Optimizing Water Recovery and Energy Consumption for Seawater RO Systems

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Introduction

The costs of seawater desalination have been reduced greatly over the last twenty years, most notably through the advances in reverse osmosis. In 1978, the cost to produce 1,000 U.S. gallons of potable water from seawater was over U.S. $20. Today, the cost has decreased by a factor of six, to about U.S. $3 per 1,000 U.S. gallons.

Recent advances in seawater reverse osmosis (SWRO) that have allowed this reduction in the cost of desalinated water include the application of energy recovery devices and the utilization of ultra-high-pressure RO membranes in a system to recover brine from the first-stage RO system.

This paper presents operating data from several sites using the brine recovery system, including a 23,400 m^3/day plant at Maspalomas, Gran Canaria, and a 10,000 m^3/day plant in Curaçao. The paper will discuss how the combination of energy recovery devices and a second stage RO system can minimize the cost of producing desalinated water.

Brine Conversion Systems

Conventional wisdom has held for years that to maximize efficiency of the systems, the optimum recovery and configuration was 35 to 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, pumped to high pressure, and then 60 to 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 (84.2°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 would have 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 99.3% rejection working on the concentrate reject from the first-stage unit.1 This second-stage system, called a Brine Conversion System (BCS), is capable of recovering additional product for recoveries of up to 60% with only minor changes in product salinity. Two plants that use the BCS system are Aqualectra and Maspalomas II. The following sections will discuss these plants in detail.

Case Study 1: Aqualectra

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 5,100 m^3/day. The plant was expanded in 1999 and 2000, and now produces 14,800 m^3/day.

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 1 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 permeate from the BCS. However, it can be seen that the BCS permeate is actually slightly better than the first-stage permeate. This may be due to differences in age of the membranes, but it does show that the use of the BCS makes no detrimental difference to the product water quality.

Table 1: Water Quality Data

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

Case Study 2: Maspalomas II SWRO Plant

The authors' company owns and operates this 20,400 m^3/day SWRO plant as well as a 20,000 m^3/day 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. 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 BCS was undertaken at the site.[2] Table 2 compares the actual data from the pilot tests to the targets.

Table 2: 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 BC3 consists of 28 vessels of five elements per vessel. Train BCS4 has 56 vessels of five membrane elements per vessel. Table 3 compares the product flow rate, the water recovery, and the product quality of the three BCS units. Figure 1 shows the process flow diagram for one of the trains and Figure 2 illustrates the module rack.

Table 3: 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

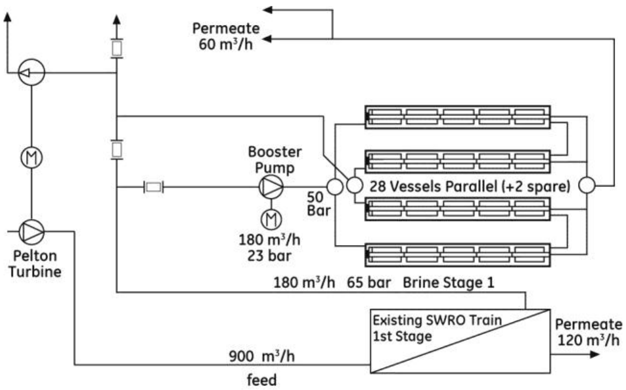

Figure 1: Process Flow Diagram for one BCS Unit at Maspalomas II

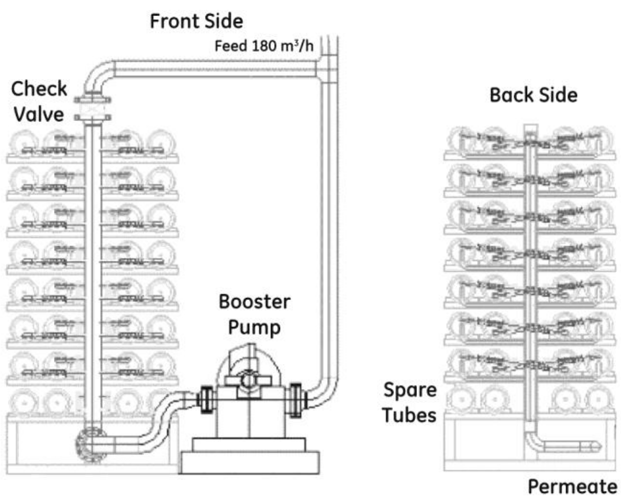

Figure 2: BCS Module Rack at Maspalomas II

Performance: Table 4 shows the water quality of the feed, first stage and BCS permeates, and first stage BCS 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 3 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 4 plots the first stage and BCS product quality, as well as the percent water recovery versus time.

Table 4: 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

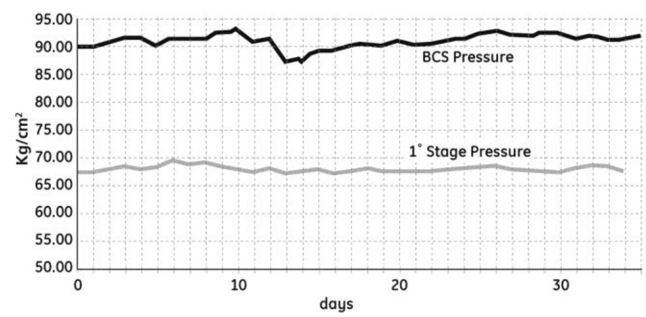

Figure 3: Feed Pressure versus Time

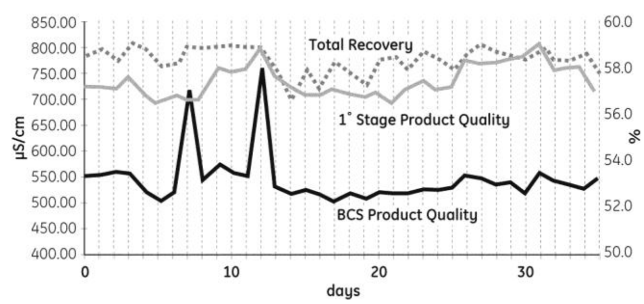

Figure 4: Product Quality and Water Recovery versus Time

Table 5 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 of installed capacity for the pretreatment and discharge systems.

Table 5: Maspalomas II Flowrates

	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. 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, and the BCS product flow is 41 m3/h, so the total flow is 159 m^3/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.[3] This study showed that the discharge from Maspalomas II did not have any effect on flora and fauna near the outfall.

Energy Recovery Devices

A high pressure pump provides the pressure required for RO treatment. 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 approximately 50% of the initial pumping energy. There are a number of devices available commercially that are capable of reducing the unit power consumption of reverse osmosis units.

The case studies above used either Francis Turbines or Pelton wheels for energy recovery. Recently, other, more efficient devices that directly exchange pressure from the reject to the feed water have improved significantly. These devices offer superior energy recovery to the Pelton wheel, but have not yet been used on large seawater plants.

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.[1] 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.[4] The turbocharger recovers the energy it uses to boost the first-stage reject from the BCS reject.

Conclusions

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.

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References

1. 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.
2. 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.
3. Talavera, J.; Ruiz, J., "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.
4. Toray, "Brine Conversion 2-stages Seawater Desalination System", commercial literature.