts. It is marketed as having the same type of efficiencies but has not been adequately proven in long-term operation and only used to-date on smaller plants.

Comparison of Energy Recovery Devices

When selecting the most appropriate energy recovery device for a given application, one needs to consider several factors including the cost of power, expected variation in plant operating conditions, maintenance requirements and capital cost. Table 1 compares the features of the three energy recovery devices discussed above. Note that the capital cost refers to only the capital cost of the energy recovery device; when selecting an energy recovery device in a particular application, one needs to look at the overall cost of pumps, energy recovery devices and VFDs to determine which scheme is optimum in that case. Recent innovative approaches include combining the turbocharger and Pelton wheel to minimize energy consumption and to recover energy as efficiently as possible over a wide range of operating conditions.

Table 1: Comparison of Energy Recovery Devices

Device	Turbocharger	Pelton Wheel	Work Exchanger
Capital Cost	Low	Low-Medium	High
Efficiency	Low (55-60%)	Medium (84-90%)	High (> 95%)
Efficiency Curve	Slopes downwards at lower flows	Varies	Flat
Crossleak from reject to feed	Minor via center journal bearing	Connected via motor so not an issue	Low (< 3%)
Capacity Range	< 2.5 mgd	Up to multi mgd	< 2.5 mgd
Reliability	High-speed rotary machine—easy to overhaul	High-speed rotary machine—easy to overhaul	Multiple valves and other parts subject to wear
Footprint	Compact	Compact, but requires civil work for atmospheric drain	Large
Discharge Pressure	Pressurized	Atmospheric	Pressurized
Effect of deviation from design point	Wide operating range	Wide operating range	Moderate impact on performance

Toray Seawater Second-Stage Brine Recovery

Conventional wisdom has held for years that to maximize efficiency of the systems, the optimum recovery and configuration was 35-40% recovery and a single stage system.

It has always been apparent that the low recovery of historical SWRO meant that a lot of water had to be pretreated, then pumped to high pressure, and then 60-65% of this water was just dumped back to the sea. Limitation in the membrane module design, however, prevented SWRO systems from operating at higher water recoveries.

As the water recovery increases, the concentration of salt in the brine stream also increases. Hence, the pressure that must be applied to overcome the osmotic pressure of the brine stream increases. Most spiral wound RO membranes can operate up to 82.7 bar (1,200 psi) at temperatures below 29°C (84°F). If water recovery is increased, the pressure limitation of the membrane becomes a limit on recovery before any limits on water chemistry are reached. If water recovery were to be increased to the water chemistry limit rather than the membrane pressure limit, then the RO membrane had to be capable of operating at pressures up to 98 bar (1,420 psi).

Toray Industries, Inc., for some years now, has been manufacturing with great success a spiral wound RO membrane that can operate at high pressure and can achieve over 99.7% rejection working on the concentrate reject from the first stage unit. This brine second-stage system, called a Brine Conversion System (BCS), is capable of recovering an additional 50% of the concentrate for recoveries of up to 60% with no appreciable increases in product salinity or energy per unit of product produced.

The authors' company has formed a joint-venture company with Toray to manufacture and sell these membranes in the Americas and the Caribbean.

Single-Stage versus Two-Stage System

Table 2 compares the performance of a conventional one-stage SWRO system with that of a two-stage system employing the Toray brine recovery membrane. The performance of the desalination system is based on typical Caribbean seawater composition and a process temperature of 28°C (83°F). As feed water conditions vary, system performance will change. Table 3 compares the relative cost of water production for a traditional single-stage system and a two-stage system.

The two stage system saves a good deal of capital costs and footprint area because the intake, outfall, the pretreatment, and the amount of seawater taken in by the intake pumps is only 67% of that for a conventional first-stage system. The energy of this second stage can be minimized by using an energy recovery device such as a turbocharger to boost the pressure of the first stage concentrate using the second-stage brine. Hence, the electricity consumption of the twostage system can be lower than that of the single stage system. These savings in water production cost can reduce the cost of desalinated seawater by 16%.

Table 2: Comparison of One- and Two-Stage SWRO Plants

Parameter	Performance 1 Stage	Performance 2 Stage
Net Production	7,500 m^3/day (2 mgd)	11,300 m^3/day (3 mgd)
Product Salinity	200-350 mg/l TDS	220-375 mg/l TDS
Salt Removal Rate	99.9% +	99.9% +
Product Water Recovery	40%	60%
Operating Temperature	24-28°C (75-83°F)	24-28°C (75-83°F)
Operating Pressure	55-62 bar (800-900 psi)	76-83 bar (1,100-1,200 psi)

Table 3: Comparison of Water Production Cost

%	1 Stage	2 Stage
Capital Cost	46%	37%
Electricity	36%	30%
Membrane Replacement	5%	6%
Chemicals	4%	2.5%
Other	9%	8.5%
(Labor, maintenance, etc.)		
Savings	—	16%

Case Study 1: Maspalomas II SWRO Plant

The authors' company owns and operates this 20,400 m^3/day (5 mpd) SWRO plant as well as a 20,000 m^3/day (5 mpd) electrodialysis reversal (EDR) plant for brackish water desalting. The facility is located on Gran Canaria, Spain. The original SWRO system was installed in 1987 and has since been expanded.

Description of Conventional SWRO Plant

The raw seawater is delivered via an offshore, open, submerged intake. The seawater is filtered though two sets of vertical media filters containing anthracite and sand. The filtered seawater then passes though two sets of cartridge filters sized at 10 and 5 microns. The conventional SWRO plant at Maspalomas II consisted of five trains. The seawater intake capacity is 41,000 m^3/day (11 mpd). The SWRO system recovered 40% of the seawater as product water, with 60% of the water being rejected to the sea through a brine water outfall system. The seawater feed contains 35,000 mg/l TDS. The original SWRO plant used Francis Turbines for energy recovery.

Pilot Test of Toray Brine Conversion System

In the late 1990s, the system needed to expand again. A pilot test of the Toray[6] BCS was undertaken at the site. Table 4 compares the actual data from the pilot tests to the targets.

Table 4: Pilot Test Data from Maspalomas

	Feed	1st Stage Permeate	BCS Permeate	Product
Actual				
Water Quantity (m3/day)	350	140	70	210
Water Quality (mg/l)	35,438	165	173	168
Water Recovery	–	40%	33%	60%
Target				
Water Quantity (m3/day)	350	140	70	210
Water Quality (mg/l)	–	< 350	< 350	< 350
Water Recovery	–	40%	33%	60%

Full-scale Brine Conversion System

Based on successful pilot testing of the Brine Conversion System at the SWRO plant, the decision was made to expand the facility using a second-stage SWRO system to recover reject from one train of the existing single-stage SWRO facility. The advantage of this approach was that the seawater intake and pretreatment systems did not require expansion. This was the first full-scale plant in the world to use the new BCS, and it has been in operation since 1999. In this system, the brine from the conventional SWRO system is pressurized up to 90 bar with booster pumps. The pressurized brine then flows into the brine concentrator membranes, which recover 33% of the water as product water. A Pelton wheel recovers the residual energy in the reject water. At the time of writing, a BCS has been installed on three of the five SWRO trains. Trains BCS1 and BCS3 consists of 28 vessels of five membrane elements per vessel. Train BCS4 has 56 vessels of five membrane elements per vessel. Table 5 compares the product flow rate, the water recovery, and the product quality of the three BCS units. Figure 9 shows the process flow diagram for one of the trains and Figure 10 illustrates the module rack.

Table 5: BCS Trains at Maspalomas II

	BCS1	BCS3	BCS4
Product flow (m3/h)	40	44	110
Recovery (%)	26	28	29
Product Quality (µS/cm)	960	920	560

Performance

Table 6 shows the water quality of the feed, first-stage and BCS permeates and first-stage BCS

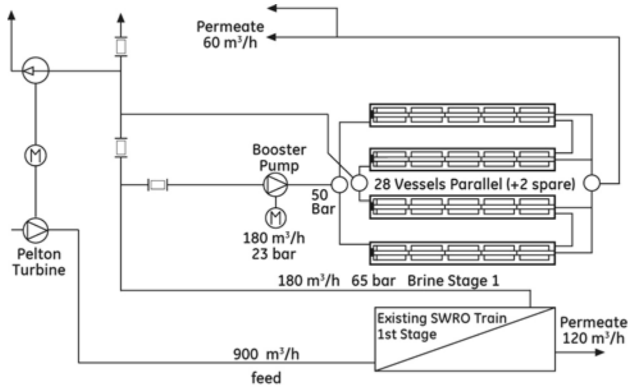

Figure 9: Process Flow Diagram for One BCS Unit at Maspalomas II

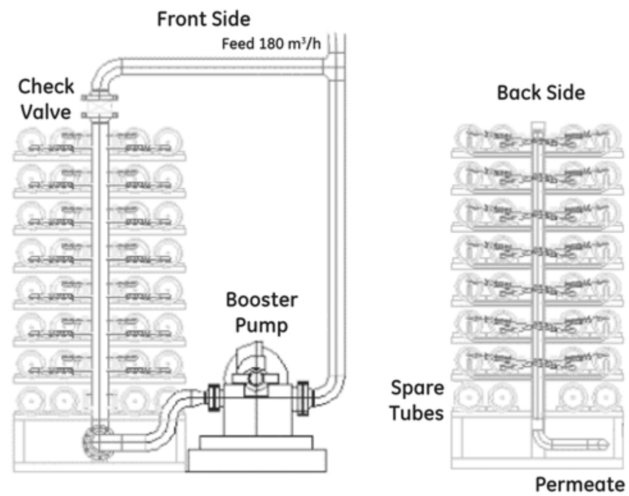

Figure 10: BCS Module Rack at Maspalomas II

Table 6: Water Quality Data

	RO Feed	1st Stage Permeate	BCS Permeate	1st Stage Reject	BCS Reject
Sodium (mg/l)	11,900	134	106	19,700	31,000
Calcium (mg/l)	432	1.6	0.8	780	1,080
Magnesium (mg/l)	1,407	3.4	2.9	2,549	3,635
Potassium (mg/l)	430	5.0	4.0	650	1,075
Chloride (mg/l)	21,800	222	170	37,000	55,200
Bicarbonate (mg/l)	115.9	43.7	3.7	190.3	345.3
Sulfate (mg/l)	3,300	9.0	9.0	5,400	7,200
TDS (mg/l)	39,391	379	298	66,282	99,547
pH	6.98	6.14	6.18	7.15	7.37

rejects. The BCS is producing permeate of higher quality than the first stage, even though the concentration of feedwater to the BCS is higher than to the first stage. The membranes in the BCS were installed later than the membranes in the first stage, and this is the reason for the better quality from the second stage.

Figure 11 plots the feed pressure to the first stage and the BCS versus time. The feed pressure to both stages has been constant during the operation of the plant, at about 68 bar for the first stage and 90 bar for the BCS. Figure 12 plots the first stage and BCS product quality as well as the percent water recovery versus time.

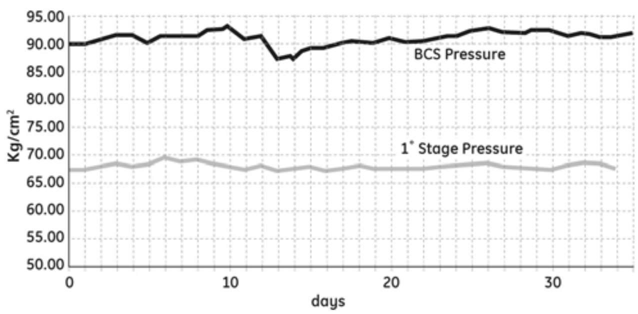

Figure 11: Feed Pressure versus Time

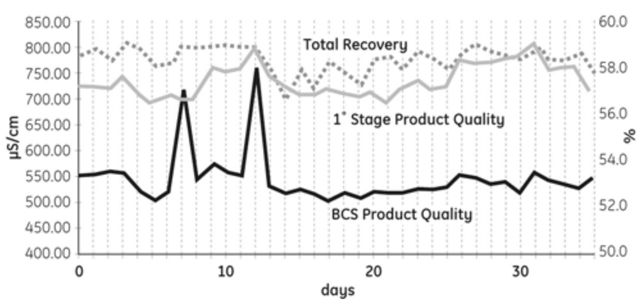

Figure 12: Product Quality and Water Recovery versus Time

Table 7 compares the single-stage SWRO system, the combined SWRO and BCS system, and the projected system with a BCS added to all trains. Since both systems use the same feed flowrate, the intake system did not have to be expanded to achieve more production. Also, the pretreatment system did not have to be expanded, and the amount of chemicals used in the pretreatment system per m^3 of product is reduced. The projected maximum water recovery with all SWRO brine feeding a BCS system is 60% rather than 40%. The costs of operation of the intake and pretreatment system would be reduced by 33% per m^3 of product. This expansion was possible with no capital investment in seawater intake, pretreatment system or brine outfall system. For a new facility designed with a BCS, there would be capital cost savings of 33% per m^3/day (264 gpd) of installed capacity for the pretreatment and discharge systems.

Table 7: Maspalomas II Flowrate

	SWRO System	SWRO + BCS System	Projected System
Feed Intake (m3/day)	41,000	41,000	41,000
SWRO Product	16,400	16,400	16,400
SWRO Waste	24,600	12,479	-
BCS Feed	-	12,121	24,600
BCS Product	-	4,000	8,000
Total Product	16,400	20,400	24,600
Total Waste	24,600	20,600	16,400
Water Recovery	40%	49.75%	60%

Energy Balance

For the conventional SWRO train, the production rate is 118 m^3/h (31,000 g/h). The total power consumed by the high pressure pump, minus the power recovered by the Francis turbine, is 445 kW. The total electrical energy consumption of this train is 3.77 kWh/m^3.

For the trains with BCS units installed, the SWRO product flow is 118 m^3/h (31,000 g/h), and the BCS product flow is 41 m^3/h (11,000 g/h), so the total flow is 159 m^3/h (42,000 g/h). The total power consumed by the high pressure pump and the BCS booster pump, minus the power recovered by the Pelton wheel, is 533 kW. Hence, the total electrical energy consumption of this train is 3.35 kWh/m^3.

The energy consumption per unit of water produced by the SWRO train with BCS is lower than the energy consumption per unit of water produced by the conventional SWRO train.

Concentrate Disposal

The average concentration of the reject from Maspalomas II is over 90,000 µS/cm. A study was performed to evaluate the effect on flora and fauna in the area near the discharge. This study showed that the discharge from Maspalomas II did not have any effect on flora and fauna near the outfall.

Case Study 2: Aqualectra, Curaçao

Aqualectra is the municipal supplier of potable water and electricity for the Caribbean Island of Curaçao, the largest of the five islands of the Netherlands Antilles. Faced with increasing demand for potable water and an aging distillation plant, Aqualectra awarded a contract to the authors' company to build, own and operate a SWRO facility. The original facility became operational in 1996. The original capacity was 3,000 m^3/day (800,000 gpd). The plant was expanded in 1999 and 2000, and now produces 10,200 m^3/day (3 mpd).

Description of System

This SWRO system consists of a first stage RO system using conventional SWRO membranes and a second stage BCS to improve water recovery. Pelton wheels are used to recover energy from the SWRO reject. The SWRO permeate is fed to a BWRO system so that the product of the reverse osmosis facility matches the product quality of the thermal desalination units at about 20 mg/l TDS (Total Dissolved Solids).

Water Quality

Table 8 shows the water quality of the feed, first stage and BCS permeates and first stage and BCS rejects. One might expect that the permeate from the first stage would be lower salinity than the BCS permeate. However, it can be seen that the BCS permeate is actually slightly better than the first stage permeate. This is due to differences in age of the membranes, and shows that the use of the BCS makes no detrimental difference to the product water quality.

Table 8: Water Quality Data

	RO Feed	1st Stage Permeate	BCS Permeate	1st Stage Reject	BCS Reject	2nd Pass Permeate
Sodium (mg/l)	11,741	200	167	18,263	23,074	10
Calcium (mg/l)	466	3.6	1.6	696	937	0.03
Magnesium (mg/l)	1,406	10.4	4.8	2,179	2,800	0.07
Potassium (mg/l)	460	8.1	7.5	714	936	0.42
Chloride (mg/l)	20,695	330	272	32,553	41,922	15.2
Bicarbonate (mg/l)	142	4.9	4.9	221	288	3.66
Sulfate (mg/l)	2,952	19.3	8.4	4,596	6,045	0.13
TDS (mg/l)	37,862	576	466	59,222	107,208	29.48
PH	8.1	6.8	6.6	8.0	7.9	6.5

Aqualectra Plant Summary:

- 10,200 CMD (2,692,800 US GPD)
- Configuration: Open seas intake, Feedwater Pumps, MMF's, CF, Positive Displacement HP Pumps, Calder Pelton Wheel Turbines, Conventional 1st pass, BCS Pass, 3 stage second pass, UV disinfection, and product pumping
- Recovery: 40% first pass, 58% overall
- Product Quality: < 40 mg/l
- Power: 2.6 kWhr/m^3 1st pass / 4.2 kWhr/m^3 overall (includes 1st pass, BCS stage, 3 stage 2nd pass, UV disinfection, and product pumping)
- Performance: Some start-up problems, currently over 95% on-line

Case Study 3: Anguilla Plant Expansion

The Crocus Bay desalination Plant in Anguilla, West Indies is the municipal supplier of potable water and electricity for the Eastern Caribbean Island of Anguilla. Faced with increasing demand for potable water and brackish water wells that were becoming increasingly saline, The Anguillian Government awarded a contract to the authors' company to build, own and operate a SWRO facility. The original facility became operational in 1999. The original capacity was 60,000 gpd (227 m^3/day). The plant was expanded in 2000 to produce 90,000 gpd (341 m^3/day) by installing a BCS system on each of the four independently operating SWRO single-stage trains.

Description of System

This SWRO system consists of a first-stage RO system using conventional SWRO membranes and a second-stage BCS to improve water recovery. Pelton wheels are used to recover energy from the SWRO reject. The SWRO permeate is fed to a BWRO system so that the product of the reverse osmosis facility matches the product quality of the thermal desalination units at about 20 mg/l TDS.

Crocus Bay, Anguilla Plant Summary:

- 3,409 CMD (900,000 U.S. GPD)
- Configuration: Open sea intake, Feedwater Pumps, MMF's, CF, Positive Displacement HP Pumps, Calder Pelton Wheel Turbines, Conventional 1st pass, BCS pass, substantial product pumping
- Recovery: 58%
- Product Quality: < 800 μS/cm

- Power: 2.85 kWhr/m^3 1st pass, 4.0 kWhr/m^3 overall
- Performance: Over 95% on-line after initial shakeout of plant

Case Study 4: WEB, Bonaire

WEB is the municipal supplier of potable water and electricity for the Caribbean Island of Bonaire, part of the Netherlands Antilles. Faced with increasing demand for potable water and an aging distillation plant, WEB Bonaire awarded a contract to the authors' company to build, own and operate a SWRO facility. The original facility became operational in 1998. The present capacity is 1,633 m^3/day (431,000 gpd).

Description of System

This SWRO system consists of a first-stage RO system using conventional SWRO membranes and a second-stage BCS to improve water recovery. A Dyprex work exchanger is used to recover energy from the SWRO reject. A portion of the SWRO permeate is fed to a BWRO system so that the product of the reverse osmosis facility meets the stringent product quality standards of the Bonairian government at about 40 µS/cm.

WEB, Boniare Plant Summary:

- 1633 CMD (431,112 U.S. GPD)
- Configuration: Open sea intake, Feedwater Pumps, MMF's, CF, Positive Displacement HP Pumps, DYPREX Work Exchanger, Conventional 1st pass, partial 2nd pass, product pumping
- Recovery: 58% overall
- Quality: < 40 µS/cm
- Power: 2.85 kWhr/m^3 overall
- Performance: Over 95% on-line since commissioning

Case Study 5: Handsome Bay, BVI

The GE plant at Handsome Bay is one of several municipal plants, strategically located to supply potable water for the many islands of the British Virgin Islands. The BVI government awarded a contract to the authors' company to build, own and operate a SWRO facility in Handsome Bay in 1993. The present capacity is 568 m^3/day (150,000 gpd).

Description of System

This SWRO system consists of a first-stage RO system using conventional SWRO membranes. A Dyprex work exchanger is used to recover energy from the SWRO reject.

Handsome Bay, BVI Plant Summary:

- 568 CMD (150,000 U.S. GPD)
- Configuration: Open sea intake, Feedwater Pumps, MMF's, CF, Positive Displacement HP Pumps, DYPREX Work Exchanger, Conventional 1st pass
- Recovery: 40% overall
- Quality: < 400 mg/l TDS
- Power: 3.00 kWhr/m^3 overall
- Performance: Over 95% available on-line since commissioning

Environmental Advantages

When considering seawater desalination processes, an important factor is the potential effect on the environment. Using the Toray brine recovery system does increase the concentration of the brine discharge[7] to the ocean, and at first glance, one might consider this to be a disadvantage of this process. However, when one considers the overall advantages of the process, the environmental benefits of the two-stage process are significant.

The size of the seawater intake system is 33% smaller than a one-stage system, so this system has less of an effect on the environment. Since the pretreatment system is smaller, the chemical consumption and related waste is reduced by 33%.

While the total salt concentration in the brine is higher, the volume of brine is reduced by 50% over a one-stage plant. Since the volume is lower, the area around the brine discharge point that sees an increased salinity over normal seawater concentrations is much smaller than with a single stage plant.

Also, since the electricity consumption is reduced, the amount of CO_2 gas exhausted in the electricity generation process is reduced by 10-15%.

Optimizing Energy Recovery and Brine Recovery

In a single-stage SWRO plant, as water recovery increases, energy consumption decreases since less water has to be pressurized to produce the required amount of product water.[5] The relationship that higher water recovery will reduce energy is one of the reasons for the development of the BCS. Obviously, since the salinity is higher in the second stage, the pressure required for the BCS is much higher than for the first stage, and so as water recovery increases, the benefit of energy savings decreases. Also, the efficiency of pumps and energy recovery devices working at different operating conditions changes the amount of electrical energy consumed, and the amount of energy that can be recovered. There is also power consumed by the intake, pretreatment and outfall systems, and this power is lower with a higher water recovery system.

In situations analyzed by the authors' company, the comparison of power consumption between a lower recovery single-stage SWRO design and a higher recovery two-stage design varies depending on the feedwater salinity and the type of pumps and energy recovery devices selected. In some cases, the single-stage design uses the least energy. In other cases, as demonstrated at Maspalomas II, less energy is consumed with a two-stage than with a single-stage design.

There are several ways to combine energy recovery devices with a BCS to minimize the electrical energy required per unit volume of water produced. The right choice for a particular plant will depend on several factors including the size of the plant, the cost of power, the capital cost of various energy recovery devices and the maintenance requirements of the customer.

At the Maspalomas II plant, energy is recovered from the BCS brine reject by a Pelton wheel attached to the first-stage high-pressure pump. A booster pump is used to increase the pressure of the first-stage reject to the BCS feed pressure.

An alternative way to minimize the overall energy consumption per unit of water produced would be to use a combination of a BCS with a turbocharger. A high-pressure pump is used to feed the first stage SWRO system. The reject from the first stage can be boosted to the BCS feed pressure using a turbocharger. The turbocharger recovers the energy it uses to boost the first stage reject from the BCS reject.

Conclusions

Over the last 20 years, innovation in the RO field such as in the areas of RO membrane design and application, and energy recovery devices has significantly reduced the cost of producing desalinated seawater with RO. In the 21st century, developments in these areas and others will continue to improve upon seawater desalination technology, delivering more options and more affordable water for the Caribbean.

The Brine Conversion System is a proven technology for recovering up to 60% of seawater as product water. The BCS produces water of approximately the same quality as a conventional SWRO plant. Higher water recovery allows existing plants to expand without requiring additional investment in intake and discharge structures, and pretreatment.

The electrical energy consumed per unit volume of water produced is approximately the same for a system using a BCS as for a single-stage SWRO system, and in some cases is lower for the high recovery system. The combination of BCS and the appropriate energy recovery device can minimize the electrical energy consumption of a plant. As the BCS is applied more widely to full-scale plants, it is expected that energy recovery devices will be used in creative ways to reduce power consumption further.

Energy recovery devices need to be evaluated on a case-by-case basis. Turbochargers, Pelton wheels and work exchangers each have different merits and each produce energy savings with the greatest savings inversely proportional to their relative capital costs.

Work exchangers have proven, reliable performance histories and have demonstrated significantly lower energy consumption than other available products. For long-term, larger applications where energy costs are high, although they have higher capital costs, work exchangers can be the least expensive overall solution (considering operating and capital costs).

References

1. Morris, A. B., "Curaçao, K. A. E. World Leader in Seawater Desalination Since 1928 Adds Seawater Reverse Osmosis Plant in 1997," Int'l Desalination & Water Reuse Quarterly.
2. Gruendisch, A., "Re- Engineering of the Pelton Turbine for Seawater & Brackish Water Energy Recovery," Int'l Desalination & Water Reuse Quarterly, Vol. 9/No. 3, November/ December 1999.
3. Calder Bulletin, "Pelton Wheel Energy Recovery Turbines," PUB. 9008, 1997.
4. Uchiyama, T.; Oklejas, M. and Moch, Jr., I., "Using a Hydraulic Turbo Charger and Pelton Wheel for Energy Recovery in the Same Seawater RO Plant," Proceedings, IDA World Congress on Desalination and Water Reuse, San Diego, CA, September 1999.
5. Moch, Jr., I., "The Case for and Feasibility of Very High Recovery Sea Water Reverse Osmosis Plants", Proceedings, ADA North American Biennial Conference & Exposition, South Lake Tahoe, NV, August 2000.
6. Toray, "Brine Conversion 2-stages Seawater Desalination System", commercial literature.
7. Kurihara, M.; Yamamura, H. and Nakanishi, T., "High Recovery/High Pressure Membranes for Brine Conversion SWRO Process Development and its Performance Data", Desalination 125 (1999), pp. 9-15.
8. Talavera, J. and Ruiz, J. Quesada, "Identification of the Mixing Processes in Brine Discharges Carried Out in Barranco del Toro Beach, South of Gran Canaria", Desalination 139 (2001), pp. 277-286.