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Unprecedented system efficiency and simplicity yields exceptionally low cost of permeate in 5,000 ton/day SWRO system

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ABSTRACT

The rising cost of energy has put extreme pressures on the design and operation of municipal seawater reverse osmosis (SWRO) facilities especially in localities where electricity rates are high. To meet this challenge, creative approaches to SWRO system design and energy recovery devices (ERD) selection and utilization are required. Any successful approach will have to take into consideration not only the energy transfer efficiency of the particular ERD, but its level of complexity, ease of start-up, and capital costs in order to build a system with the lowest possible specific energy consumption (SEC). This paper will describe how a 4,500 m^3/day municipal SWRO facility with energy costs exceeding 0.28 kH-h and an ERD supplier recently met this challenge and produced a system with a SEC of < 2.46 kW-h/m^3. The first section of this paper will review three ERD technologies available on the market today: the Pelton impulse turbine; isobaric chambers; and hydraulic pressure boosters. Attention will be given to not only how their brine energy transfer efficiency is arrived at, but also to each system's level of complexity, ease of start-up and operation, and capital costs. The second section will describe the final system design including the selection of the high pressure feed pump and membrane design. The final section will review actual performance data from the facility showing how the system ran with a SEC of 2.46 kW-h/m^3.

Keywords: SWRO; ERD; Turbocharger; Specific energy consumption; Life cycle cost; Low capital cost

1. Introduction

While the rising cost of energy has considerable influence on the economics of seawater reverse osmosis (SWRO) systems throughout most of the world, the impact on areas without access to large power facilities producing low-cost energy is considerable. This was particularly challenging to the customer's site located in the Caribbean, where energy rates are higher than most other areas. This paper discusses how Pioneer Management Ltd.,[1] the builder and operator of SWRO facilities in the Caribbean, and Fluid Equipment Development Company (FEDCO) developed a system that recently achieved a specific energy consumption (SEC) of 2.46 kW-h/m^3.

In 2009, the decision was made to expand a current Caribbean facility by increasing its capacity by 4,500 m^3/day. The original facility consisted of nine

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[1]All site data courtesy of Jared Fulton of Pioneer Management Ltd.

trains each of which utilized energy recovery devices (ERD) from FEDCO. Because the cost of energy was steadily increasing, reaching \$0.28/kW-h, it was critical that the 4,500 m^3/day expansion be designed in way to significantly reduce the existing nine RO trains SEC of 3.16 kW-h/m^3.

Proposals from several ERD suppliers including FEDCO were evaluated on their ability to reach this goal. The contract was awarded to FEDCO for both the HPP and the energy recovery device. FEDCO shipped one SSD-500 high pressure feed pump and one HPB-500 energy recovery device to meet the facilities requirements.

The first section of this paper will review three ERD technologies available on the market today: the Pelton impulse turbine (PIT); isobaric chambers (IC); and hydraulic pressure boosters (HPB). Attention will be given to not only how their brine energy transfer efficiency is arrived at, but also to each system's level of complexity, ease of start-up and operation, and capital costs. The second section will describe the final system design including the selection of the high-pressure feed pump and the design of the membrane arrays. The final section will review performance actual data from the facility showing how the system ran with a SEC of 2.46 kW-h/m^3.

2. ERD technologies

There are three ERD technologies that are well established in the SWRO/brackish water reverse osmosis markets: the PIT, IC, and HPB. Each one of these technologies converts brine energy into feed energy. However, there is considerable confusion in the market how the advertised brine energy transfer efficiency of each of these three ERD technologies relates to one another. As important as determining how much of the energy in the brine stream actually makes it to the membranes themselves is, the system complexity, ease of start-up, maintenance, and capital expenditure are equally critical factors.

2.1. Pelton impulse turbines

PIT was the first energy recovery devices used in the SWRO market. As such, they have been used extensively in SWRO before the introduction of IC and HPB. The PIT uses a turbine runner on a shaft coupled to a motor which drives the high-pressure feed pump. Mechanical energy is delivered from the brine stream through a brine jet directed to a series of specially designed cups on a wheel with a shaft in the center that transmits the rotational energy of the wheel into torque, thus lowering the amount of

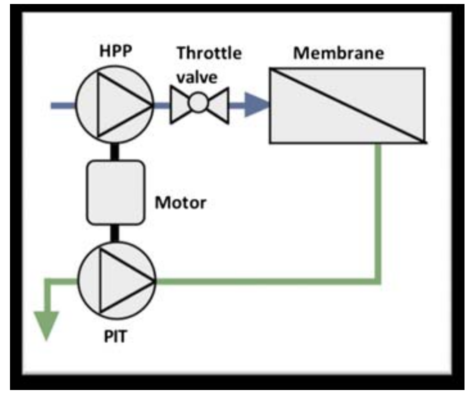

Fig. 1. P&ID for Pelton impulse turbine (PIT) in SWRO system.

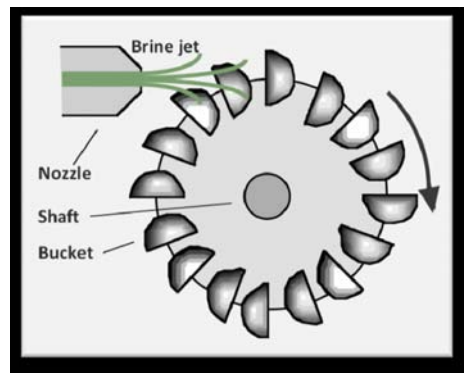

Fig. 2. Pelton wheel illustration.

energy required of the motor to drive the high-pressure feed pump. Regulation of membrane pressure is normally accomplished through the use of a throttle valve between the high-pressure pump (HPP) and the membranes. System PI&D and illustration of the Pelton wheel are depicted in Figs. 1 and 2.

The PIT is enclosed in a casing at ambient atmospheric pressure with grease lubricated bearings at each end to support the shaft. The spent brine is collected in a tank at the bottom of the unit where a sump pump is required to empty the tank. Since the casing and the brine tank are at ambient atmospheric pressure, it is not possible to apply back pressure on the brine stream (Fig. 3).

PIT transfer efficiency[2]: The efficiency of the PIT itself is only part of the system transfer efficiency. The important value to be determined is how much of the available brine energy is converted into feed energy, not just how much available brine energy is converted into mechanical energy within the PIT itself. Therefore, because the PIT is coupled to the HP feed pump

[2]"Comparison of the HPB with the Pelton Turbine for Seawater RO Energy Recovery" White Paper ©2011 FEDCO.

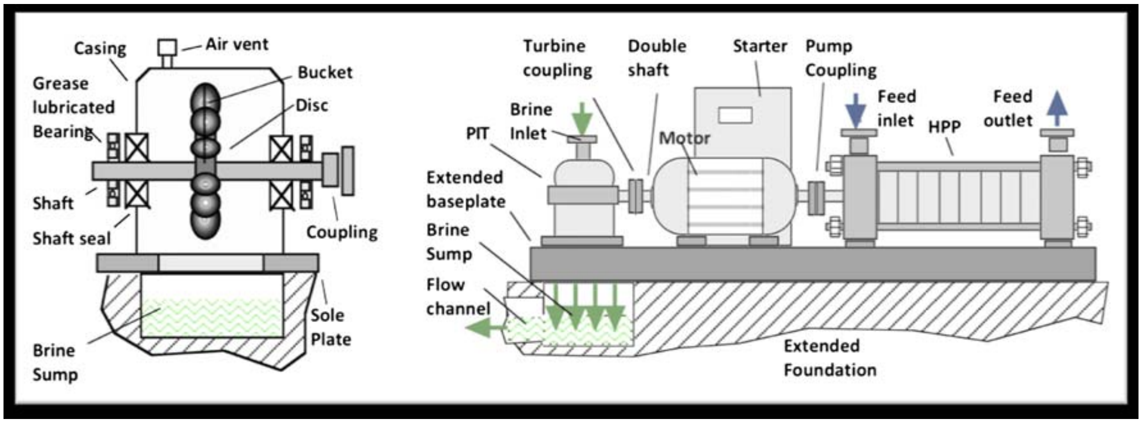

Fig. 3. Pelton impulse turbine (PIT) system drawing.

through the motor, transfer efficiency in a PIT system must include the efficiency of the HP feed pump. Transfer efficiency is therefore expressed as the product of PIT turbine efficiency times HPP efficiency. For example, a system employing a PIT with an 88% turbine efficiency coupled to a HP feed pump with 82% efficiency would have a system transfer efficiency of 72.2% (0.88×0.82).

2.2. Isobaric chambers

IC work by having the low-pressure feed seawater come into direct contact with the high-pressure brine within an isobaric (pressure equalizing) chamber in order to raise the pressure of the seawater feed stream. Pressure is "equalized" in the chamber when the high-pressure brine transfers its energy to the low pressure feed thereby increasing the feed pressure. The pressurized feed coming from several IC is joined into a single stream through a series of piping and manifolds to a high pressure inlet booster pump with a variable frequency drive (VFD) that further raises its pressure and controls the isobaric chamber rotor rotation. This is critical for maintaining the IC system balance, because controlling the timing of the IC's rotor rotation is necessary to limit brine/feed mixing which, in normal operations, ranges between 5 and 8%. Finally, this high pressure inlet booster pump stream

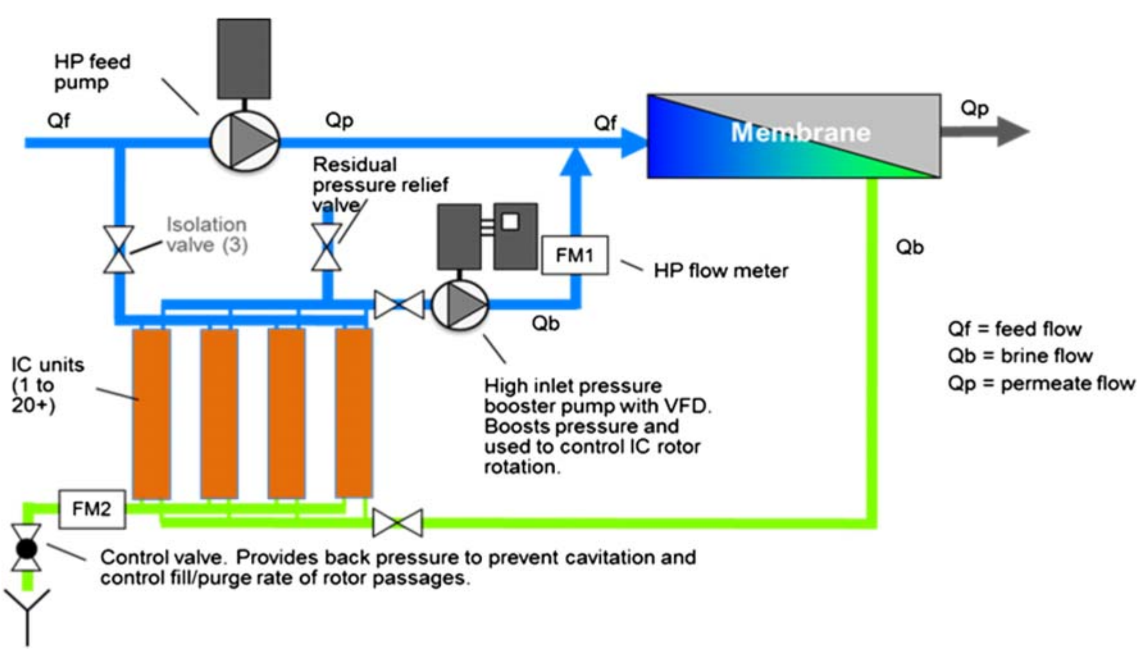

Fig. 4. P&ID for Isobaric chamber (IC) in SWRO system.

is joined with the stream from the main high-pressure feed pump and is fed into the membrane. The system is depicted in Fig. 4.

2.3. IC transfer efficiency

Manufactures of IC report that up to 97% of the available brine energy is transferred to the low-pressure feed stream. However, it is important to note that this transfer energy efficiency is within the IC. It does not account for the feed stream's loss of energy as it travels through a series of piping, manifolds, and numerous Victaulic™ fittings that connect the flow from several IC into a single stream feeding the high inlet pressure booster pump and its high pressure flow meter. When these factors are taken into account, the amount of boost to the main HPP stream feeding the membranes results in a final transfer efficiency substantially lower than the advertised levels. Equally important to note is that all the auxiliary equipments required for the proper operation of an isobaric chamber system greatly adds to the capital cost of an IC system.

2.4. Hydraulic pressure booster

HPB entered the SWRO market in 1990. Since then, over 2,000 HPB's have been installed worldwide. In the past few years, large HPB units have been installed around the world. In 2009, the HPB-1400, the world's first turbocharger with > 80% energy transfer efficiency was selected for the 240,000 m^3/day Jeddah III SWRO facility. In 2011, the HPB-2800 was selected for the 366,000 m^3/day Ras Al Khair facility.

The HPB transfers brine energy to the feed stream through the use of a turbine and pump impeller on opposite ends of a rotor, custom machined out of solid bar stock to the end user's duty point. A custom machined multi-vane diffuser surrounds the pump impeller to ensure radial pressure balance on the rotor. All bearings are water lubricated. The center bearing, within which the rotors spins, seals off the feed and brine sections of the HPB providing zero brine mixing with the feed. Fig. 5 illustrates a cut-away view of the HPB model turbocharger.

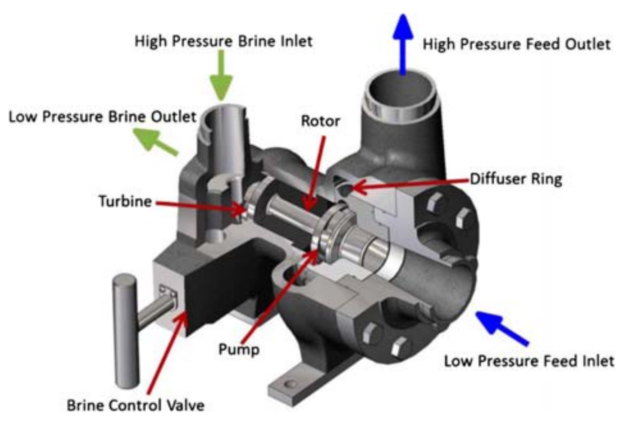

Fig. 5. HPB illustration.

2.5. HPB transfer efficiency

In a turbocharger, energy transfer efficiency is the ratio representing how much of the turbine stream power is applied to increasing the power of the pump stream. Thus, turbocharger transfer efficiency is expressed as the ratio of pump power to turbine power.

Again, it is important to note that a HPB's brine energy transfer efficiency is directly related to the increase in boost for the HPP stream feeding the membrane array because the HPB does not have additional equipment (valves, HP inlet pumps, and HP flow balancing meters) between the HPB feed boost outlet and the membrane array itself. This fact is one of the main contributing factors why systems utilizing HPB ERD's have substantially lower capital costs than IC or PIT systems.

2.6. Simplicity of installation and operation

Fig. 6 illustrates the difference in complexity between a system using an IC and a system using a HPB unit. With its required high inlet pressure booster pump, multiple valves, manifolds, pipe connections, and a HP flow meter, an IC system is significantly more expensive to install than a HPB system. Unlike an IC system, the HPB system does not require a high inlet pressure booster pump with VFD, a high pressure flow meter, a series of manifolds, piping, and numerous Victaulic™ fittings that connect the flow from several IC into a single stream feeding the high pressure inlet pump. HPB units are sized to provide the entire flow and pressure boost for a train from a single HPB ERD, whereas in an IC system, several IC are required per train adding to the complexity and capital costs.

Quick system start-up is critical for facilities that require their system to start and stop several times during a 24 h period. If, for example, an ERD system takes 15–20 min to begin producing water and the system starts and stops seven times a day, the facility will be burning electricity for 2 h per day without producing any water. IC systems require a lengthy and

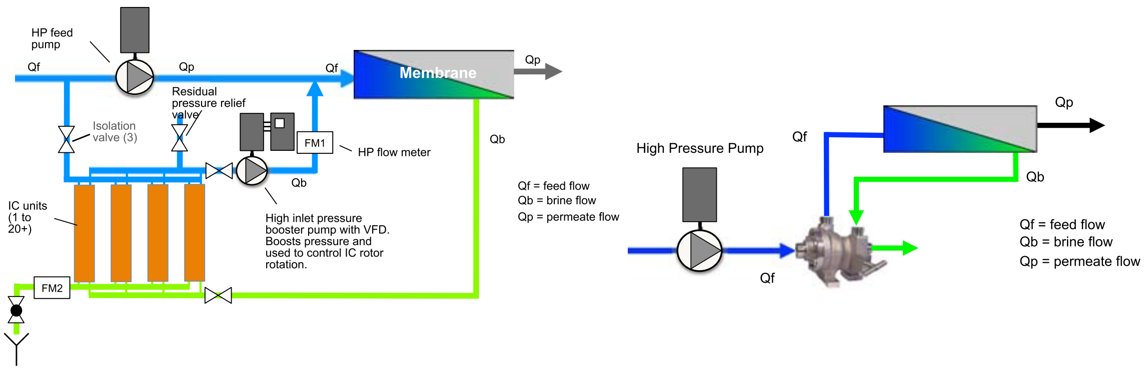

Fig. 6. IC SWRO system complexity compared to HPB SWRO system.

detailed start-up procedure that if not followed correctly could cause significant damage to the units. This is summarized in the following four steps:

- Start the feed pump and let it run for 5–10 min to purge the air out of the system.
- Start booster pump and let that continue to run for another 5–10 min to insure all of the air is out of the system.
- Ramp up HPP.
- Once the system is up to pressure, you must adjust the speed of the booster and dial in the feed stream to the IC in order to minimize brine mixing.

A system that is built with a HPB ERD begins producing water almost immediately. Without the need to purge air from a HPB, start-up takes only two simple steps:

(1) Start pretreatment low-pressure pump.
(2) Start high-pressure feed pump.
(3) Finished—the HPB begins providing pressure boost to the high-pressure feed pump as soon as the high-pressure brine stream enters the HPB.

2.7. *High-pressure pump*

In addition to selecting FEDCO's HPB-500 for the ERD unit, FEDCO's SSD-500 was chosen as the high-pressure feed pump for the new system.

In a HPB ERD system, only one HP pump is required as opposed to IC systems, which require two HP pumps: a HP feed pump and a high pressure inlet booster pump as shown in Fig. 6. With only a single

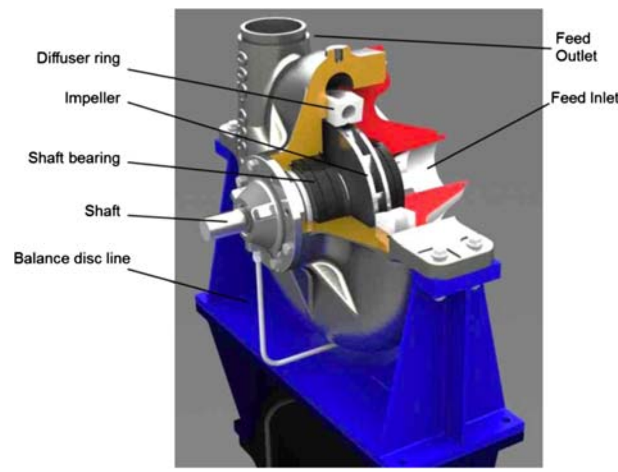

Fig. 7. SSD illustration.

HP pump required in a HPB system, pump efficiency can be maximized to meet the specific duty points of the facility.

The SSD series or single-stage centrifugal HPP performs just like any heavy-duty SWRO feed pump. The difference, however, is that it performs at a higher efficiency and lower capital cost. Fig. 7 shows a cutaway view of the SSD HPP.

Presently, FEDCO produces four SSD pump models with flows up to 1,600 m^3/h (5,700 gpm) and a maximum pressure of up to 80 bar (1,150 psi) when used with the HPB. Presently, these models include: SSD-500; SSD-700; SSD-1000; and SSD-1400. The model numbers correspond to the nominal flow in m^3/h.

Additionally, as with all high- and low-pressure FEDCO pumps bearing lubrication is based on FEDCO's patented Water Bearing Technology™ that uses pumpage to lubricate the bearings eliminating the need for oil or grease-based bearing assemblies.

3. System design and operating conditions

Production	4,500 m^3/day
Membrane pressure	855 psi
Brine pressure	835 psi
Feed flow	2,044 gpm
Brine flow	1,132 gpm
Total dissolved solids (TDS)	41,000 ppm
Temperature	27 C
Recovery rate	44.6%
HP pump	SSD-500
ERD	HPB-500
Motor	700 hp

3.1. Membrane configuration

The builder made the decision to use internally staged membranes for this new facility. The primary reason for this was to minimize fouling, thus keeping membrane pressure requirements steady over a longer period of time.

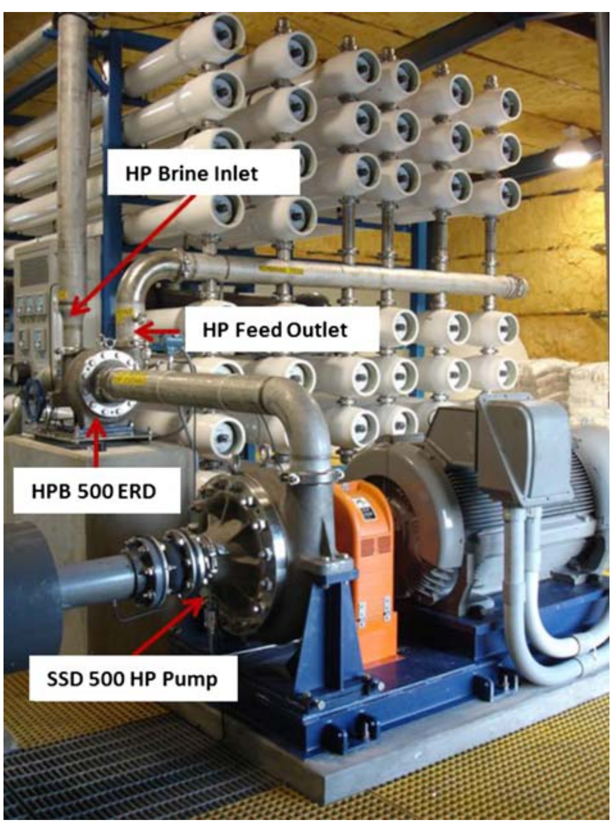

Fig. 8. SSD and HPB installation in Caribbean.

3.2. System start up

The SSD-500 HPP motor was not equipped with a VFD. Due to fairly consistent total dissolved solids (TDS) and temperature, the motor was equipped with a soft starter. All FEDCO HPB ERD's operate with either a direct start or soft starter, distinguishing it from IC systems that require a slow ramp to calibrate and balance the flows of each IC unit as well as between several IC units feeding a single train. In addition, please note in Fig. 8, a throttling valve was not used between the SSD-500 HPP and the HPB-500.

4. On site data

4.1. FEDCO test data

All FEDCO products are 100% performance tested in one of its four calibrated test loops. The results of these tests at FEDCO prior to shipment are given below:

HPB-500	76.5% transfer efficiency
SSD-500	83.5% pump efficiency

4.2. 2011–2012 SEC data

The following data show two SEC values. First, the SEC for the entire 4,500 m^3/day facility includes well pump, degass, office, and transfer pumps and does not include transmission pumping costs to customers. Second, the SEC for the RO train only.

	SEC (kW-h/m^3)							
	2011						2012	
	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb
Entire facility	3.09	3.13	3.22	3.11	3.12	3.13	3.1	3.08
RO train	2.56	2.57	2.56	2.62	2.54	2.55	2.50	2.46

4.3. February 2012 train SEC detail

Water			
TDS	41,000 ppm		
Temp	24 C		
Membrane		HPB	
Feed flow	464.2 m^3/h	Transfer efficiency	76.2%
Brine flow	257.1 m^3/h	Pump flow	464.2 m^3/h
Product flow	207.1 m^3/h	Pump inlet	35.3 bar

(*Continued*)

(*Continued*)

Recovery	44.6%	Pump outlet	59.0 bar
Reject	55.4%	Turbo boost	23.7 bar
Feed pressure	59.0 bar	Turbine flow	257.1 m^3/h
Brine pressure	57.6 bar	Turbine inlet	57.6 bar
Prod. pressure	0.5 bar	Turbine outlet	1.5 bar
		Turbine dP	56.1 bar
Feed pump		Electrical	
Efficiency	83.5%	Starter efficiency	97.0%
Inlet	4.4 bar		
Outlet	35.3 bar	Motor efficiency	96.5%
Pump boost	30.9 bar		
Pump flow	464.2 m^3/h	Electrical power	509.7 kw
Shaft power	477.1 kw		
		SEC	2.46 kwh/m^3

Note: Per customer specification, the inlet pressure to the HP pump is 4.4 bar. With the inlet pressure normalized to two bar, the SEC would be 2.6 kwh/m^3.

5. Conclusions

Though a number of factors contributed to exceptional SEC achieved by this Caribbean facility, the following 4 factors were the most critical:

- High ERD and HP feed pump efficiencies.
- Low pressure loss between ERD and membranes: This is directly attributable to the fact that with a HPB energy recovery device no valves, manifolds, gages, and booster pump are required to be placed between the energy recovery device and the membrane array.
- Start-up sequence: HPB start-up is short and water is produced in a matter of seconds as opposed to other ERD's that can take 10–15 min to begin producing water.
- Staged membranes: Allowed the system to run at a lower pressure and avoid fouling for well over a year greatly reducing pressure variations.