Desalination Technologies (II)

PRODES

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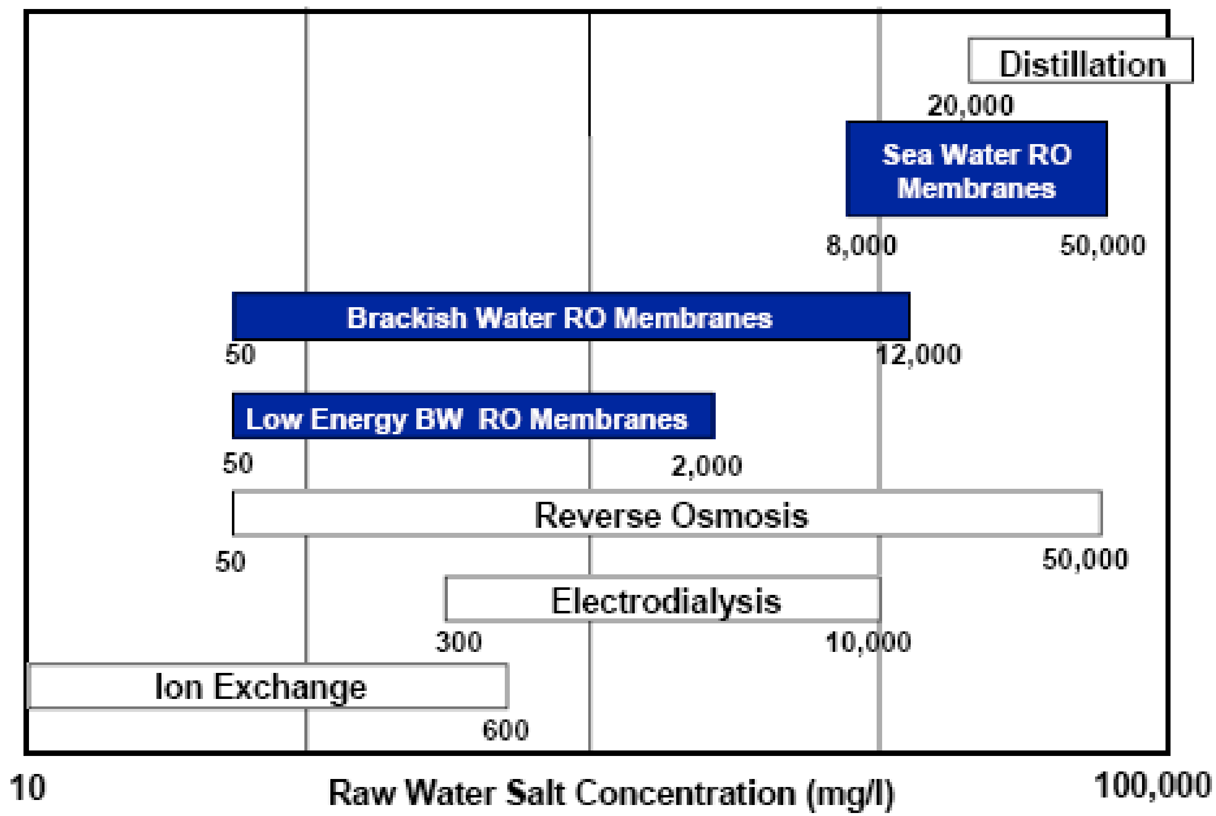
Membrane Processes

Major desalination processes



Source: Dow/FilmTec

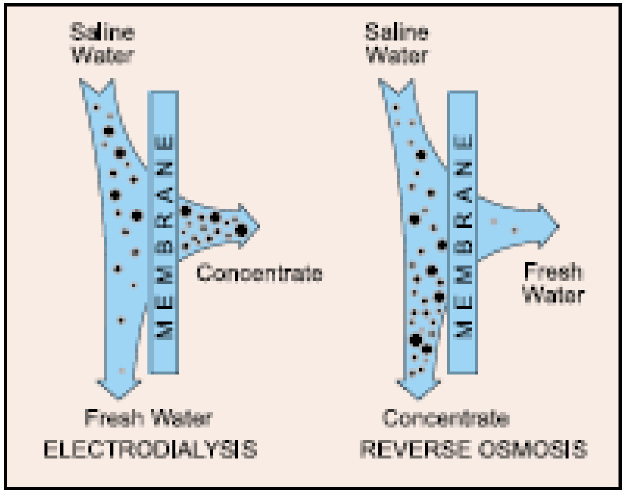
Membrane Processes

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

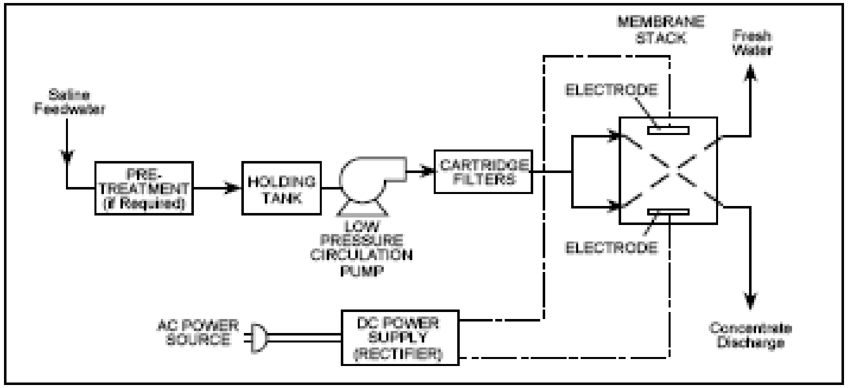
ED / EDR

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



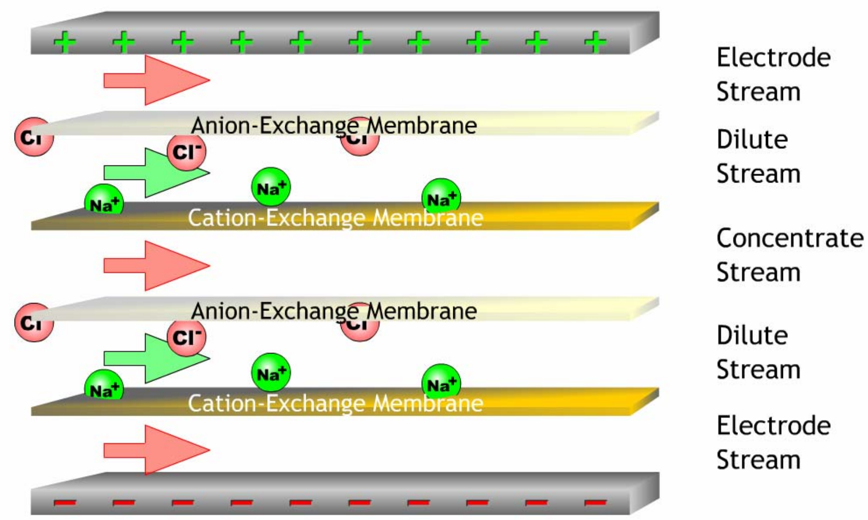
Components of an electrodialysis plant *USAID*

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.

ED membrane spacer

EDR membranes and spacers
Photo — Ionics

ED stack

Source: IONICS

EDR Process

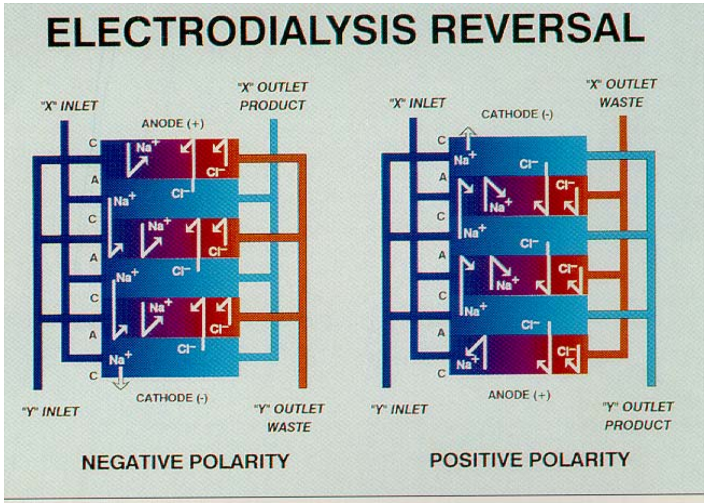
A modification to the basic Electrodialysis process is the **Reversal Electrodialysis**, EDR.

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 Faradays Law yields:

$$\Delta C = \frac{I}{F * U_D * n}$$

where

ΔC: 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/m^3 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

Ref.	Investment cost [$]	Plant capacity [m^3/d]	Notes	Specific plant cost [$\$/(m^3/d)$]
IDA World Inventory (2002)	3,490,000	3,788	USA (1999)	921
IDA World Inventory (2002)	40,870,000	45,420	USA (1994)	900
IDA World Inventory (2002)	620,000	600	Japan (2000)	1,033
IDA World Inventory (2002)	13,300,000	15,000	Iran (1994)	887
IDA World Inventory (2002)	7,320,000	8,000	Spain (1987)	915
IDA World Inventory (2002)	13,900,000	14,400	Italy (1992)	965

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.

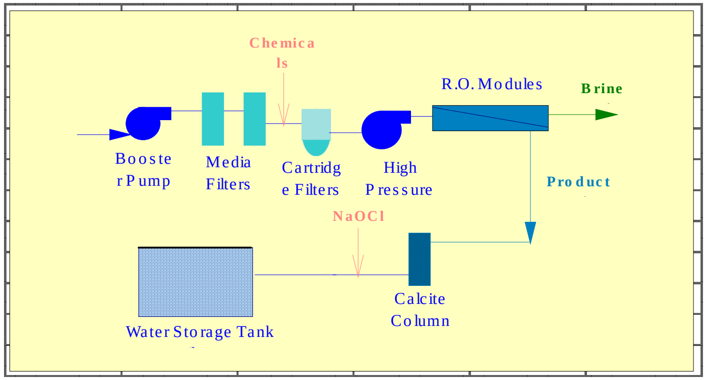
RO process involves the forced passage of water through a membrane against the natural osmotic pressure to accomplish separation of water and ions.

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.

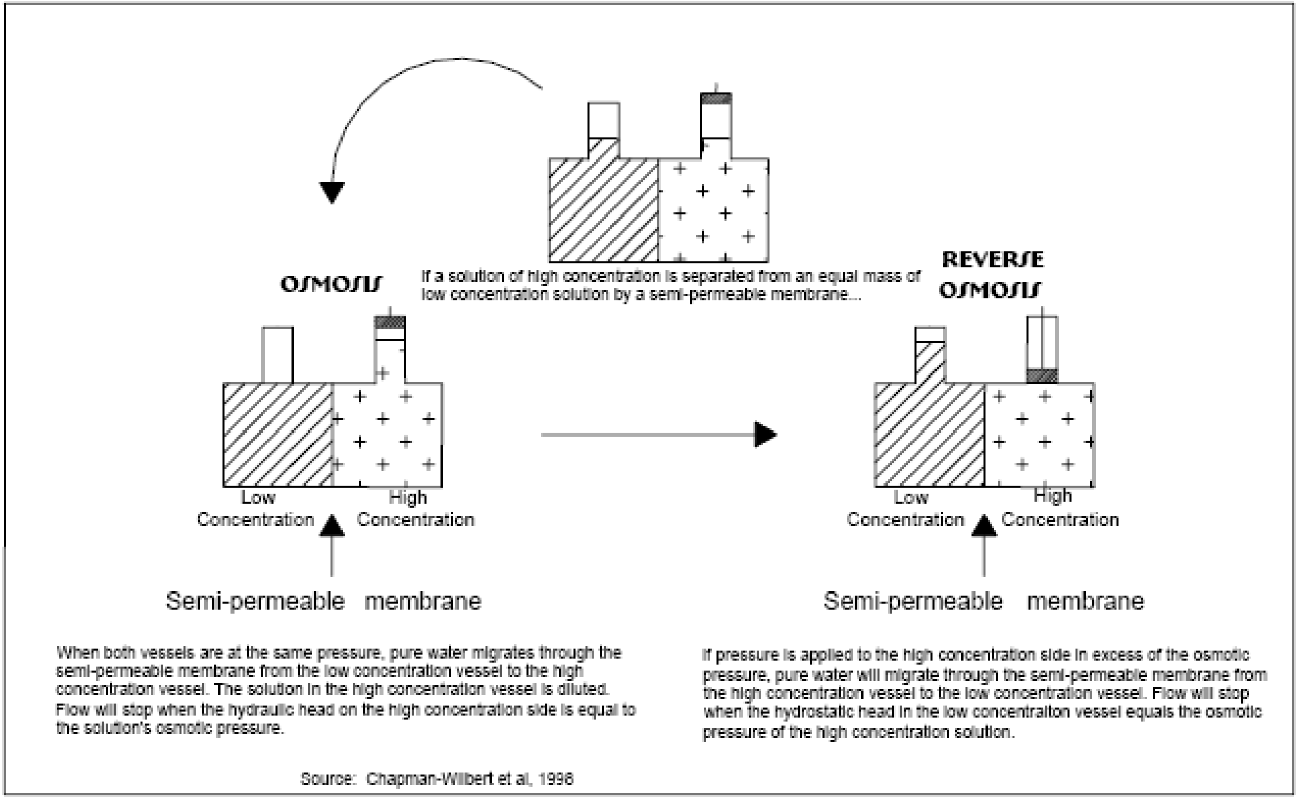
As a portion of the water passes through the membrane, the remaining feed water increases in salt content.

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

Osmotic Pressure

The osmotic pressure, P_{osm}, of a solution can be determined experimentally by measuring the concentration of dissolved salts in solution:

$$P_{osm} = 1.19(T + 273) * \sum(m_i) \qquad (1)$$

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.

Salinity [g/lt]	Molarity (≈NaCl) [mol/lt]	P @ T=25°C ≈ [atm]
5	0.086	4
10	0.172	8
35	0.603	29
50	0.862	42
70	1.207	59

*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:

$$Q_W = (\Delta\Pi - \Delta P_{osm}) * K_w * \frac{S}{d} \qquad (2)$$

Where

Q_w:	rate of water flow through the membrane
ΔP:	hydraulic pressure differential across the membrane
ΔP_{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

$$Q_W = (NDP) * A \qquad (3)$$

Where

Qw: 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

$$NDP = P_F + \Pi_P - \Pi_F - P_P$$

Salt Transport (1)

The rate of salt through the membrane is defined by

$$Q_S = \Delta C * K_S * \frac{S}{d} \qquad (4)$$

Where

Q_s:	flow rate of salt through the membrane
ΔC:	salt concentration differential across the membrane
Ks:	membrane permeability coefficient for salt
S:	membrane area
d:	membrane thickness

Salt Transport (2)

The above equation could be simplified by

$$Q_S = B * (\Delta C) \qquad (5)$$

Where

Q_s:	flow rate of salt through the membrane
ΔC:	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:

$$C_p = \frac{Q_S}{Q_W} \tag{6}$$

Where

Q_s: flow rate of salt through the membrane

Qw: rate of water flow through the membrane

The Salt passage trough the membrane is

$$SP = 100\,\% * \frac{C_P}{C_{fm}} \tag{7}$$

Where

C_p: salt concentration in the permeate

C_fm: mean salt concentration in feed stream

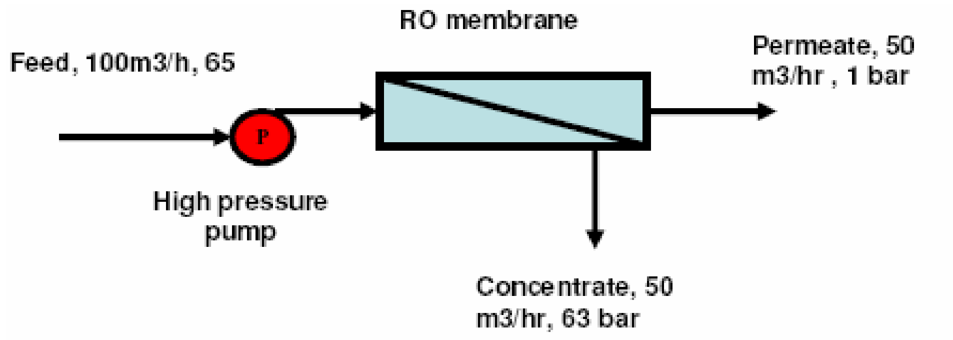
Salt rejection

$$SR = 100\,\% - SP \tag{8}$$

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:

$$R = \frac{Qp}{Qf} * 100\ \%$$

Where

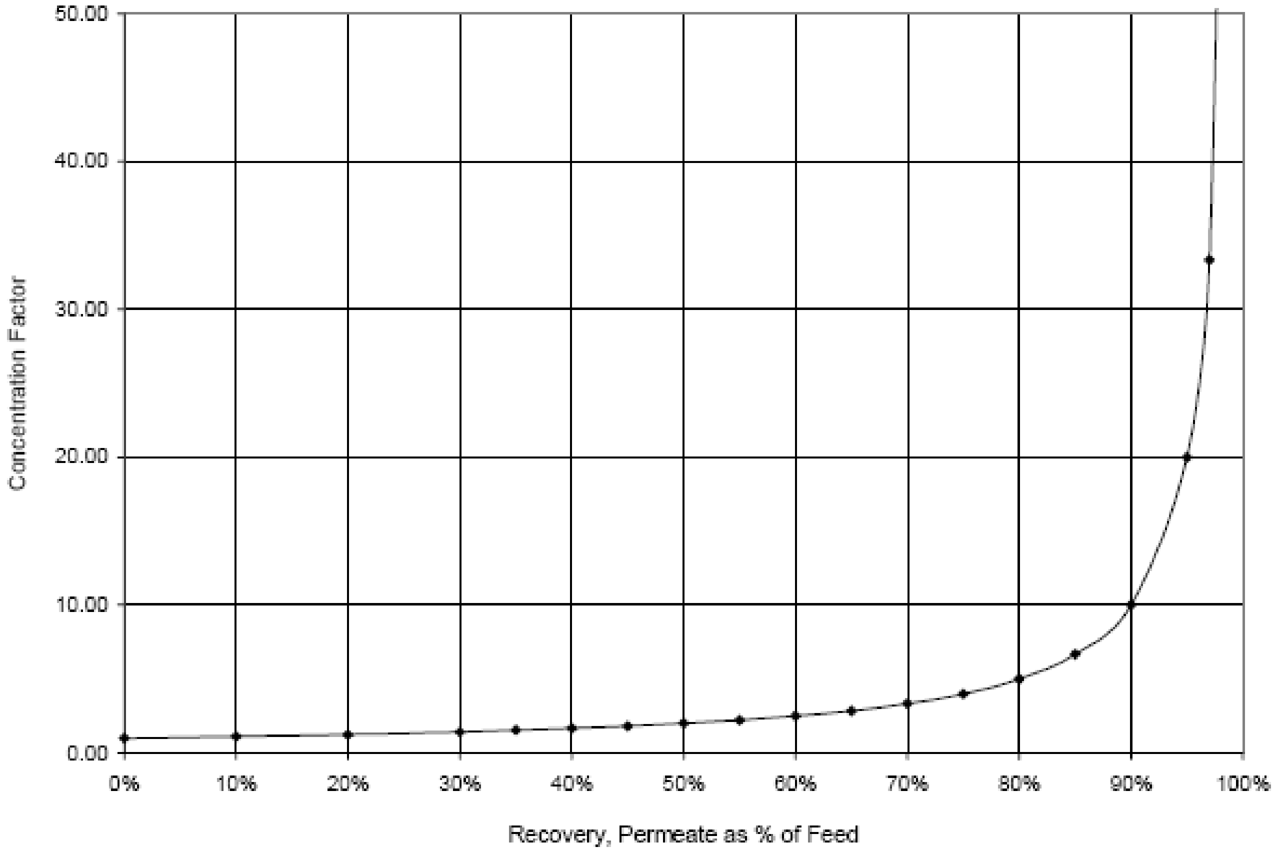
Qp: permeate flow rate

Qf: 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:

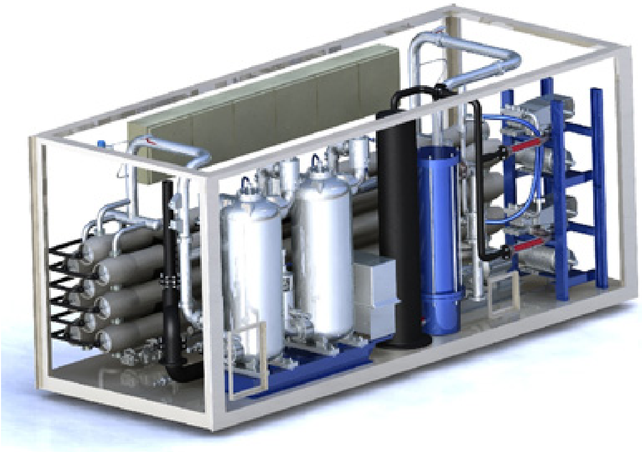
- Pressure
- Temperature
- Recovery
- Feed water salt concentration

Increasing	Permeate flow	Salt passage
Effective pressure	↑	↓
Temperature	↑	↑
Recovery	↓	↑
Feed Salt concentration	↓	↑

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



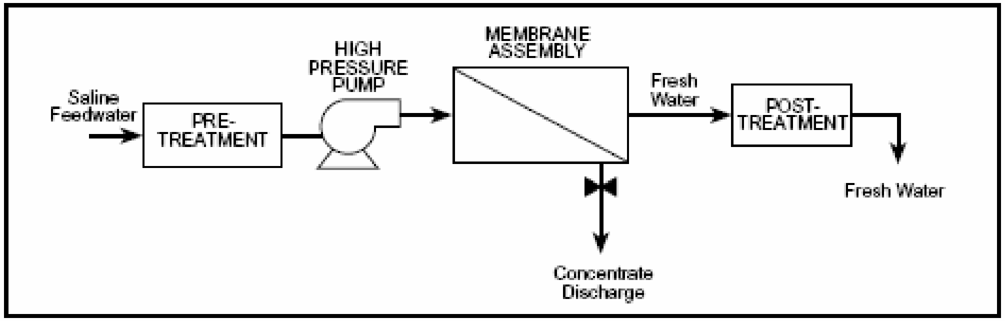
- Instrumentation and control
- Electric system
- Membrane cleaning system

RO Description (2)

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.



RO Description (3)

- **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.

RO Description (4)

- **Post-treatment procedure**
  - Enrichment (Ca, Mg)
  - Stabilization
  - Sterilization

- **Brine disposal (outfall system)**

Brine outfall, Spain

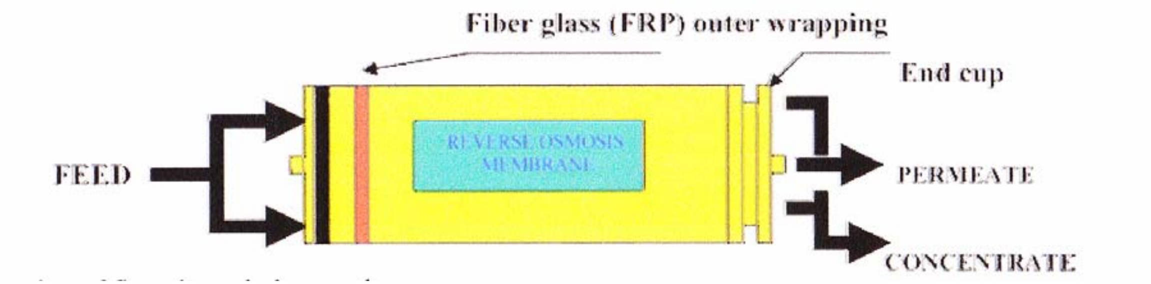
Source: WWF, Spain

Beach well in Spain

Source: WWF, Spain

Reverse Osmosis Membranes

Membrane system



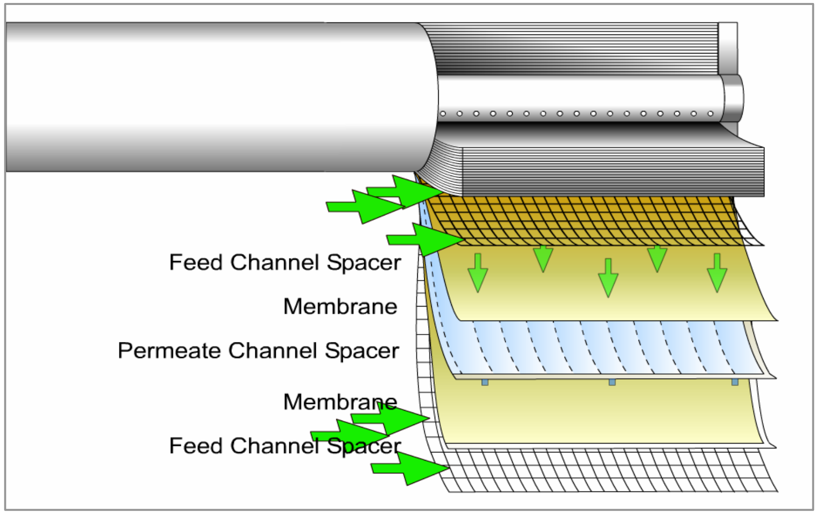
Two types of RO membranes are used commercially. These are:

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

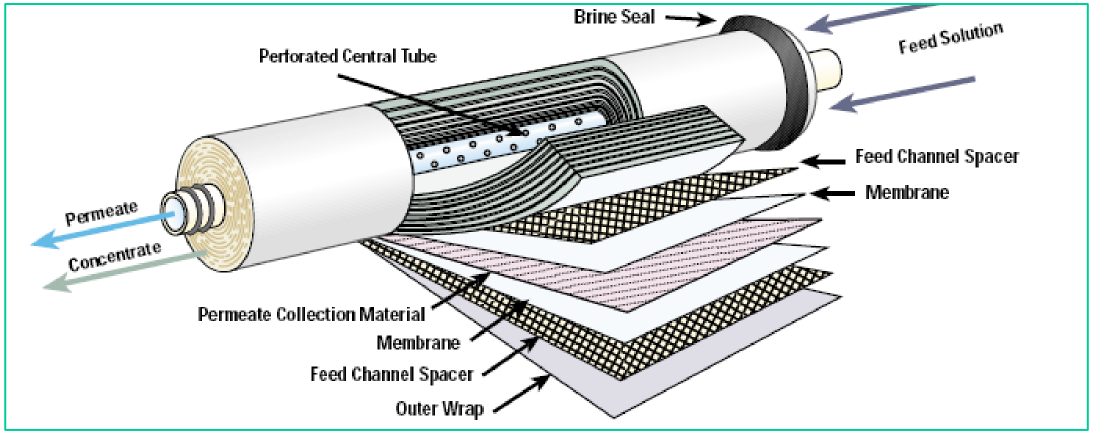
SW and HF membranes are used to desalt both sea water and brackish water.

The choice between the two is based on factors such as cost, feed water quality and product water capacity.

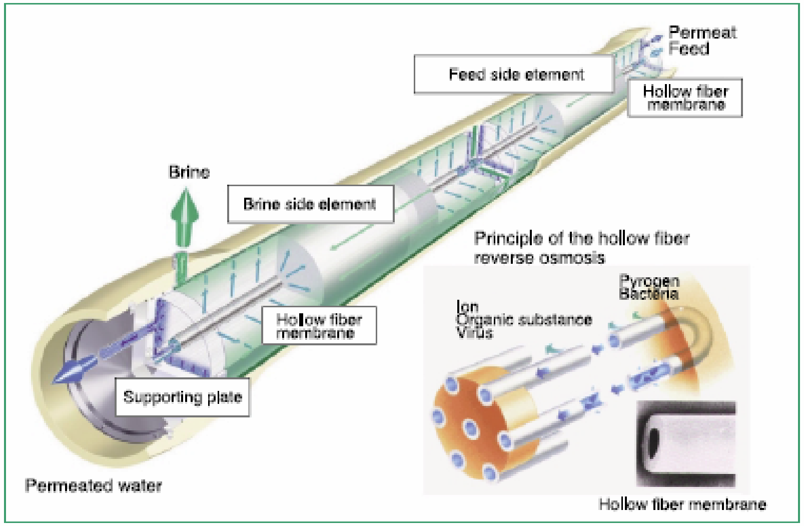
Spiral wound membranes



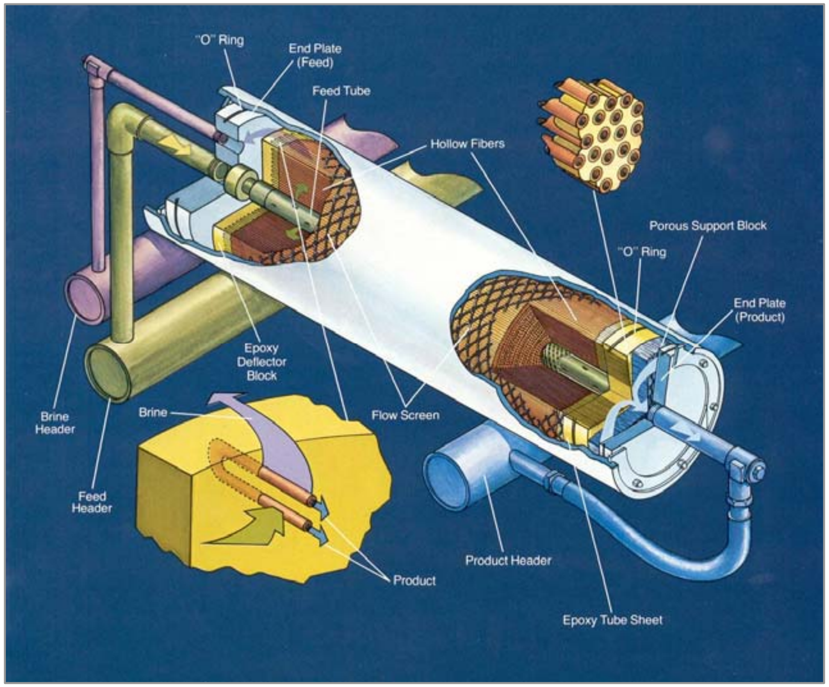
Source: Dow/FilmTec



Hollow fibres module



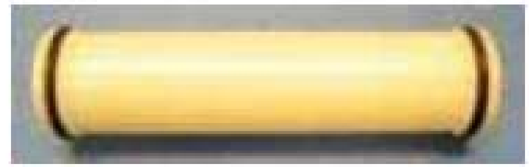
Hollow fiber reverse osmosis membrane module



Source: Dupont

RO Membrane Characteristics

TW30-4040



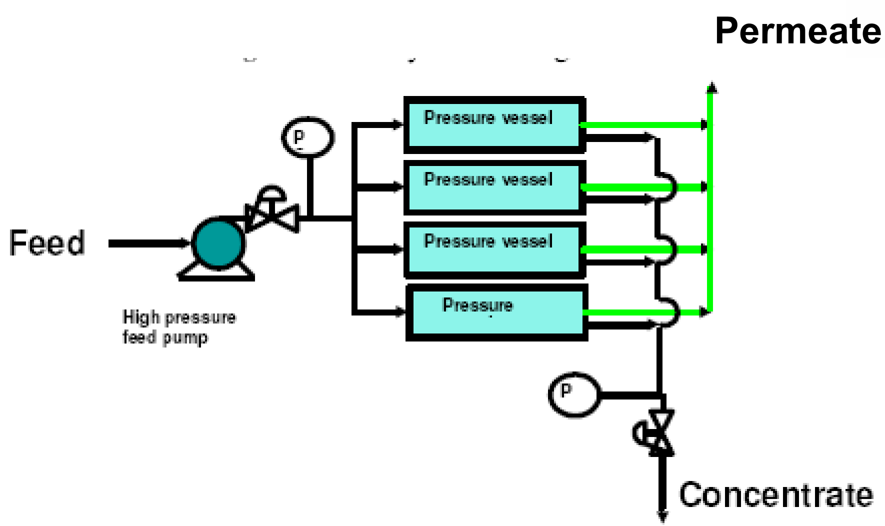
The element nomenclature for FILMTEC elements is for example as follows:

```
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
```

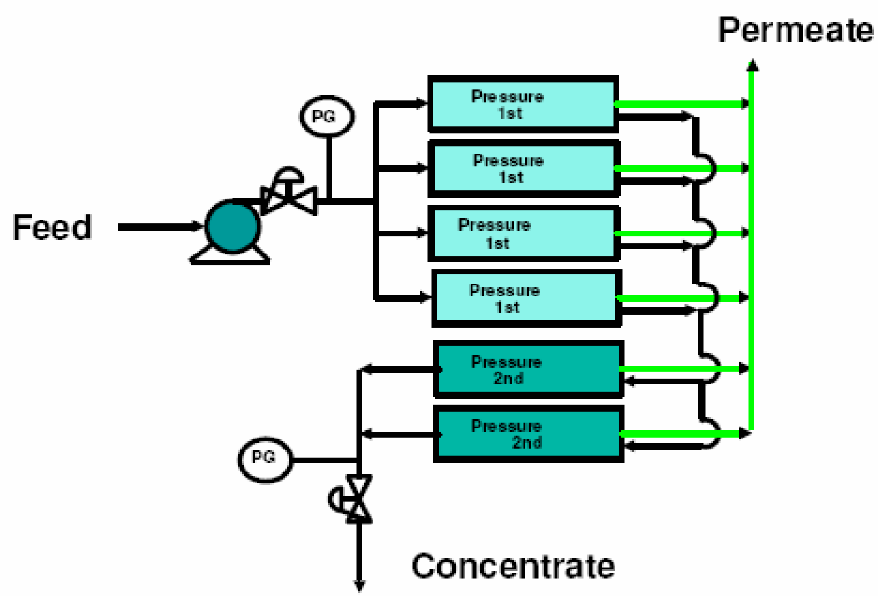
Source: DOW/Filmtec

RO Configurations

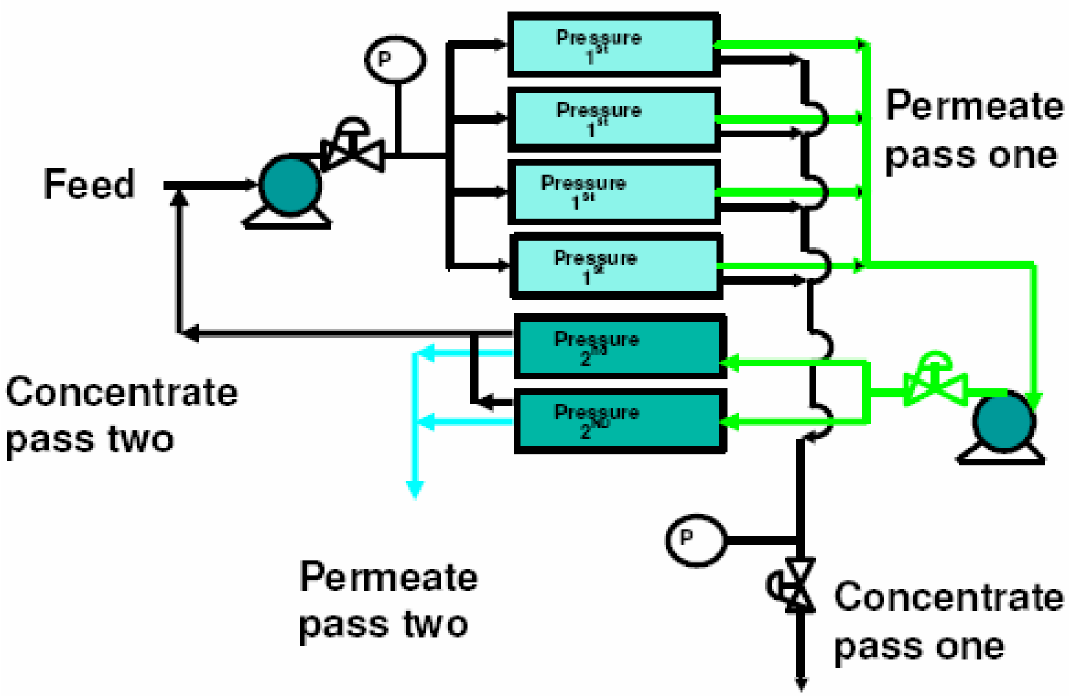
Single array RO system



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 $L/m^2/hr$

For seawater RO: 12-17 $L/m^2/hr$

Most brackish water membranes have an active area of about $37 m^2$, while most seawater membrane elements have an active area of 30 – $34 m^2$.

Translating flux to element projection:

For brackish water RO: 0.93-1.11 m^3/hr

For seawater RO: 0.36-0.51 m^3/hr (for $30 m^2$ active membrane area)
0.41-0.58 m^3/hr (for $34 m^2$ 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

215 / 25 = 8612= ~8600 m^2

8600 / 37m^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 =~ 39 vessels with 6 elements each

RO Membranes

An significant number of Reverse Osmosis membrane manufacturers exit around the world

- Dow/FilmTec (USA)
- Toray (Japan)
- Hydranautics (USA)
- Trisep (USA)
- Koch Membrane Systems (USA)
- Saehan (S. Korea)
- GE Osmonics (USA)

Dow FilmTec (USA) - www.dow.com

GE Osmonics (USA) www.gewater.com

Hydranautics (USA) - www.membranes.com

Toray Japan - www.appliedmembranes.com

RO Membranes

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

Feed source		RO Permeate	Well Water	Surface Supply		Wastewater (Filtered Municipal Effluent) MF[1]	Wastewater (Filtered Municipal Effluent) Conventional	Seawater Well or MF[1]	Seawater Open intake
Feed silt density index		SDI < 1	SDI < 3	SDI < 3	SDI < 5	SDI < 3	SDI < 5	SDI < 3	SDI < 5
Average system flux	gfd	21-25	16-20	13-17	12-16	10-14	8-12	8-12	7-10
	l/m²h	36-43	27-34	22-29	20-27	17-24	14-20	13-20	11-17
Maximum element recovery %		30	19	17	15	14	12	15	13
Active Membrane Area		**Maximum permeate flow rate, gpd (m^3/d)**							
320 ft² elements		9,000 (34)	7,500 (28)	6,500 (25)	5,900 (22)	5,300 (20)	4,700 (18)	6,700 (25)	6,100 (23)
365 ft² elements		10,000 (38)	8,300 (31)	7,200 (27)	6,500 (25)	5,900 (22)	5,200 (20)		
380 ft² elements		10,600 (40)	8,600 (33)	7,500 (28)	6,800 (26)	5,900 (22)	5,200 (20)	7,900 (30)	7,200 (27)
390 ft² elements		10,600 (40)	8,900 (34)	7,700 (29)	7,000 (26)	6,300 (24)	5,500 (21)		
400 ft² elements		11,000 (42)	9,100 (34)	7,900 (30)	7,200 (27)	6,400 (24)	5,700 (22)		
440 ft² elements		12,000 (45)	10,000 (38)	8,700 (33)	7,900 (30)	7,100 (27)	6,300 (24)		
Element type		**Minimum concentrate flow rate[2], gpm (m^3/h)**							
BW elements (365 ft²)		10 (2.3)	13 (3.0)	13 (3.0)	15 (3.4)	16 (3.6)	18 (4.1)		
BW elements (400 ft² and 440 ft²)		10 (2.3)	13 (3.0)	13 (3.0)	15 (3.4)	18 (4.1)	20 (4.6)		
NF elements		10 (2.3)	13 (3.0)	13 (3.0)	15 (3.4)	18 (4.1)	18 (4.1)		
Full-fit elements		25 (5.7)	25 (5.7)	25 (5.7)	25 (5.7)	25 (5.7)	25 (5.7)		
SW elements		10 (2.3)	13 (3.0)	13 (3.0)	15 (3.4)	16 (3.6)	18 (4.1)	13 (3.0)	15 (3.4)
Element type	**Active area ft² (m²)**	**Maximum feed flow rate[2], gpm (m^3/h)**							
BW elements	365 (33.9)	65 (15)	65 (15)	63 (14)	58 (13)	52 (12)	52 (12)		
BW or NF elements	400 (37.2)	75 (17)	75 (17)	73 (17)	67 (15)	61 (14)	61 (14)		
BW elements	440 (40.9)	75 (17)	75 (17)	73 (17)	67 (15)	61 (14)	61 (14)		
Full-fit elements	390 (36.2)	85 (19)	75 (17)	73 (17)	67 (15)	61 (14)	61 (14)		
SW elements	320 (29.7)	65 (15)	65 (15)	63 (14)	58 (13)	52 (12)	52 (12)	63 (14)	56 (13)
SW elements	380 (35.3)	72 (16)	72 (16)	70 (16)	64 (15)	58 (13)	58 (13)	70 (16)	62 (14)

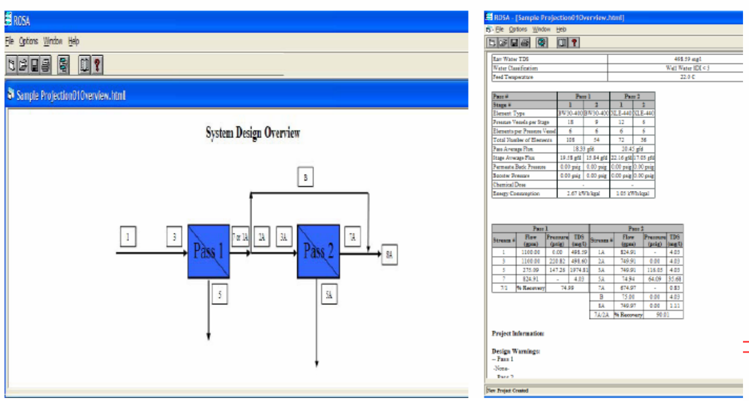
[1] MF: Microfiltration - continuous filtration process using a membrane with pore size of <0.5 micron.

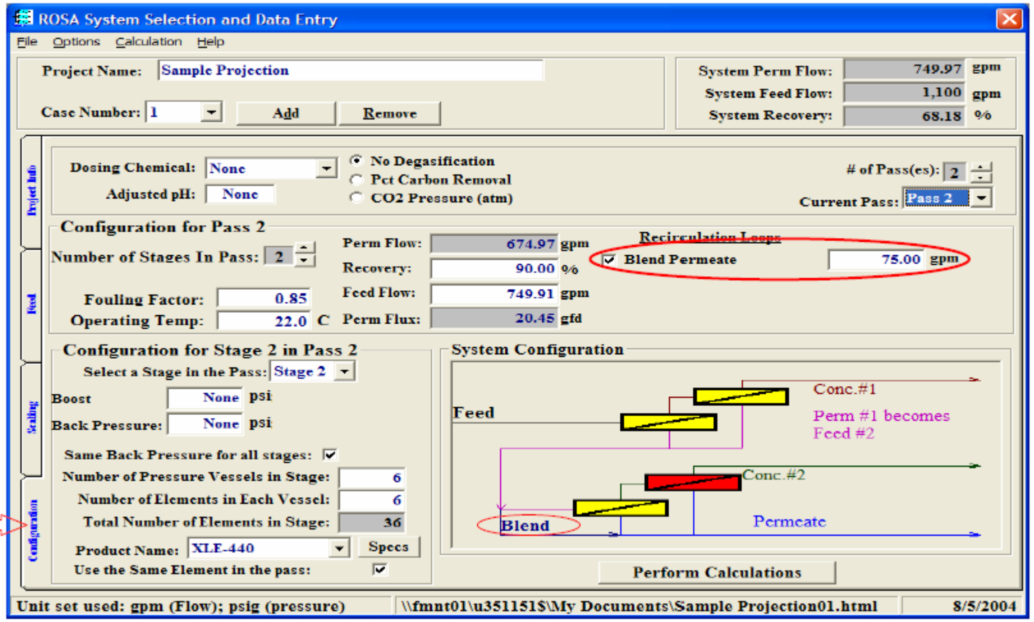
[2] The maximum recommended pressure drop across a single element is 15 psid (1bar) or 50 psid (3.5 bar) across multiple elements in a pressure vessel, whichever value is more limiting. We recommend designing at maximum of 80% (12 psid) for any element in a system.

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.

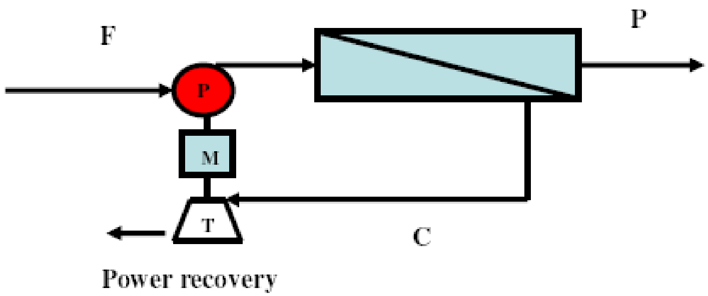
Power consumption of reverse osmosis (RO) desalination process is the lowest among the commercial desalination methods. RO facilities are most economical for desalinating brackish water, and the product water increases in cost as the salt content of the source water increases.

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

Energy Requirements (2)

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/m^3 is quite common in seawater desalination systems.

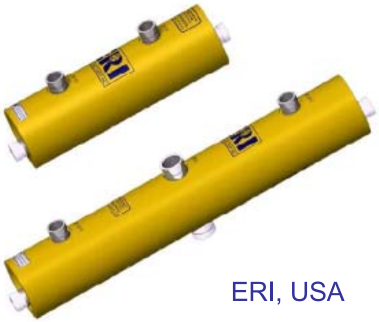


Energy Recovery Devices

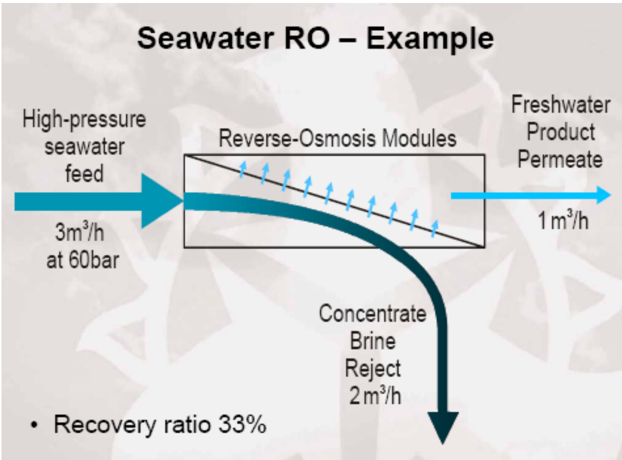
The fraction of power, recovered by the power recovery device, depends on the type and efficiency of the power recovery equipment used. Energy recovery devices connected to the concentrate stream as it leaves the pressure vessel at about 1 to 5 bar less than the applied pressure from the high-pressure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

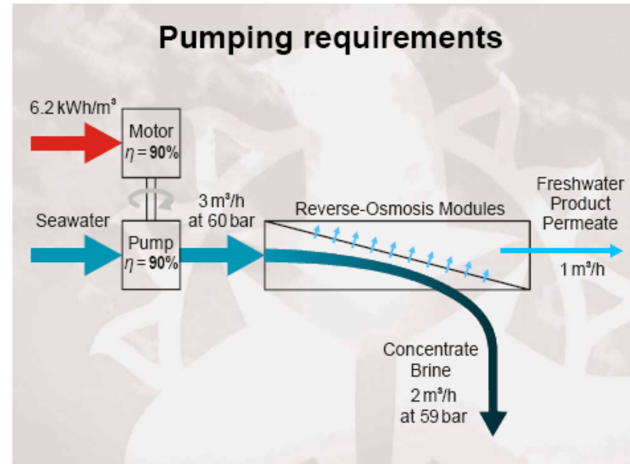
Energy recovery devices are mechanical and generally consist of work or pressure exchangers, turbines, or pumps of some type that can convert the pressure difference to rotating or other types of energy that can be used to reduce the energy needs in the overall process. The most known ERD are:

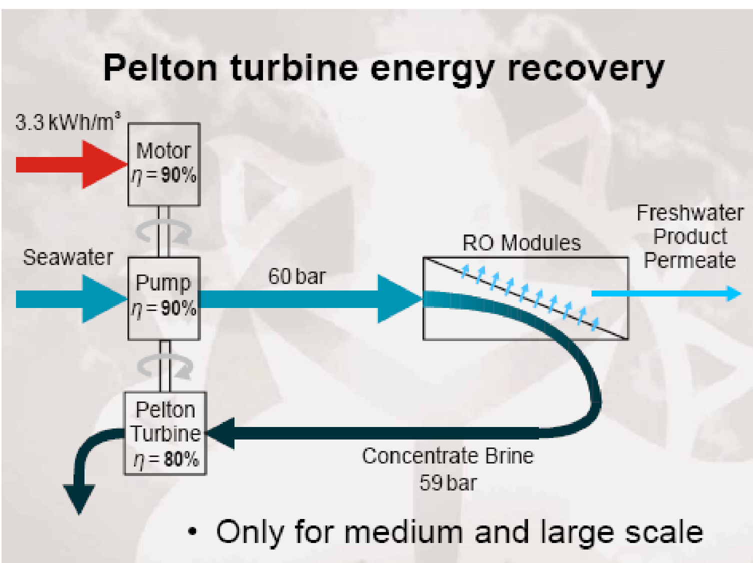
- Pelton wheel
- Pressure Exchanger
- Work Exchanger
- Hydraulic Turbocharger

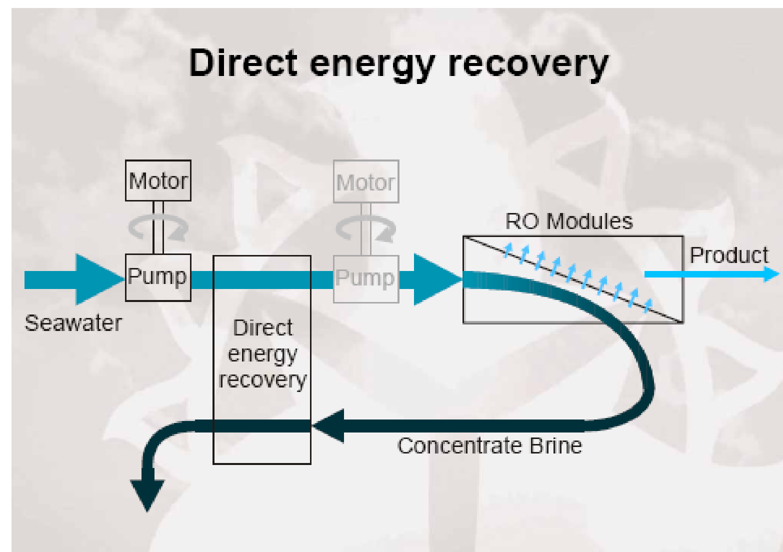


ERI, USA

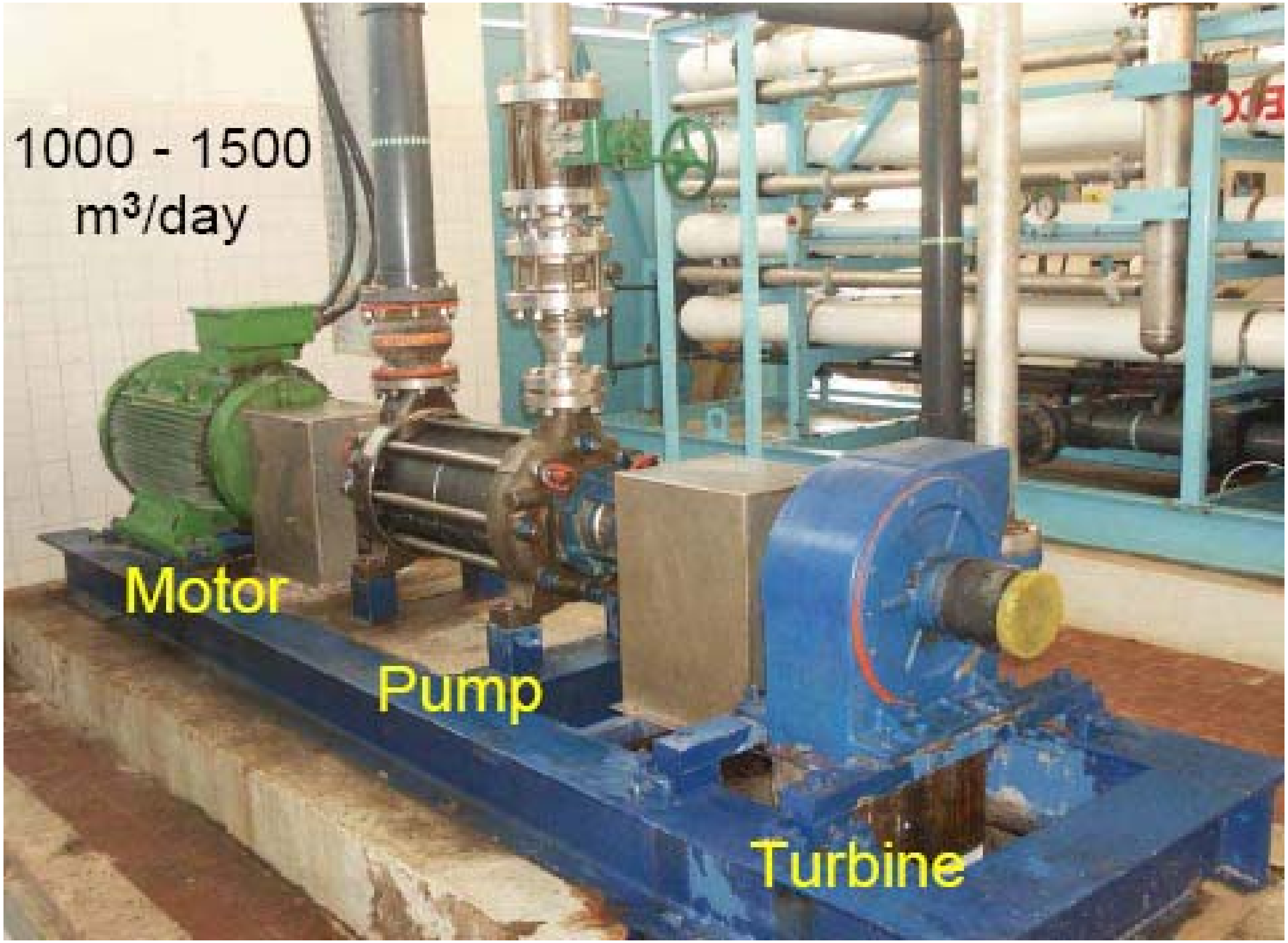




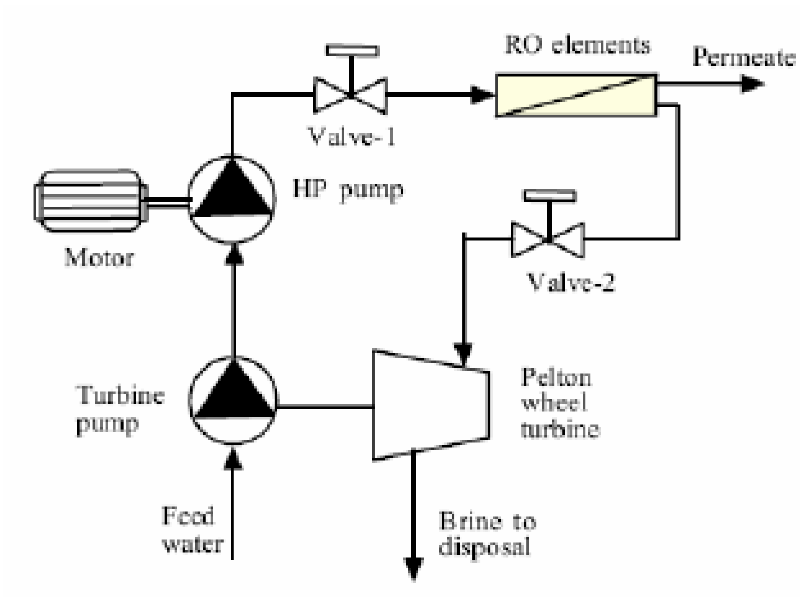


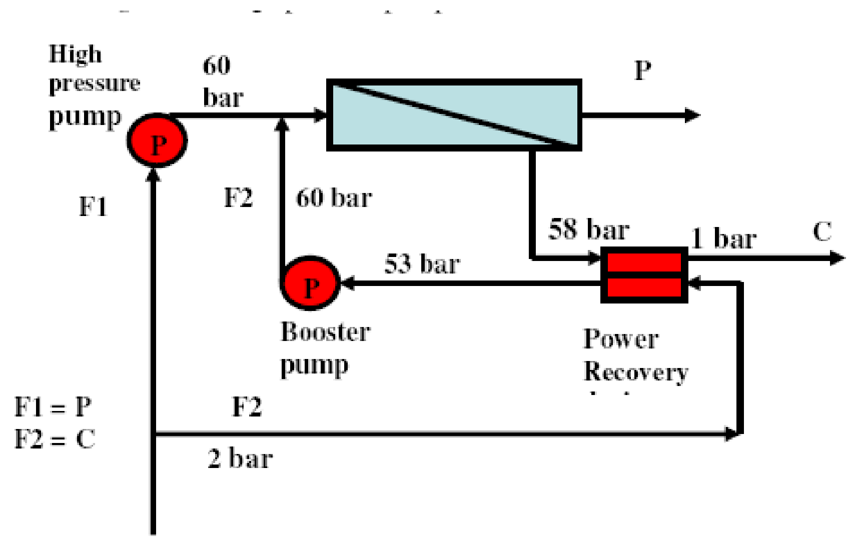


Source: Thomson M. , CREST



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

$$P_{bp} = \frac{\rho * g * h * Qf}{n_p}$$

Where

ρ:	Feed water density, at 25°C, kg/m^3
h:	Manometric height, m
g:	Acceleration due to gravity, 9.81 m/sec^2
Qf:	Feed flow rate, m^3/sec
n_p:	Pump efficiency, %

Energy Requirements Modeling (2)

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

$$P_{HPP} = \frac{P_f * Q_f}{n_p}$$

Where

P_{HPP}:	Power of HPP, kW
Pf:	Feed pressure, N/m^2
Qf:	Feed flow rate, m^3/sec
n_p :	Pump efficiency, %

Energy Requirements Modeling (3)

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

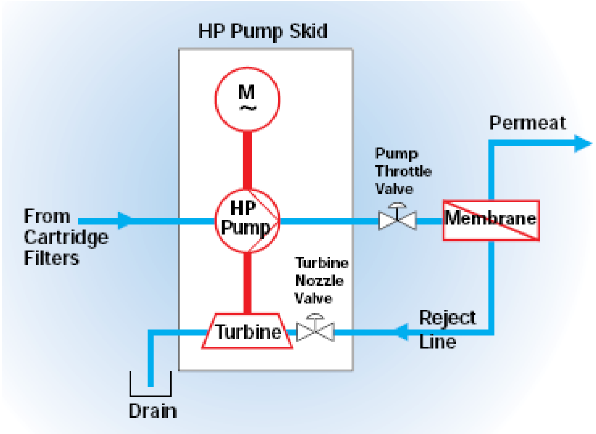
$$ER = \mathrm{Pr}_b * Q_b * n_t$$

Where

P_{rb}: brine pressure, N/m^2

Q_b: brine flow rate, m^3/sec

n_t : turbine efficiency, %



Energy Requirements Modeling (4)

Specific Energy Consumption: The energy consumption per m^3 of water produced

$$Sp.En.Con.(kWh/m3) = \frac{(P_{bp} + P_{HPP} - ER) * 24\,hours}{Q_p}$$

Where

P_{pb}:	booster pump power, kW
P_{HPP}:	high-pressure pump power, kW
ER:	energy recovered, kW
Q_p:	permeate flow rate, m^3/day

Energy Requirements Modeling (5)

Membrane Cleaning pump: the energy required to drive the pump for the flushing procedure after the shutdown of the plant.

$$P_{MFP} = \frac{P * Q}{n_p}$$

Where

P:	pressure, N/m^2
Q:	flow rate, m^3/sec
n_p :	pump efficiency, %

Energy Recovery Example

Typical Plant Example

Train Capacity:	10,000 m³/ day (2.64 MGD)
Product Flow:	417 m³/h (1,836 USGPM)
Conversion:	50%
Membrane configuration:	Single Stage
Req. Membrane pressure:	68 bar (986 PSI)

HP-Pump

Type:	Centrifugal
Flow:	834 m³/h (3,672 USGPM)
Suction Pressure:	2 bar (29 PSI)
Discharge Pressure:	68 bar (986 PSI)
Pump Efficiency:	87%

Energy Recovery Turbine

Type:	RO-350-100-2
Flow:	417 m³/h (1,836 USGPM)
Brine Pressure:	67 bar (972 PSI)
ERT Efficiency:	90%

Electric Motor

Speed:	2,985 rev/min (for 50 Hz application)
Power:	1,300 kW (1,730 HP)
Motor Efficiency:	96.5%

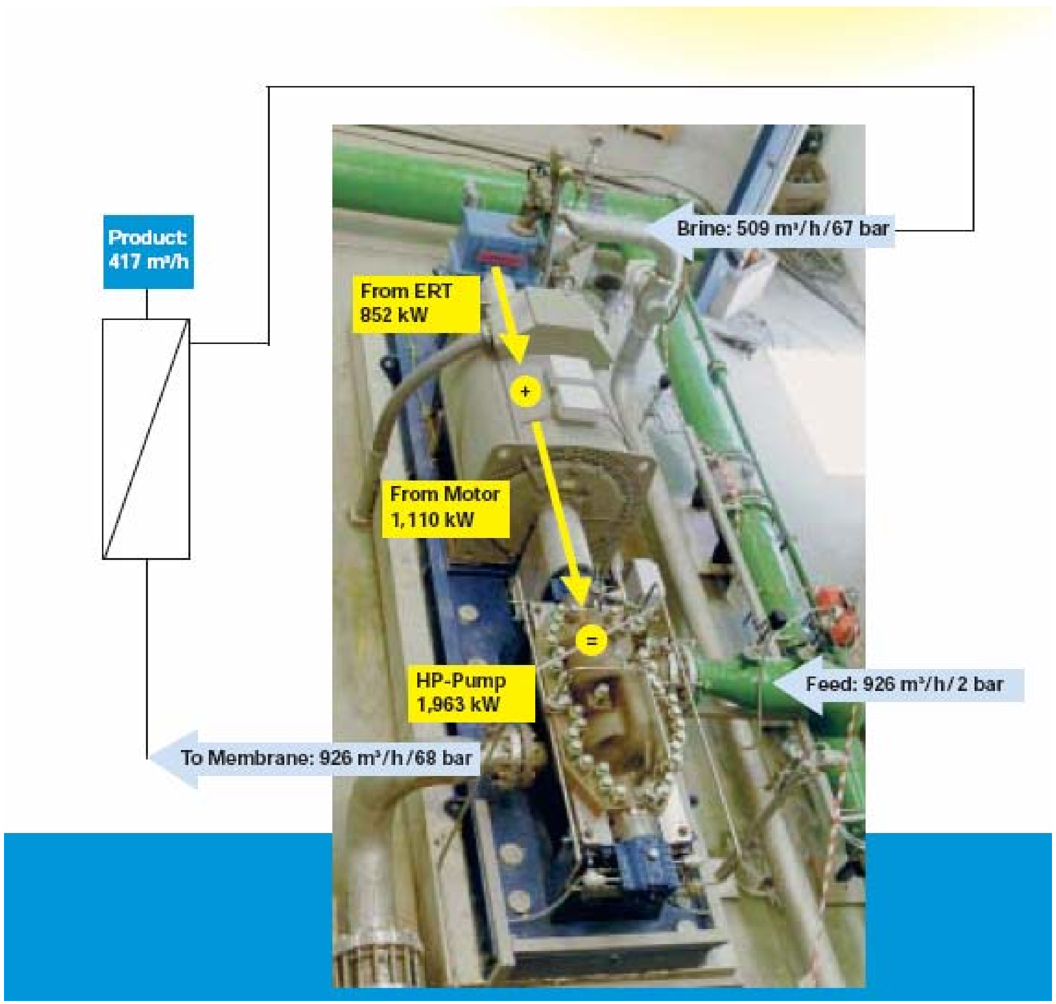
Calculation of Energy Consumption

Required Pump Power = 834 m³/h x (68-2) bar / 0.87 / 36 = 1,757.5 kW (2,356 HP)

Turbine Recovered Energy = 417 m³/h x 67 bar x 0.90 / 36 = 698.5 kW (936 HP)

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

Specific Energy Consumption =
1,059 kW / 0.965 / 417 m³/h =
2.63 kWh/m³ Product


Product 417 m³/h
Brine: 509 m³/h/67 bar
From ERT 852 kW
+
From Motor 1,110 kW
=
HP-Pump 1,963 kW
Feed: 926 m³/h/2 bar
To Membrane: 926 m³/h/68 bar

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 m^3/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 m^3/hr.

Typical RO feed pump power consumption

Location	Feed TDS (mg/l)	Recovery (percent)	Temperature ($^{\circ}$C)	Feed pressure (bars)	Feed pump power (kWh/m^3)	Feed pump type
Jupiter, FL[1] (Phase I)	5,000	75	21	24	1.125	VT
Jupiter, FL[2] (Phase II)	5,000	75	21	[6]14.4/17.2	0.650	VT
Cape Coral, FL Plant 2	1,300	85	28	12.5	0.454	VT
Kill Devil Hills, NC[3]	[3]2,300	75	20	18.2	0.828	VT
Santa Barbara, CA	SSW	40	10-15	60-65	3.5-4.0	HMS
Key West, FL[4]	SWW	30	20-28	55-60	4.0-4.5	VT
Arlington, CA[4]	1,200	77	21	14.5	0.515	VT
Marco Island, FL[5]	• 40,000	75	21	[6]23.1/27.2	1.111	VT

[1] Hydranautics 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™ 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

Summary of Reported First-Year Cost of Produced Water for RO Plants

Facility or Location	US$/kgal (first year)	US$/m³ (first year)	Operational?	Year	Source
Ashkelon, Israel	2.03	0.54	Yes	2002	EDS (2004), Segal (2004), Zhou & Tol (2005)
Ashkelon, Israel	2.00	0.53	Yes	2003	NAS (2004)
Ashkelon, Israel	2.10	0.55	Yes	2004	Wilf & Bartels (2005)
Ashkelon, Israel	2.34	0.62	Yes	2005	Red Herring (2005), Semiat (2006)
Bahamas	5.60	1.48	Yes ?	2003	NAS (2004)
Carlsbad, CA (Poseidon)	2.90	0.77	No	2005	San Diego Daily Transcript (2005)
Dhekelia, Cyprus	4.14	1.09	Yes	1996	Segal (2004)
Dhekelia, Cyprus	5.40	1.43	Yes	2003	NAS (2004)
Eilat, Israel	2.80	0.74	Yes	1997 ?	Wilf & Bartels (2005)
Hamma, Algiers	3.19	0.84	No	2003	EDS (2004), Segal (2004)
Larnaca, Cyprus	2.84	0.75	Yes	2000	Segal (2004)
Larnaca, Cyprus	3.20	0.85	Yes	2003	NAS (2004)
Larnaca, Cyprus	3.23	0.85	Yes	2001 ?	Wilf & Bartels (2005)
Moss Landing, CA (Cal Am)	4.75[1]	1.28[1]	No	2005	MPWMD (2005b)
Moss Landing, CA (Poseidon)	3.63	0.96	No	2005	MPWMD (2005b)
Perth, Australia	3.49	0.92	No	2005	Water Technology (2006)
Singapore	1.75	0.46	Yes	2002	Segal (2004)
Singapore	1.70	0.45	Yes	2003	NAS (2004)
Sydney, Australia	4.21[2]	1.11[2]			
Tampa Bay, FL	Four bids from 1.75 to 2.18	0.46 to 0.58	No	1999	Semiat (2000)
Tampa Bay, FL	2.10	0.55	No	2003	Segal (2004)
Tampa Bay, FL	2.18	0.58	No	2003 ?	Wilf & Bartels (2005)
Tampa Bay, FL	2.49	0.66	No	?	Arroyo (2004)
Trinidad	2.77	0.73	Yes	?	Segal (2004)
Trinidad	2.80	0.74	Yes	2003	NAS (2004)

Source: Pacific Institute, 2006

RO main advantages

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)

Source: ERI

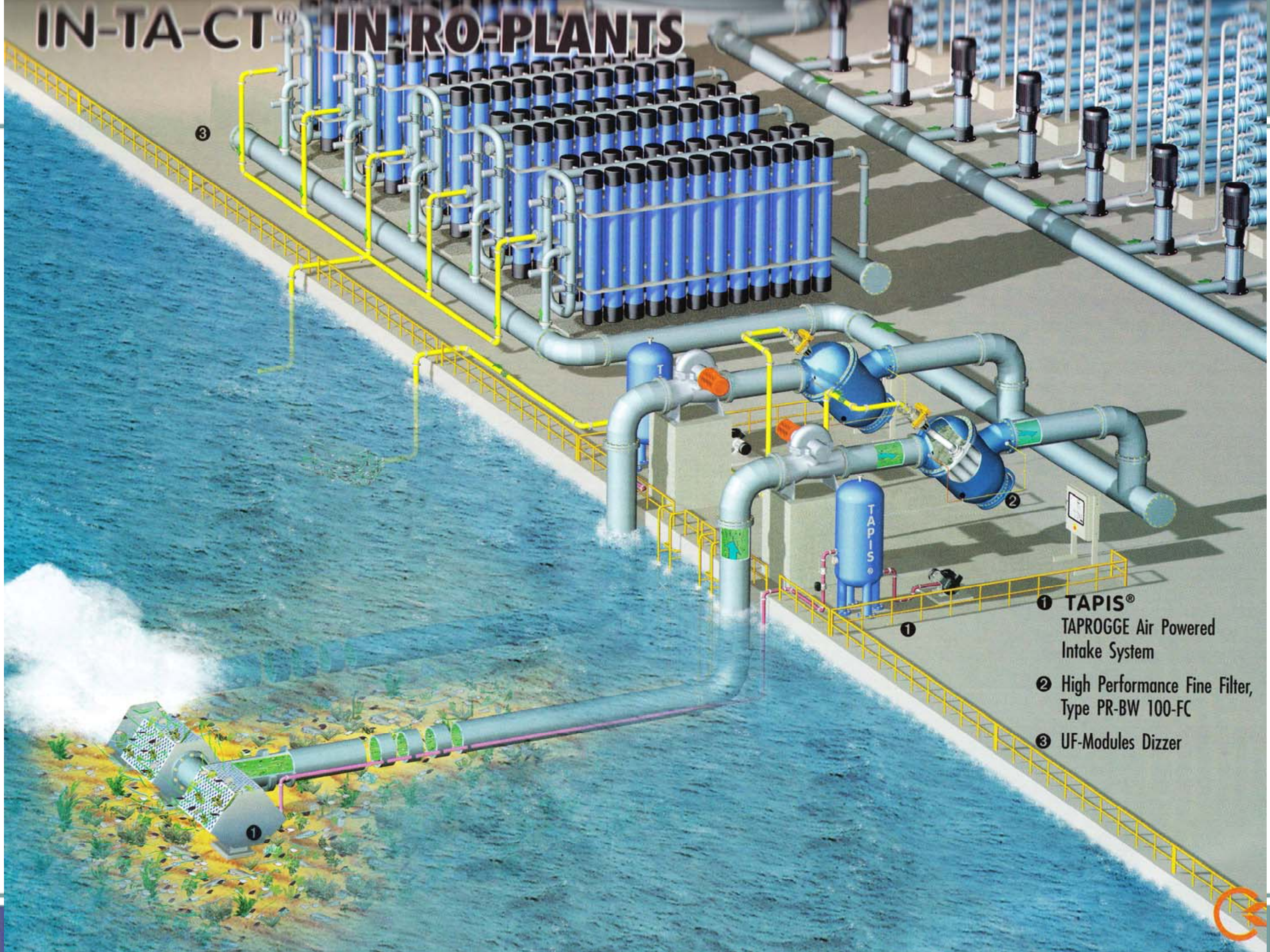
Source: ERI

Source: ERI

Source: CRES

Source: ERI

IN-TA-CT® IN RO-PLANTS



❶ **TAPIS®**
TAPROGGE Air Powered Intake System

❷ High Performance Fine Filter, Type PR-BW 100-FC

❸ UF-Modules Dizzer

Gela site RO site, Sicily

RO units (15000 m^3/d)

RO plant in Giglio Island (Italy)

•Capacity: 1800m³/d;

•Desalinated ater 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/m^3 for seawater RO (with energy recovery) plants has been reported.

CRES RO plant (1)

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 m3/day

$$R = \frac{Qp}{Qf} * 100\,\%$$

P_{BP} =0.294 kW

$$P_{bp} = \frac{\rho * g * h * Q_f}{n_p} = \frac{1.026 * 9.81 * 85 * (0.99 / 3600)}{0.8} = 0.294\,kW$$

CRES RO plant (2)

P_{HPP} = 1.7 kW

P_T =1.7 + 0.294 = 2 kW

$$P_{HPP} = \frac{P_f * Q_f}{n_p} = \frac{53 * (0.99 / 36)}{0.85} = 1.7 kW$$

Sp.En. Consumption = 2 kW * 24/3.1= 15.4 kWh/m^3