Desalination Technologies (II)

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Membrane Processes
Major desalination processes

Source: Dow/FilmTec
Membrane Processes

In nature, membranes play an important role in the separation of salts, including both the process of dialysis and osmosis, occurs in the body. Membranes are used in two commercially important desalting processes: Electrodialysis (ED) and Reverse Osmosis (RO).

Each process uses the ability of the membranes to differentiate and selectively separate salts and water.

ED is a voltage driven process and uses an electrical potential to move salts selectively through a membrane, leaving fresh water behind as product water.

RO is a pressure-driven process, with the pressure used for separation by allowing fresh water to move through a membrane, leaving the salts behind.
Electrodialysis

ED / EDR
Electrodialysis Process Description

ED is an electrochemical process and a low cost method for the desalination of brackish water. Due to the dependency of the energy consumption on the feed water salt concentration, the ED process is not economically attractive for the desalination of sea water.

In Electrodialysis (ED) process, ions are transported through a membrane by an electrical field applied across the membrane. An ED unit consists of the following basic components:
- pre-treatment system
- membrane stack
- low pressure circulation pump
- power supply for direct current (rectifier)
- post-treatment
The Principle of Electrodialysis

When electrodes are connected to an outside source of direct current like a battery and placed in a container of saline water, electrical current is carried through the solution, with the ions tending to migrate to the electrode with the opposite charge. Positively charged ions migrate to the cathode and negatively charged ions migrate to the anode.

If between electrodes a pair of membranes (cell), anion permeable membrane followed by a cation permeable membrane is placed, then, a region of low salinity water (product water) will be created between the membranes.

Between each pair of membranes, a spacer sheet is placed in order to permit the water flow along the face of the membrane and to induce a degree of turbulence. One spacer provides a channel that carries feed (and product water) while the next carries brine. By this arrangement, concentrated and diluted solutions are created in the spaces between the alternating membranes.
An anion membrane, a diluting spacer, a cation membrane, and a concentrating spacer comprise a repeating unit called a “cell pair.” ED cells can be stacked either horizontally or vertically.

Multiple cell pairs between an anode and a cathode comprise a “stack.”

Several membrane pairs are used between a single pair of electrodes, forming an ED stack. Feed water passes simultaneously in parallel paths through all the cells, providing a continuous flow of product water and brine to come out from the stack. Stacks on commercial ED plants contain a large number, usually several hundred of cell pairs.
EDR Process

A modification to the basic Electrodialysis process is the Reversal Electrodialysis, EDR.

An EDR unit operates on the same general principle as a standard ED plant, except that both, the product and the brine channels, are identical in construction.

In this process the polarity of the electrodes changes periodically of time, reversing the flow through the membranes. Immediately following the reversal of polarity and flow, the product water is dumped until the stack and lines are flushed out and the desired water quality is restored.

This flush takes only 1 or 2 minutes, and then the unit can resume producing water. The reversal process is useful in breaking up and flushing out scales, slimes, and other deposits in the cells before they can build up and create a problem.

Flushing allows the unit to operate with fewer pretreatment chemicals and minimizes membrane fouling.

Source: IONICS, USA
Output & Degree of Desalination

The rate of salt removal from the diluate streams is essentially controlled by Faraday’s Law, being proportional to the amount of charge passing (i.e. current) per unit time. For the situation comprising flow of a single-salt (NaCl) solution through one pair of perfect membranes and with no other current losses, the application of Faraday’s Law yields:

\[
\Delta C = \frac{I}{F \cdot U_D \cdot n}
\]

where

\(\Delta C\): reduction of concentration of salt, mole/Lt

\(I\): current flowing, Amp

\(F\): Faraday’s constant, 96,500 Coulombs per equivalent

\(U_D\): diluate stream flow rate, Lt/sec

\(n\): total number of positive or negative charges per molecule, for NaCl, \(n=1\), for CaCl\(_2\), \(n=2\)

One Faraday is the amount of electric energy required to transfer 1 gram equivalent of salt.

\(F = 96,500\) ampere-seconds = 26.8 ampere-hours
Electrodialysis Process Characteristics

ED has the following characteristics that make it suitable for a number of applications:

- Capability for high recovery (more product and less brine)
- Energy usage that is proportional to the salts removed
- Ability to treat feed water with a higher level of suspended solids than RO
- Low chemical usage for pretreatment

ED units are normally used to desalinate brackish water. The major energy requirement is the direct current used to separate the ionic substances in the membrane stack.

In general, the total energy consumption, under ambient temperature conditions and assuming product water of 500 ppm TDS, would be around 1.5 and 4 kWh/m³ for a feed water of 1,500 to 3,500 ppm TDS, respectively. Additionally, pumping energy requirements are minimum.
# Process and Cost analysis

## Investment costs for Electro Dialysis plants

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Investment cost [$]</th>
<th>Plant capacity [m³/d]</th>
<th>Notes</th>
<th>Specific plant cost [$/m³/d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDA World Inventory (2002)</td>
<td>40,870,000</td>
<td>45,420</td>
<td>USA (1994)</td>
<td>900</td>
</tr>
<tr>
<td>IDA World Inventory (2002)</td>
<td>620,000</td>
<td>600</td>
<td>Japan (2000)</td>
<td>1,033</td>
</tr>
<tr>
<td>IDA World Inventory (2002)</td>
<td>13,300,000</td>
<td>15,000</td>
<td>Iran (1994)</td>
<td>887</td>
</tr>
<tr>
<td>IDA World Inventory (2002)</td>
<td>7,320,000</td>
<td>8,000</td>
<td>Spain (1987)</td>
<td>915</td>
</tr>
<tr>
<td>IDA World Inventory (2002)</td>
<td>13,900,000</td>
<td>14,400</td>
<td>Italy (1992)</td>
<td>965</td>
</tr>
</tbody>
</table>
Electrodialysis Reversal drinking water plant in Texas

Source: IONICS, USA
Reverse Osmosis

RO
**RO Process**

RO is the most widely used process for seawater desalination.

RO process involves the forced passage of water through a membrane against the natural osmotic pressure to accomplish separation of water and ions.

In practice, the saline feed water is pumped into a closed vessel where it is pressurized against the membrane.

The major energy required for desalting is for pressurizing the feed water.

As a portion of the water passes through the membrane, the remaining feed water increases in salt content.

At the same time, a portion of this feed water is discharged without passing through the membrane.

Source: METITO
Osmosis and Reverse Osmosis (RO)

A rough value of osmotic pressure of water can be calculated roughly by the following rule:

Osmotic pressure (PSI) = Total Dissolved Solids / 100
The osmotic pressure, $P_{osm}$, of a solution can be determined experimentally by measuring the concentration of dissolved salts in solution:

$$P_{osm} = 1.19(T + 273) \cdot \Sigma(m_i)$$  \hspace{1cm} (1)

Where

- $P_{osm}$: osmotic pressure in psi
- $T$: temperature, C°
- $\Sigma(m_i)$: sum of molar concentration of all constituents in a solution*

An approximation of $P_{osm}$ may be made by assuming that 1000 ppm TDS equals about 0.76 bar of osmotic pressure.

<table>
<thead>
<tr>
<th>Salinity [g/l]</th>
<th>Molarity (=NaCl) [mol/l]</th>
<th>$P @ T=25°C$ ≈ [atm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.086</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>0.172</td>
<td>8</td>
</tr>
<tr>
<td>35</td>
<td>0.603</td>
<td>29</td>
</tr>
<tr>
<td>50</td>
<td>0.862</td>
<td>42</td>
</tr>
<tr>
<td>70</td>
<td>1.207</td>
<td>59</td>
</tr>
</tbody>
</table>

*Molarity is defined as moles of solute per litre of solution
Water Transport (1)

The rate of water passage through a semi-permeable membrane is:

\[ Q_w = (\Delta \Pi - \Delta P_{osm}) \times K_w \times \frac{S}{d} \]  \hspace{1cm} (2)

Where

- \( Q_w \): rate of water flow through the membrane
- \( \Delta P \): hydraulic pressure differential across the membrane
- \( \Delta P_{osm} \): osmotic pressure differential across the membrane
- \( K_w \): membrane permeability coefficient for water
- \( S \): membrane area
- \( d \): membrane thickness
Water Transport (2)

The above equation could be simplified by

\[ Q_w = (NDP) \times A \tag{3} \]

Where

- \( Q_w \): rate of water flow through the membrane
- \( NDP \): net driving pressure
- \( A \): a constant for each membrane material type

The NDP required for any given membrane application in RO is a function of both the osmotic pressure change and hydraulic resistance

\[ NDP = P_F + \Pi_P - \Pi_F - P_P \]
The rate of salt through the membrane is defined by

\[ Q_s = \Delta C \times K_s \times \frac{S}{d} \]  

(4)

Where
- \( Q_s \): flow rate of salt through the membrane
- \( \Delta C \): salt concentration differential across the membrane
- \( K_s \): membrane permeability coefficient for salt
- \( S \): membrane area
- \( d \): membrane thickness
Salt Transport (2)

The above equation could be simplified by

$$Q_s = B \times (\Delta C)$$  \hspace{1cm} (5)

Where

$Q_s$: flow rate of salt through the membrane

$\Delta C$: salt concentration differential across the membrane or the driving force for the mass transfer of salts

$B$: constant for each membrane type

The above equations (4,5) show that for a given membrane

• The rate of water flow through a membrane is proportional to the net driving pressure differential across the membrane
• The rate of salt flow is proportional to the concentration differential across the membrane
The Salinity of the permeate water depends on:

\[ C_p = \frac{Q_s}{Q_w} \]  \hspace{1cm} (6)

Where
- \( Q_s \): flow rate of salt through the membrane
- \( Q_w \): rate of water flow through the membrane

The Salt passage through the membrane is

\[ SP = 100 \% \times \frac{C_p}{C_{fm}} \] \hspace{1cm} (7)

Where
- \( C_p \): salt concentration in the permeate
- \( C_{fm} \): mean salt concentration in feed stream

Salt rejection

\[ SR = 100 \% - SP \] \hspace{1cm} (8)
Reverse Osmosis Technology

Reverse osmosis uses pressure on solutions with concentrations of salt to force fresh water to move through a semi-permeable membrane, leaving the salts behind.

The amount of desalinated water that can be obtained (recovery ratio) ranges between 30% and 75% of the volume of the input water, depending on the initial water quality, the quality of the product needed, and the technology and membranes involved.
Recovery ratio, $R$ - is an important parameter in the design and operation of RO systems. Recovery ratio affects salt passage and product flow and is defined as follows:

$$ R = \frac{Q_p}{Q_f} \times 100\% $$

Where

$Q_p$: permeate flow rate

$Q_f$: feed water flow rate

Concentration Factor is the salinity of the concentrate divided by the salinity of the plant feed water.

$$ CF = \frac{1}{1 - R} $$
Solute concentration factor as a function of recovery

Source: Bureau of Reclamation
Concentration polarization – the increase of salt concentration near to the membrane surface. As water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration exceeds the salt concentration in the bulk solution. The concentration polarization factor, CPF, is defined as:

\[ CPF = \frac{C_s}{C_b} \]

Where

- \( C_s \): salt concentration at the membrane surface
- \( C_b \): bulk concentration
RO Performance Parameters

Factors influence RO performance

The permeate flux and the salt rejection are the key performance parameters. Mainly they are influenced by variable parameters such as:

- Pressure
- Temperature
- Recovery
- Feed water salt concentration

<table>
<thead>
<tr>
<th>Increasing</th>
<th>Permeate flow</th>
<th>Salt passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective pressure</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Temperature</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Recovery</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Feed Salt concentration</td>
<td>↓</td>
<td>↑</td>
</tr>
</tbody>
</table>
Reverse Osmosis System Description (1)

An RO system is made up of the following basic components:

- Intake system
- Pretreatment system
- High-pressure pump
- Membrane assembly
- Post-treatment system
- Brine Disposal

- Instrumentation and control
- Electric system
- Membrane cleaning system
The pre-treated feed water is forced by a high-pressure pump to flow across the membrane surface. RO operating pressure typically varies from 14-25 bar for brackish water and from 55-80 bar for sea water.

Part of the feed water, the product or permeate water, passes through the membrane, removing from it the majority of the dissolved solids.

The post-treatment system consists of sterilisation, stabilisation and mineral enrichment of the product water.
• **Intake System (for seawater desalination)**
  - Open intake
  - Beach wells

• **Pretreatment Procedure**
  - Filtration
  - Chemicals Dosing

  Usually, the pretreatment consists of fine filtration and the addition of acid or other chemicals to inhibit precipitation and the growth of microorganisms. Purpose: reduction of contamination of the membrane surfaces (calcium precipitates, metal oxides, organics and biological matters).

• **High-pressure pumping unit**
  The high-pressure pump supplies the pressure needed to enable the water to pass through the membrane and have the salts rejected.

• **Energy recovery device**
  The pressure of the brine disposal is high and around 2-5 bar less the pressure of the feed water.
• Post-treatment procedure
  - Enrichment (Ca, Mg)
  - Stabilization
  - Sterilization

• Brine disposal (outfall system)
Two types of RO membranes are used commercially. These are:

- the Spiral Wound (SW) membranes and
- the Hollow Fiber (HF) membranes

SW and HF membranes are used to desalt both sea water and brackish water. The choice between the two is based on factors such as cost, feed water quality and product water capacity.
Spiral wound membranes

Source: Dow/FilmTec
Hollow fibres module

Source: Dupont
RO Membrane Characteristics

**TW30-4040**

The element nomenclature for FILMTEC elements is for example as follows:

- **TW** 30 - 40 40
  - _____ Length of Element in inches
  - _____ Diameter of Element, divided by 10, in inches
  - _______ FT30 - Element Family
- TW - Tap Water
- BW - Brackish Water
- SW - Seawater
- SWHR - Seawater High Rejection

*Source: DOW/Filmtec*
RO Configurations

Single array RO system

Two array RO system
Two pass RO system
Membrane Modeling (1)

Before utilizing the projection software it is advisable to perform some preliminary calculations.

These are as follows:

1. Estimation of the RO units required
   RO units are classified based on permeate production, not feed water quantity.

2. Estimation of the membranes required
   The rough number of membrane elements can be calculated, based on typical average flux
   For brackish water RO: 25-30 L/m²/hr
   For seawater RO: 12-17 L/m²/hr

   Most brackish water membranes have an active area of about 37 m², while most seawater membrane elements have an active area of 30 – 34 m².

   Translating flux to element projection:
   For brackish water RO: 0.93-1.11 m³/hr
   For seawater RO: 0.36-0.51 m³/hr (for 30 m² active membrane area)
   0.41-0.58 m³/hr (for 34 m² active membrane area)
Membrane Modeling (2)

By dividing the required RO unit permeate production by the average membrane element production, an estimate of the number of elements required for the RO unit can be obtained.

Example: 215 m$^3$/hr of permeate water required from a brackish water RO plant

Dividing by the lowest average flux for brackish RO, 25 L/m$^2$/hr

$\frac{215}{25} = 8612 \approx 8600$ m$^2$

$\frac{8600}{37}$m$^2$ (typical membrane area for BW RO elements) = 232 membranes

3. Estimation of vessels required

In order to obtain the number of vessels and the vessel array, the recovery to be used must be assumed. Typical seawater RO units have a recovery in the order of 35-45%, while recovery of brackish RO plants could range up to 75 or 80%.

Regarding the vessels array, vessels are available in length ranging 1 to 8 elements. In general the use of 6 to 7 elements per vessel is most common.

Example: 232 membranes / 6 elements/vessel

$38.67 \approx 39$ vessels with 6 elements each
An significant number of Reverse Osmosis membrane manufacturers exit around the world

- Dow FilmTec (USA) - [www.dow.com](http://www.dow.com)
- GE Osmonics (USA) - [www.gewater.com](http://www.gewater.com)
- Hydranautics (USA) - [www.membranes.com](http://www.membranes.com)
- Toray Japan - [www.appliedmembranes.com](http://www.appliedmembranes.com)
All the major RO membrane manufacturers maintain computer programs to design and predict the performance of their membranes when placed in an RO desalination plant.

### Table 3.4 Design guidelines for 8-inch FILMTEC elements in water treatment applications

<table>
<thead>
<tr>
<th>Feed source</th>
<th>RO Permeate</th>
<th>Well Water</th>
<th>Surface Supply</th>
<th>Wastewater (Filtered Municipal Effluent)</th>
<th>Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MF&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Conventional</td>
<td>Well or MF</td>
<td>Open intake</td>
<td></td>
</tr>
<tr>
<td>Feed sol. density range</td>
<td>500&lt;sup&gt;-&lt;/sup&gt;</td>
<td>600&lt;sup&gt;-&lt;/sup&gt;</td>
<td>700&lt;sup&gt;-&lt;/sup&gt;</td>
<td>800&lt;sup&gt;-&lt;/sup&gt;</td>
<td>900&lt;sup&gt;-&lt;/sup&gt;</td>
</tr>
<tr>
<td>Average</td>
<td>2/3</td>
<td>2/3</td>
<td>2/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>System flux, gpm/h</td>
<td>10–20</td>
<td>20–40</td>
<td>20–40</td>
<td>20–40</td>
<td>20–40</td>
</tr>
<tr>
<td>Maximum element recovery %</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

#### Active Membrane Area / Maximum permeate flow rate, gpd (m<sup>3</sup>/h)

<table>
<thead>
<tr>
<th>Element type</th>
<th>Active Membrane Area</th>
<th>Maximum permeate flow rate, gpd (m&lt;sup&gt;3&lt;/sup&gt;/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW elements (365 ft²)</td>
<td>10 (3.3)</td>
<td>13 (4.0)</td>
</tr>
<tr>
<td>BW elements (400 ft² and 440 ft²)</td>
<td>10 (3.3)</td>
<td>13 (4.0)</td>
</tr>
<tr>
<td>NF elements</td>
<td>10 (3.3)</td>
<td>13 (4.0)</td>
</tr>
<tr>
<td>Full-fit elements</td>
<td>25 (9.7)</td>
<td>25 (9.7)</td>
</tr>
<tr>
<td>SW elements</td>
<td>10 (3.3)</td>
<td>13 (4.0)</td>
</tr>
</tbody>
</table>

1. MF - Microfiltration - continuous filtration process using a membrane with pore size of <0.5 microns.
2. The maximum recommended pressure drop across a single element is 10 psi (0.7 bar) or 50 psi (3.4 bar) across multiple elements in a pressure vessel, whichever value is more limiting. We recommend designing at maximum of 80% (12 psi) for any element in a system.
3. Note: The limiting values listed above have been incorporated into the ROSA (Reverse Osmosis System Analysis) software. Designs of systems in excess of the guidelines results in a warning on the ROSA printout.
Membrane Modeling Software

FILMTEC Modeling Software
Energy Requirements (1)

The energy requirements for RO depend directly on the concentration of salts in the feed water and, to a lesser extent, on the temperature of the feed water. Because no heating or phase change is necessary for this method of separation, the major use of energy is for pressurizing the feed water.

Power consumption of reverse osmosis (RO) desalination process is the lowest among the commercial desalination methods. RO facilities are most economical for desalinating brackish water, and the product water increases in cost as the salt content of the source water increases.

The main load of an RO unit is the high-pressure pumps. In seawater systems, usually the high pressure pumping unit provides the major contribution (over 85%) to the combined power consumption of the process. Other loads are:

- Booster pump
- Dosing Pumps
- Membrane Cleaning Pump
- Permeate Pump
The efficiencies of pumps, electric motors and power recovery devices have been improved considerably during the last few years. Due to these improvements, power consumption in the range of 3 – 4 kwhr/m³ is quite common in seawater desalination systems.
Energy Recovery Devices

The fraction of power, recovered by the power recovery device, depends on the type and efficiency of the power recovery equipment used. Energy recovery devices connected to the concentrate stream as it leaves the pressure vessel at about 1 to 5 bar less than the applied pressure from the high-pressure pump.

Energy recovery devices are mechanical and generally consist of work or pressure exchangers, turbines, or pumps of some type that can convert the pressure difference to rotating or other types of energy that can be used to reduce the energy needs in the overall process. The most known ERD are:

- Pelton wheel
- Pressure Exchanger
- Work Exchanger
- Hydraulic Turbocharger
Seawater RO – Example
- Recovery ratio 33%

Pumping requirements
- Motor 6.2 kWh/m³

Pelton turbine energy recovery
- Only for medium and large scale

Direct energy recovery
Source: Thomson M., CREST
1000 - 1500 m$^3$/day

Motor

Pump

Turbine

Source: Thomson M., CREST
Pelton Wheel energy recovery system

Pressure Exchanger energy recovery system
Energy Recovery Devices for small RO units

- PX Pressure Exchanger (ERI)
- Clark Pump (Spectra)
- Ultra Whisper (Sea Recovery) and
- Ingeniatec system

Very small energy recovery devices are not very efficient, improvement is required.
Energy Requirements Modeling (1)

Booster pump: the power required to run a booster pump is given by

\[ P_{bp} = \frac{\rho \cdot g \cdot h \cdot Q_f}{n_p} \]

Where
- \( \rho \): Feed water density, at 25°C, kg/m³
- \( h \): Manometric height, m
- \( g \): Acceleration due to gravity, 9.81 m/sec²
- \( Q_f \): Feed flow rate, m³/sec
- \( n_p \): Pump efficiency, %
Energy Requirements Modeling (2)

High-pressure pump: The power required to run a high-pressure pump is given by

\[
P_{HPP} = \frac{P_f \times Q_f}{n_p}
\]

Where
- \( P_{HPP} \): Power of HPP, kW
- \( P_f \): Feed pressure, N/m²
- \( Q_f \): Feed flow rate, m³/sec
- \( n_p \): Pump efficiency, %
Energy Requirements Modeling (3)

Energy Recovered: The energy recovered by an energy recovery device is:

\[ ER = Pr_b \cdot Q_b \cdot n_t \]

Where
- \( Pr_b \): brine pressure, N/m²
- \( Q_b \): brine flow rate, m³/sec
- \( n_t \): turbine efficiency, %
Energy Requirements Modeling (4)

Specific Energy Consumption: The energy consumption per m³ of water produced

\[
Sp\cdot En\cdot Con\ .(kWh \ / \ m^3) = \frac{(P_{bp} + P_{HPP} - ER) \times 24\ hours}{Q_p}
\]

Where
- \(P_{bp}\): booster pump power, kW
- \(P_{HPP}\): high-pressure pump power, kW
- \(ER\): energy recovered, kW
- \(Q_p\): permeate flow rate, m³/day
Membrane Cleaning pump: the energy required to drive the pump for the flushing procedure after the shutdown of the plant.

\[ P_{MFP} = \frac{P \times Q}{n_p} \]

Where
- \( P \): pressure, N/m²
- \( Q \): flow rate, m³/sec
- \( n_p \): pump efficiency, %
## Energy Recovery Example

### Typical Plant Example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Capacity:</td>
<td>10,000 m³/day (2.64 MGD)</td>
</tr>
<tr>
<td>Product Flow:</td>
<td>417 m³/h (1,836 USGPM)</td>
</tr>
<tr>
<td>Conversion:</td>
<td>50%</td>
</tr>
<tr>
<td>Membrane configuration:</td>
<td>Single Stage</td>
</tr>
<tr>
<td>Req. Membrane pressure:</td>
<td>68 bar (986 PSI)</td>
</tr>
</tbody>
</table>

### Electric Motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>2,985 rev/min (for 50 Hz application)</td>
</tr>
<tr>
<td>Power</td>
<td>1,300 kW (1,730 HP)</td>
</tr>
<tr>
<td>Motor Efficiency</td>
<td>96.5%</td>
</tr>
</tbody>
</table>

### Calculation of Energy Consumption

Required Pump Power = \(834 \text{ m}^3/\text{h} \times (68 - 2) \text{ bar} / 0.87/36 = 1,757.5 \text{ kW} (2.356 \text{ HP})\)

Turbine Recovered Energy = \(417 \text{ m}^3/\text{h} \times 67 \text{ bar} \times 0.90/36 = 698.5 \text{ kW} (936 \text{ HP})\)

Power absorbed by Motor = 1,757.5 kW - 695.5 kW = 1,059 kW (1,420 HP)

### Energy Recovery Turbine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>RO-350-100-2</td>
</tr>
<tr>
<td>Flow</td>
<td>417 m³/h (1,836 USGPM)</td>
</tr>
<tr>
<td>Brine Pressure:</td>
<td>67 bar (972 PSI)</td>
</tr>
<tr>
<td>ERT Efficiency:</td>
<td>90%</td>
</tr>
</tbody>
</table>

**Specific Energy Consumption** = \(1,059 \text{ kW} / 0.965 / 417 \text{ m}^3/\text{h} = 2.63 \text{ kWh/m}^3 \text{ Product}\)
Energy Recovery Devices - Applications

The large seawater plants being built today in Spain, Trinidad, and at Tampa Bay, Florida all use Pelton Wheel energy recovery devices. In these sizes, 454 m³/hr and larger, recovery efficiency is high, above 80% in most cases.

The pressure exchanger is currently used for smaller systems and has even higher efficiency (above 90%).

Turbocharger efficiency is currently between 60 and 70 % and is also size limited, with the largest unit currently in production sized for 409 m³/hr.
### Typical RO feed pump power consumption

<table>
<thead>
<tr>
<th>Location</th>
<th>Feed TDS (mg/l)</th>
<th>Recovery (percent)</th>
<th>Temperature (°C)</th>
<th>Feed pressure (bars)</th>
<th>Feed pump power (kWh/m³)</th>
<th>Feed pump type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter, FL(^1) (Phase I)</td>
<td>5,000</td>
<td>75</td>
<td>21</td>
<td>24</td>
<td>1.125</td>
<td>VT</td>
</tr>
<tr>
<td>Jupiter, FL(^2) (Phase II)</td>
<td>5,000</td>
<td>75</td>
<td>21</td>
<td>14.4/17.2</td>
<td>0.650</td>
<td>VT</td>
</tr>
<tr>
<td>Cape Coral, FL Plant 2</td>
<td>1,300</td>
<td>85</td>
<td>28</td>
<td>12.5</td>
<td>0.454</td>
<td>VT</td>
</tr>
<tr>
<td>Kill Devil Hills, NC(^3)</td>
<td>2,300</td>
<td>75</td>
<td>20</td>
<td>18.2</td>
<td>0.828</td>
<td>VT</td>
</tr>
<tr>
<td>Santa Barbara, CA</td>
<td>SSW</td>
<td>40</td>
<td>10-15</td>
<td>60-65</td>
<td>3.5-4.0</td>
<td>HMS</td>
</tr>
<tr>
<td>Key West, FL(^4)</td>
<td>SWW</td>
<td>30</td>
<td>20-28</td>
<td>55-60</td>
<td>4.0-4.5</td>
<td>VT</td>
</tr>
<tr>
<td>Arlington, CA(^4)</td>
<td>1,200</td>
<td>77</td>
<td>21</td>
<td>14.5</td>
<td>0.515</td>
<td>VT</td>
</tr>
<tr>
<td>Marco Island, FL(^5)</td>
<td>≤ 40,000</td>
<td>75</td>
<td>21</td>
<td>23.1/27.2</td>
<td>1.111</td>
<td>VT</td>
</tr>
</tbody>
</table>

1. Hydronautics CPA-2  
2. Hydranautics ESPA with interstage boost  
3. Feed water now ≤ 4,000 mg/l TDS  
4. With energy recovery, reverse running turbine between pump and motor  
5. Uses hydraulic Turbocharger\(^\text{TM}\) as interstage boost  
6. First and boosted second stage pressures

Note: VT = vertical turbine, can type  
HMS = horizontal, multi-stage with energy recovery turbine

Source: Bureau of Reclamation
<table>
<thead>
<tr>
<th>Facility or Location</th>
<th>US$/AqL (first year)</th>
<th>US$/m³ (first year)</th>
<th>Operational?</th>
<th>Year</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashkelon, Israel</td>
<td>2.03</td>
<td>0.54</td>
<td>Yes</td>
<td>2002</td>
<td>EDS (2004), Segal (2004), Zhou &amp; Tol (2005)</td>
</tr>
<tr>
<td>Ashkelon, Israel</td>
<td>2.00</td>
<td>0.53</td>
<td>Yes</td>
<td>2003</td>
<td>NAS (2004)</td>
</tr>
<tr>
<td>Ashkelon, Israel</td>
<td>2.10</td>
<td>0.55</td>
<td>Yes</td>
<td>2004</td>
<td>Wiff &amp; Barts (2005)</td>
</tr>
<tr>
<td>Ashkelon, Israel</td>
<td>2.34</td>
<td>0.62</td>
<td>Yes</td>
<td>2005</td>
<td>Red Herring (2005), Semiat (2006)</td>
</tr>
<tr>
<td>Carlsbad, CA (Proeldon)</td>
<td>2.90</td>
<td>0.77</td>
<td>No</td>
<td>2005</td>
<td>San Diego Daily Transcript (2005)</td>
</tr>
<tr>
<td>Dhakella, Cyprus</td>
<td>5.40</td>
<td>1.43</td>
<td>Yes</td>
<td>2003</td>
<td>NAS (2004)</td>
</tr>
<tr>
<td>Ellot, Israel</td>
<td>2.80</td>
<td>0.74</td>
<td>Yes</td>
<td>1997</td>
<td>Wiff &amp; Barts (2005)</td>
</tr>
<tr>
<td>Hamma, Algiers</td>
<td>3.19</td>
<td>0.84</td>
<td>No</td>
<td>2003</td>
<td>EDS (2004), Segal (2004)</td>
</tr>
<tr>
<td>Lamaca, Cyprus</td>
<td>2.84</td>
<td>0.75</td>
<td>Yes</td>
<td>2000</td>
<td>Segal (2004)</td>
</tr>
<tr>
<td>Lamaca, Cyprus</td>
<td>3.20</td>
<td>0.85</td>
<td>Yes</td>
<td>2003</td>
<td>NAS (2004)</td>
</tr>
<tr>
<td>Lamaca, Cyprus</td>
<td>3.23</td>
<td>0.85</td>
<td>Yes</td>
<td>2001</td>
<td>Wiff &amp; Barts (2005)</td>
</tr>
<tr>
<td>Moss Landing, CA (Posidcon)</td>
<td>3.63</td>
<td>0.86</td>
<td>No</td>
<td>2005</td>
<td>NPWMD (2005b)</td>
</tr>
<tr>
<td>Perth, Australia</td>
<td>3.49</td>
<td>0.92</td>
<td>No</td>
<td>2005</td>
<td>Water Technology (2006)</td>
</tr>
<tr>
<td>Singapore</td>
<td>1.75</td>
<td>0.48</td>
<td>Yes</td>
<td>2002</td>
<td>Segal (2004)</td>
</tr>
<tr>
<td>Singapore</td>
<td>1.70</td>
<td>0.45</td>
<td>Yes</td>
<td>2003</td>
<td>NAS (2004)</td>
</tr>
<tr>
<td>Tampa Bay, FL</td>
<td>Four bids from 1.75 to 2.18</td>
<td>0.46 to 0.53</td>
<td>No</td>
<td>1999</td>
<td>Semiat (2000)</td>
</tr>
<tr>
<td>Tampa Bay, FL</td>
<td>2.10</td>
<td>0.55</td>
<td>No</td>
<td>2003</td>
<td>Segal (2004)</td>
</tr>
<tr>
<td>Tampa Bay, FL</td>
<td>2.18</td>
<td>0.58</td>
<td>No</td>
<td>2003</td>
<td>Wiff &amp; Barts (2005)</td>
</tr>
<tr>
<td>Tampa Bay, FL</td>
<td>2.49</td>
<td>0.66</td>
<td>No?</td>
<td>Arroyo (2004)</td>
<td></td>
</tr>
<tr>
<td>Trinidad</td>
<td>2.77</td>
<td>0.73</td>
<td>Yes?</td>
<td></td>
<td>Segal (2004)</td>
</tr>
<tr>
<td>Trinidad</td>
<td>2.80</td>
<td>0.74</td>
<td>Yes</td>
<td>2003</td>
<td>NAS (2004)</td>
</tr>
</tbody>
</table>

Source: Pacific Institute, 2006
Reverse Osmosis unit is characterized by:

- Modularity/Compactness
- No empirical technical staff is required
- Satisfactory performance in all sizes
- Easy operation
- Low energy requirements (use of energy recovery devices)
Promotion of Renewable Energy for Water production through Desalination

Source: ERI
Gela site RO site, Sicily

RO units (15000 m³/d)
RO plant in Giglio Island (Italy)

- Capacity: 1800m³/d;
- Desalinated water cost: 0.76 €/m³
- Water cost with ships: 10÷15 €/m³
RO Process Developments

Two developments have helped to reduce the operating cost of RO plants during the past decade: the development of more efficient membranes and the use of energy recovery devices.

In RO units the use of energy recovery devices is common, energy recovery devices connected to the concentrate stream as it leaves the pressure vessel at about 1 to 4 bar less than the applied pressure from the high-pressure pump. These energy recovery devices are mechanical and generally consist of work or pressure exchangers, turbines, or pumps of some type that can convert the pressure difference to rotating or other types of energy that can be used to reduce the energy needs in the overall process.

These can have a significant impact on the economics of operating large plants. They increase in value as the cost of energy increases. Now, energy usage in the range of 3-3.5 kWh/m³ for seawater RO (with energy recovery) plants has been reported.
Seawater water RO desalination unit

Input Data

Qp= 0.130 lt/hr = 3.1 m$^3$/day  
Cf= 37,000 ppm TDS  
R= 13%  
Tf= 20°C  
Pop.= 53 bar  
Qf= 991 lt/hr= 23.8 m$^3$/day=0.99m$^3$/h

Output Data

Qf=0.95 lt/hr= 23 m$^3$/day

\[
R = \frac{Qp}{Qf} \times 100 \%
\]

\[
P_{bp} = 0.294 \text{ kW}
\]

\[
P_{bp} = \frac{\rho \cdot g \cdot h \cdot Q_f}{n_p} = \frac{1.026 \times 9.81 \times 85 \times (0.99 / 3600)}{0.8} = 0.294 \text{ kW}
\]
CRES RO plant (2)

\[ P_{\text{HPP}} = 1.7 \text{ kW} \]

\[ P_t = 1.7 + 0.294 = 2 \text{ kW} \]

\[ P_{\text{HPP}} = \frac{P_f \cdot Q_f}{n_p} = \frac{53 \cdot (0.99 / 36)}{0.85} = 1.7 kW \]

Sp.En. Consumption = 2 kW * 24/3.1 = 15.4 kWh/m³