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INTERNATIONAL OVERVIEW OF SEAWATER DESALINATION PLANTS BY REVERSE OSMOSIS TECHNOLOGY

Written by:

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ABSTRACT

In a world faced with increased urbanization, population growth, climate change and degradation of water supplies, the importance of a reliable source of technology to provide fresh water emphasizes the importance of seawater desalination.

Over the years a variety of seawater desalination methods have been developed throughout the world. The most common technologies available for desalination around the world are membrane reverse osmosis (RO), thermal distillation (TD) and electrodialysis (ED).

In this thesis, thermal distillation and membrane technologies are described. Thermal distillation is a process that boiling of saline water with condensation and recovery of the vapors. For many years distillation was the predominant process for the treatment of seawater. In the last two decades, due to the membrane technology improvements, seawater desalination by reverse osmosis is now considered a viable alternative technology for production of potable water on a large scale, membrane plants have captured an increasing share of the seawater desalination market. As compared to other technologies, it has low energy consumption, low costs and easier to operate.

5 SWRO plants around the world with different production capacity, membrane types and process designs are described. These plants have similar process designs, including pretreatment, reverse osmosis and post-treatment processes. However, they are very different in the details of the design, including conventional or UF/MF method for pretreatment, double or triple pass system for reverse osmosis, the selection of reverse osmosis membrane and discharge of concentrated water. There are many different kinds of combinations for a SWRO plant. This is determined by many factors. But no matter which one we choose, the aim is to spend less energy consumption to produce fresh water as much as possible from seawater.

Reverse osmosis membranes will be dominant technology for seawater desalination in the future. The paper will give the valued customers an insight about how does the SWRO plant work and how far the trend of the reverse osmosis technologies has gone in the seawater desalination market.

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INTRODUCTION

Water is an essential element for the survival of all living organisms. Depending on the concentration of total dissolved solids (TDS), water on our planet can be divided into four categories: fresh water, brackish water, saline water and brine. Water covers 70.9% of the earth surface, 97% of the Earth's water is found in oceans, only 3% of the Earth's water is fresh water. However, about 69% of the freshwater is frozen in glaciers and icecaps. Most of the remaining is underground and only 0.3% of fresh water is readily available to us.

The TDS level of seawater ranges from 3000 mg/L to 4000 mg/L. It is so polluted that it is impossible to be used by humans directly other than flushing toilets. You will die if you drink more than a few liters seawater, this is because the water in cell will flow from intracellular into extracellular through the cell membrane, leading to cell dehydration and death. This situation has existed for millions of years, and evolution has made it possible for only 2 types of mammals to exist and filter out most of these toxins from seawater by a process which is used in all living cells called OSMOSIS

Fresh water is a very important resource for the whole ecosystem. The term is used to describe the water with less than 500 ppm of total dissolved salts. Water makes up almost 60% of an adult's total body weight. Many scientists believe that water is one of the powerful solvents available. Thereby it is used in our body to carry most nutrients, salts and minerals in and out of us in a finely tuned balance. Water also plays an important role in the regulation of our body temperature.

Demand for fresh water is rising due to a lot of factors including world population growth, industrial development, water pollution, rapid urbanization, increased farming and climate change. However, the total quantity of fresh water is very small, and the water resources have an uneven distribution in spatial and geographical. The world is facing a severe shortage of fresh water.

Awareness of growing water scarcity has led to a higher interest in seawater desalination, which has been considered the most practical method to solve the water shortage problem. Thermal distillation is the oldest method for seawater desalination. It is based on evaporating water and collecting the condensate. However, energy consumption is a very serious problem due to phase-change in this process.

A great discovery was made only 70 years ago - by reversing the osmosis process, man can make crystal clear, fresh water from seawater by a process called REVERSE OSMOSIS. RO technological process was used in desalination commercially in the early 1960s. There has been a rapid increase in the number of SWRO plants around the globe due to higher efficiency, lower capital and operating cost, simpler installation process, and lower energy consumption. It is beginning to dominate the current and future desalination markets.

The purpose of the thesis is to take a closer look at the various RO membrane seawater desalination plants worldwide, and utilizes case studies to describe different designs of seawater desalination plants. Chapter 1 describes various methods and technologies used worldwide to separate salt from water. Chapter 2 focus on the reverse osmosis membranes. Chapter 3 describes a typically design of seawater reverse osmosis desalination plant, including pretreatment, RO process and post-treatment process. 5 SWRO desalination plants around the world are described in Chapter 4, and the discussion and conclusion are contained in Chapter 5.

CHAPTER 1

DESALINATION METHODS AND TECHNOLOGY

Desalination is a process that removes salts and other dissolved minerals from seawater, brackish water and treated wastewater. In generally, seawater is desalinated in order to produce fresh water that is suitable for human consumption or irrigation, in seawater desalination process, the salinity of seawater of more than 35000 parts per million (ppm) is reduced to a satisfactory level of less than 500 ppm, which is called fresh water (Dore 2005). Desalination processes also remove other contaminants from water, such as dissolved minerals (e.g., calcium, magnesium), heavy metals (e.g., copper, zinc), dissolved organic matter, pathogens (bacteria and viruses) and known carcinogens (cancer causing agents) (SFBCDC 2005).

There are more than 15000 desalination plants operating around the world. It is predicted by Veolia Environment that the reverse osmosis's market share will climb to 70% (compared with 20% for thermal desalination and 10% for other methods) by 2020.

Although there are a number of methods and technologies available to desalt water, all of them work towards the common aim of producing a stable supply of potable water. The most prevalent desalination methods worldwide are thermal methods (involve boiling saline water and collecting the purified vapor) and membrane processes (utilization of a membrane to create two zones of varying concentrations so as to turn out fresh water). The thermal processes include multi-stage flash distillation (MSF), multiple-effect distillation (MED) and vapor compression distillation (VCD). The membrane processes consists of electrodialysis (ED) and reverse osmosis (RO) (Khawaji, Kutubkhanah et al. 2008).

1.1 Thermal Processes

Thermal desalination is the oldest and most commonly used method of desalination. It is generally called distillation. Approximately more than 50% the world's desalted water is produced using thermal processes, the basic process is to heat the water to boiling point so that the maximum amount of water vapor is produced, and then condensing the water vapor to form fresh water. All distillation methods are based on a similar principle, the dissolved salts and other minerals or impurities have the higher boiling point than water, so the water starts boiling, while the salt and the impurities remain in the desalination chamber. Thermal processes are used primarily in Middle Eastern countries that have a plentiful supply of relatively cheap oil for fuel to heat the source water (SFBCDC 2005). Two forms of thermal technology are commonly used to desalt source water: multi-stage flash and multi-effect distillation. A third thermal method, vapor compression, is not widely used.

Multi-Stage Flash Distillation (MSF): In the multi-stage flash distillation process, the saline water is heated in the brine heater by low pressure steam, then the heated saline water flows into the flash chambers (stages) which have even lower pressure and temperature. In each stage, as the heated saline water enters, its temperature is above the boiling point at the pressure of the stage, and a small fraction of the brine water boils ("flashes") to steam thereby reducing the temperature until equilibrium is reached. The resulting steam is a little hotter than the feed water in the tube, and condenses into distillate (fresh water) inside the chamber (Saidur, Elcevvadi et al. 2011). Multiple flash distillation process is illustrated in Figure 1.1.

MSF facilities usually operate at maximum design temperature of 90-120ºC. Although by operating the plant at the upper temperature limit increases efficiency in desalination, it also increases the likelihood for unwanted scale build up and accelerated corrosion of metal surfaces.

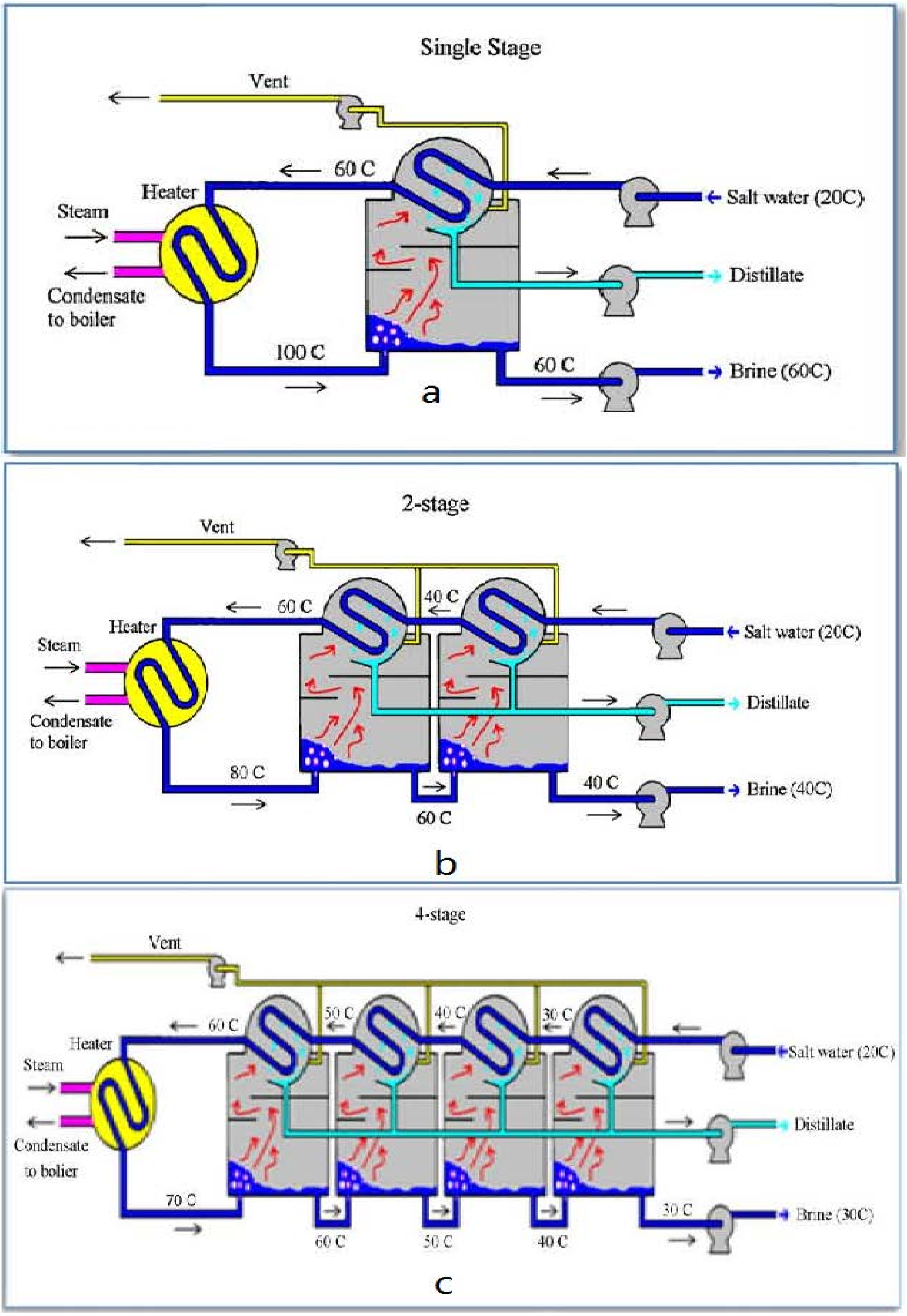


Figure 1.1: (a) 1 stage flash distillation (b) 2 stage flash distillation and (c) 4 stage flash distillation (Saidur, Elcevvadi et al. 2011)

Multiple-Effect Distillation (MED): The multi-effect distillation is a similar process to the MSF distillation. It takes place in a series of chambers (effects) and uses the principle of decreasing the ambient pressure in each successive chamber as the temperature declines. This enables the seawater to undergo multiple boiling without additional energy being supplied after the first chamber. In MED units, heated steam and/or vapour from source water is directed inside a series of tubes where the heat is transferred to the tubes and then to a thin layer of source water that flows over the outside of the heated tube (SFBCDC 2005). The energy used to evaporate the saline water is from the steam inside the tube. The seawater in the first effect is converted to vapour, which is fed to the next tube where it condenses to fresh water product, while heating that tube to evaporate a portion of the remaining seawater (Buros 2000). This process is illustrated in Figure 1.2.

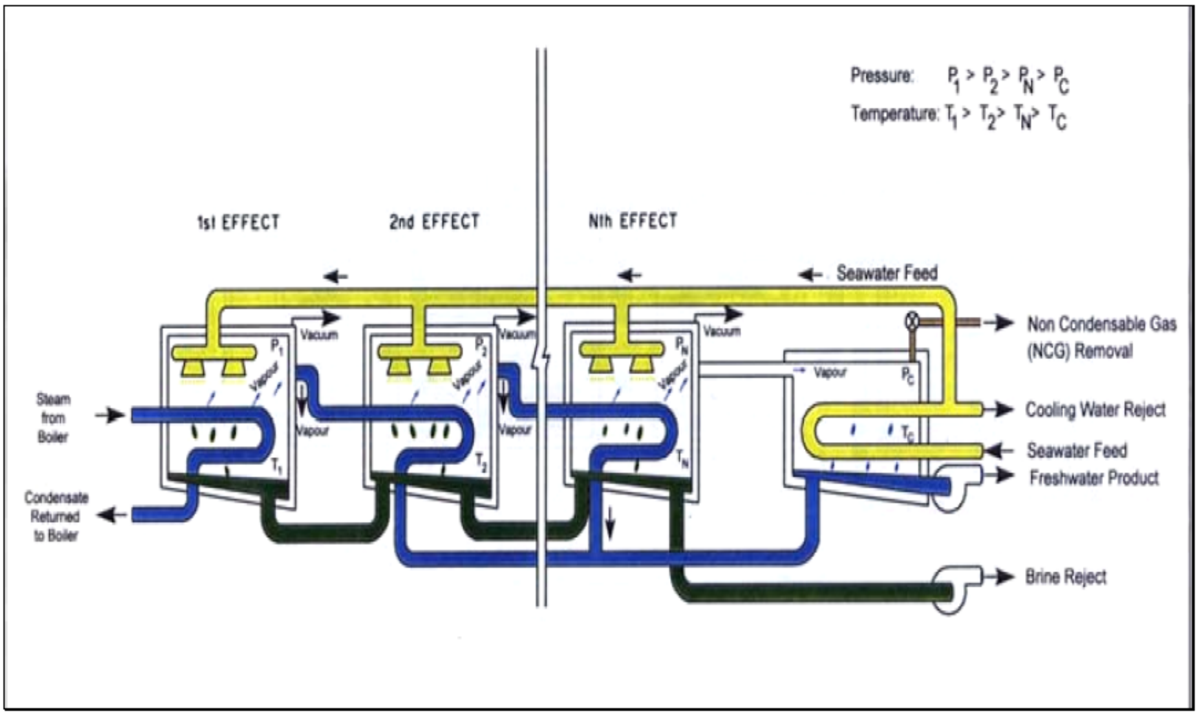


Figure 1.2: Typically illustration of the MED process (Land & Water Australia 2002)

Vapor Compression Distillation (VCD): This process is commonly utilized by small sized (less than 100 m^3 per day) desalination facilities. It differs from the above distillation methods in that the heat energy used for evaporating the source water comes from the compression of vapor by mechanical means rather than direct heat as a source of thermal energy. Compression, which produces the heat, is created by an electrical or diesel powered motor.

1.2 Membrane Processes

Membranes are used in two important methods of desalting water: reverse osmosis and electrodialysis. Although each of these methods of desalination uses semi-permeable membranes to separate salt and other contaminants from water, they each use a different approach to separate salt from water. Reverse osmosis relies on high pressure to force water molecules through the membrane leaving the salts and other contaminants behind. In electrodialysis, on the other hand, an electrical current is applied to extract salts and contaminants from saline water, leaving the fresh water behind.

Electrodialysis (ED): Electrodialysis desalination is a process by which electrically charged salt particles are transferred through an ion exchange membrane by an electrical force leaving water molecules on the other side of the membrane. Figure 1.3 shows an electro-dialysis unit. Voltage is applied across a pair of electrodes causing positive charged ions to move towards one electrode (the cathode) and negatively charged ions to move toward the other electrode (the anode). The membranes are placed between the two electrodes forming several cells or compartments. As the source water flows along a passage lined with membranes, electrically charged salts are attracted by either the cathode or anode through the membrane leaving the fresh water behind (Antonia von Gottberg 1998).

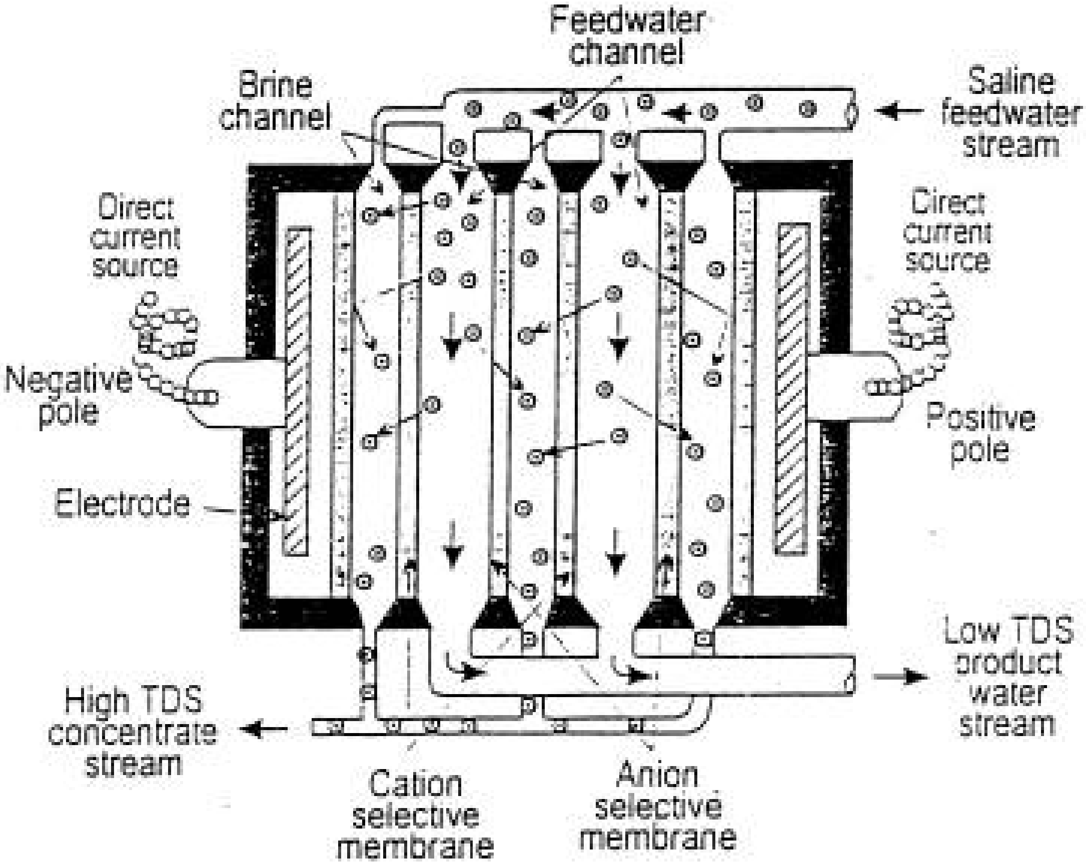


Figure 1.3: Sequence of ion flow in an electro-dialysis unit (Buros 2000)

Reverse osmosis (RO): Fresh water and brine are separated by a semi-permeable membrane in a system. The solvent flows from the fresh side to the brine side under the influence of a concentration gradient if the system is not subject to any external influence. This phenomenon is known as osmosis.

As fresh water passes through the membrane, the levels of the two solutions become unequal. At osmosis equilibrium, there is no flow of water across the membrane. The difference in pressure between each side is called osmotic pressure. A pressure applied to the salt side over the osmotic pressure will force water from the salt side through a membrane to the fresh water side --- this process is called Reverse Osmosis (RO). The reverse osmosis will be described in Chapter 2.

1.3 Cost Comparisons of the Major Desalination Processes

The financial characteristics of seawater desalination plants are usually expressed in three ways: the initial capital costs, operating costs and the eventual cost of producing water, these are the imperative factors relating to the selection of desalination technology as a water treatment process. Table 1.1 shows the costs of the various types of desalination.

Table 1.1: The relative costs to produce a kiloliter of water for the different methods of desalination (AUD= Australian dollar) (Water Corporation. 2003)

Process	Capital investment (AUD/kL/day)	Unit cost of water (AUD/kL)
MSF	1550-3100	1.5-4.2
SWRO	1240-2480	1.1-3.8
MED	1400-2800	1.3-3.3
METC	1380-2780	1.2-3.1
MVC	1390-3880	1.8-5.9

The feed water salinity level, cost of energy and size of desalination facility are the most important factors calculating the costs for desalination listed above.

1.4 Energy Consumption

Energy consumption is an important consideration in desalination applications. Desalination by reverse osmosis membrane is a mechanical process while thermal distillation processes are phase-changing processes, which requires large amounts of thermal energy in order to heat and vaporize the water. Table 1.2 shows a comparison of energy consumption in seawater desalination to produce one cubic meter of water by different methods.

In SWRO plants, recovery of energy contained in the pressurized reject brine is economically feasible, as shown in the table, about 30% of the energy can be recovered with an energy recovery device.

Table 1.2: Energy consumption in seawater desalination (Sackinger 1980)

	Multi-flash	Multi-effect	Vapor compression	RO without energy recovery	RO with energy recovery
Maximum temperature	90 ºC	70 ºC	100 ºC	24-32 ºC	
Energy of vaporization (kWh/m^3)	11.5	12.3	-	-	-
Auxiliaries/compressor (kWh/m^3)	4	1.5	11	Incl.	Incl.
Total power consumption (kWh/m^3)	15.5	13.8	11	7.9-10	4.7-6.6

1.5 Advantages and Disadvantages

The comparison of advantages and disadvantages of thermal processes and membrane processes is presented in Table 1.3.

Table 1.3: The comparison of thermal distillation and membrane technology (Land & Water Australia 2002)

	Advantages	Disadvantages
Thermal method	Usually not require the addition of chemicals or water softening agents A minimal requirement for pre-treatment of the feed water The salinity of the feed water does not have much impact on the process or cost The water produced by thermal distillation is very pure, less than 10 mg/L of total dissolved solids (TDS)	Energy consumption is very high Recovery ratio is low Expensive to build and operate The water is very aggressive, and has a “flat” taste
Membrane method	Energy consumption is low The use of chemicals for maintaining cleaning membrane are low Quick and cheap to build and simple to operate	RO membranes are expensive and have a life expectancy of 2-5 years Pre-treatment processes are required

1.6 Summary

RO plants are cheaper to operate than thermal distillation plants. EDR systems are much expensive than RO system, however as the plant capacity increases, the difference decreases. Typically the costs of EDR systems are approximately 10% higher than RO systems for a high capacity plants. The limitation of applying EDR plants are mainly due to the TDS of the feed water, thereby EDR systems are only economically viable when the TDS of feed water is between 3000mg/L to 12000mg/L (brackish water). Therefore it is not suitable for seawater desalination.

CHAPTER 2

AN INTRODUCTION TO REVERSE OSMOSIS MEMBRANES

2.1 A Brief History of Reverse Osmosis

The first published works on what we now call reverse osmosis dates back to about 1930 (Mcbain 1931). They found that if salty solution was driven on to cellulose nitrate membranes, the concentration of the solution on the other side of the membrane was lower than the feed solution. This result proved that cellulose nitrate membranes could prevent the passage of salts. However, the important discovery was ignored by these early researchers.

Until 1953 the formal research on reverse osmosis processes was done by Reid at the University of Florida (U.S.A). He suggested that reverse osmosis membranes could be used in seawater desalination processing and tested the penetration of a variety of synthetic membranes. After some efforts, in 1957 Reid and Breton discovered that cellulose acetate derivative membrane was suitable as a selectively permeable membrane, but the membranes had very low water flux rates and was unreliable for practical applications. In the early 1960s, the first asymmetric cellulose acetate membrane with higher flux and salts rejection rates was made in United States by Sid Loeb and Srivasa Sourirajan (Sid Loeb and Sourirajan 1961).

2.2 Reverse Osmosis

Osmosis is a natural phenomenon where solvent molecules pass through a semi-permeable membrane from the lower concentration level side to the higher concentration level side. It is a spontaneous process in order to balance the solution concentration on both of sides, which means that no external energy is required for the osmosis process. As shown in Figure 2.1, the two solutions are separated by an ideal semi-permeable membrane, the left one is a solution containing high concentration of dissolved solutes. The other one is a dilute solution or pure water. If the system is not subject to any external influence, the solvent (usually water) would flow from the right side to the left side under the chemical potential gradient.

The standard chemical potential is defined as the free energy change per mole of substance formed, consumed, or transferred from one phase to another in its standard state, the standard state is usually defined as being 1 atmosphere pressure at a particular temperature (normally at 25ºC) and in a certain reference form, usually the pure state of the component (Cheryan 1987).

In thermodynamics, the entropy is defined as the degree of randomness or disorder in a thermodynamics system. For a solution, the higher solute concentration, the higher entropy, because adding dissolved solute in the solvent will result in an increase in the disorder of the system. In other words, the entropy of a higher concentration solution is higher than that of the lower concentration solution. From the Gibbs free energy Equation (1):

$$G=H-TS \qquad (1)$$

$$H=E+PV \qquad (2)$$

Where

G = Gibbs free energy
H = enthalpy
T = absolute temperature
S = entropy
E = internal energy
P = pressure
V = volume

The Gibbs free energy (G) decreases with the increase of entropy (S), a pure solvent has the lowest entropy and the highest Gibbs free energy. Referring to Figure 2.1, the dissolved solute solution in the left side has a lower free energy than the right one, this means that the chemical potential of pure water is higher than when it contains dissolved solute. The water will flow from right side to left.

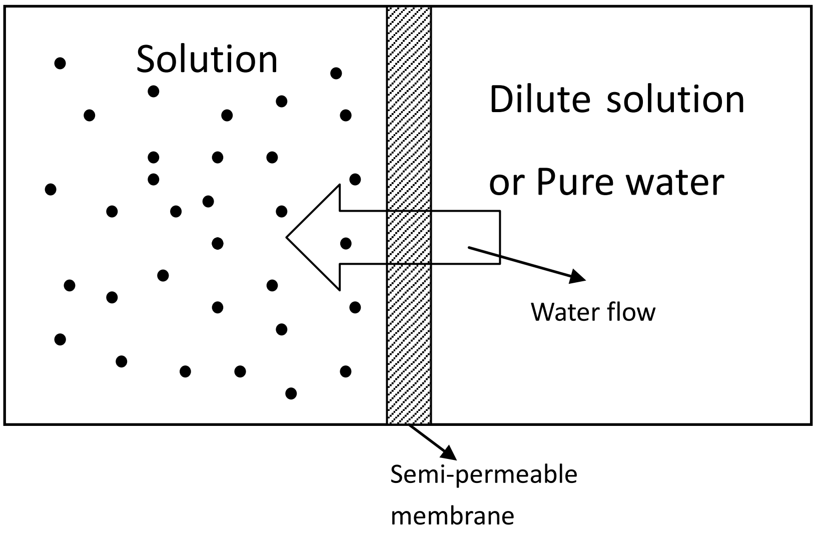


Figure 2.1: Osmosis phenomenon

Reverse osmosis is the process opposite to osmosis. Pressure is used to the high concentration side to force the solvent molecules back to the low concentration side across a semi-permeable membrane. The solute is rejected by the selective membrane and retained in the high solute concentration side. The pure solvent pass to the low solute concentration side through membrane is unimpeded.

2.3 Osmotic Pressure

Osmosis pressure in a membrane system is the pressure on the solution side that will prevent the tendency of water to flow from the pure water to solution side. As mentioned before, water in the lower concentration side will pass through a semi-permeable membrane to the higher concentration side, and is driven by the chemical potential gradient. As shown in the Figure 2.2a (left side), when the chemical potential of side 1 is equal to side 2, the net solvent flux is zero, and the system is at osmotic equilibrium, which is not absolute static of water flow, water molecules still pass through the membrane but the flux is the same in both directions.

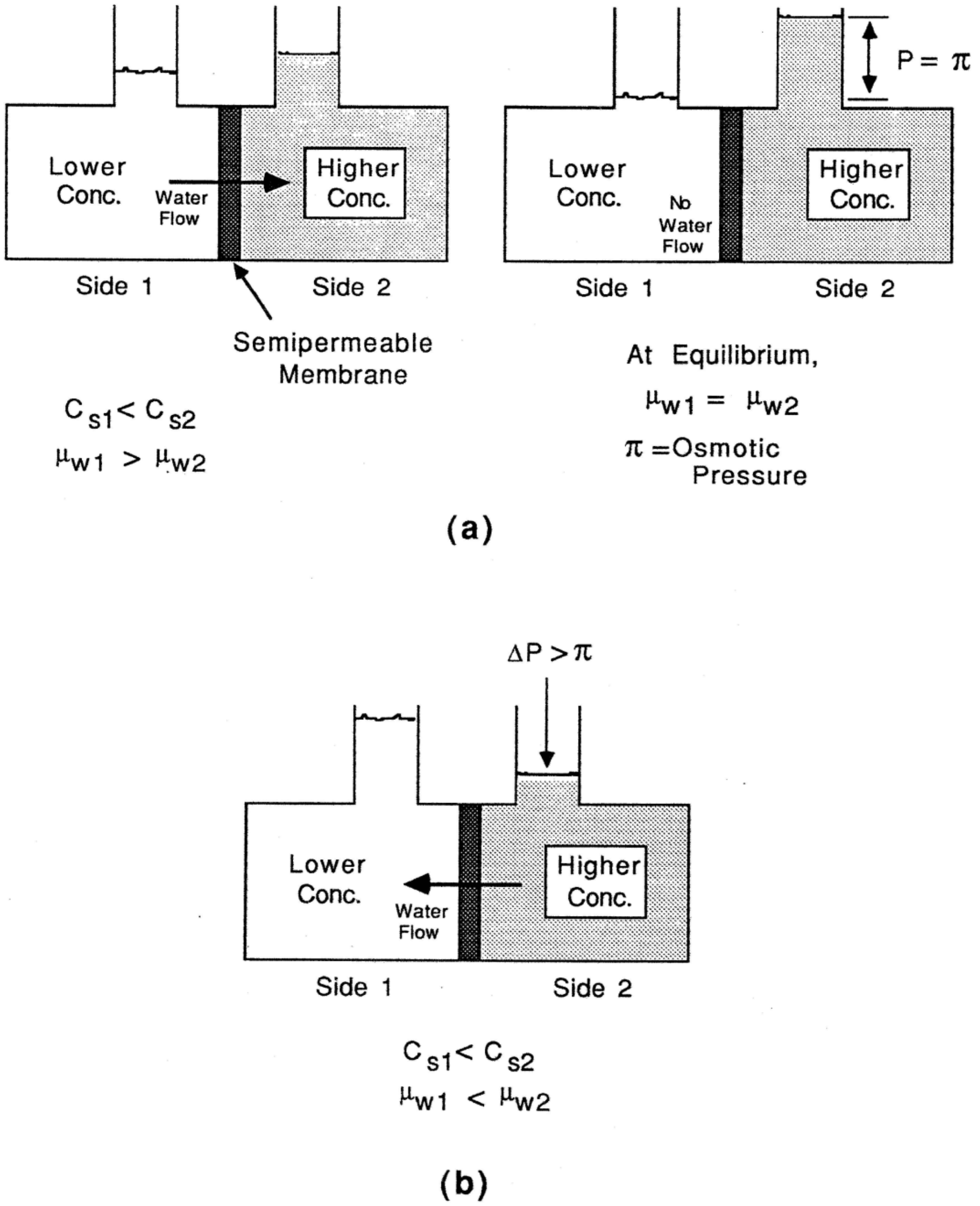


Figure 2.2: Schematic of osmosis and reverse osmosis (Michael E. Williams 2003)

At this point, there is a different hydrostatic pressure in each of sides, this is known as osmotic pressure. If a pressure overcoming the osmotic pressure is used in the higher concentration side, reverse osmosis processing will occur.

However, what is the nature and driving force of the osmotic pressure? This issue has been explored by many scientists, and the most influential view was proposed by Jacobus H. van’t Hoff in 1885. He found that the osmotic pressure of a dilute solution was equal to the vapor pressure of an ideal gas which is converted by solute at the same temperature in the solution. Therefore he considered that the nature and mechanism of the osmotic pressure was similar to any given gas pressure, not just in form. The gas pressure is caused by gas molecules which collide with the wall of a closed container; in solution, the osmotic pressure is also generated by solute molecules which collide with a semi-permeable membrane. Some of the molecules in a solution can pass through a semi-permeable membrane and exist on both sides of the membrane, resulting in no pressure on either side.

Van’t Hoff first proposed a formula for calculating the osmotic pressure of very dilute solutions:

$$\pi V = nRT \qquad (3)$$

$$\text{Or } \pi = cRT \qquad (4)$$

Where
π= osmotic pressure
V= volume of solution
n = amount of substance in moles
c = molar concentration of the solute in moles per liter of the solution
R = ideal gas constant
T = temperature of the solution in the absolute scale

If the solute dissociates or associates, equation (4) must be modified.

$$\pi = icRT = iCRT/M \qquad (5)$$

Where
C = concentration of solutes in g/L of solution
M = molecular weight of solute
i = number of ions for ionized solutes (e.g., i = 1 for sugars, i = 2 for NaCl)
R = ideal gas constant (0.082 atom-L/gmole·K)

From the equation (5), it can be seen that the osmotic pressure is proportional to the concentration of solute and inversely proportional to the molecular weight. Some examples calculated are given in the Table 2.1.

Table 2.1: Calculation of osmotic pressures of some solutions

Calculate the osmotic pressure:
(1) Normal seawater (33000 ppm NaCl) at25 ºC
(2) 3% albumin (M = 65000) by weight at25 ºC

Solution:

(1) Seawater contains a variety of salts, but the calculation will be simplified by assuming that all the salt is sodium chloride (NaCl). From equation (5):

$\pi = iCRT/M = 2 \times 33 \times 0.082 \times 298.2/58.5 = 27.6$ bar

(2) $\pi = iCRT/M = 30 \times 0.082 \times 298.2/65000 = 0.01$ bar

In a reversible thermodynamic process, the minimal energy of seawater desalination by RO membrane can be calculated. Table 2.2 shows the calculation of the minimum energy required to desalination of one cubic meter of seawater.

Table 2.2: Calculation of the energy consumption of desalinating seawater

Calculate the minimal energy which is required to desalting 1 cubic meter seawater by Reverse Osmosis at 25 ºC and normal atmospheric pressure

Solution:

The osmotic pressure of seawater at 25 ºC is:
$\pi = iCRT/M = 2 \times 33 \times 0.082 \times 298.2/58.5 = 27.6$ bar
Or 27.6 kilogram per square centimeter

Assume now that the partition area is one square centimeter. It then has to travel a distance of 10000 meters, in order to push one cubic meter of seawater through the membrane. The work of this travel is:
$W = F \times x = 27.6 \times 1 \times 10000 = 276000$ kg meter / cubic meter
Or 2760000 Joules / cubic meter, since 10 Joules are equal to 1 kg·meter.
Or 0.77 kWh/cubic meter

Note
The work W of desalination in different units:
$W = F \times x = \pi \times A \times x = \pi \times V = \pi \times V \times 100$
for W in Joules (Watt seconds), π in bars, and V in Liters. Or:
$W = \pi \times V \times (100 / 3600) = \pi \times V / 36$
For W in kWatt hours, π in bars, and V in cubic meters.

Practical desalination systems are never fully reversible, so the actual work of desalination is considerably higher (Lachish 2000).

The amount of energy consumption depends on the type of process, the TDS concentration in the feed water, the capacity of the treatment plant, the temperature of the feed water, and the location of the plant with respect to the location of the intake water and concentrate disposal site (Tamim Younos 2005). However, the minimum energy required only depends on the properties of seawater. The Table 2.3 and Table 2.4 show the minimum energy required to desalinate of one cubic meter of seawater with different TDS concentrations and feed water temperatures respectively.

Table 2.3: The minimal energy of desalting 1 m^3 seawater at different TDS (25 ºC)

TDS (ppm)	Osmotic pressure (bar)	The minimal energy (kWh/m^3)
10000	8.36	0.23
20000	16.72	0.46
30000	25.08	0.69
40000	33.44	0.92
50000	41.80	1.15

Table 2.4: The minimal energy of desalting 1 m^3 seawater at different temperatures (seawater with 33000 ppm TDS concentration)

Temperature (ºC)	Osmotic pressure (bar)	The minimal energy (kWh/m^3)
10	26.19	0.73
20	27.12	0.75
30	28.05	0.78
40	28.98	0.80
50	29.90	0.83

From both tables, Increased TDS concentration and temperature cause an increase in the minimum energy required to desalinate of one cubic meter of seawater, regardless of the technology applied to the process.

2.4 Reverse Osmosis Membranes

A semi-permeable membrane is a selective barrier, which only allows certain components to pass through. This depends on the particular physical structure and chemical properties of the membrane.

Reverse osmosis membranes can be used for many industrial applications. One very important application is seawater desalination. Only RO membranes can be applied for the separation of ions from seawater. The most important qualities for the ideal RO membrane are:

- High permeability;
- Mechanical and temperature stability;
- Chemical and microbial resistance;
- High selectivity.

2.4.1 Membrane Structures

RO membranes can be divided into two categories: asymmetric membranes and thin-film, composite membranes (TFC).

Asymmetric membranes

Asymmetric membranes consist of a very dense thin skin layer on the top of a more porous sub-layer. The thickness of the thin skin layer is approximately 0.1 to 0.5 µm, compared to symmetric membranes (usually from 10 to 200 µm). They have a higher water flux rate due to the very thin top layer, where the separation process occurs. The porous sub-layer only supports the top layer (Cheryan 1987; Mulder 1992; Michael E. Williams 2003). Figure 2.3 shows the schematic of asymmetric membrane cross-sections.

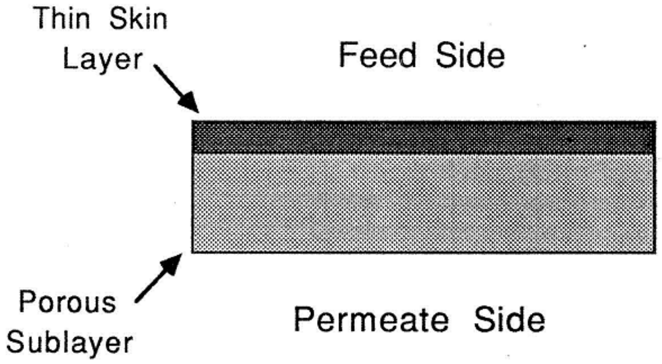


Figure 2.3: The schematic of asymmetric membrane cross-sections (Michael E. Williams 2003)

Composite membranes

Composite membranes are known as the second generation of membrane. They consist of two or more different materials. The development of composite membranes was a major breakthrough in the history of membrane separation technology. The first composite membrane for commercial use was produced by UOP (Universal Oil Products) and was named the PA-300 in 1977 (Riley R L 1977). A thin solute-rejecting film was made from polyamide on top of the polysulphone support layer. The solute rejections of this membrane are given in Table 2.5.

Table 2.5: Solute rejections of UOP PA-300 thin-film composite membrane (Riley R L 1976)

Solute	Concentration (ppm)	pH	Rejection (%)
Sodium nitrate	10000	6.0	99.0
Ammonium nitrate	9600	5.7	98.1
Boric acid	280	4.8	65-70
Urea	1250	4.9	80-85
Phenol	100	4.9	93
Phenol	100	12.0	>99
Ethyl alcohol	700	4.7	90
Glycine	1400	5.6	99.7
DL-Aspartic acid	1500	3.2	98.3
Ethyl acetate	366	6.0	95.3
Methyl ethyl ketone	465	5.2	94
Acetic acid	190	3.8	65-70
Acetonitrile	425	6.3	>25
Acetaldehyde	660	5.8	70-75
Dimethyl phthalate	37	6.2	>95
2,4-Dichlorophenoxy acetic acid	130	3.3	>98.5
Citric acid	10000	2.6	99.9
Alcozyme (soap)	2000	9.3	99.3
O-Phenyl phenol	110	6.5	>99
Tetrachloroethylene	104	5.9	>93
Sodium silicate	42	8.6	>96
Sodium chromate	1200	7.8	>99
Chromic acid	870	3.9	90-95
Cupric chloride	1000	5.0	99.2
Zinc chloride	1000	5.2	99.3
Trichlorobenzene	100	6.2	>99
Butyl benzoate	220	5.8	99.3

The high permeability to water and high non- permeability to salts and other solutes are determined by the thin polyamide top layer. From the Table 5, it can be seen that the UOP PA-300 composite membrane could be operated over a much wider PH range (2.6-12). under high temperatures (up to 50 ºC) and high pressures (55 bar) conditions, the PA-300 still gave a high water flux due to the thickness of the surface layer, it is extremely thin, usually around 0.1 µm or less, thus allowing high water fluxes. However, the PA-300 was found to be extremely sensitive to the presence of free chlorine. That is because chlorine will oxidize the surface of PA-300 polyamide membranes, causing the membrane to lose its ability to repel or reject salts (Gutman 1987).

Since the appearance of the PA-300 polyamide membrane, a number of other companies began to manufacture the composite membrane. The most successful composite membrane is the FT30 membrane that is produced by Film Tec Corporation (Larson R E, Cadotte J E et al. 1981). The FT30 membrane is a thin-film composite membrane consisting of three layers: a polyester support web, a microporous (polysulfone) interlayer, and an ultrathin polyamide barrier (skin layer) on top, typical thin-film thicknesses are 0.05-0.1µm. Figure 2.4 gives a schematic illustration of a generic thin-film composite (TFC) membrane construction resembling that of FT30.

The performance of the FT30 membrane is similar to that of the UOP PA-300 membrane. Compared with PA-300 membrane the FT30 membrane has some tolerance to free chlorine. The FT30 also has very high organics removal efficiency.

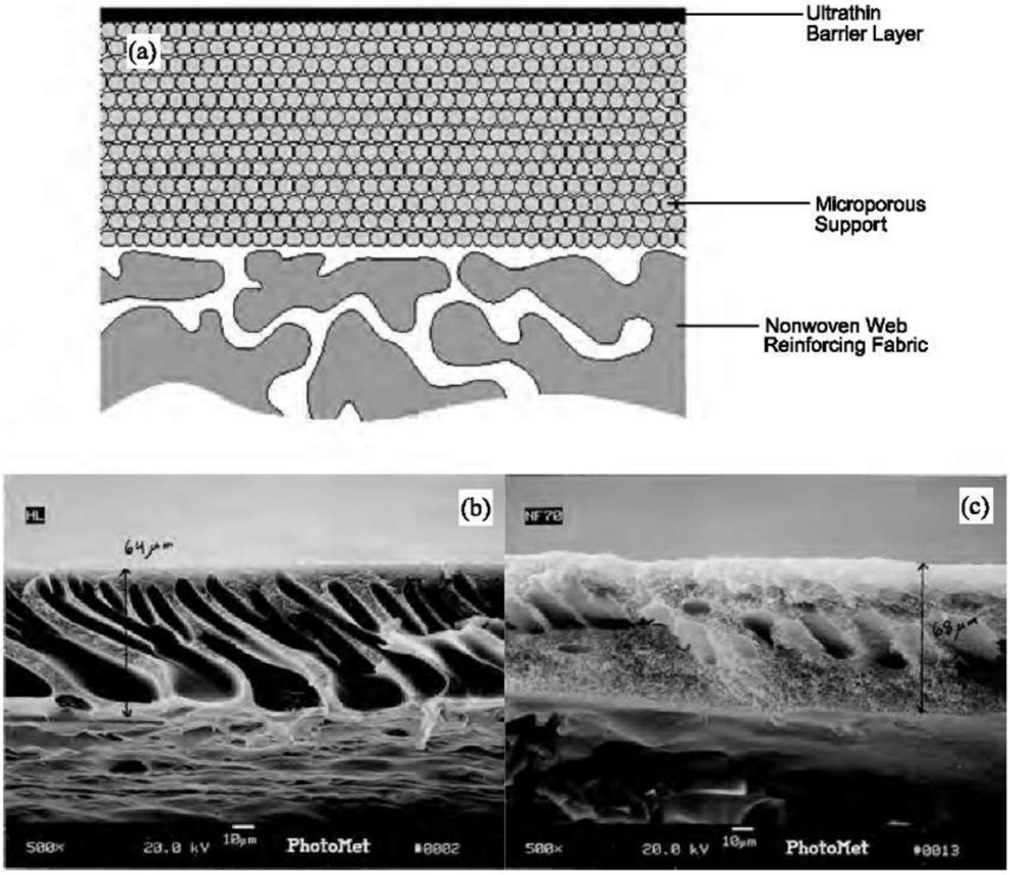


Figure 2.4: Cross-section illustration of (a) thin-film composite membrane, plus SEM cross sections of two commercially available polyamide membranes manufactured by (b) GE-Osmonics Inc. and (c) Dow-Film Tec (Jawor 2009)

The exact nature of the structure of the thin skin of asymmetric or thin-film, composite RO membranes are unclear and are still a point of debate. Some researchers assumed that the thin top layer is a homogeneous film of polymer containing no pores, the solvent molecules pass through the interstitial spaces of the polymer chains (Lonsdale 1965; Sherwood 1967; Burghoff 1980; Bitter 1991). Other researchers have assumed that the solute-rejecting barrier is a porous structure, containing extremely small pores (usually <30 A radius) (Sourirajan 1985; Mehdizadeh 1989). However, others have considered a more complex view of the barrier layer in RO membranes. Kesting (1990) postulated that the layer consists of polymer nodules (clusters of polymer macromolecules) and nodule aggregates. He indicated that transport can occur through chain segment displacements in the polymer nodules (interstitial spaces) and through spaces between nodule aggregates (defect pores). In addition, Tam et al. (1991) considered the fractal (random) nature of pore distribution and geometry in the barrier layer; their analysis recognized the randomness that could occur during formation of the barrier layer pores. Even though the simpler concepts (homogeneous versus pores) describing the barrier have been used successfully in model development, the approaches of Kesting and Tam et al. probably represent more realistic descriptions of the barrier layer. However, as of yet, no technique is available to exactly determine the barrier layer structure (Michael E. Williams 2003).

2.4.2 Membrane Materials

The separation characteristics such as water flux and salt rejection of reverse osmosis membrane mainly depends on the intrinsic properties of the material, also including chemical and mechanical stability, tolerance to temperature variation, resistance to fouling, and cost. Therefore, a number of polymer materials such as cellulose acetates, polyamides, cross-linked poly (furfural alcohol) and sulfonated polyethersulfone have been used to make RO membranes. Of these, the following two have been the most successful.

Cellulose acetate (CA) was the first high-performance RO membrane material discovered. A typical CA membrane exhibits an average NaCl rejection of 97.5% from a 2000 mg/L NaCl feed solution. The main advantage of CA is its low price and hydrophilic nature which makes it less prone to fouling. CA also has a good chlorine resistance up to 5 ppm. Thus, today, CA membranes still maintain a small fraction of the market. However, an inherent weakness of CA is that it can be attacked by microorganisms. It also slowly hydrolyzes over time and is generally not used above 35 ºC (Baker 2004).

Aromatic polyamide is a more successful membrane material for seawater desalination. It is most commonly used in the manufacturing of thin-film composite membrane. However, aromatic polyamides have several disadvantages including (Chaoyi Ba. 2010):

- Low resistance to fouling
- Limited oxidant tolerance due to the existence of secondary amides and electron-rich aromatic rings
- Low chemical and thermal stabilities. They could hardly be used at temperature higher than 50 ºC. They are also seldom used in non-aqueous systems because the substrate material, polysulfone, can be attacked by many organic solvents

2.4.3 Membrane Formation

So far, two different techniques have been adopted for the development of polymeric RO membranes, namely (I) the phase inversion method for asymmetric membranes and (II) the interfacial polymerization technique for composite membranes (I. Pinnau. and B.D.Freeman. 2000).

Phase inversion is a process in which a polymer in solution is converted to a solid in a controlled manner. The change in phase can be initiated in a number of ways, such as solvent evaporation, thermal precipitation, immersion precipitation and vapor precipitation (M.H.V. Mulder 1996). Table 2.6 shows production stages of the phase inversion method.

Table 2.6: Production stages of the phase inversion method (R. Rautenbach. 1989)

1. Production of a homogenous polymer solution of suitable viscosity
2. Casting of a polymer solution film
3. Evaporation of part of the solvent
4. Precipitation of the polymer
5. Tempering (annealing)

Interfacial polymerization has been employed to prepare a thin layer of cross-linked polyamide depositing on a substrate ultrafiltration membrane. The performance of the membrane is mainly determined by the monomers used in the interfacial polymerization. Even small changes in the monomer's structure can strongly influence the membrane properties. So far, the best results were obtained using trimesoyl chloride and m-phenylene-diamine as monomers (R.J. Petersen 1993).

2.4.4 RO Membrane Permeation Mechanism

Many mechanistic models have been proposed to describe desalination by reverse osmosis membranes. Some of these descriptions rely on relatively simple concepts while others are far more complex and require sophisticated solution techniques. Models of reverse osmosis systems can be divided into three types: "black-box" irreversible thermodynamics models; porous membranes models; and non-porous membrane models (Michael E. Williams 2003).

Irreversible thermodynamics models

In this model the membrane is considered as a black box, irreversible thermodynamics models assume the membrane is not far from equilibrium and so fluxes can be described by phenomenological relationships.

Solution-Diffusion Model (non-porous models)

In 1965, Lonsdale proposed the solution-diffusion model at the first time, this model assumes that the RO membrane has a nonporous diffusion surface layer, solvent and solute molecules dissolve into this layer and then disuse through it by a solid or liquid diffusion mechanism. The diffusion of solution dissolves is caused by chemical potential gradient which are the result of the concentration and pressure differences across the membrane (Michael E. Williams 2003).

Preferential sorption-capillary flow model (porous models)

This model assumes that the mechanism of separation is determined by both surface phenomena and fluid transport through pores in the RO membrane. In contrast to the solution-diffusion model, the membrane is assumed to be microporous (Sourirajan 1970). The model states that the membrane barrier layer has chemical properties such that it has a preferential sorption for the solvent or preferential repulsion for the solutes of the feed solution. As a result, a layer of almost pure solvent is preferentially sorbed on the surface and in the pores of the membrane. Solvent transport occurs as solvent from this layer is forced through the membrane capillary pores under pressure.

2.4.5 Water Flux

The mass flux of water, J_w, through reverse osmosis membrane is given by the expression (Lonsdale 1982):

$$Jw = \frac{D_W C_W V_W\ (\Delta p - \Delta\pi)}{RT\Delta x} \qquad (6)$$

Where,

D_W= the diffusivity of water dissolved in the membrane
C_W= the concentration of water dissolved in the membrane
V_W= the partial molar volume of water in the membrane
Δp= the applied pressure difference across the membrane
$\Delta\pi$= the osmotic pressure difference across membrane
Δx= the effective membrane thickness

For a given membrane, many of these quantities are fixed and equation (6) reduces to

$$Jw = A_w\ (\Delta p - \Delta\pi) \qquad (7)$$

Where A_w is a constant of the membrane

2.4.6 Fouling of RO Membranes

Fouling is a phenomenon in which the membrane adsorbs or interacts in some manner with some materials in the feed stream, resulting in a decrease in membrane performance (lowering the flux and/or increase in rejection of solutes) when all operating parameters are kept constant, fouling decreases the membranes performance. RO membrane elements are subject to fouling by suspended or sparingly soluble materials that may be present in the feed water, Common examples of foulants are (Nitto Denko Corporation. 2011):

- Metal oxides
- Calcium carbonate scale
- Sulfate scale of calcium, barium or strontium
- Colloidal foulants
- NOM organic material (Natural Organic Matter)
- Biological

2.4.6.1 Fouling Components

Metal Oxide/Hydroxide Foulants: Typical metal oxide and metal hydroxide foulants are iron, zinc, manganese, copper, aluminum, etc. They can be the result of corrosion products from unlined pipes and tanks, or result from the oxidation of the soluble metal ion with air, chlorine, ozone, potassium permanganate, or they can be the result of a pretreatment filter system upset that utilizes iron or aluminum-based coagulant aids.

Calcium Carbonate Scale: Calcium carbonate is a mineral scale. Calcium carbonate scale can be removed by lowering the feed water pH to between 3.0 and 4.0 for one or two hours when it has been detected early. Longer resident accumulations of calcium carbonate scale can be removed by recirculating a citric acid solution of 2-percent strength and a pH of no less than 2.0 through the RO membrane elements (Nitto Denko Corporation. 2009).

Calcium, Barium & Strontium Sulfate Scale: Sulfate scale is a much "harder" mineral scale than calcium carbonate and is harder to remove. Barium and strontium sulfate scales are particularly difficult to remove as they are insoluble in almost all cleaning solutions, so special care should be taken to prevent their formation.

Colloidal Foulants: Colloids are inorganic or mixed inorganic/organic based particles that are suspended in water and will not settle out due to gravity. Colloidal matter typically contains one or more of the following major components: iron, aluminum, silica, sulfur, or organic matter.

Dissolved NOM Organic Foulants: The sources of dissolved NOM (Natural Organic Matter) foulants are typically derived from the decomposition of vegetative material into surface waters or shallow wells. The chemistry of organic foulants is very complex, with the major organic components being either humic acid or fulvic acid.

Microbiological Deposits: Organic-based deposits resulting from bacterial slimes, fungi, molds, etc. can be difficult to remove, particularly if the feed path is plugged. Plugging of the feed path makes it difficult to introduce and distribute the cleaning solutions. To inhibit additional growth, it is important to clean and sanitize not only the RO system, but also the pretreatment, piping, dead-legs, etc.

2.4.6.2 Factors Affecting Fouling

Some factors affecting the fouling of membrane are:

- Membrane properties
- Solution properties
- Operating conditions, such as feed pressure and temperature.

2.4.6.3 Control of RO Membrane Fouling

Membrane fouling is an inevitable problem, but it can be minimized by strategies, fouling control involves pretreatment of the feed water to minimize fouling control as well as regular cleaning to handle nay fouling that still occurs.

Usually the need for pretreatment depends on the feed water composition, the solubility of the particular salt and the characteristics of RO system. It will consist of one or more following operations:

- Filtration to remove large particles
- Adjustment of solubility parameters to prevent precipitation of sparingly soluble salts (scaling) as a result of concentrating action of the RO process
- Coagulation of colloidal matter
- Chemical treatment to prevent biological growth

Membrane cleaning includes:

- Physical cleaning---sponges, water jets or backflushing using a permeate
- Chemical cleaning---use of acids and bases to remove foulants and impurities
- Biological cleaning--- uses biocides to remove all viable microorganisms

CHAPTER 3

SEAWATER REVERSE OSMOSIS DESALINATION PLANT DESIGNS

3.1 Feed and Product Water Analysis

In simple terms, the main purpose of seawater desalination is to obtain fresh water from seawater, no matter what technical method you use, both feed water (seawater) and product water (fresh water) quality analysis are the most important things. In reverse osmosis membrane seawater desalination plants, the system designs are mainly determined by the properties of intake seawater, and drinking water quality standards. Figure 3.1 shows the seawater composition.

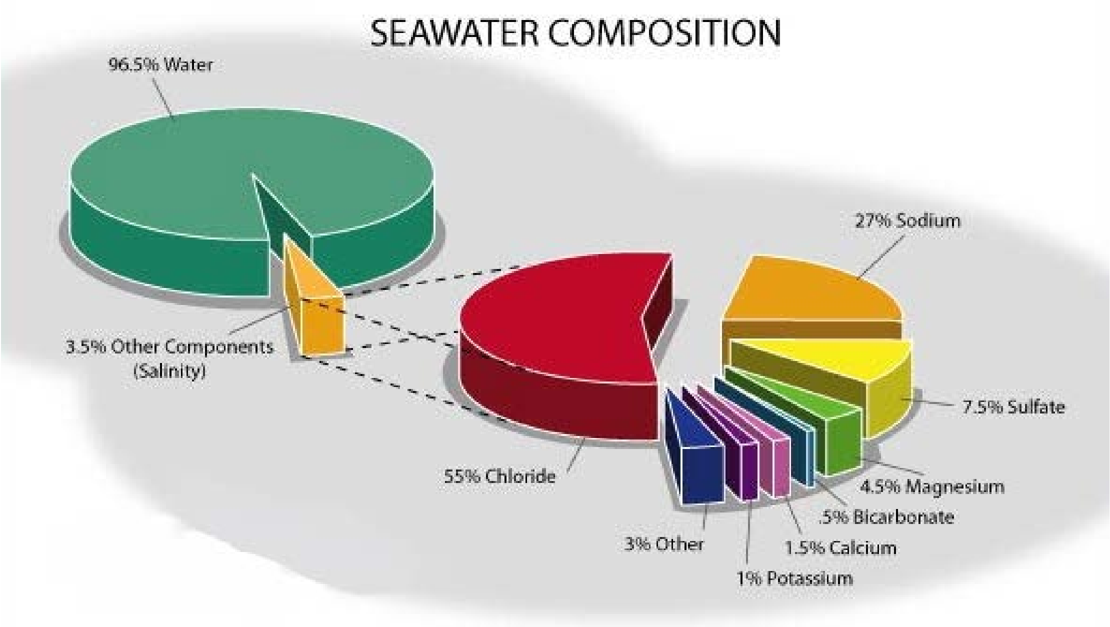


Figure 3.1: The seawater composition

The main component of seawater is water, however, the most important components of seawater are all the dissolved salts which are known as salinity, and it is usually 3.5 parts per hundred in most marine areas. Although 35 parts per thousand is not very concentrated the water in the oceans tastes very salty. Therefore, the seawater desalination means removing dissolved salts or decreasing the salinity of seawater. Table 6 shows the main salt ions that make up 99.99%.

Table 3.1: The main salt ions of seawater (based on chlorinity = 19‰)

Material	g/1 kg seawater	Element/Cl‰	Percent salt by weight
Chloride, CL^-	18.980	0.99894	55.04
Sodium, Na^+	10.556	0.5556	30.61
Sulfate, SO_4^{2-}	2.649	0.1394	7.68
Magnesium, Mg2+	1.272	0.06695	3.69
Calcium, Ca^{2+}	0.400	0.02106	1.16
Potassium, K^+	0.380	0.02000	1.10
Bicarbonate, HCO_3^-	0.140	0.00735	0.41
Bromide, Br^-	0.065	0.00340	0.19
Boric acid, H_3BO_3	0.026	0.00137	0.07
Strontium, Sr^{2+}	0.013	0.00070	0.04
Fluoride, F^-	0.001	0.00007	0.00
Total	34.482‰		99.99%

From H.U.Sverdrup, M.W.Johnson, and R.H.Fleming, The Oceans, 1942. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J.

Usually, there are many indicators of water quality, such as TDS, conductivity, turbidity, SDI, total hardness, pH and temperature, these values are important to the plant design.

3.1.1 Water Quality Indicators

Total Dissolved Solids (TDS): Total Dissolved Solids (TDS) are the total amount of mobile charged ions, including minerals, salts, or metals dissolved in a given volume of water. TDS, which is based on conductivity, is expressed in parts pr. million (ppm) or milligrams pr. liter (mg/L). TDS includes any conductive inorganic element present other than the pure water molecules (H_2O) and suspended solids. Most TDS meters convert the total amount of dissolved solids as NaCl ions for simplicity.

Conductivity: Conductivity is a measure of the ability of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids, organic compounds and temperature. In a SWRO plant, conductivity not only be used to monitor water quality, but also can be used to indicate when a bank should be cleaned, or to pinpoint a damaged permeator. Because fouling or damage to the membrane result in either gradual or rapid conductivity increases (Albert B. Mindler. and Epstein 1985).

Turbidity: The cloudiness or haziness of a fluid caused by individual particles (suspended solids) that are generally invisible to the naked eye, similar to smoke in air. The measurement of turbidity is a key test of water quality. If the water sample is regularly agitated, the very small suspended particles in the water will settle very slowly, these small solid particles cause the liquid to appear turbid.

Silt Density Index (SDI): The SDI value is regarded as an indicator for potential colloidal fouling. For successful RO operation, an SDI of less than 4.0 is required for the hollow fine-fiber (HFF) membranes and less than 5 for the spiral-wound (SW) membranes. SDI is measured by taking a 500 ml sample and filters it through a 0.45 micro filter dish for a specified time. The pressure is measured at the beginning and the end of the test. From these values: volume, time and pressure differential SDI is calculated.

Total Hardness: Hard water is water that contains high levels of dissolved calcium, magnesium, and other mineral salts such as iron. The greater the amount of dissolved minerals in the water, the harder it is. Total hardness is measured in grains per gallon (gpg) or parts per million (ppm). It is an important parameter for SWRO plant, depend on pH. Hardness water may cause scale deposition, which will reduce the life of equipment and the production rates.

pH: pH is a water parameter, it indicates the activity of the hydrogen ion and describes the acidity or alkalinity of the solution. In most potable waters, the activity of hydrogen ion is nearly equal to its concentration. pH is defined as the negative logarithm of the hydrogen ion concentration. The pH scale ranges from 0 to 14. A pH of 7 is neutral. A pH less than 7 is acidic. A pH greater than 7 is basic.

Temperature: Temperature variation can impact the scaling potential of the reverse osmosis system, especially when silica levels in the feed water are high.

3.2 System Designs

It is impossible to design a good SWRO desalination plant only with RO membrane technology alone. A SWRO desalination plant typically consists of three parts: pre-treatment, reverse osmosis system and post-treatment

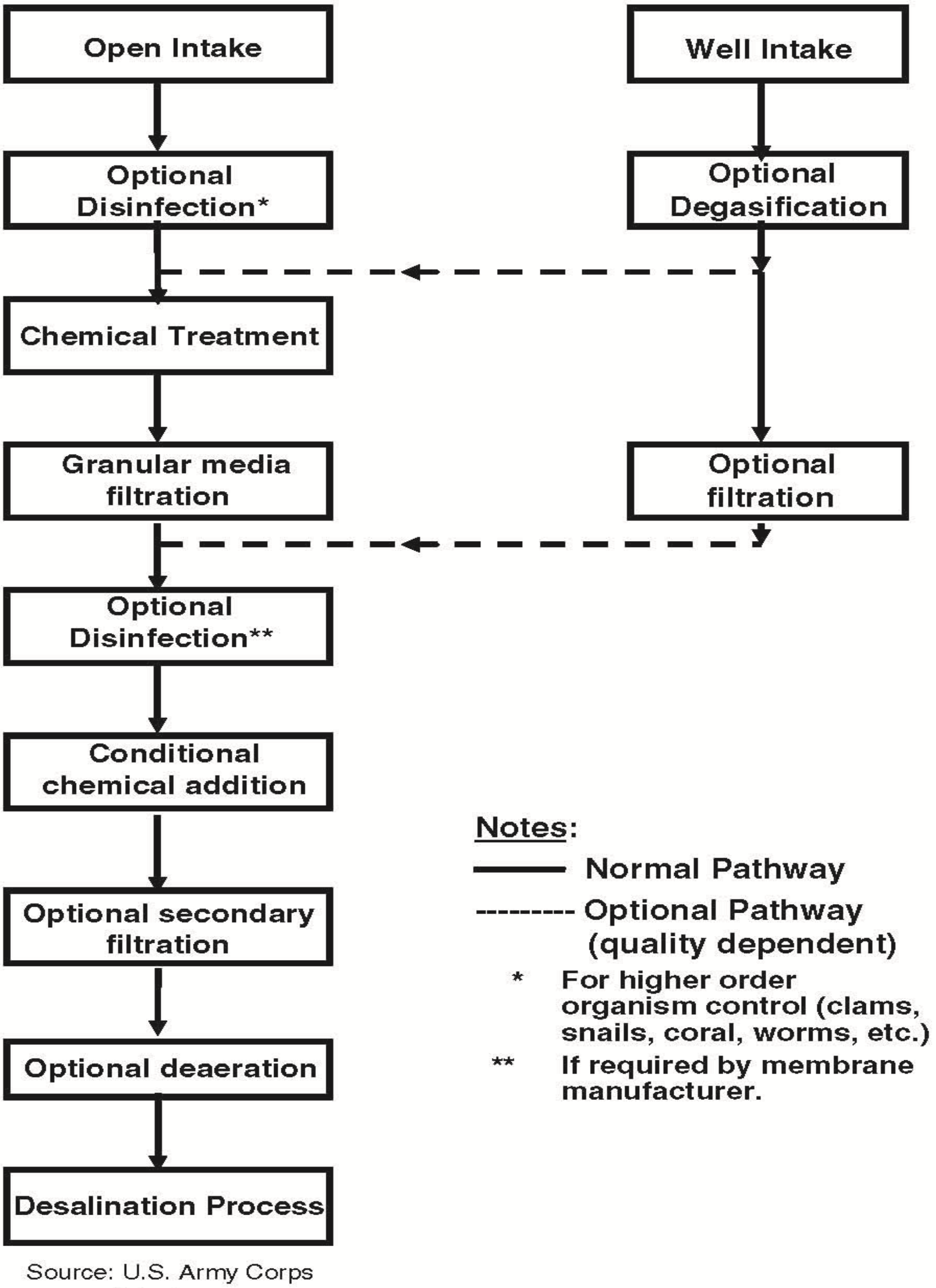
3.2.1 Pre-treatment

Seawater resources typically have particulate matters, organic substances and other solids, which cause membrane fouling, and not suitable for RO membrane processes. Therefore a pre-treatment system is an essential element for SWRO desalination plants. The primary objective of a RO pretreatment system is to make the feed water to compatible with the RO the membrane, in other words, a proper pretreatment can increase the efficiency and life expectancy of the membrane elements, and decrease the operating costs of the entire system.

The design of a RO pretreatment system largely depends on the raw water composition, water quality variability and RO membrane operational parameters. The main factors affecting pretreatment design are (Alawadhi 1997):

- Feed water salinity
- Silt density index
- Feed water pollution
- Temperature of the feed water
- Biological activity

If membrane cleaning frequency is controlled on 3-4 times per year or less, life expectancy of the membranes could last five years or more. If productivity and salt rejection rate remains within the desired range, the pretreatment is considered to be sufficient. Figure 3.2 shows the pretreatment techniques.



Source: U.S. Army Corps of Engineers

Figure 3.2: Pretreatment techniques (Sutzkover-Gutman and Hasson 2010)

3.2.1.1 Chemical Pretreatment Options

Acid: Acids are used in the pretreatment process to reduce pH levels, and therefore reduce the scaling potential of some compounds such as Carbonates. Generally hydrochloric [HCl] or sulfuric [H_2SO_4]. Sulfuric acid is used more often than hydrochloric acid. This is because there are some benefits of using sulfuric acid.

- Lower operation cost
- Less corrosion to surrounding metal components
- The membrane rejection of the sulfate ion is better than the chloride ion

However, sulfuric acid increases the concentration of sulfate ion in the feed water, when the presence of a large number of calcium ions, barium ions or strontium ions in the feed water will directly increase the potential for sulfate-based scaling by using sulfuric acid. In this situation, hydrochloric acid is considered to be a better choice. Another reason is that sulfuric acid can attack gaskets and sealings containing rubber in pumps and other components.

Anti-scalants: also known as Scale inhibitors, anti-scalants are a family of chemicals designed to inhibit the formation and precipitation of most scales. Most anti-scalants are proprietary organic man-made polymers (e.g. polyacrylic acids, carboxylic acids, polymaleic acids, organo-phosphates, polyphosphates, phosphonates, anionic polymers, etc.).

3.2.1.2 Coagulation and Flocculation

Coagulation and flocculation are two distinct, successive processes. The main purpose of the coagulation system is to achieve uniform mixing of the added coagulant with the source seawater and efficient coagulation of the particles contained in the seawater. The two types of mixing systems most widely used in seawater desalination plants are in-line static mixers and mechanical flash mixers installed in coagulation tanks. This neutralizes charges between particles, creating coagulated water that is ready for flocculation (Steven I. Safferman Ph.D. 2003).

The coagulated water is then mixed gently in the presence of a flocculant, causing flocs of the formerly dissolved particles to precipitate on the surface of the water. Flocs are then removed in subsequent sedimentation and filtering processes, ensuring that effluent is completely free of precipitate.

3.2.1.3 Filtration Pretreatment Options

Screens: trash racks and traveling screens are used to remove larger solid particles from the chemically treated seawater.

Media filtration: all media filters function in a similar way in that the feed water is passed through a bed of media where most smaller particles are retained by the filter media. After a designated period the media must be cleaned to prevent it to become compacted or clogged. The rate at which raw water can be applied, the type of media, the depth of the media and the frequency, rate and method of backwashing are all variables that must be considered based upon the volume of water to be treated, the quality to be processed and the quality required.

Cartridge filters: almost universally used in all RO systems prior to the high pressure pump. They serve as the final barrier to water born particles. The nominal rating commonly used in RO applications is in the range of 5 - 20 microns. Some systems use cartridges with micron ratings as low as 1 micron. There seems to be little benefit from lower micron rated filters as such filters require a high replacement rate with relatively small improvement in the final feed water quality.

3.2.1.4 Disinfection

Sea water contains various microorganisms, bacteria, protozoan that would contributes to a biofilm formation on the membrane surface, this is called biological fouling, which will result in flux reduction, operating pressure increased and membrane damage. Table 3.2 summarizes the chemical and physical disinfection methods.

Table 3.2: Comparison chart for disinfectants used for bio-fouling control of SWRO membranes (Kim, Jung et al. 2009).

	Disinfection	Advantage	Disadvantage
Physical	UV	•Easy installation and maintenance •Effective inactivation • Oxidation of organic matter	• Scale formation • No residual effect
	Membrane	• Combined with membrane pretreated	• High capital and operation cost • Low bacterial removal efficiency
	Sand filtration	• Low installation and operation cost	• Chemical corrosion of RO membrane
Chemical	HOCl, OCl^-	• High inactivation efficiency • Organic matter removal • Relatively low cost	• THMs, HAAs formation • Relatively low efficiency
	NH_2Cl	• Less harmful on membrane than HOCl • Residual inactivation	• chlorite toxicity • Bromate formation
	ClO_2	• No damage on membrane	• Very small half life
	Ozone	• Effective inactivation • High oxidation potential for organic matter	• Damage by residual ozone

The most common methods of disinfection in RO membrane seawater desalination are chlorination, ozonation and Ultraviolet (UV).

Chlorination:

Chlorine is a very effective biocide, it is used in the raw seawater to control biological growth, in SWRO desalination process, free chlorine has been used to inactivate microbial growth, but membranes have a poor resistance to its strong oxidation potential. Polyamide (PA) membranes do not tolerate chlorine at all while Cellulose Acetate (CA) membranes have some tolerance. Chlorine disinfection must be followed by strict removal of the residual chlorine in the water by sulfite treatment or carbon adsorption.

Chlorine works not only as a disinfectant. It will also oxidize some dissolved metals which can be found in seawater. Chlorine splits into two forms in water: Hypochlorite ions (OCl^-) and Underchloric acid (HOCl).

When chlorine is added to water, underchloric acid partly expires to hypochlorite ions (World Health Organization. 2000):

$Cl2 + H2O \rightarrow HOCl + H^+ + Cl-$

$HOCl + H2O \rightarrow H3O^+ + OCl-$

This falls apart to chlorine and oxygen atoms:

$OCl- \rightarrow Cl^- + O$

Underchloric acid (HOCl) is much more reactive and is a powerful disinfectant than hypochlorite (OCl-), since underchloric acid (HOCl) will split into hydrochloric acid (HCl) and atomar oxygen (O). So the disinfecting properties of chlorine in water are based on the oxidizing power of free oxygen atoms and on chlorine substitution reactions (Helle Frank Skall. 2011).

The effectivity of disinfection is determined by the pH of the water. HOCl reacts faster and is more effective than OCl-. Disinfection with chlorine will take place optimally when the pH is between 5.5 and 7.5. Figure 3.3 illustrates Distribution of Underchloric Acid and Hypochlorite Ion in Water at Different pH Values and Temperatures.

HOCl and OCl^- exist in an equilibrium that is pH dependent. The equilibrium is also slightly affected by temperature. The level of HOCl will decrease as the pH value goes up. When the pH value fewer than 5.5, underchloric acid (HOCl) is 100% effective.

With a pH value of 7 the level of underchloric acid is 80%, whereas the concentration of hypochlorite ions is 20%. When the pH value is 7.5, concentrations of underchloric acid and hypochlorite ions are equally high. Above a pH of 7.5, hypochlorite ion is the dominant species (Anon 2012).

Because HOCl is a stronger disinfectant than OCl–. Therefore, the chlorination process is pH dependent. The germicidal effects of HOCl will be realized by chlorination at a lower pH.

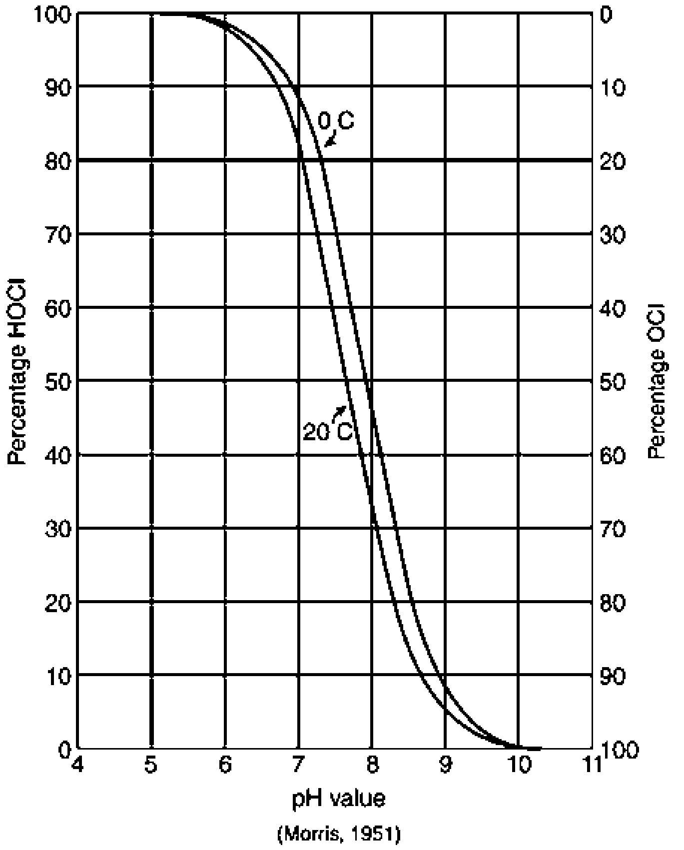


Figure 3.3: Distribution of hypochlorous acid and hypochlorite ion in water at different pH values and temperatures (Morris J.C. 1951)

Ozonation:

Ozone has been used to inactivate micro-organisms due to its very strong oxidation potential and fewer disinfection by-products. However, compared to chlorine, equipment for ozone production is quite expensive to purchase, but operating costs are low.

UV

Ultraviolet (UV) disinfection uses a UV light source, which is enclosed in a transparent protective sleeve. It is mounted so that water can pass through a flow chamber, and UV rays are admitted and absorbed into the stream. When ultraviolet energy is absorbed by the reproductive mechanisms of bacteria and viruses, the genetic material (DNA/RNA) is rearranged and they can no longer reproduce. They are therefore considered dead and the risk of diseases due to harmful microorganisms is eliminated. The advantages of UV disinfection are:

- Not alter taste, odour, colour or pH of the water
- Does not require the addition of chemicals
- Do not impart toxic by-products into the water
- UV systems are compact and easy to install
- UV systems require very little maintenance. Lamps are usually replaced after every 10,000 hours of running time.

3.2.1.5 Ultrafiltration

Ultrafiltration (UF) is a membrane separation process using membranes with pore sizes in the range of 0.1 to 0.001 micron. Typically, UF membranes will remove high molecular-weight substances, colloidal materials, and organic and inorganic polymeric molecules. Low molecular-weight organics and ions such as sodium, calcium, magnesium chloride, and sulfate are not removed by UF Membranes (Gil Dhawan. 2010). Figure 3.4 shows the useful ranges of various separation processes.

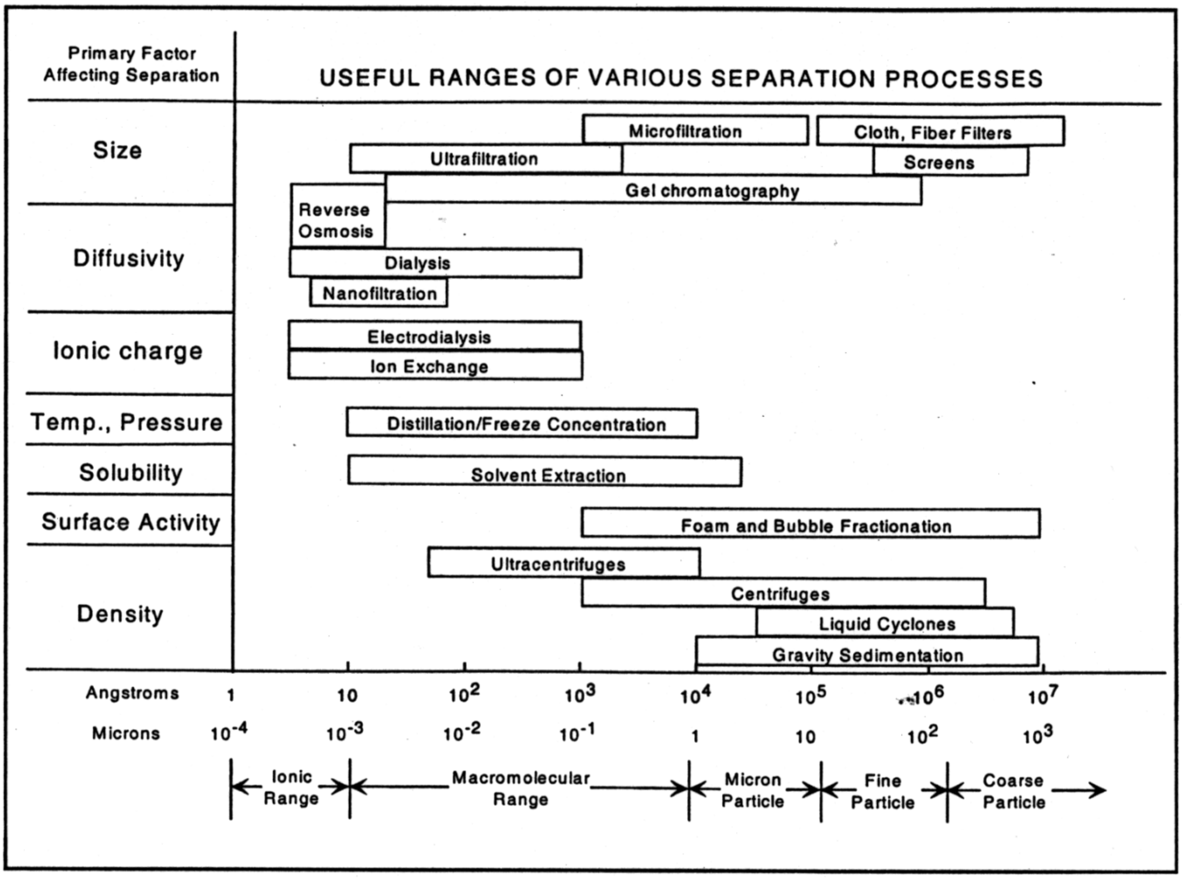
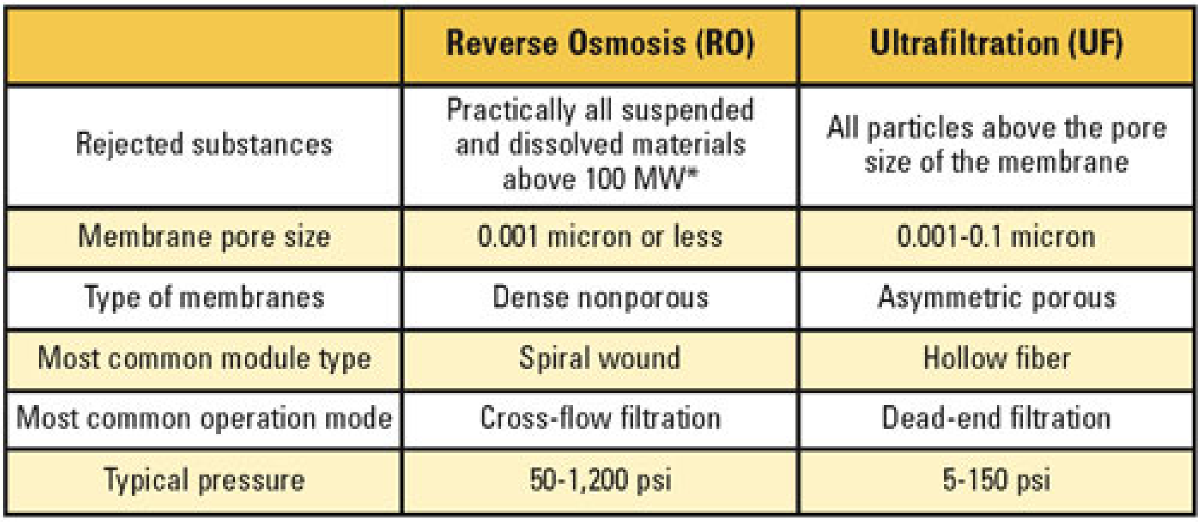


Figure 3.4: Useful ranges of various separation processes (Cheryan 1987)

The points of difference between reverse osmosis and ultrafiltration are that in the latter process the operating pressures required are much lower and the membranes used are highly permeable. Because only high-molecular weight species are removed, the osmotic pressure differential across the UF Membrane surface is negligible. Low applied pressures are therefore sufficient to achieve high flux rates from an Ultrafiltration membrane.

The materials and configurations of UF membranes are very similar to RO membranes. UF membranes are most commonly made from various organic polymers such as different cellulose derivatives, polysulfones, polypropylene, and polyvinylidene fluoride (PVDF). Physical configurations include hollow fiber, spiral wound, cartridge, and tubular.

The separation performance of the RO membranes is often described in terms of their rejections of certain minerals (mainly NaCl). UF membranes are characterized by their nominal pore size or molecular weight cut-off (MWCO) because the separation is based almost entirely upon the differences between the pore size of the membrane and that of the particles themselves. Figure 3.5 shows a comparison of RO and UF membranes.



	Reverse Osmosis (RO)	**Ultrafiltration (UF)**
Rejected substances	Practically all suspended and dissolved materials above 100 MW*	All particles above the pore size of the membrane
Membrane pore size	0.001 micron or less	0.001-0.1 micron
Type of membranes	Dense nonporous	Asymmetric porous
Most common module type	Spiral wound	Hollow fiber
Most common operation mode	Cross-flow filtration	Dead-end filtration
Typical pressure	50-1,200 psi	5-150 psi

Figure 3.5: RO and UF—technical comparison

Despite the fact that both RO and UF are membrane treatment technologies, the two are quite different in terms of performance characteristics and claims. In most applications either one or the other will be most suitable, though in many applications RO and UF complement each other, and the two technologies can be combined to provide additional benefits to customers.

Very often UF is used as RO pretreatment. The longevity and efficient operation of RO membranes often depend upon on the quality of the feed water. The flow diagram of Ultrafiltration process is shown in Figure 3.6.

UF membranes are relatively insensitive to upsets caused by high turbidity or variable raw water quality and can consistently produce RO feed water with a turbidity of less than 0.1 NTU (nephelometric turbidity units) and a low silt density index (SDI), often less than 2.5. UF can also be used as post-treatment for RO applications where bacteriological disinfection is desired.

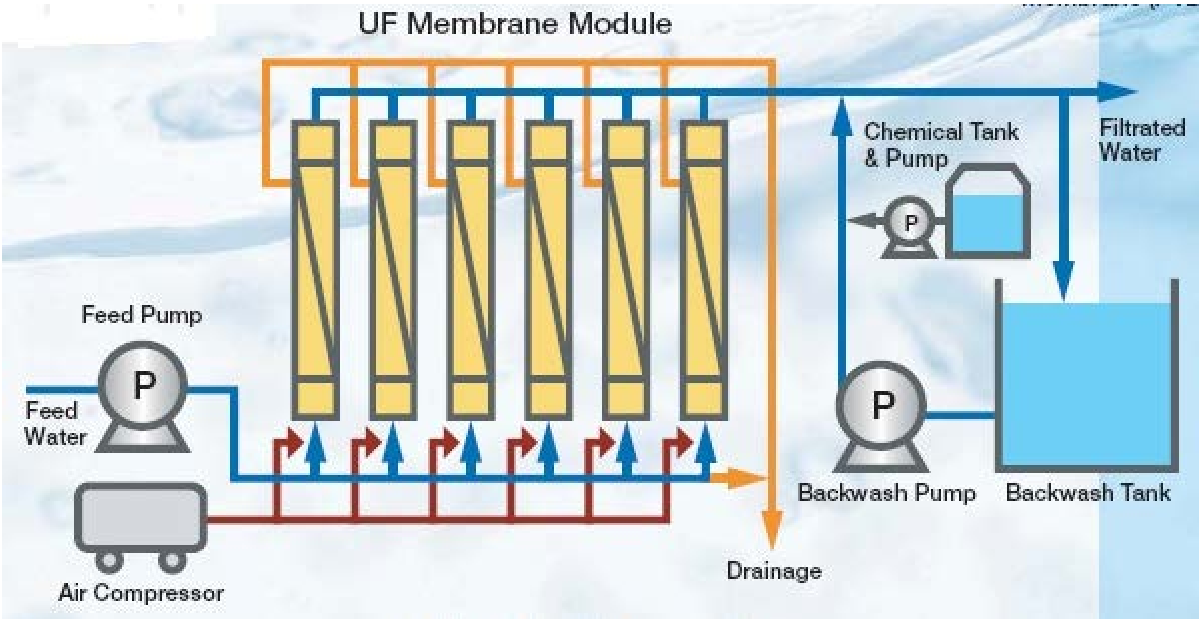


Figure 3.6: The flow diagram of Ultrafiltration process (Toray Industries 2012)

3.2.1.5 Conventional and Non-conventional Pretreatments

The pretreatment process of SWRO membrane desalination plants can be divided into conventional and non- conventional design. Conventional pretreatment (Figure 3.7) usually includes an open seawater intake, screens, chemical additions, flocculation/coagulation, filtration processes (media filtration and cartridge filtration) and disinfection.

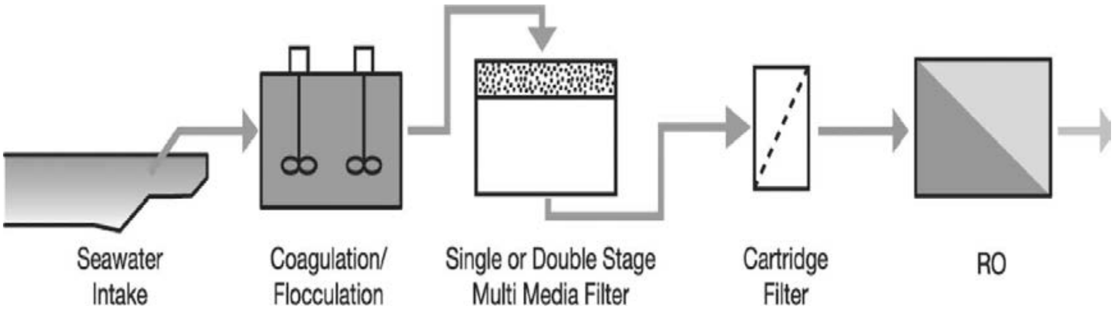


Figure 3.7: Typical conventional pretreatment (Wolf, Siverns et al. 2005)

The disadvantages of a conventional pretreatment are:

- More sensitive to changes in seawater characteristics
- Higher filtrate turbidity and SDI
- Requires more space and process chemicals
- More cartridge filter changes -every 2 to 3 months, sometimes a few weeks

As technology advanced, MF/UF membrane separation is used as a non- conventional pretreatment in SWRO plants, Figure 3.8 shows the membrane pretreatment processes, and Table 3.3 shows a comparison of conventional and UF pretreatments

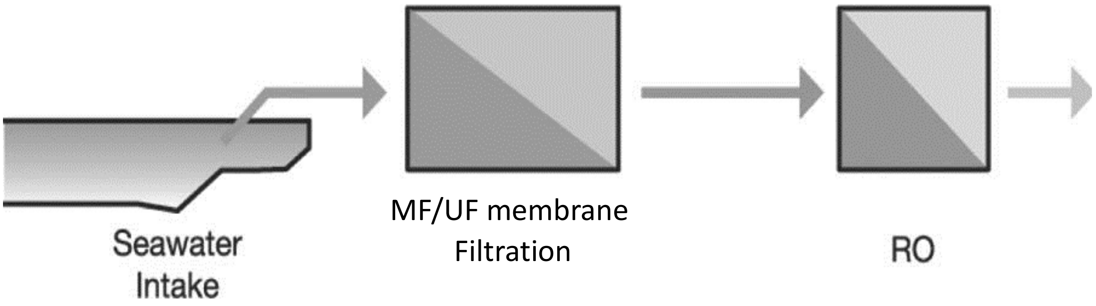


Figure 3.8: Typical MF/UF membrane pretreatment (Wolf, Siverns et al. 2005)

Compared with the conventional pretreatment processes, there are several advantages of MF/UF membrane pretreatment processes, such as:

- Lower filtrate turbidity and SDI
- Less particulate fouling of the RO membranes
- Simplicity of operation and maintenance
- Fewer cartridge filter changes –4 to 5 months
- Reduction of the overall dimensions of plant and footprints
- Less or no process chemicals

Table 3.3: summarizes the significant differences between conventional and UF pretreatments (Kim, Kim et al. 2009)

	Conventional pretreatment	UF membrane pretreatment
Treated water quality	Unstable and fluctuating water quality depending on raw seawater (Silt Density Index, SDI <4.0)	Stable and constant water quality (SDI <2.0)
	100%	
Average RO flux	High fouling potential	20% higher
RO membrane fouling rate	1-2 times per year	Lower fouling potential
RO membrane cleaning frequency	Filters: 20–30 years, Cartridges: 2–8 weeks	4-12 times per year UF/NF membranes: 5–10 years,
Typical life time	100%	Cartridges: often not needed
	100%	33% lower
RO membrane replacement rate	100%	0–25% higher
Capital cost	Lower than UF	30–60% smaller
Footprint	High	Higher than conventional
Energy consumption	Long	Lower
Chemical dosing rate	High	Shorter
Intake line	—	Lower
Operation/management costs		Better boron control
Miscellaneous		

3.2.2 RO Membrane Process

RO membrane process is the core part of any RO membrane seawater desalination plant.

3.2.2.1 Module Types

In a reverse osmosis plant, a minimum module is called an element, and a unit that put some modules in a pressure vessel is called a module. There are four different types of reverse osmosis module configurations, which are mainly used for desalination processes. These are the plate and frame, tubular, hollow-fiber and spiral-wound modules. Table 3.4 shows the comparison of these modules, the costs per unit capacity for seawater desalination are same for hollow-fiber modules and spiral-wound modules, and the use of hollow-fiber modules and spiral-wound modules is very cheaper than that of tubular modules and plate-and-frame modules. The pretreatment costs for seawater desalination are higher when hollow fiber membranes are used, because these membranes are more susceptible to fouling. The required minimal operating pressure for the modules is low when hollow fiber modules or spiral-wound modules are used.

Table 3.4: Reverse osmosis membrane module comparison (P.M. Bungay, H.K. Lonsdale et al. 1982)

characteristic	Hollow-fiber	Spiral-wound	Tubular and plate-and-frame
Flux and rejection range	High	High	High
Range of pH tolerance	4-10	4-7	4-7
Production per unit space	Excellent	Good	Fair
Resistance to fouling	Low	Medium	High
Ease of cleaning	Fair	Good	Excellent
Cost per unit capacity	Low	Low	Higher
Operating pressure (psi)	250-800	250-800	400-800
Product pumping required	Rarely	Occasionally	Always

For seawater desalination plants using RO membranes, the hollow fiber modules and spiral-wound modules are used most often.

Hollow Fiber Modules

The hollow fiber membrane module is essentially a tubular membrane, the continuous fiber is looped over both sides of a flat porous web, which is then wound around a pipe which acts as the central feed distributor of the final module. As the web is wrapped around the distributor, an epoxy adhesive is applied to one end of the web/fiber bundle. The resultant epoxy block is then sectioned, producing an epoxy header into which are sealed both ends of a large number of loops of fiber. Permeate that collects in the fiber bores is withdrawn from the module via the header. The type of construction is illustrated by the Dupont B9 hollow fiber modules shown in Figure 3.9.

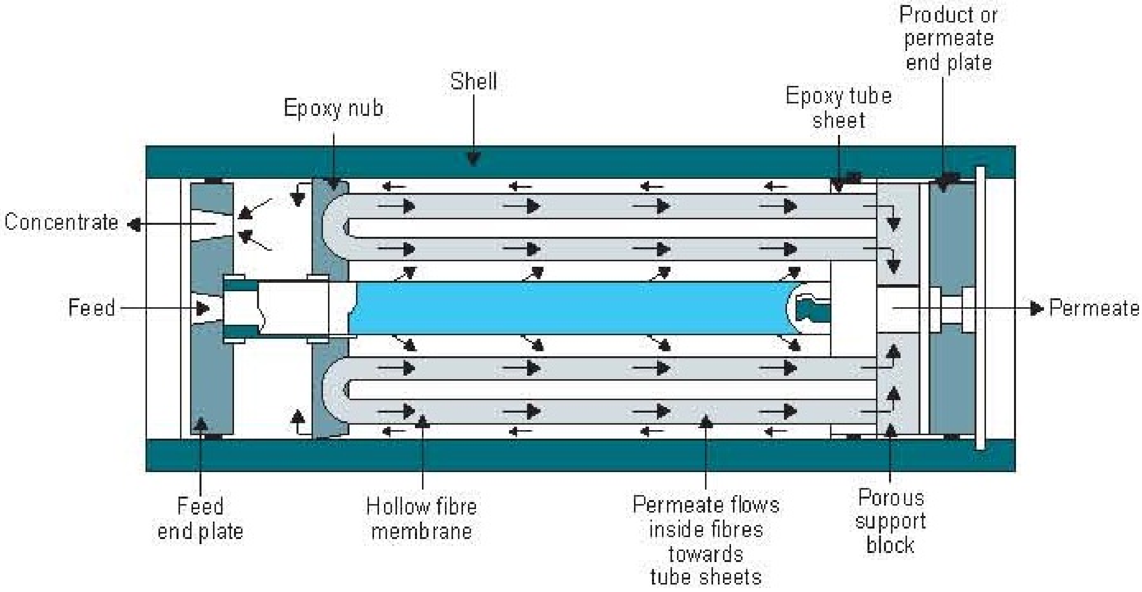


Figure 3.9: Cross section of a Dupont B-9 module (Madaeni and Delijani 2004)

Spiral Wound Modules

The first spiral wound, reverse osmosis modules were produced by the American Gulf Atomic Corporation, which later became part of Universal Oil products (UOP), the construction of a spiral wound module is illustrated in Figure 3.10

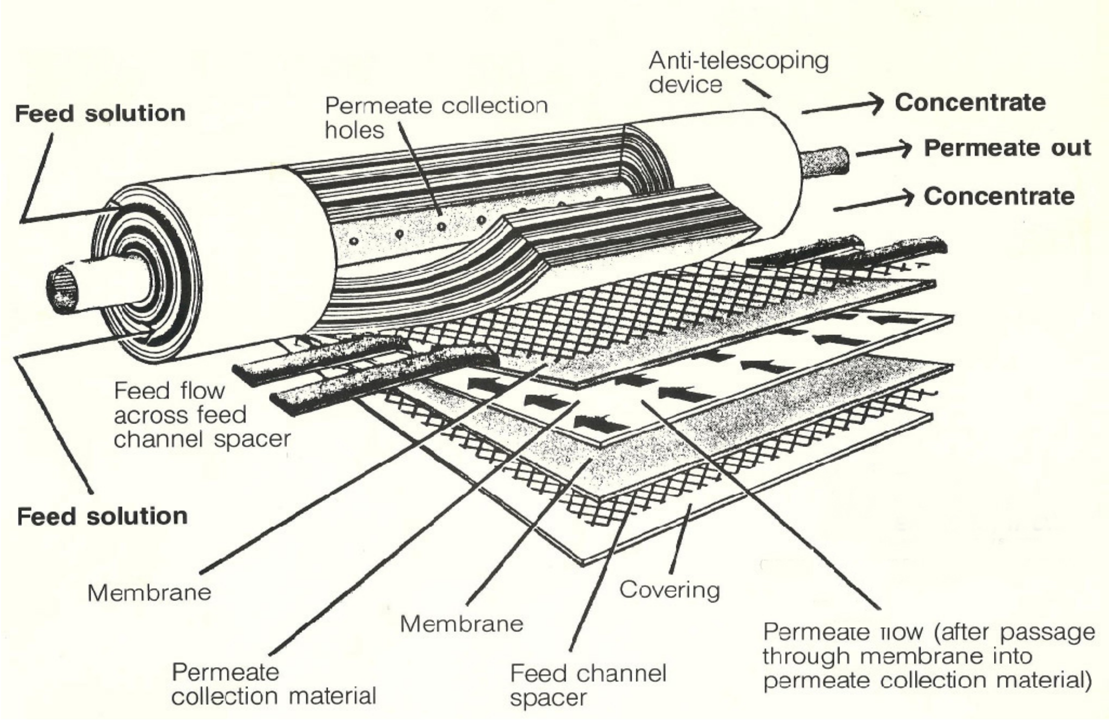
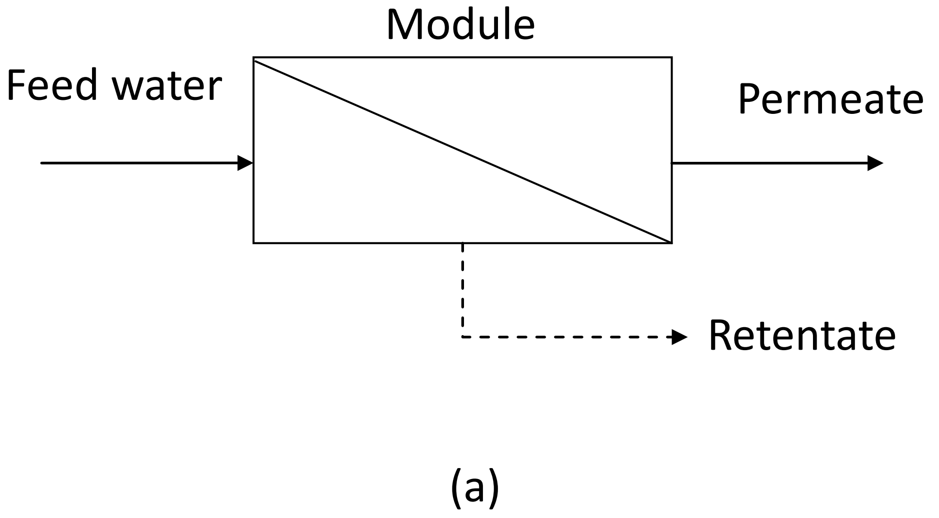


Figure 3.10 Construction of a spiral wound module (Courtesy of Koch Membrane System Inc.)

The spiral-wound modules are designed around flat sheets. Two flat sheets are placed together with their active sides facing away from each other. They are separated by a thin, mesh-like spacer material and are glued together on three sides. The fourth open side is fixed around a perforated center tube. Another mesh-like spacer of the required thickness is placed on one side of this envelope and the whole assembly rolled around the center tube in a spiral configuration.

3.2.2.2 Module Assembly

Continuous and batch flow systems are used in the reverse osmosis process. There are one-pass or multistage one-pass flow systems, as shown in Figure 3.11.



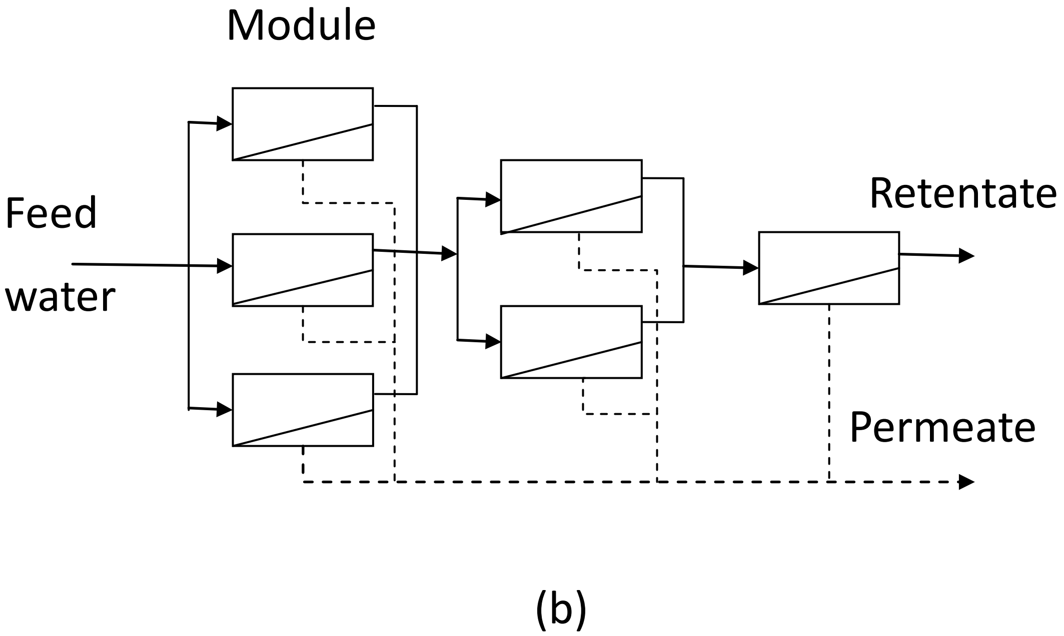


Figure 3.11: (a) one-pass and (b) multistage one-pass system (tapered cascade)

In order to get a higher product water quality, a double pass RO system is used in the design of SWRO desalination plants. In this system, permeate from the first pass is fed to the second pass, as shown in the Figure 3.12.

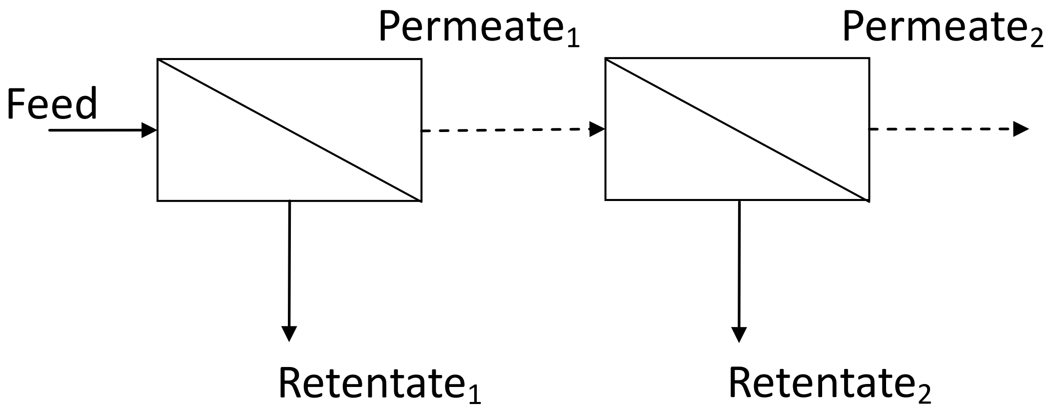


Figure 3.12: The double pass system

In a module, high feed flow rate is very important to reduce the concentration polarization and avoid adsorption of suspended solid on the surface of membranes. As shown in the Figure 3.13, in a circulation system, most of the retentate stream is fed back to the module by a pump, since this system have a high recovery rate.

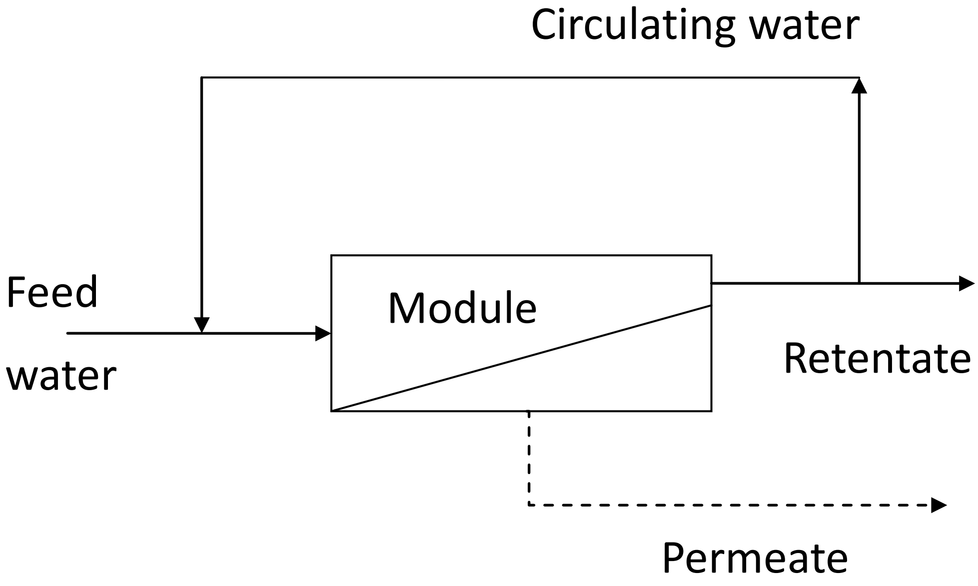


Figure 3.13: Circulation system

3.2.3 Post-treatment

The water treatment processes that take place downstream of RO facilities are called post-treatment processes. Permeate from RO system cannot be distributed directly into the distribution systems. It cannot meet to the public water supply requirements, they are:

- The water shall contain no disease producing organisms.
- It is good tasting, free from odors.
- It is colorless and clear.
- It is free from objectionable gases, and objectionable staining materials, such as Iron and too much Total Hardness (minerals which can be dissolved from concrete/cement pipes due to insufficient post-treatment)
- It is plentiful and low in cost.

The post-treatment of desalination plant is so important, not just for making the water safe to drink, but also to avoid damage to the pipes which delivers water to consumers. The post-treatment generally includes pH adjustment, addition of suitable corrosion inhibitors, removal of dissolved gases such as H_2S (if any) and CO_2, and disinfection (Khawaji, Kutubkhanah et al. 2008).

3.2.3.1 Disinfection

There are a number of ways of disinfecting water. Among these are boiling, ultraviolet light , ozonation and a number of chemicals, the most widely used is chlorine. Each method has its advantages. In evaluating them the following points should be considered:

- A disinfectant should destroy the pathogens within the time available for disinfection.
- A disinfectant should be able to destroy all types of pathogens and in whatever number present in water.
- A disinfectant should function within the temperature and pH range of the water.
- A disinfectant should be safe and easy to handle.
- A disinfectant should not cause the water to become toxic or unpalatable.
- A disinfectant should provide residual protection against the water to be contaminated again.
- A disinfectant`s concentration in water should be easy to determine.

Chlorine is used as a disinfectant in the post-treatment stage. It is normally fed into water with the aid of chemical feed pump(s). The rate of feed is controlled by a Oxidation/Reduction Potential (ORP) probe, which produces a low current measured and amplified. This unit is made such as it has two different "set-points" - which by the operator is adjusted in order to control the feed of chlorine into the water.

Another way to control the needed amount of chlorine is to use a special probe which is designed to measure the chlorine directly. Chlorine needs some contact time in order to work properly, depending on temperature and the pH in the water. What is left after this contact time - is called "residual chlorine".

3.2.3.2 Re-mineralization

Desalinated water is very pure and poor in minerals, it is cannot directly sent to the end users as drinking water, a Double-pass SWRO system designed in order to enhance Boron removal, however the desalinated water from a Double-pass SWRO system will have a low mineralization,

The World Health Organization (WHO) recommends 10 mg/L of Magnesium and 30 mg/L of Calcium for drinking water (F. Kozisek. 2004). There are few adverse effects for low mineralized water:

- High corrosion potential
- Dietary deficiency causing risks of ischaemic heart and cerebrovascular disease

The three most common methods of re-mineralization of desalinated water are:

Addition of chemicals containing calcium and magnesium

Typically only calcium is added to the desalinated water in the form of lime, because lime is less expensive to use for achieving the same target level of total water hardness as compared to using magnesium salts. Most of seawater desalination plants use a sequential feed of calcium hydroxide (hydrated lime) and carbon dioxide to supply hardness and alkalinity to the product water needed to protect distribution system and household plumbing from corrosion. The chemical reaction of re-mineralization using lime and carbon dioxide is (Nikolay Voutchkov 2011):

$$2CO_2+Ca(OH)_2 \rightarrow Ca(HCO_3)_2 \qquad (8)$$

Lime slurry is fed into lime saturators and blended with the desalinated water produced by the desalination process, then it is thoroughly mixed in lime saturator tanks to create saturated limewater which is then injected into the unconditioned desalinated water, as shown in Figure 3.14.

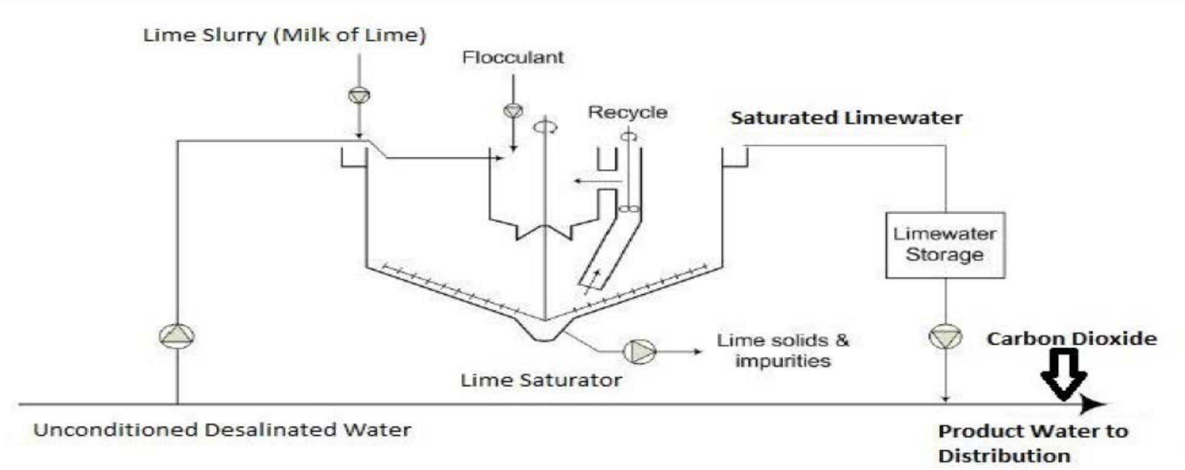


Figure 3.14: Schematic of typical lime/carbon dioxide addition system (Nikolay Voutchkov 2011)

Calcium is added into finished water only for the purpose of corrosion control, however, such water provides limited human health protection, today, magnesium is added in desalinated water as a commercially available food grade product of magnesium sulfate or magnesium chloride.

Mixing of desalinated water with a portion of the source water used for desalination, or with other fresh water sources with high calcium and magnesium content

If desalinated water and seawater are blended, the high level of bromide in the seawater will lead to excessive formation of disinfection byproducts in the product water, which are considered carcinogenic. Therefore mixing of desalinated water with seawater is typically not practiced.

However, in many countries, blending of desalinated water with brackish water is practiced, the brackish water must be treated prior to its mixing with desalinated water, the common treatment methods are cartridge filtration, granular activated carbon filtration and addition of acid.

Addition of dissolving naturally occurring minerals such as limestone (calcium carbonate/calcite) and dolomite (calcium and magnesium carbonate)

Desalinated water through calcite media allows to dissolve this calcium source and in reaction with carbon dioxide to add both calcium hardness and bicarbonate alkalinity to the water. The chemical reaction is:

$$CO_2+CaCO_3+H_20\rightarrow Ca(HCO_3)_2 \qquad (9)$$

From equations (8) and (9), in order to increase 1.0 mg/L of alkalinity and hardness, re-mineralization using calcite requires two times less carbon dioxide. Although 1.0 mg/L of calcite is required as compared to 0.74 mg/L of lime, the cost of lime usually is over two times higher than that of calcite, therefore, the use of calcite usually more cost effective than the use of lime (Nikolay Voutchkov 2011).

Figure 3.15 shows the flow diagram of typical limestone contactor system. The carbon dioxide or sulfuric acid is injected to reduce the pH of desalinated water down to 4.5 or less, then this water pass through a filter bed composed of calcite granules at a contact time of 10-30 minutes, so the target hardness and alkalinity levels are achieved.

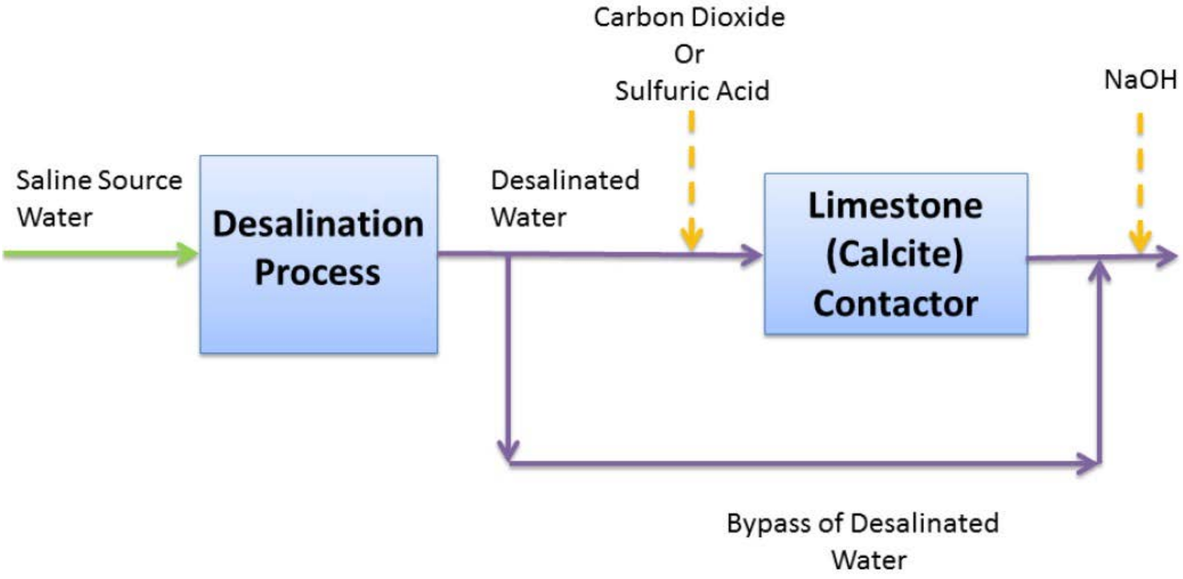


Figure 3.15: The flow diagram of typical limestone contactor system (Nikolay Voutchkov 2011)

Calcite contactors has been successfully applied at a number of SWRO desalination plants, such as Ashkelon 330000 m3/day SWRO plant, Israel; Barcelona 200000 m3/day SWRO plant; Larnaka 60000 m3/day SWRO plant in Cyprus.

As compared to lime system, the advantages of calcite contactor system are:

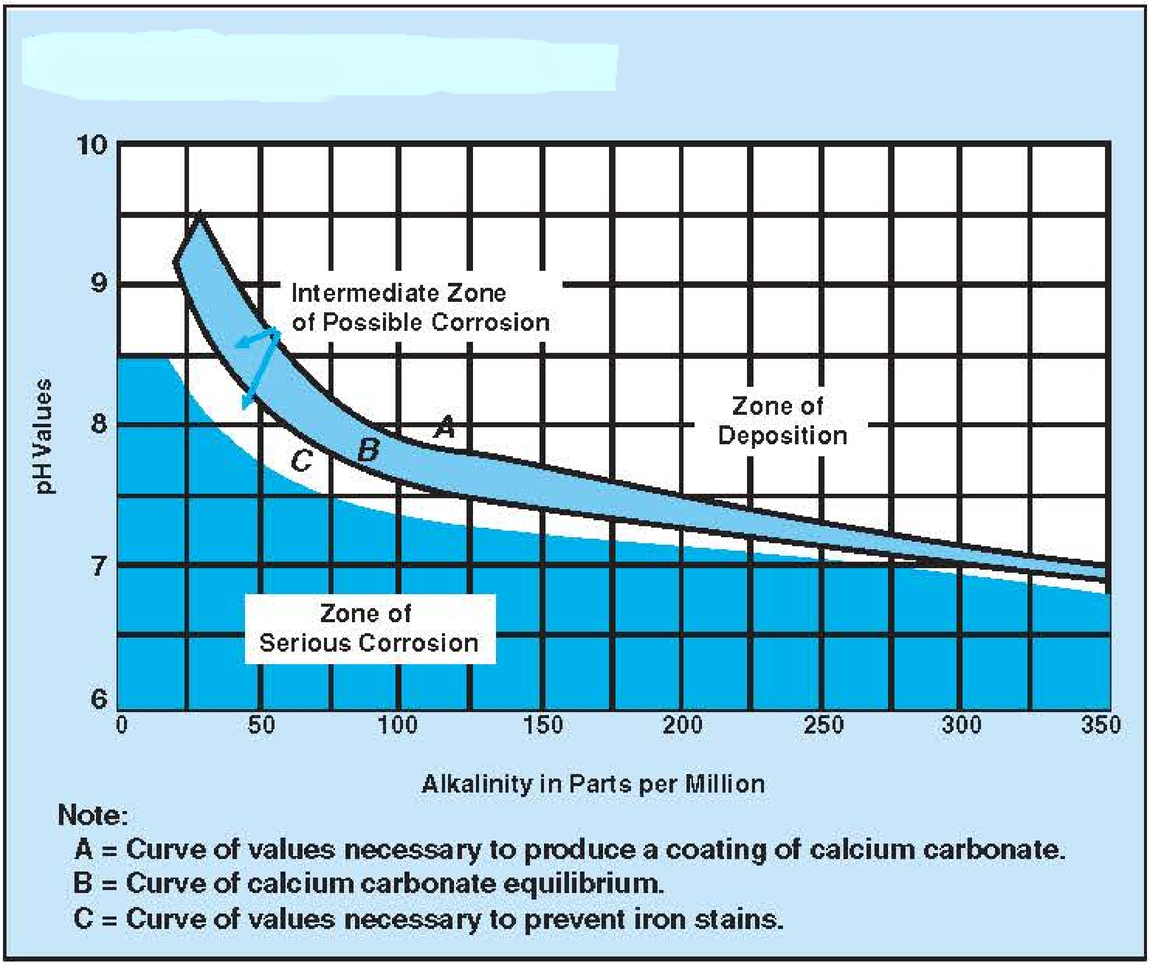
- Less costly in terms of both capital and chemical expenditures
- Require less carbon dioxide
- Produce lower turbidity finished water

However, because the high quality food grade calcite is not as readily available as lime, most of large SWRO desalination plants in many countries, such as Australia, the USA, the Middle East, Spain and North Africa using a combination of lime and carbon dioxide for re-mineralization of desalinated water.

3.2.3.3 Corrosion Control

Judging the corrosivity of a water supply takes technical knowledge, testing, and practical observations. Two measurements of corrosivity are the Baylis curve and the Langelier calcium carbonate saturation index.

The Baylis curve (Figure 3.16) shows the relationship between the pH values and the alkalinity or the solubility of calcium carbonate. Plotting the pH and alkalinity of the water on this chart this chart will indicate whether the water is corrosive or not. If the point where the pH and alkalinity cross is below the curve the water is corro-sive and will attack metal tanks and pipes in the system. If the point is above the curve the water is not corrosive but does have excessive amounts of alkalinity present, which will cause the formation of lime scale in the lines. This scale formation can restrict the flow of water in the line if allowed to build up over a long period of time and can be as bad for the system as corrosive water. Stable water is found in the blue area between the lines and will not cause corrosion problems.



Note:
A = Curve of values necessary to produce a coating of calcium carbonate.
B = Curve of calcium carbonate equilibrium.
C = Curve of values necessary to prevent iron stains.

Figure 3.16: The Baylis curve (Stornes 1996)

The Langelier calcium carbonate saturation index determines the tendency of water to either scale or corrode piping and tanks. This method is based on the assumption that every water has a pH value at which it is stable—that is, it will neither deposit scale nor cause corrosion. This condition is termed saturation. The pH value, called saturation pH (pHs), varies depending on calcium hardness, alkalinity, and temperature. After the pHs is calculated, the Langelier index is found as follows:

Langelier index = pH – pHs

If the pH is less than the pHs, then the water is corrosive. If the pH is greater than the pHs, then the water is likely to form scale. If the pH and pHs are equal, the Langelier index is zero and, theoretically, the water is stable.

Corrosion Iinhibitors

Corrosion inhibitors are used to control corrosion. The most prominent forms of inhibitors used are polyphosphates, zinc phosphates, and silicates. The mechanisms of corrosion control by inhibitors are:

- Sequestering the corrosion byproducts, specifically lead and copper
- Inhibiting scale
- Developing a coating film on the pipe walls
- Buffering the water at the desired pH

pH Adjustment

Adjustment of pH is used to induce the formation of insoluble compounds on the exposed pipe walls. pH adjustment is accomplished with the addition of chemicals, such as lime, soda ash, sodium hydroxide, potassium hydroxide, and carbon dioxide.

The prevention of corrosion and scaling inside delivering system and pipes is very important. Because:

Corrosion can cause aesthetic problems. When corrosion occurs in steel pipes, the rust can break free and be carried to the customer in the water. This phenomenon, known as red water, can stain laundry and plumbing fixtures. In addition, corrosion in the distribution system can result in taste problems.

Corrosion can increase the operating expenses of a water distribution system. For example, when iron mains build up with tuberculation, flow rates and efficiency are reduced. This could lead to the premature replacement of mains.

Corrosive water can cause the leaching of lead and copper into a water supply. Unfortunately, lead leaching problems are not as visible as other types of corrosion problems. To determine lead leaching, the water must be tested for the presence of lead.

Corrosion in delivery system lowers the final product water quality, and causes health hazards. When pipes are corroded, some of the metal from the pipes enters the drinking water and is consumed by the customer.

The formation of scale inside pipelines is a serious problem. It is inconvenient and expensive to clean up. Scaling can impact the performance of pump systems, and decrease the efficiency of entire plant. It is very expensive to clean and replace the pumps, even need stop the plant.

Scaling also causes loss of productivity. Because it forms on the insides of pipes and reduces the area available to carry water.

CHAPTER 4

CASE SYUDIES

In this chapter, some SWRO plants around the world with different production capacity, membrane types and process designs are described. These case studies focus mainly on the location, production capacity, pretreatment system, RO membrane processes, post-treatment of the SWRO plant, the water quality of raw seawater and production water and the production water cost.

4.1 Ashkelon Seawater Desalination Plant

Ashkelon seawater desalination plant in Israel was the world's largest desalination plant by reverse osmosis membrane technology in 2006. The design capacity is 330,000 m^3/d of potable water.

Middle Eastern countries experience shortage of water, due to little rain, long-term droughts and increase in domestic water demand. In 2000 the Israeli governments plan to implement a national Desalination Master Plan, which included the Ashkelon seawater desalination plant.

4.1.1 Plant Design

The first part of Ashkelon seawater desalination plant contract for production of 50 million m^3 per year was signed in November 2001. The second part for the additional 50 million m^3 per year was signed in April 2002 (Sauvet-Goichon 2007). That is why Ashkelon plant has two identical facilities. Each part can produce 165000 m^3 per day of potable water. The plant flow diagram is shown in Figure 4.1.

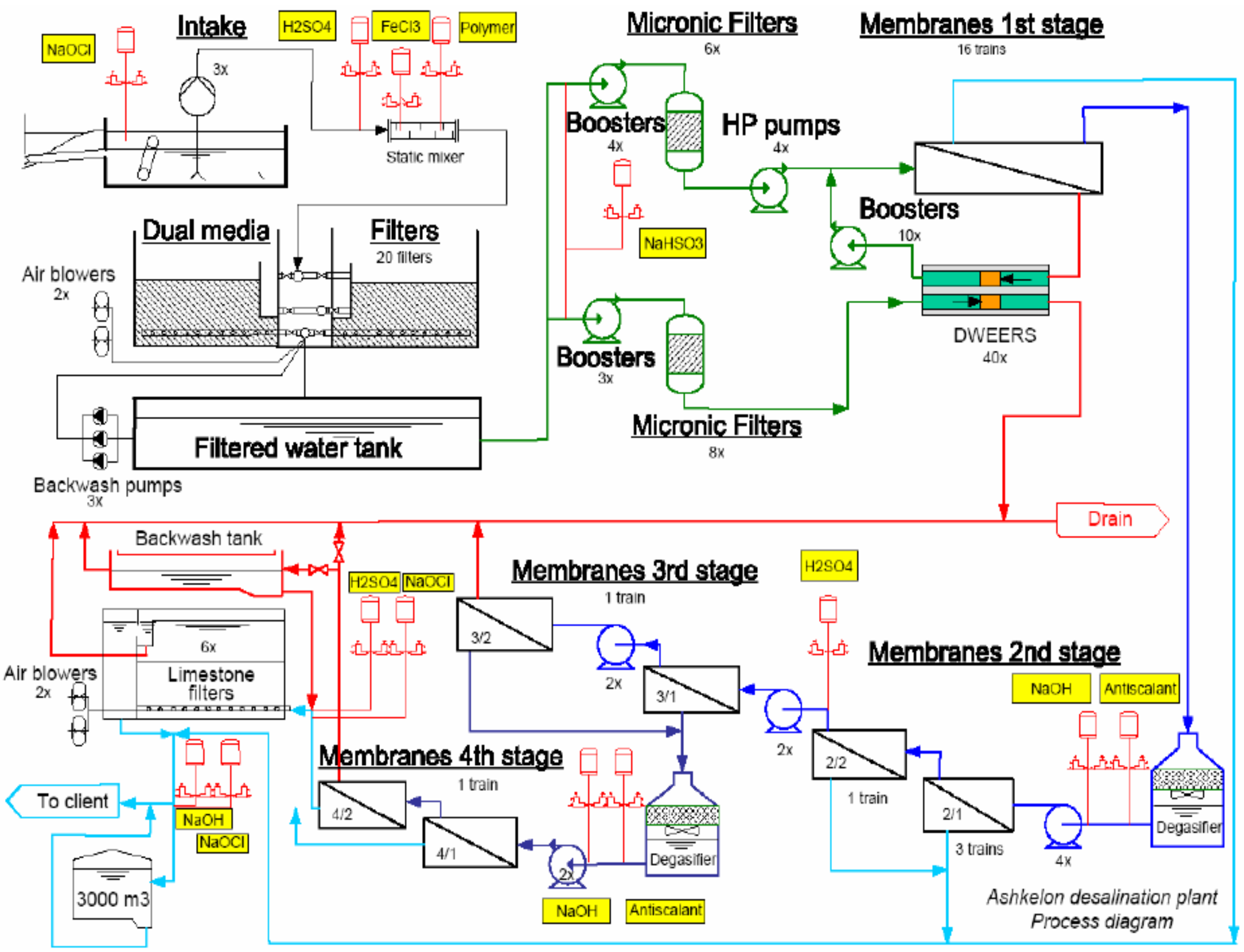


Figure 4.1: The flow diagram of Ashkelon seawater desalination plant(Sauvet-Goichon 2007)

4.1.1.1 Seawater Intake and Pretreatment

There are five vertical pumps providing 35000 m^3/h seawater to the pretreatment process, which contains two separate lines, each of 20 dual media gravity filters. Different kinds of chemicals like ferric sulfate, sulfuric acid and polymer, are added and mixed through static mixers before the water enters the gravity filtration process. Iron chloride is added to coagulate colloids and other particles. Sulfuric acid is added to adjust pH (Kronenberg 2004).

The pretreatment consist two filtration stages. The first stage is two granulated media gravity filters; the second stage is by MF. The first process works by passing the feed water through quart sand and anthracite media inside each of the tanks where the velocity of filtration is 8 m/h. The second process consists of 6 Micronic filters as the final protection barrier of the RO membranes (Lokiec and Kronenberg 2003).

4.1.1.2 Reverse Osmosis Plant

The reverse osmosis seawater desalination plant consists of 4 RO stages, an unusual design made in order to satisfy the water quality requirements. Chloride concentration was required to be less than 20 mg per liter, and the amount of Boron must not exceed 0.4 mg per liter. A flow diagram is shown in Figure 4.2.

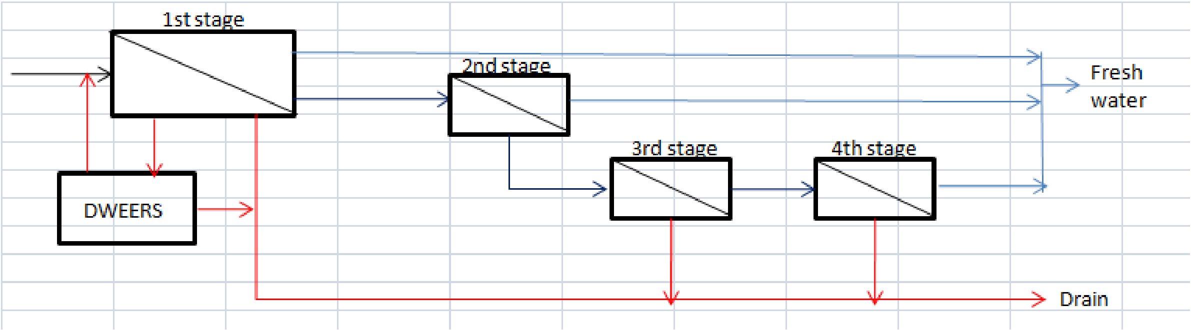


Figure 4.2: Flow diagram of RO membrane process of Ashkelon SWRO plant

1st stage

1st stage consisted of three different units, which at the time was quite unique and contained high pressure pumps, energy recovery devices and membrane units; a design offering flexibly and efficient. At the Ashkelon desalination plant this construction was the first time such a design was used on a large scale. However, it is a conventional RO desalination system, 4 high pressure pumps are used to feed the filtered water to the membrane units, which contain 16 trains. An energy recovery device consists of 40 DWEERtm units which are used to recover energy which in turn decreases net demand for power to the high-pressure pumps (Gorenflo, Brusilovsky et al. 2007).

Some of the permeate go directly to the end user. The remaining part of the permeate from the 1st stage will go to the 2nd stage. The recovery of 1st stage is approximately 45%.

2nd stage

The 2nd stage contains 4 trains, operated at pH >10 in order to remove the Boron. Recovery of this stage is 85%, and permeate has low concentration of Boron ions.

The 3rd stage

In this stage, one train is used. The purpose is to remove Ca and Mg ions as much as possible, operated at low pH which leads to a high concentration of Boron in the permeate. Therefore this permeate is not mixed with permeate from 1st and 2nd stage, must be treated by a 4th stage (Gorenflo, Brusilovsky et al. 2007).

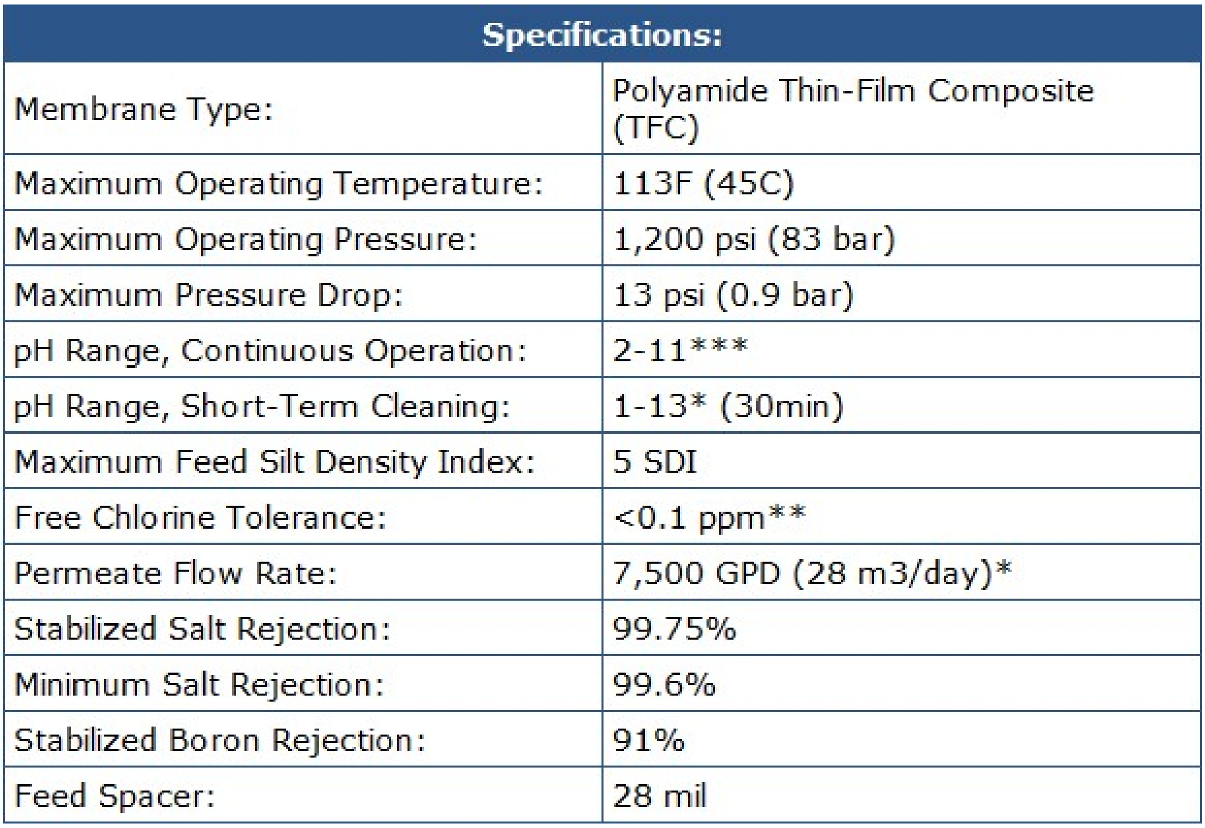
The 4th stage

The fourth stage uses one train which is operated at a high pH level, similar to the 2nd stage, as the high pH level assists in the removal of Boron-as in the 2 stage. Most of the Boron be now removed, and permeate is blended with the other permeates.

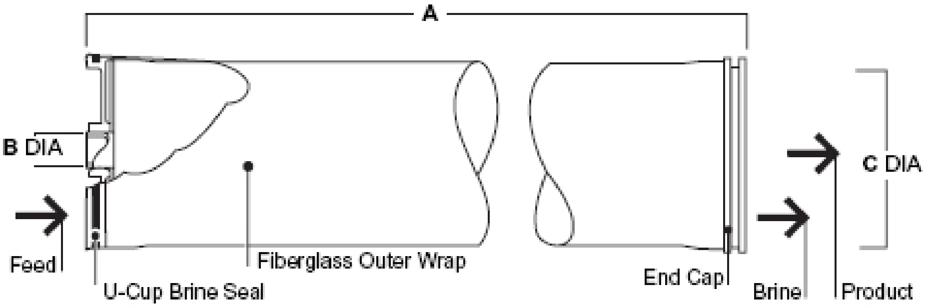
Film Tec membrane have been selected for the RO process. The total quantity of membrane:

25600 Film Tec (DOW) seawater type membranes, type SW30HRLE-400 (flow rate 7500 GPD, stabilized salt rejection 99.75%) are used for 1st stage (Brusilovsky and Faigon 2005). The Specifications and dimensions of the Film Tec SW30HR LE-400 element are shown in Figure 4.3.

15600 Film Tec (DOW) brackish water membranes are installed in 2nd stage, 3rd stage and 4th stage. 10400 BW30LE-440 membranes in 2nd stage, 2600 BW30-400 membranes in 3rd stage and 2600 BW30LE-440 membranes in 4th stage. The product information of BW30LE-440 and BW30-400 membranes is shown in APPENDIX 1.



Specifications:	
Membrane Type:	Polyamide Thin-Film Composite (TFC)
Maximum Operating Temperature:	113F (45C)
Maximum Operating Pressure:	1,200 psi (83 bar)
Maximum Pressure Drop:	13 psi (0.9 bar)
pH Range, Continuous Operation:	2-11***
pH Range, Short-Term Cleaning:	1-13* (30min)
Maximum Feed Silt Density Index:	5 SDI
Free Chlorine Tolerance:	<0.1 ppm**
Permeate Flow Rate:	7,500 GPD (28 m3/day)*
Stabilized Salt Rejection:	99.75%
Minimum Salt Rejection:	99.6%
Stabilized Boron Rejection:	91%
Feed Spacer:	28 mil



A: 40.0" (1,016mm)
B: 1.125" (29mm)
C: 7.9" (201mm)

Figure 4.3: Specifications and dimensions of the Film Tec SW30HR LE-400 element

4.1.1.3 Post-treatment

Usually a post treatment process is needed for the product water before it is sent to the end user, in order to achieve the drinking water quality standards and to prevent corrosion of the transport pipes. In the Ashkelon plant six limestone filters be installed to remineralise the water, and to adjust alkalinity, hardness and pH.

4.1.2 Ashkelon SWRO Plant Data

Some key data is presented in Table 4.1.

Table 4.1: Key data of the Ashkelon SWRO plant (Sauvet-Goichon 2007)

Key data	
Maximum total production capacity	110 million m^3/y
Government purchase agreement	100 million m^3/y
Water price	＄0.527/m^3
Project cost	NIS 1000million(＄212 million)
Plant footprint	75000 m^2 (300×200m)
Power plant	Dedicated gas turbine---80MW capacity
Grid connection	161 kV overhead line
Maximum nominal electrical consumption	< 3.9 kWh/m^3

The quality of the product water is very important, it must cope with the potable water quality standards in this area. The data show in the Table 4.2

Table 4.2: The water quality data of Ashkelon plant (Dreizin Yosef. 2006; Sauvet-Goichon 2007)

Water data	
Feed seawater temperature	15-30 ºC
Feed seawater salinity	40679 ppm TDS
Product water before post treatment	<80 ppm TDS <20 ppm Cl <40 ppm Na <0.4 ppm Boron
Product water after post treatment	<300 ppm TDS
Product water pH	7.5-8.2
Product water Langlier Index	0-0.5
Product water turbidity	<0.5 NTU

4.2 Barcelona-Llobregat Desalination plant

Barcelona-Llobregat desalination plant was the largest seawater desalination plant in Europe with a production of 200,000m^3/d and one of the largest in the world. The desalination plant is designed to produce approximately 20% of the total potable water demand for Barcelona's metropolitan area and will also improve the water quality (especially TDS) in Barcelona's southwest area.

4.2.1 Location

The RO plant is located at El Prat, an industrial area between Barcelona Harbour and Llobregat mouth. This is not far from Barcelona airport and close to one of the waste water treatment plants of Barcelona, Baix Llobregat WWTP (Miguel Angel SANZ., Carlos MIGUEL. et al. 2011).

4.2.2 Plant Design

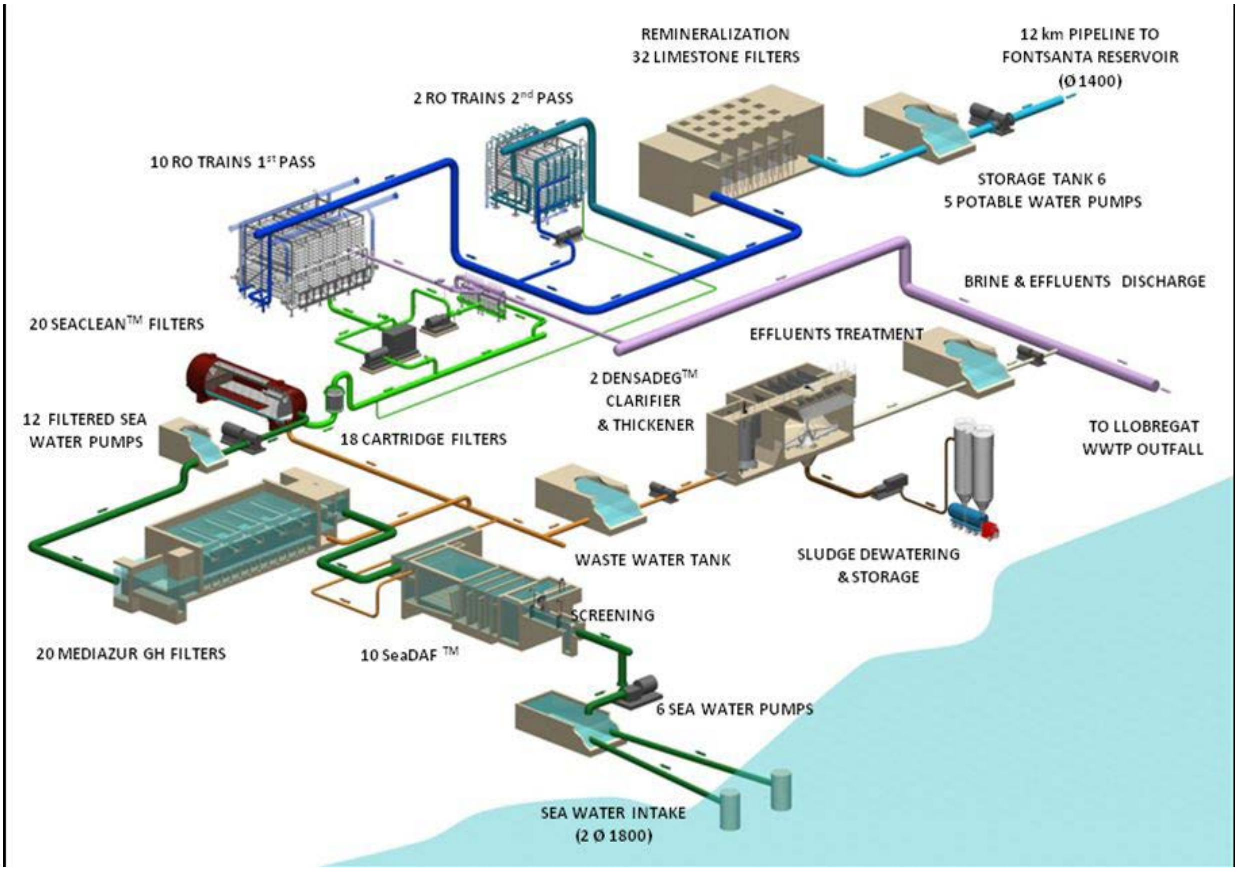


Figure 4.4: Plant flow sheet of Barcelona-Llobregat desalination plant (Miguel Angel SANZ., Carlos MIGUEL. et al. 2011)

4.2.2.1 Pretreatment

The pretreatment contain three stages, as shown in Figure 4.5.

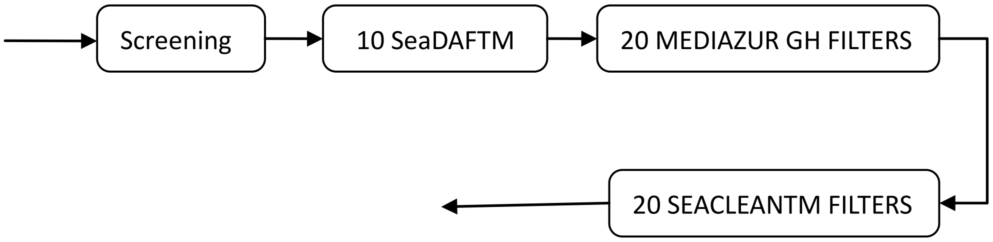


Figure 4.5: The pretreatment process of Barcelona-Llobregat desalination plant

The first stage is clarification with 10 SeaDAF® flotators, 5 per line. SeaDAF™ (Figure 4.6) is an air flotation system for seawater clarification. Its unique design allows the treatment of very large volumes of water. It is adapted to the clarification of seawater presenting occasional peaks in suspended solids and algal bloom.

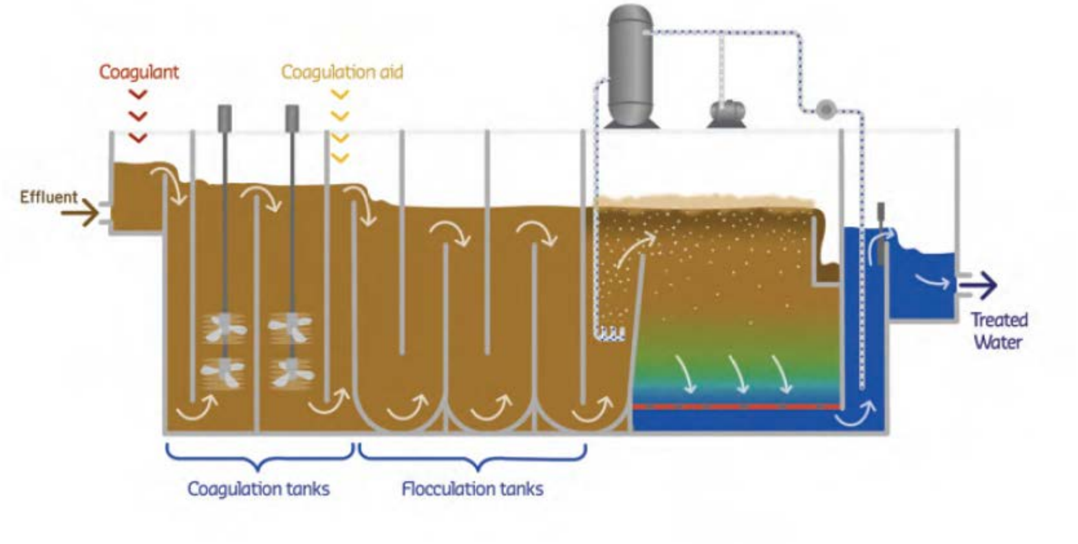


Figure 4.6: The SeaDAF™ process (environnement---Degremont 2011)

The seawater will pass through four automatic 3 mm sieves, after disinfection, chlorine dioxide, hypochlorite or potassium permanganate. the water enters the SeaDAF™ process which contain two coagulation chambers, each of 250 m^3 and 10 floaters, 78m^2 in size.

Then the clarified water enters three consecutive filtration stages. the first filtration stage composed of two lines in parallel with 10 Mediazur® filters (Degrémont's Mediazur type), totally using twenty opened gravity double-layered filters with a uniform surface of 155 m^2 with two different types of filter beds. The upper one is made up of a coarser, low density material which retains most particles. The lower filter bed is finer and dense.

The second filtration stage have 20 SeaClean® dual media pressurized filters (Degrémont's FH type), divided in two lines. The unitary surface is 66 m2, one of the largest in the World for pressurized filters.

The third and last filtration stage is carried out using 18 cartridge filters with 360 cartridges of 5 μm each that provide reverse osmosis protection (medioambiente 2008).

4.2.2.2 Reverse Osmosis Process

The RO plant is composed of two pass stages as follow:
1st pass contain 10 trains of 240 pressure vessels with 7 elements inside, a hybrid design be used in here with two types of membranes, SWC4+ and SWC5 of Hydranautics. The recovery rate is 45% (Miguel Angel SANZ 2008). The information of SWC4+ and SWC5 membrane is shown in APPENDIX 2.

2nd pass contain 4 trains of 48 pressure vessels with 7 elements (ESPAB) inside, the recovery rate is 85%. The trains have two stages (36 pressure vessels in the 1st stage and 12 in the 2nd).

4.2.3 Parameters of Treated Water

The quality of treated water achieved the expected target values shown in Figure 4.7-4.13 (Miguel Angel SANZ., Carlos MIGUEL. et al. 2011):

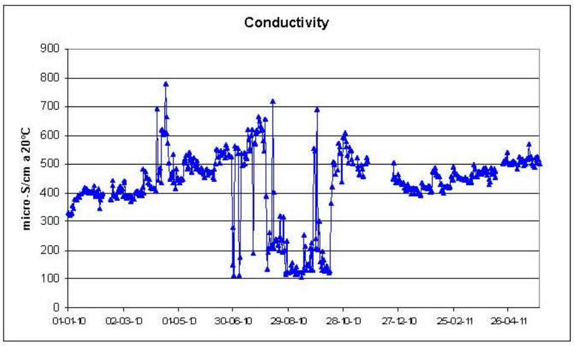


Figure 4.7: Potable water conductivity

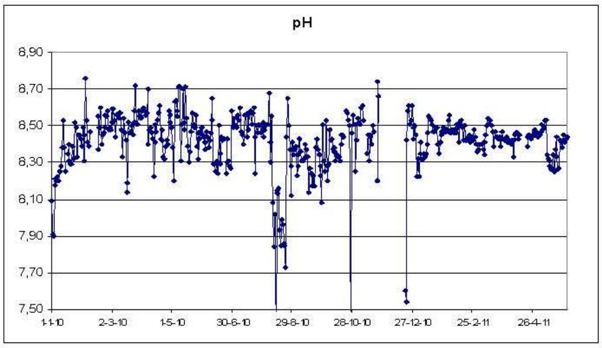


Figure 4.8: Potable water pH

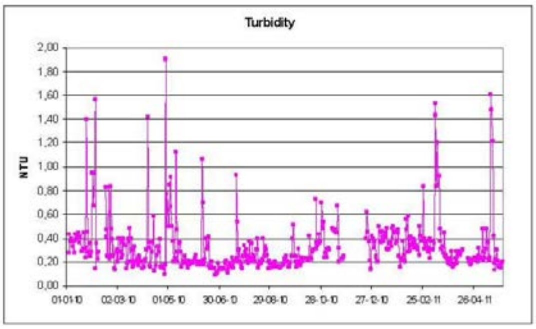


Figure 4.9: Potable water turbidity

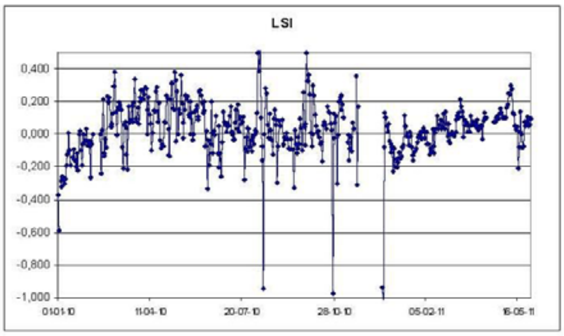


Figure 4.10: Potable water LSI

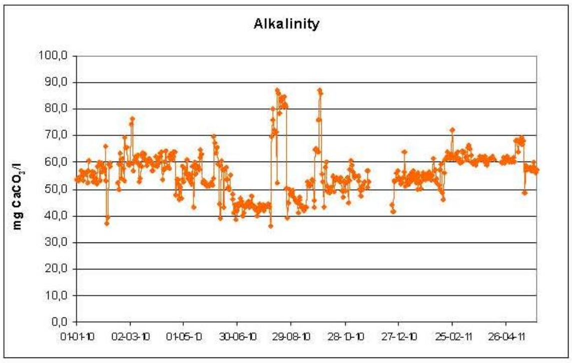


Figure 4.11: Potable water alkalinity

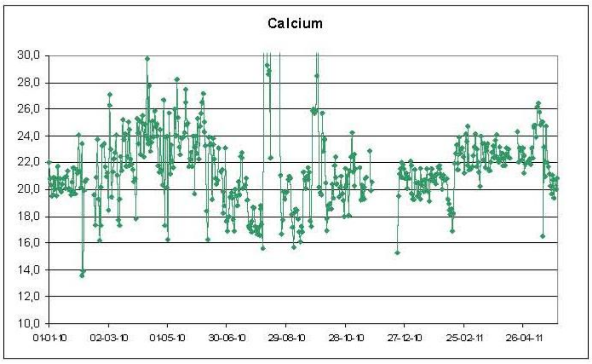


Figure 4.12: Calcium in potable water

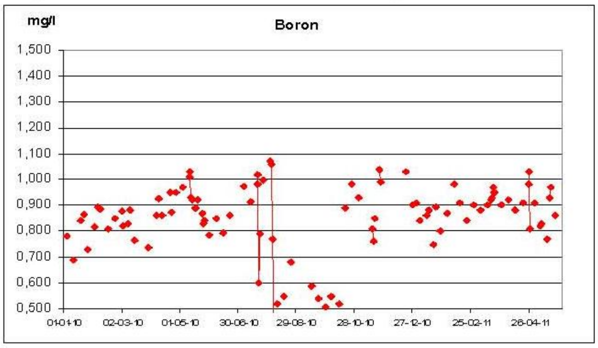


Figure 4.13: Boron in potable water

4.3 Uminonakamichi Nata seawater desalination plant

The Uminonakamichi Nata sea water desalination project is a part of the Fukuoka Wide Area Water Supply Improvement Project, also known as Fukuoka seawater desalination plant. The daily production capacity of this plant is 50,000 m^3. The total project cost including the convey pipe is 40.8 billion yen.

4.3.1 Background of the project

The preparation and construction of the desalination plant have lasted approximately 10 years (from 1996 to 2005). Table 4.3 shows the main events.

Table 4.3: Background of the Uminonakamichi Nata sea water desalination project (Fukuoka District Waterworks Agency. 2007)

Year	Events
1996	An exploratory committee on the sea water desalination project was established in the Fukuoka urban areas.
1997	The Fukuoka Wide Area Water Supply Improvement Plan was established.
1998	The Sea Water Desalination Project was approved.
1999	An open-type technical proposal evaluating method was adopted for the construction of plan facilities and water intake system; Acquisition of the plant facilities building site and Aqueduct pipe laying.
2000	Contract for the construction of plant facilities and the water intake system was signed; Piling, water intake well construction, start of shaft construction; Verification test facility construction (Nata fishery harbor); Aqueduct pipe laying; Ceremony to pray for safety.
2001-2004	Plant facilities construction; Water intake system installation; Construction of the Tatara facility complex; Discharge facilities construction; Overall adjustment, trial ran
2005	Service commenced and official name and common name were determined

4.3.2 Plant Design

The Uminonakamichi Nata Seawater Desalination Plant produces maximum 50,000 m^3 per day of freshwater from approximately 103,000 m^3 per day of seawater, leaving 53,000 m^3 per day of concentrated seawater. The desalination process main contains seawater intake system, pretreatment, RO process and post-treatment. The flow diagram is shown in Figure 4.14.

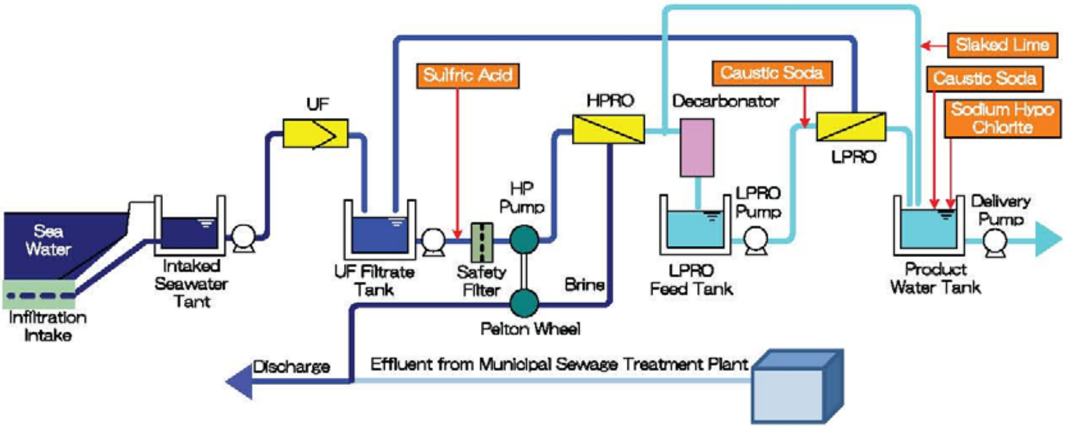


Figure 4.14: The flow diagram of the Uminonakamichi Nata desalination plant (SHIMOKAWA 2008)

4.3.2.1 Seawater Intake System

The intake system of Uminonakamichi Nata desalination plant was called as an open sea water osmosis intake system, a natural sand filtration method was used in this system to collect clear seawater of four or less in the SDI value, as shown in the Figure 4.15.

Water intake pipes which have tiny holes are installed at the bottom of the sea underground, and the clear seawater will flow into the intake pipe, for the water level of intake tank is lower than the sea level, the water flow rate is very slow approximately 6m/day. There are no protruding structures in the sea, so it does not have a harmful impact on the surrounding environment (Fukuoka District Waterworks Agency. 2007).

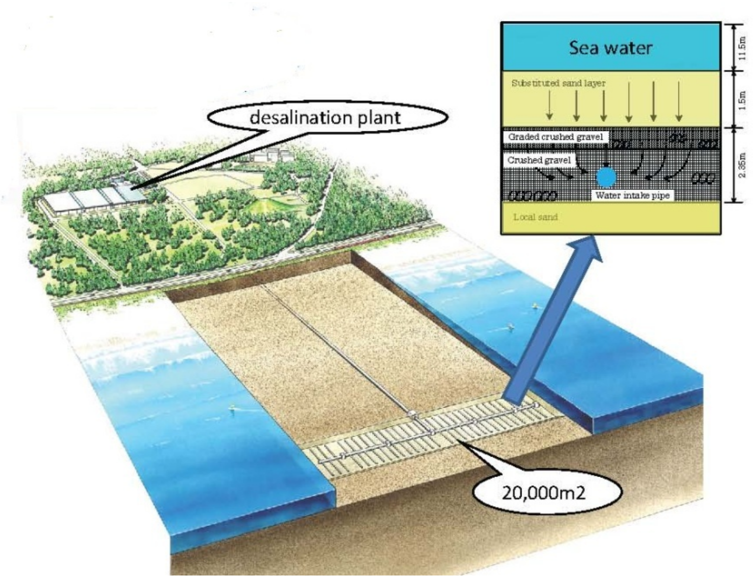


Figure4.15: The open sea water osmosis intake system (SHIMOKAWA 2008)

4.3.2.2 Pre-treatment

There is a unique method for per-treatment process – UF membrane preprocessing, this is the first time that UF membrane is used in Japan instead of the sand filtration. The clear seawater is pumped to 12 UF membrane units by six intake pumps. Compared with the conventional dual media filter, the advantages of UF membrane are:

- Perfect removal of turbidity
- Consistent low SDI
- Easy operation
- Easy maintenance
- The frequency of cleaning is decreased

3060 Nitto Denko Corporation UF membranes, type RS50-S8, arranged in 3 membranes per pressure vessel. RS50-S8 is a back-washable spiral wound element.

4.3.2.3 Reverse Osmosis Process

The RO plant contains high-pressure RO stage and low-pressure RO stage, it is composed of five lines, each line has maximum capacity of 10000m3/d.

<u>The high-pressure RO stage</u>

Each line consists of high-pressure pump, cartridge filter, high-pressure RO membrane unit and an energy recovery device. The seawater filtrated by UF membrane flows into the 50 µm cartridge filter which act as final safety barrier for RO membranes by high-pressure pump, then seawater is converted to freshwater by the RO membrane of the hollow fiber type, a part of fresh water flows directly into the product water intake, the rear fresh water is sent as feed to the low-pressure RO stage.

Toyobo Co., Ltd. is supplying the high-pressure hollow fiber type reverse osmosis membrane modules to the Fukuoka seawater desalination plant. 2100 elements, type HB10255FI, are installed in this stage.

<u>The low-pressure RO stage</u>

The low-pressure RO stage aims to achieve optimal Boron removal, after the first high-pressure RO membrane stage, the Boron concentration of pure water is approximately 4mg per liter, however, the standard of water quality for Boron is less than 1.0 mg per liter in Japan, the secondly low-pressure membrane produces pure water with Boron concentration less than 1.5 mg per liter, then mixing the product water with purified river water meets the water quality standard (Boron ≤ 1.0 mg/L) (SHIMOKAWA 2008).

1200 Nitto Denko Corporation low-pressure RO membranes, type ES20B-D8, are installed. ES20B-D8 is a fully aromatic polyamide super low-pressure spiral RO membrane element. It removes boron in high-pressure RO membranes permeate. The rejection is about 80% at pH 9. The product information of ES20B-D8 is shown in Table 4.4.

Table 4.4: The product information of ES20B-D8 (Nitto Denko Corporation 2012)

ES20B-D8

<table>
<tr><td>Features</td><td colspan="2">The NaCl rejection is as high as 99.7%
Enables extremely low-pressure operations at 0.5-0.6MPa</td></tr>
<tr><td>Sizes [mm]</td><td colspan="2">Φ201×1,016L</td></tr>
<tr><td rowspan="2">Permeate Flow [m3/d]</td><td>Nominal</td><td>Minimum</td></tr>
<tr><td>30</td><td>26</td></tr>
</table>

<table>
<tr><td colspan="5">Operating Conditions</td></tr>
<tr><td colspan="2">Item</td><td>Unit</td><td>Recommended operating condition</td><td>Usage Limit</td></tr>
<tr><td colspan="2">Operating pressure</td><td>MPa</td><td>Set according to the designed flux</td><td>Max.4.1</td></tr>
<tr><td colspan="2">Operating temperature</td><td>°C</td><td>5-30</td><td>Max.4.1</td></tr>
<tr><td colspan="2">Turbid content in feed water as FI value</td><td>-</td><td>≤3</td><td>Max.4</td></tr>
<tr><td colspan="2">Concentration of residual chlorine</td><td>Mg / L</td><td>0</td><td>Max.1.0(during cleaning)</td></tr>
<tr><td colspan="2">pH range</td><td>-</td><td>6-8(permissible range: 2-10)</td><td>1-11 (during cleaning)</td></tr>
<tr><td rowspan="2">Pressure drop</td><td>1 element</td><td rowspan="2">KPa</td><td><50</td><td>Max.82</td></tr>
<tr><td>Over 5 element</td><td><200</td><td>Max.420</td></tr>
</table>

* *Above figures are only for the purpose of guidelines and not the guaranteed figures*

4.3.2.4 Brine Water Discharge

Only the brine water from high-pressure RO membrane stage is discharged to the sea, the retentate from low-pressure RO membrane stage flows back to UF membrane filtration tank as the feed water of high-pressure RO membrane stage. The salinity concentration of concentrated seawater is approximately 7%, so it cannot be discharged directly into the HAKATA bay. The concentrated seawater is mixed with the sewage disposal water which is produced from Wajiro water treatment center in the discharge tank, because there is no salt in the sewage water, the salinity concentration of the mixed water will be reduced to 3.5%, then it is discharged to the HAKATA bay.

Figure4.16 shows the conceptual diagram and detailed data

4.3.3 Water Quality

The seawater quality after preprocesses and it of the production water and the blend water are steady. Table 4.5 shows the water quality of The Uminonakamichi Nata seawater desalination plant in 2007.

Table 4.5: The water quality of The Uminonakamichi Nata seawater desalination plant in 2007 (SHIMOKAWA 2008)

	Filtrated sea water	Desalted water	Mixed water	standard
Total dissolved solids	40200	108	138	=<500mg/l
Chloride ion	20300	42.1	32.0	=<200mg/l
Sodium and its compounds	10800	26.1	23.7	=<200mg/l
Sulfate ion		2.5		
Hardness	6580	19.1	50.5	=<300mg/l
Electric conductivity	51700	178	225	
Boron and its compounds	4.5	1.4	0.61	=<1.0mg/l

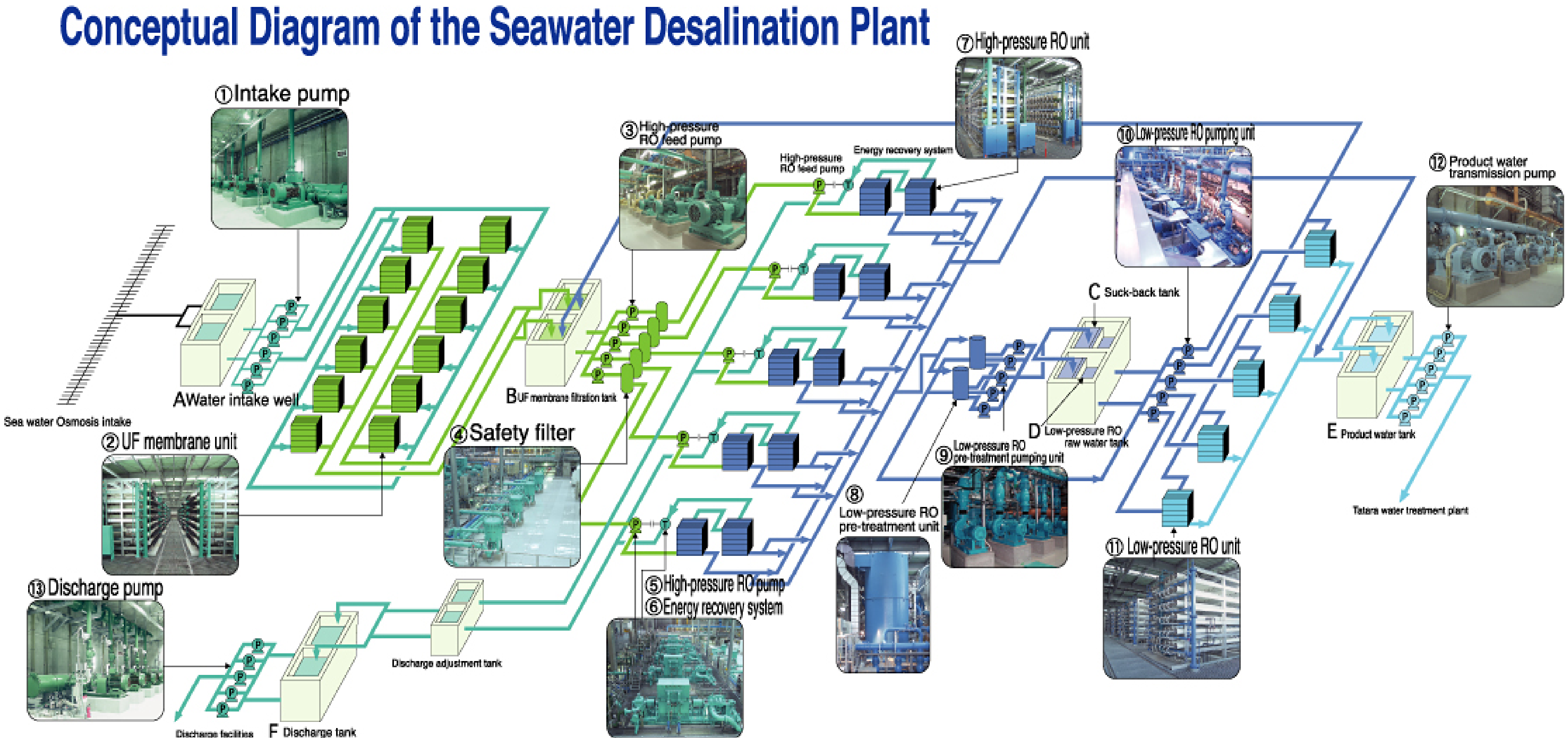
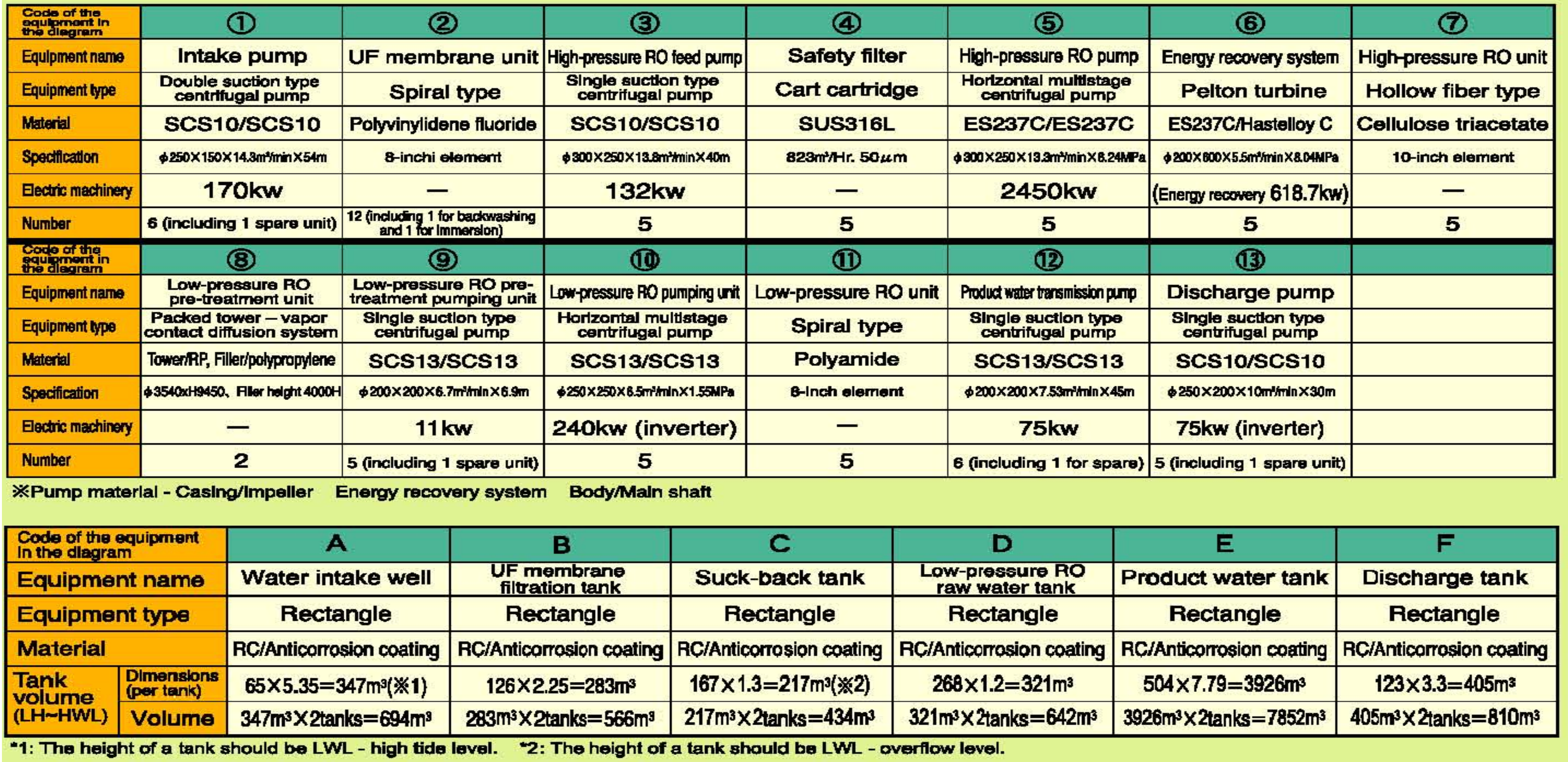


Figure 4.16: (a) The conceptual diagram of the Uminonakamichi Nata seawater desalination plant (Fukuoka District Waterworks Agency. 2007)



Code of the equipment in the diagram	①	②	③	④	⑤	⑥	⑦
Equipment name	Intake pump	UF membrane unit	High-pressure RO feed pump	Safety filter	High-pressure RO pump	Energy recovery system	High-pressure RO unit
Equipment type	Double suction type centrifugal pump	Spiral type	Single suction type centrifugal pump	Cart cartridge	Horizontal multistage centrifugal pump	Pelton turbine	Hollow fiber type
Material	SCS10/SCS10	Polyvinylidene fluoride	SCS10/SCS10	SUS316L	ES237C/ES237C	ES237C/Hastelloy C	Cellulose triacetate
Specification	ϕ250×150×14.3m^3/min×54m	8-inchi element	ϕ300×250×13.8m^3/min×40m	823m^3/Hr. 50μm	ϕ300×250×13.3m^3/min×6.24MPa	ϕ200×600×5.5m^3/min×8.04MPa	10-inch element
Electric machinery	170kw	—	132kw	—	2450kw	(Energy recovery 618.7kw)	—
Number	6 (including 1 spare unit)	12 (including 1 for backwashing and 1 for immersion)	5	5	5	5	5

Code of the equipment in the diagram	⑧	⑨	⑩	⑪	⑫	⑬	
Equipment name	Low-pressure RO pre-treatment unit	Low-pressure RO pre-treatment pumping unit	Low-pressure RO pumping unit	Low-pressure RO unit	Product water transmission pump	Discharge pump	
Equipment type	Packed tower – vapor contact diffusion system	Single suction type centrifugal pump	Horizontal multistage centrifugal pump	Spiral type	Single suction type centrifugal pump	Single suction type centrifugal pump	
Material	Tower/RP, Filler/polypropylene	SCS13/SCS13	SCS13/SCS13	Polyamide	SCS13/SCS13	SCS10/SCS10	
Specification	ϕ3540xH9450、Filler height 4000H	ϕ200×200×6.7m^3/min×6.9m	ϕ250×250×6.5m^3/min×1.55MPa	8-inch element	ϕ200×200×7.53m^3/min×45m	ϕ250×200×10m^3/min×30m	
Electric machinery	—	11kw	240kw (inverter)	—	75kw	75kw (inverter)	
Number	2	5 (including 1 spare unit)	5	5	6 (including 1 for spare)	5 (including 1 spare unit)	

※Pump material - Casing/Impeller Energy recovery system Body/Main shaft

Code of the equipment in the diagram		A	B	C	D	E	F
Equipment name		Water intake well	UF membrane filtration tank	Suck-back tank	Low-pressure RO raw water tank	Product water tank	Discharge tank
Equipment type		Rectangle	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle
Material		RC/Anticorrosion coating	RC/Anticorrosion coating	RC/Anticorrosion coating	RC/Anticorrosion coating	RC/Anticorrosion coating	RC/Anticorrosion coating
Tank volume (LH~HWL)	Dimensions (per tank)	65×5.35=347m^3(※1)	126×2.25=283m^3	167×1.3=217m^3(※2)	268×1.2=321m^3	504×7.79=3926m^3	123×3.3=405m^3
	Volume	347m^3×2tanks=694m^3	283m^3×2tanks=566m^3	217m^3×2tanks=434m^3	321m^3×2tanks=642m^3	3926m^3×2tanks=7852m^3	405m^3×2tanks=810m^3

*1: The height of a tank should be LWL - high tide level. *2: The height of a tank should be LWL - overflow level.

Figure 4.16: (b) The conceptual diagram of the Uminonakamichi Nata seawater desalination plant (Fukuoka District Waterworks Agency. 2007)

4.4 Fujairah SWRO Desalination Plant

Fujairah SWRO desalination plant is part of the Fujairah power and desalination plant, which is a hybrid plant with a production capacity of 454,000 m^3 per day, 283,500 m^3 per day from 5 MSF units coupled with the power plant and 170,500 m^3 per day from the SWRO desalination plant.

4.4.1 Location

The plant is located next to the Qidfa Power Station 5 kilometers south of Khor Fakkan and 20 kilometers north of the city of Fujairah in the United Arab Emirates. Figure 4.17 shows the site of this plant on the Gulf of Oman just before the Hormuz strait. Most of product water will be pumped back to Abu Dhabi Emirate and mainly to the Al-Ayn area to be used there for irrigation purpose (Sanza, Bonnélyea et al. 2007).

Figure 4.17: the site of Fujairah SWRO desalination plant (Sanza, Bonnélyea et al. 2007)

4.4.2 Plant design

Intake system

The seawater intake system is located at 380 m from the seashore at 6 m above the seabed and 10 m below the surface. One of the three intake structures is used for the RO plant, and others serve the MSF plants and power stations at the same time, in order to avoid on the RO line the continuous chlorination used on all the other.

Pretreatment system

An automatic dosing system ensures that sulphuric acid, ferric chloride and polymer, are dosed proportionally to the incoming flow but the dose set points are set manually in relation to the monitored seawater quality. This system able to dose up to 25 mg/L H2SO4, 5 mg/L FeCl3 and 1.5 mg/L polymer. These chemicals are mixed with the seawater in two static mixers and two coagulation tanks.

There are 2 lines of 7 gravity dual-media filters with 8.5 to 9.5 m/h working rate, each filter being capable of handing up to 1500 m^3/h of seawater. The filters are also run automatically with backwashing initiated either on time or pressure drop. The backwash procedure is Degrémont standard air scour followed by water rinsing with at a water flow rate such as to reclassify the media by expanding both media within. Such a precise control of the expansion requires (Sanza, Bonnélyea et al. 2007):

- The right selection of the material of the 2 media (grain size and apparent density against seawater).
- The capability to vary the backwash flow rate with temperature to compensate for the associated change in seawater viscosity.

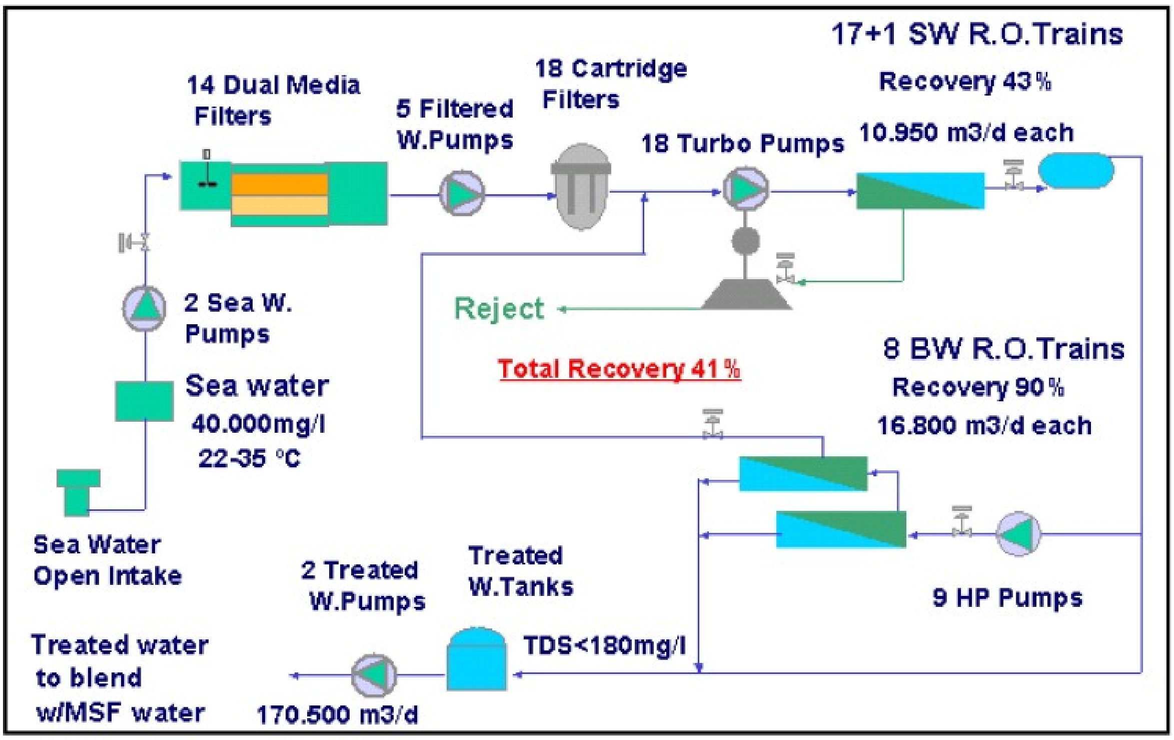


Figure 4.18: Flow diagram of Fujairah SWRO desalination plant (Sanza, Bonnélyea et al. 2007)

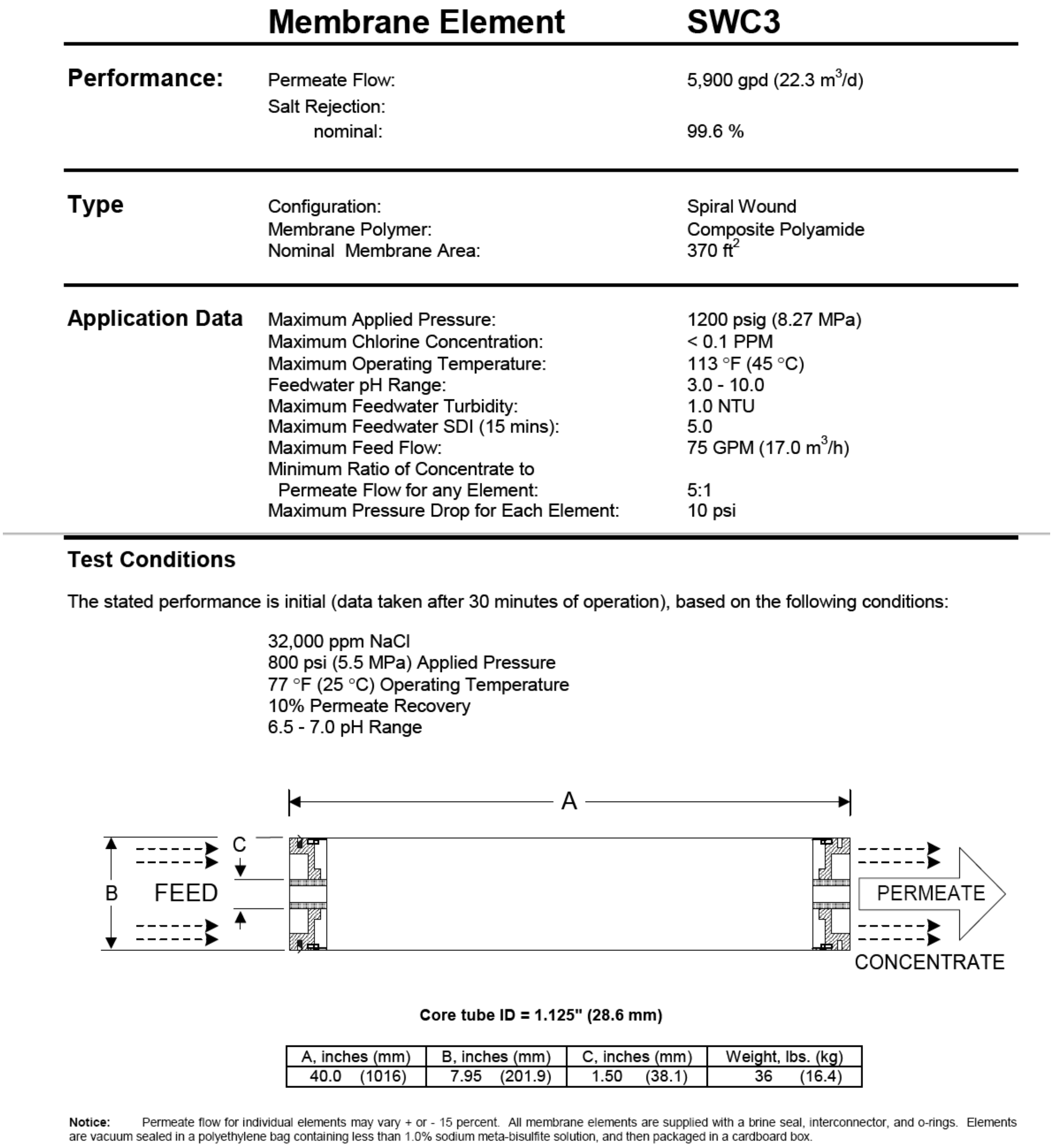
Then 2 lines of 9 cartridge filters with 360 cartridges of 5 microns each one are installed behind the dual-media filters.

RO process system

Double-pass systems are used to reduce the salinity of the product water of the SWRO plant to be less than 180 mg/L.

1st pass: 17 + 1 trains, each one with 136 PV × 7 elements SWC3 Hydranautics membranes with a recovery rate of 43%. The SWC3 membranes are manufactured by Nitto Denko Corporation. Figure 4.19 shows the specifications of the membrane.

2nd pass: 8 trains, each one with 73 PV × 7 elements ESPA1 Hydranautics low energy membranes with a recovery rate of 90%. The trains have two stages (50 PV in the 1st stage and 23 in the 2nd). 20% approximately of 1st pass permeate flow is by-passed to be blended with the 2nd pass permeate flow ensuring a blended water with less than 180 mg/L of TDS. The brine produced by the 2nd stage being of a much lower salinity than the seawater (4–5 g/L against 38.5 g/L), it is recycled in front of the first pass (Sanza, Bonnélyea et al. 2007).



	Membrane Element	**SWC3**
Performance:	Permeate Flow:	5,900 gpd (22.3 m^3/d)
	Salt Rejection:	
	nominal:	99.6 %
Type	Configuration:	Spiral Wound
	Membrane Polymer:	Composite Polyamide
	Nominal Membrane Area:	370 ft^2
Application Data	Maximum Applied Pressure:	1200 psig (8.27 MPa)
	Maximum Chlorine Concentration:	< 0.1 PPM
	Maximum Operating Temperature:	113 °F (45 °C)
	Feedwater pH Range:	3.0 - 10.0
	Maximum Feedwater Turbidity:	1.0 NTU
	Maximum Feedwater SDI (15 mins):	5.0
	Maximum Feed Flow:	75 GPM (17.0 m^3/h)
	Minimum Ratio of Concentrate to Permeate Flow for any Element:	5:1
	Maximum Pressure Drop for Each Element:	10 psi

Test Conditions

The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:

32,000 ppm NaCl
800 psi (5.5 MPa) Applied Pressure
77 °F (25 °C) Operating Temperature
10% Permeate Recovery
6.5 - 7.0 pH Range

Core tube ID = 1.125" (28.6 mm)

A, inches (mm)	B, inches (mm)	C, inches (mm)	Weight, lbs. (kg)
40.0 (1016)	7.95 (201.9)	1.50 (38.1)	36 (16.4)

Notice: Permeate flow for individual elements may vary + or - 15 percent. All membrane elements are supplied with a brine seal, interconnector, and o-rings. Elements are vacuum sealed in a polyethylene bag containing less than 1.0% sodium meta-bisulfite solution, and then packaged in a cardboard box.

Figure4.19: The specifications of SWC3 Hydranautics membrane (Nitto Denko Corporation 2012)

4.4.3 Energy Consumption

Calder Pelton turbines with a power recovery rate over 88-89% were been selected as the energy recovery devices of this SWRO plant, however, if the incoming pressure changes in a range of more than 3 to 5 bar, the recovery efficiency will decrease markedly.

Consumption of the complete RO system is approximately 3.8 kWh/m3 (less than 3.0 kWh/m3 in the first pass) while overall consumption (including pre-treatment, air conditioning, treated water pumping, etc.) is close to 4.5 kWh/m3.

4.4.4 Operational Results

The results of the plant are better than the expected and the performance guaranties of the treated water have been achieved both in quantity and quality. The main results are shown in Table.4.6.

Table 4.6: The operational results of Fujairah SWRO desalination plant (Sanza, Bonnélyea et al. 2007)

	Projected	Guaranty	Results
Seawater			
SDI, %min	< 20		10 - >50
TDS, mg/l	40,000		38000-38500
Temperature, ℃	22-35		22-35
Turbidity, NTU	0.5-1.3		0.7-2.0
Pretreatment water			
pH	6.5-7.2		6.7-7.1
SDI, %min	< 3.5 (95%ile)	< 5 (100%ile)	3.6 (90%ile) 2.7 (average)
Turbidity, NTU	0.06-0.2		0.08-0.2
Permeate TDS			
RO 1st pass, mg/l	< 650		370-480
RO 2nd pass, mg/l	< 50		10-30
Blended water, mg/l	< 165	< 180	75-120
Energy consumption			
Total plant, kWh/m3	4.9	< 5.3	4.4-4.6
RO 1st pass, kWh/m3			2.9-3.0
RO 1st and 2nd pass, kWh/m3			3.7-3.9

4.5 Perth seawater desalination plant

The Perth Seawater Desalination Plant (PSDP) was the first large-scale desalination plant to provide drinking water for public consumption in Australia, it located at Kwinana, 30 kilometers south of Perth, Western Austral. It was completed in late 2006 and was built with a total project cost of $387 million.

The daily water production capacity of the plant is 130,000 cubic meters. The plant delivers water to the Integrated Water Supply System (IWSS) that serves a population of more than 1.7 million people in Perth and parts of the South West, and the PSDP providing 17 per cent of the Perth's supply needs (CRISP 2009).

4.5.1 Plant Design

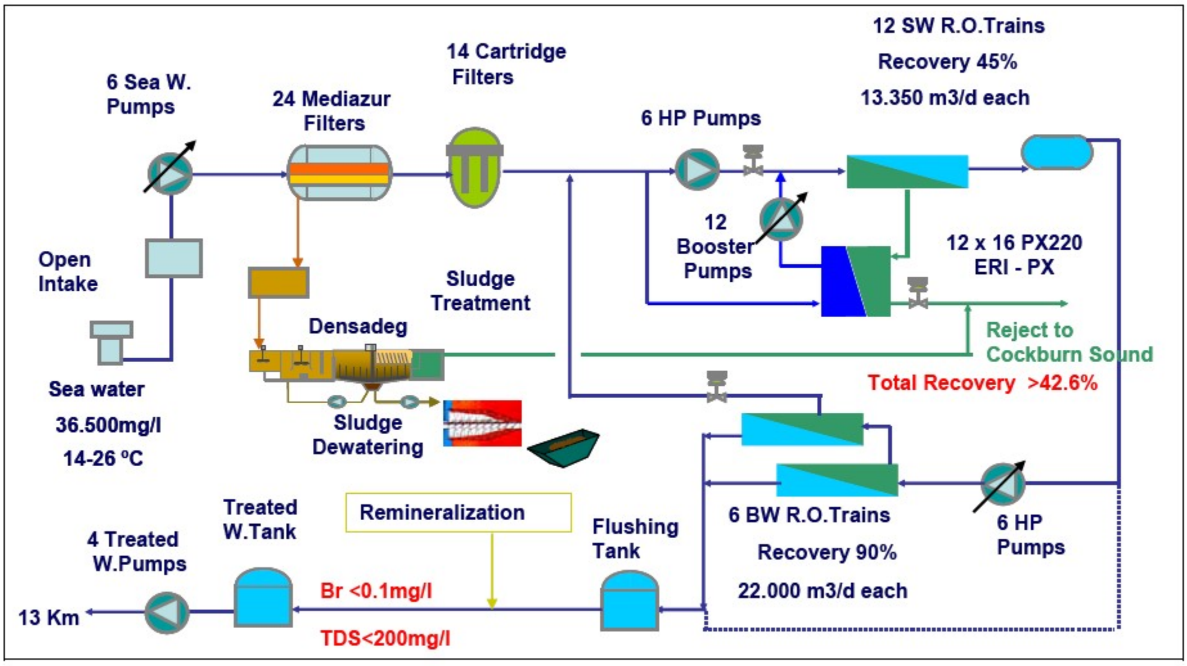


Figure 4.20: Perth seawater desalination plant process diagram (CRISP 2009)

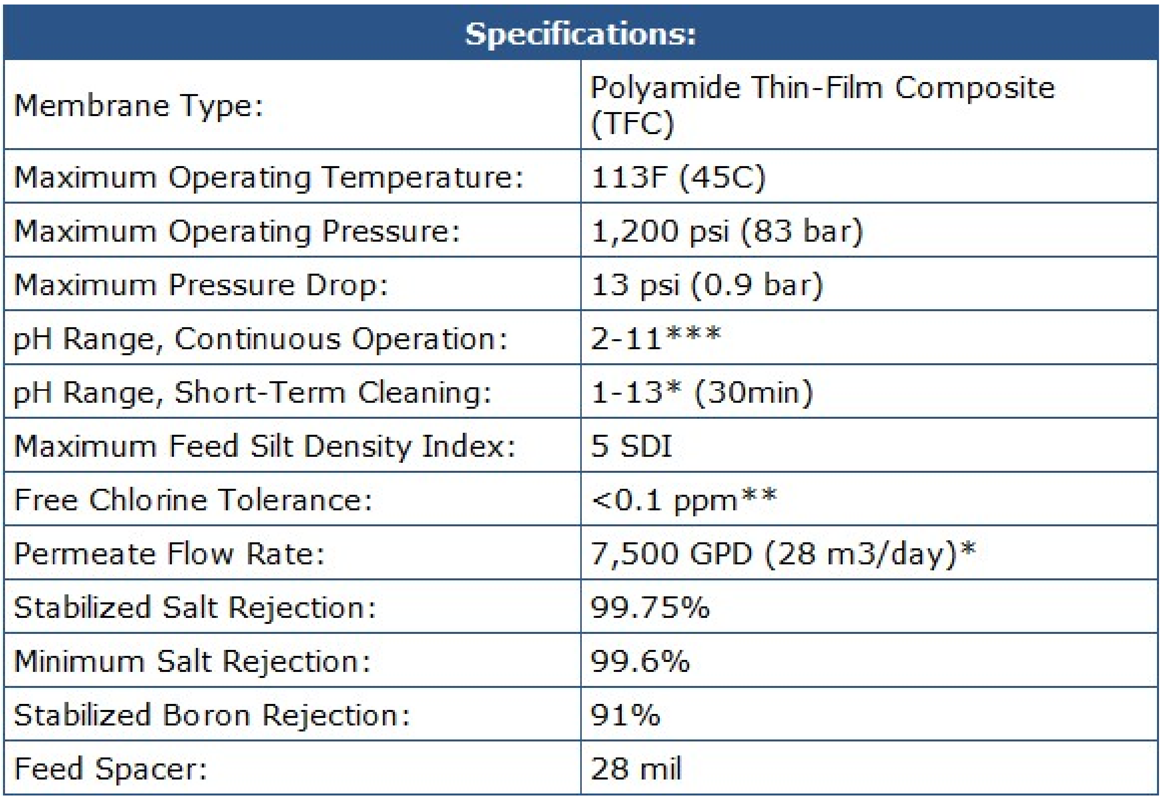
<u>Intake system and pre-treatment processes</u>

Seawater with a salinity of 35,000mg/l to 37,000mg/l at 14°C to 26°C in nearby Cockburn Sound is drawn into the plant through screens, intake screening at the intake structure consists of course barred screens offshore and automatically cleaned travelling band screens onshore. there are six supply pumps in the PSDP seawater forwarding pumping station.

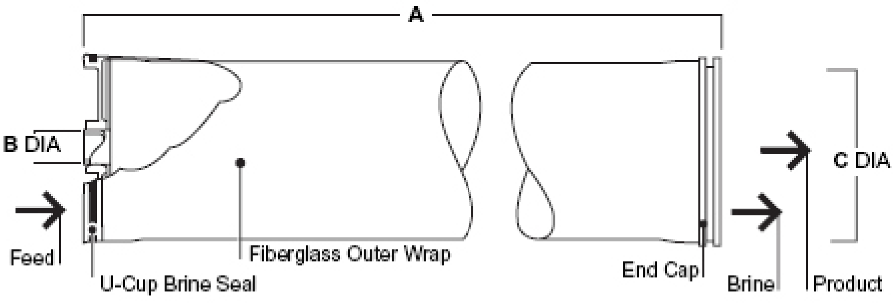
The PSDP pre-treatment process is a conventional process (addition of chemicals and filtration processes), The treatment line dosing includes pH adjustment using sulphuric acid, disinfection using sodium hypochlorite, coagulation using ferric sulphate and a coagulant aid, and dechlorination using sodium bisulfite. Filtration is performed by 24 pressurised dual media filters using anthracite and sand as filter media, and 14 cartridge filters with pore size of less than 5 micron are used to protect the RO membrane elements (TONY ROSS. and ADAM HARVEY. 2008).

Reverse osmosis processes

Perth Seawater Desalination Plant (PSDP) uses a two-pass reverse osmosis process. The first pass has twelve seawater reverse osmosis (SWRO) trains, each with a production capacity of 13,350 cubic meters per day (m3/d) or a total of 160,000 m3/d. Each train uses 1,134 Filmtec™ model SW30HR-LE400 membrane elements housed in Protec™ 7M side-port pressure vessels. The Filmtec SW30HR LE-400 element is supplied by the Dow Chemical Company, Figure 4.21 shows the specifications and dimensions.



Specifications:	
Membrane Type:	Polyamide Thin-Film Composite (TFC)
Maximum Operating Temperature:	113F (45C)
Maximum Operating Pressure:	1,200 psi (83 bar)
Maximum Pressure Drop:	13 psi (0.9 bar)
pH Range, Continuous Operation:	2-11***
pH Range, Short-Term Cleaning:	1-13* (30min)
Maximum Feed Silt Density Index:	5 SDI
Free Chlorine Tolerance:	<0.1 ppm**
Permeate Flow Rate:	7,500 GPD (28 m3/day)*
Stabilized Salt Rejection:	99.75%
Minimum Salt Rejection:	99.6%
Stabilized Boron Rejection:	91%
Feed Spacer:	28 mil



A: 40.0" (1,016mm)
B: 1.125" (29mm)
C: 7.9" (201mm)

Figure 4.21: Specifications and dimensions of the Filmtec SW30HR LE-400 element

The RO trains are fed with six Weir split-case centrifugal HP pumps, each with a capacity of 1,144 cubic meters per hour(m3/hr) at 620 meters (m) of differential head, driven by 2,600 kilowatt (kW) motors. The best efficiency point of these pumps is approximately 86%. The recovery rates of first pass about 45%.

The concentrated stream from the first-pass RO modules is fed to twelve arrays of sixteen ®ERI model PX-220 energy recovery devices, each array with a capacity of 800 kL/h, where the pressure is transferred to an equal volume of seawater. This pressure is boosted by about 5% and circulated into the RO modules by twelve Union® vertical booster pumps, each with a capacity of 661 kL/h at 39 m of differential head, driven by 112 kW motors controlled by VFDs (CRISP 2009).

The salinity of product water from first-pass RO system ranges from 150 to 300 mg/L, in order to further reduce the total dissolved solids (TDS) of product water to 10 to 50 mg/L, and reduce bromide concentration to 0.1 mg/L, the permeate from first-pass is fed to a second pass RO system consisting of six low-pressure 'brackish water' reverse osmosis (BWRO) trains, in the second pass, a brine conversion two stage system is used to increase the recovery rate, brine water from the first stage is further extracted in the second stage, this system giving a recovery of 90% (Miguel Angel Sanz 2007).

Post-treatment and Potabilisation

Post-treatment chemicals include hydrated lime, gaseous chlorine and carbon dioxide. The potabilisation treatments includes remineralisation using CO2 injection and lime (saturated lime water), and injection of fluoride and chlorine to meet the Water Corporation requirements.

Before product water is pumped to the fresh water reservoir that is 13 Km away from the PSDP plant and supplies the city of Perth with drinking water, it flows through a four-hour buffer tank.

4.5.2 Energy Consumption and Energy Recovery Devices

The PDSP is the largest facility of its kind in the world to be carbon neutral, powered by renewable energy. The plant buys its power from electricity generated by the Emu Downs Wind Farm, located 200 kilometers north of Perth. The 83 megawatt wind farm consists of 48 wind turbines and contributes over 272 giga-watt-hours (GWhr) per year into the grid, fully offsetting the Perth SWRO Plant’s estimated electrical requirement of 180 GWhr per year (G. Crisp and M. Rhodes 2007).

In the first-pass, twelve arrays of sixteen ®ERI model PX-220 energy recovery devices are adopted, as illustrated in Figure 4.22, a rotor, moving between the high-pressure and low low-pressure stream, removes the brine and replaces it with seawater. Pressure transfers directly from the high-pressure reject stream to a feed stream with no intervening piston in the flow path. The rotor spins freely, driven by the flow at a rotation rate proportional to the flow rate, so feed flow rates must be limited to avoid excess rotor speed. However, unlimited capacity is achieved by arraying multiple devices in parallel (Miguel Angel Sanz 2007).

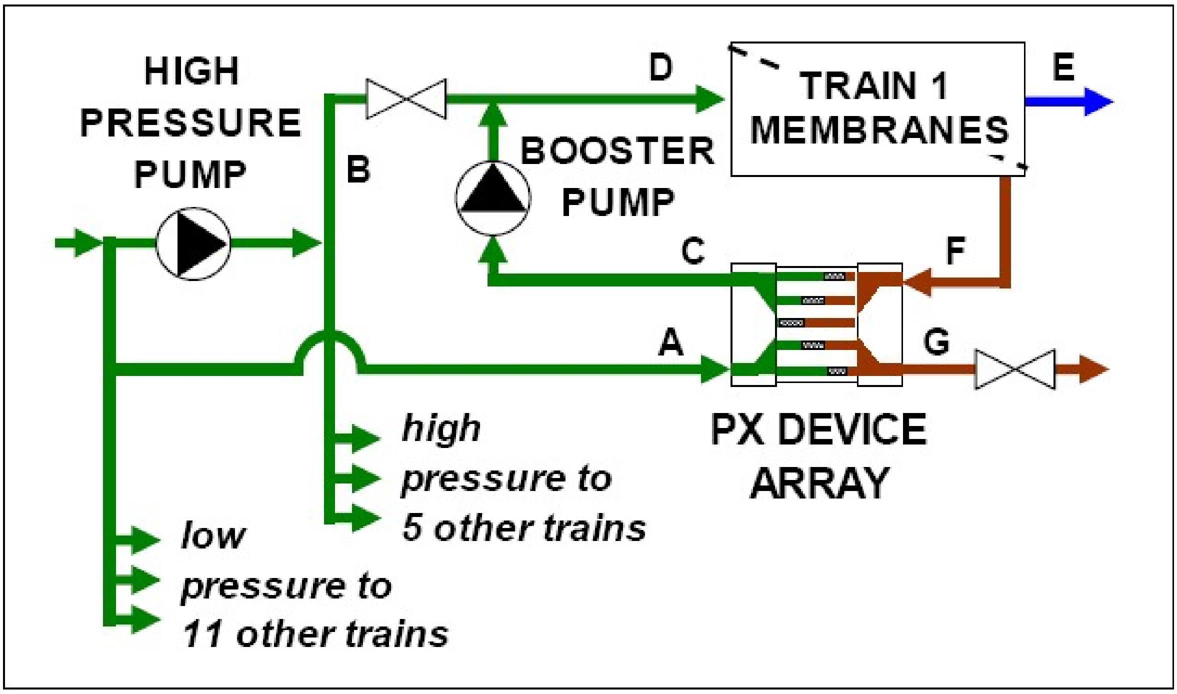


Figure 4.22: Schematic diagram of first-pass SWRO process with energy recovery device (G. Crisp and M. Rhodes 2007)

A total energy transfer efficiency of up to 98% is possible, and efficiency is nearly constant over a wide range of flow and pressure variations, the estimated total energy consumption for the plant was 3.2–3.5 kWh/m^3

CHAPTER 5
DISCUSSION AND CONCLUSIONS

5.1 Discussion

This research work was aimed at considering reverse osmosis as one of the various method of technologies used in seawater desalination. The paper seeks to take a closer look at this technology and describes some SWRO plants around the world. Information needed considering the structure for this research work was mainly questions concerning:

1. The site selection of SWRO plant
2. Plant design including intake system, pretreatment, RO process and post-treatment
3. Membrane types
4. Energy consumption and energy recovery device
5. The final water quality

Location

The site selection is one of the most important decisions, it is not only affecting the project costs but potentially the project schedule. Desalination facilities should be located as close to the raw water source as possible in order to avoid excessive pipeline or pumping costs and to minimize operation and maintenance costs for pumping raw water. Almost all desalination plants are built close to oceans. Including the 5 plants described in this thesis.

Resource water quality also is a very important factor in the sitting of a desalination plant. Seawater having low total suspended solids levels generally requires less pretreatment and less energy consumption due to low osmosis pressure.

Pretreatment

The Pretreatment process can be divided into two categories: the conventional method and UF/MF method. Four SWRO desalination plants in this paper use conventional pretreatment methods, usually chemical treatment and filtration process. As shown in the section 4.1.1.1 and 4.4.2, the pretreatment of Ashkelon SWRO plant and Fujairah SWRO plant are very similar, they both add ferric sulfate, sulfuric acid and polymer. Filtration process contains open gravity dual-media filters and 5μm cartridge filters. In the Perth SWRO plant, pressurized dual-media filters are installed instead of open gravity dual-media filters.

Only Uminonakamichi Nata Seawater Desalination Plant chose UF membranes for pretreatment. This plant needs a high feed water quality to avoid fouling and to maximize the life span of the UF membranes. Thereby an open seawater osmosis intake system is used to collect clear seawater of 4 or less in the SDI value as the feed water of UF membrane pretreatment process. The consistent low SDI permeate water quality, smaller footprint and lower operating costs of UF membranes as compared to conventional pretreatment will warrant a thorough consideration of UF membranes as pretreatment to SWRO plants in future.

RO process

The reverse osmosis unit is the main part of any SWRO desalination plant. Usually double-pass systems are used to get permeate water with a acceptable TDS concentration. In this paper, all 5 plants use double or even triple pass RO membrane systems. The TDS concentration of the product water can then have a TDS level of 120 ppm or less.

A four stage RO membrane system is adopted for Ashkelon seawater desalination plant due to the stringent water quality standards in Israel. As shown in Figure 4.2, some of the permeate from the first stage is led to the second stage in order to remove the Boron and operated at high pH (>10). In the third stage, brine water with a high Boron concentration from second stage is operated at low pH in order to remove Ca and Mg ions as much as possible. Then the high Boron concentration permeate passes through the fourth stage which is similar to the second stage, most of the Boron be removed. The Chloride concentration of permeate will be less than 20 ppm, the amount of Boron will not exceed 0.4 ppm. The TDS will be less than 80 ppm after the fourth stage RO pass

Membrane types

Membranes play a vital role in optimization of SWRO plants productivity and total project costs. Membrane cost depends on type and configuration. If this major cost component in any membrane desalination facility is not selected properly, the economic success of the project may not be attained. So, the initial selection of new membranes for a SWRO desalination plant and replacement of old or fouled membranes with new ones must be carefully considered in order to maximize the overall economic effectiveness of the RO desalination to lower water production cost.

The comparisons of membranes of these SWRO plants are shown in the table 5.1

Table 5.1: membranes comparison of 5 SWRO plants

SWRO plant	category	Membrane type	Supplier	Quantity (elements)
Ashkelon	SWRO	SW30HRLE-400	Film Tec Dow	25600
	BWRO	BW30LE-440	Film Tec Dow	13000
	BWRO	BW30-400	Film Tec Dow	2600
Barcelona-Llobregat	SWRO	SWC4+ Hydranautics	Nitto Denko Company	8400
		SWC5 Hydranautics	Nitto Denko Company	8400
		ESPAB Hydranautics	Nitto Denko Company	1344
Fukuoka	UF	RS50-S8	Nitto Denko Company	3060
	High-pressure RO	HB10255FI	Toyobo Company	2100
	Low-pressure RO	ES20B	Nitto Denko Company	1200
Fujairah	SWRO	SWC3 Hydranautics	Nitto Denko Company	17136
		ESPA1 Hydranautics	Nitto Denko Company	4088
Perth	SWRO	SW30HRLE-400	Film Tec Dow	13608

Energy consumption and energy recovery device

Almost all larger-scale SWRO plants work with energy recovery device. The energy consumption for producing one cubic meters fresh water approximately 3.2-3.9 kWh. The Perth SWRO plant is fed by renewable energy from wind farm.

Table 5.2: The comparison of 5 SWRO plants

	Ashkelon	Barcelona-Llobregat	Fujairah	Perth	Uminonakamichi Nata
Total production capacity	330,000 m^3/d	200,000 m^3/d	170,500 m^3/d	130,000 m^3/d	50,000 m^3/d
Desalted water TDS	< 80 ppm	100 ppm	75-120 ppm	118 ppm	108 ppm
Total energy consumption	< 3.9 kWh / m^3	3,5-3,9 kWh / m^3	3.7-3.9 kWh / m^3	3.2-3.5 kWh / m^3	< 3.9 kWh / m3

CO_2 emissions

CO_2 is a greenhouse gas which absorbs and emits radiation within the thermal infrared range. CO_2 in the atmosphere allows heat from the sun to reach the surface of the earth, but does not allow for the excess radiation (heat) to be reflected back into space. This raises the surface temperature of the planet and plants and animals suffer.

There is a direct relationship between the amount of carbon dioxide (CO_2) in the atmosphere and the average temperature on Earth. Increased carbon dioxide in the atmosphere is causing global warming. The increase in CO_2 results from the burning of fossil fuel.

Desalination uses huge amounts of energy and produces CO_2. Table 5.3 shows how much CO_2 will be produced by thermal distillation plants and reverse osmosis plants to produce 1000 liters of water.

Table 5.3: Comparison of CO_2 emissions

	SWRO plants	Thermal distillation plants
CO_2 emissions / m^3	3 kilograms	10 kilograms

Desalination in a modern plant using reverse osmosis technology and a gas fired power station, creates about 3 kilograms of CO_2 per 1000 liters of water. There are 10 kilograms of CO_2 will be produced for 1000 liters of water from thermal distillation desalination plants. SWRO plants are much better than thermal distillation desalination plants in CO_2 emissions. Even some SWRO plants without any carbon dioxide emission, in Perth seawater desalination plant, renewable energy (wind energy) are used to run the plant.

Reverse osmosis is a pressure-driven process so no energy-intensive phase changes or potentially expensive solvents or adsorbents are needed for RO separations. Reverse osmosis is a process that is inherently simple to design and operate compared to many traditional separation processes.

reverse osmosis technology can also be combined with ultrafiltration, pervaporation, distillation, and other separation techniques to produce hybrid processes that result in highly efficient and selective separations.

5.2 Conclusion

As the world’s population is growing, more and more people from the suburban areas are moving into larger and larges cities. Many countries have decided to build new cities in new areas. All of these consume large amounts of fresh water – not only for drinking, almost all modern industries are highly dependent on the availability of fresh water.

Agriculture has enormous needs for fresh water, and is the dominant consumer of water globally. Countries, particular those situated in the arid and semi-arid regions of the world, this dependency can be expected to intensify. Globally, irrigation now accounts for 69 percent of the 3,240 cubic kilometres (772 cubic miles) of water withdrawn for human use, and 87 percent of all water being consumed.

An average person in the developing world uses 10 litres (2.64 gallons) of water per day.
The average person in the United Kingdom uses 136 litres (35.66 gallons) of water per day.
The average person in the United States uses between 380 to 665 litres (100 – 175 gallons) per day at home.
The sources we have for fresh water on our planet will not meet future demands!

Seawater desalination is considered to be the most efficient way to help solve our world’s water shortage. Most of the early seawater desalination plants used Thermal distillation methods, particularly in the Middle East, where there is a large amount of fossile fuels.

Along the evolution of membrane science, it was discovered that Reverse Osmosis Membranes are very suitable for the removal of salts from seawater. Reverse Osmosis requires less energy, it has less environmental impact, and lower CO2 emissions – compared to any other desalination technologies. It is therefore a “Green Technology”.

Although that investment for the construction of Thermal Distillation Plants are lower, and they are easier to design and install, they are much more expensive to run and operate, compared to fresh water plants using Membrane technology.

Although Reverse Osmosis membranes are expensive, they are very reliable, and have a typical lifespan of 5 years. The primary reason to why Reverse Osmosis is today`s best choice for the production of fresh water from seawater, is the difference in energy consumption. While more than 13 kWh is required to produce one cubic meter of fresh water by distillation, a modern SWRO Plant utilizing energy recovery can produce the same amount of fresh water with using only 3.2 – 3.9 kWh.

In SWRO Plants, Pre-Treatment of the seawater plays a important part in order to protect the reverse osmosis elements. In a Conventional Pre-Treatment design, chemicals are added, and large filters are required, which in turn creates a larger need for space.

SWRO Plants with “Non Conventional” Pretreatment are using MF/UF membranes to get rid of most unwanted materials from seawater without the same amount of chemicals, and deliver pretreated water with lower SDI levels.

Ultrafiltration is safer due to less use of chemicals, and operation is also less complicated, which in turn puts decreases operation costs.

Our planets recourses for fossile fuels are limited, the world population is growing larger and larger, and everyone needs fresh water.

In my opinion, the most important thing for any further development of SWRO, is to let as many people as possible to know and understand this fantastic technology

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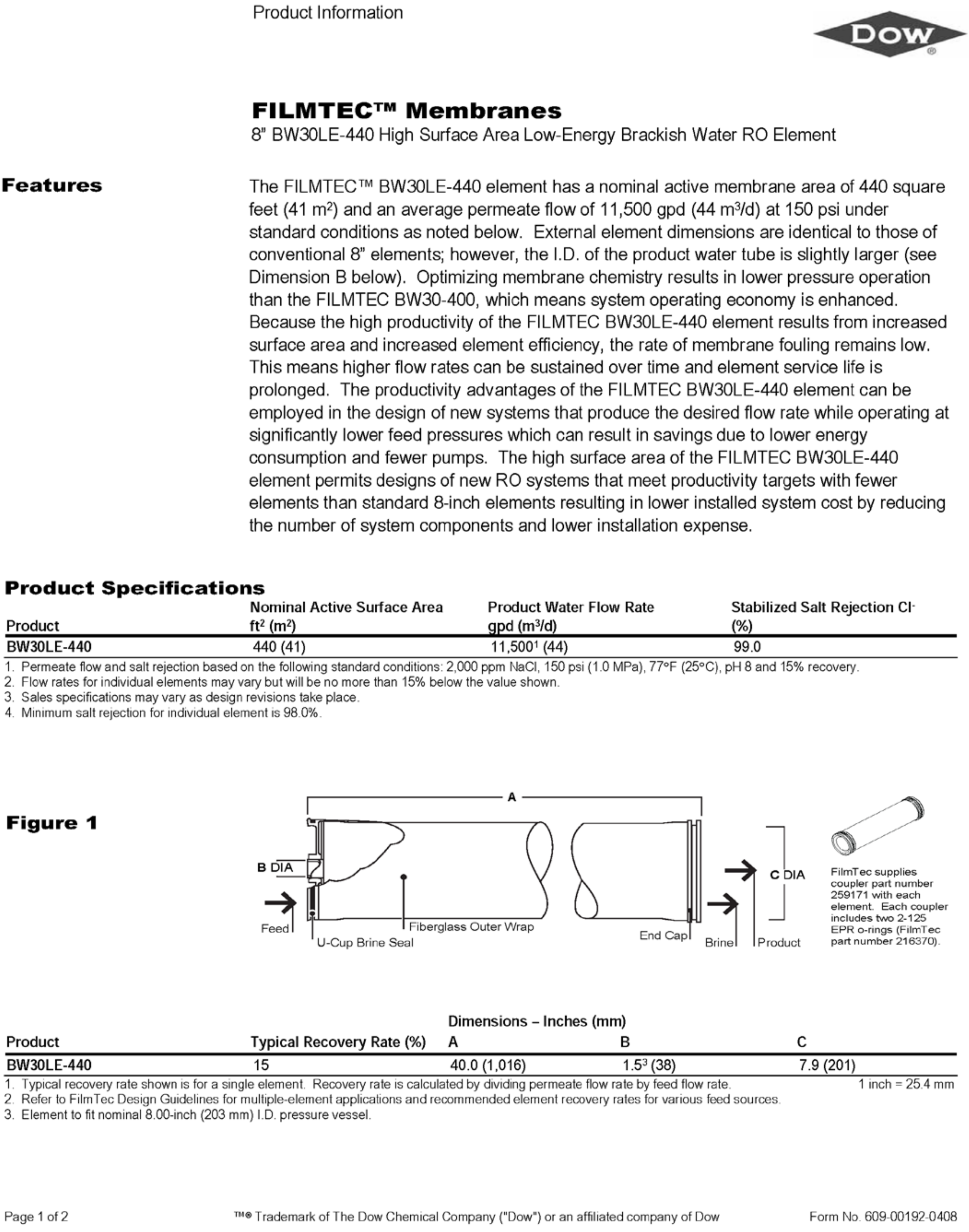
APPENDIX 1 – Product information of BW30LE-440 and BW30-400 membranes



Product Information

DOW

FILMTEC™ Membranes

8" BW30LE-440 High Surface Area Low-Energy Brackish Water RO Element

Features

The FILMTEC™ BW30LE-440 element has a nominal active membrane area of 440 square feet (41 m^2) and an average permeate flow of 11,500 gpd (44 m^3/d) at 150 psi under standard conditions as noted below. External element dimensions are identical to those of conventional 8" elements; however, the I.D. of the product water tube is slightly larger (see Dimension B below). Optimizing membrane chemistry results in lower pressure operation than the FILMTEC BW30-400, which means system operating economy is enhanced. Because the high productivity of the FILMTEC BW30LE-440 element results from increased surface area and increased element efficiency, the rate of membrane fouling remains low. This means higher flow rates can be sustained over time and element service life is prolonged. The productivity advantages of the FILMTEC BW30LE-440 element can be employed in the design of new systems that produce the desired flow rate while operating at significantly lower feed pressures which can result in savings due to lower energy consumption and fewer pumps. The high surface area of the FILMTEC BW30LE-440 element permits designs of new RO systems that meet productivity targets with fewer elements than standard 8-inch elements resulting in lower installed system cost by reducing the number of system components and lower installation expense.

Product Specifications

Product	Nominal Active Surface Area ft^2 (m^2)	Product Water Flow Rate gpd (m^3/d)	Stabilized Salt Rejection Cl^- (%)
BW30LE-440	440 (41)	11,500[1] (44)	99.0

1. Permeate flow and salt rejection based on the following standard conditions: 2,000 ppm NaCl, 150 psi (1.0 MPa), 77°F (25°C), pH 8 and 15% recovery.
2. Flow rates for individual elements may vary but will be no more than 15% below the value shown.
3. Sales specifications may vary as design revisions take place.
4. Minimum salt rejection for individual element is 98.0%.

Figure 1

FilmTec supplies coupler part number 259171 with each element. Each coupler includes two 2-125 EPR o-rings (FilmTec part number 216370).

Product	Typical Recovery Rate (%)	Dimensions – Inches (mm) A	B	C
BW30LE-440	15	40.0 (1,016)	1.5[3] (38)	7.9 (201)

1. Typical recovery rate shown is for a single element. Recovery rate is calculated by dividing permeate flow rate by feed flow rate.
2. Refer to FilmTec Design Guidelines for multiple-element applications and recommended element recovery rates for various feed sources.
3. Element to fit nominal 8.00-inch (203 mm) I.D. pressure vessel.

1 inch = 25.4 mm

Page 1 of 2 ™® Trademark of The Dow Chemical Company ("Dow") or an affiliated company of Dow Form No. 609-00192-0408

Operating Limits

Membrane Type	Polyamide Thin-Film Composite
Maximum Operating Temperature[a]	113°F (45°C)
Maximum Operating Pressure	600 psig (41 bar)
Maximum Pressure Drop	15 psig (1.0 bar)
pH Range, Continuous Operation[a]	2 - 11
pH Range, Short-Term Cleaning (30 min.)[b]	1 - 13
Maximum Feed Flow	85 gpm (19 m^3/hr)
Maximum Feed Silt Density Index	SDI 5
Free Chlorine Tolerance[c]	< 0.1 ppm

[a] Maximum temperature for continuous operation above pH 10 is 95°F (35°C).

[b] Refer to Cleaning Guidelines in specification sheet 609-23010.

[c] Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure. Since oxidation damage is not covered under warranty, FilmTec recommends removing residual free chlorine by pretreatment prior to membrane exposure. Please refer to technical bulletin 609-22010 for more information.

Important Information

Proper start-up of reverse osmosis water treatment systems is essential to prepare the membranes for operating service and to prevent membrane damage due to overfeeding or hydraulic shock. Following the proper start-up sequence also helps ensure that system operating parameters conform to design specifications so that system water quality and productivity goals can be achieved.

Before initiating system start-up procedures, membrane pretreatment, loading of the membrane elements, instrument calibration and other system checks should be completed.

Please refer to the application information literature entitled “Start-Up Sequence” (Form No. 609-02077) for more information.

Operation Guidelines

Avoid any abrupt pressure or cross-flow variations on the spiral elements during start-up, shutdown, cleaning or other sequences to prevent possible membrane damage. During start-up, a gradual change from a standstill to operating state is recommended as follows:

- Feed pressure should be increased gradually over a 30-60 second time frame.
- Cross-flow velocity at set operating point should be achieved gradually over 15-20 seconds.
- Permeate obtained from first hour of operation should be discarded.

General Information

- Keep elements moist at all times after initial wetting.
- If operating limits and guidelines given in this bulletin are not strictly followed, the limited warranty will be null and void.
- To prevent biological growth during prolonged system shutdowns, it is recommended that membrane elements be immersed in a preservative solution.
- The customer is fully responsible for the effects of incompatible chemicals and lubricants on elements.
- Maximum pressure drop across an entire pressure vessel (housing) is 50 psi (3.4 bar).
- Avoid permeate-side backpressure at all times.

Regulatory Note

These membranes may be subject to drinking water application restrictions in some countries: please check the application status before use and sale.

FILMTEC™ Membranes

For more information about FILMTEC membranes, call the Dow Water Solutions business:

North America:	1-800-447-4369
Latin America:	(+55) 11-5188-9222
Europe:	(+32) 3-450-2240
Pacific:	+60 3 7958 3392
Japan:	+813 5460 2100
China:	+86 21 2301 9000

http://www.filmtec.com

Notice: The use of this product in and of itself does not necessarily guarantee the removal of cysts and pathogens from water. Effective cyst and pathogen reduction is dependent on the complete system design and on the operation and maintenance of the system.

Product Information

DOW™ FILMTEC™ Membranes

DOW FILMTEC BW30-400 High Rejection, High Surface Area Brackish Water RO Element

Features

The DOW™ FILMTEC™ BW30-400 is the product of choice when the highest quality permeate is required. It was the first 400 square foot membrane element on the market and continues to be widely used in new equipment and retrofits where system capital and productivity are factors.

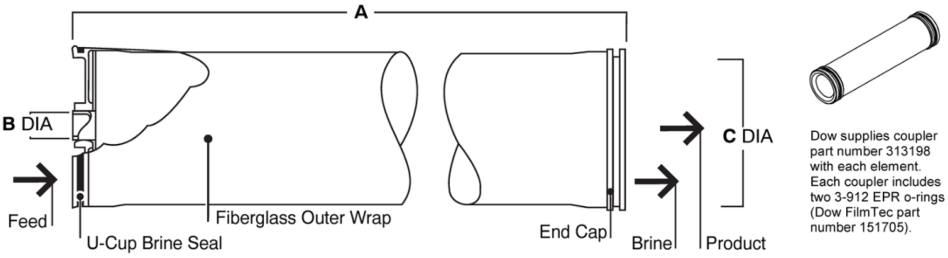
- Dow's superior automated manufacturing technology results in the most consistent performance element-to-element and year-after-year.
- BW30-400 elements deliver high flow and high rejection without being chlorinated during the manufacturing process. This is one reason why DOW FILMTEC elements are more durable and may be cleaned over a wider pH range (pH 1-13) than other RO elements.
- With more than a decade of proven performance, BW30-400 is the product you can rely on for years of trouble-free operation.

Product Specifications

Product	Part number	Active area ft^2 (m^2)	Feed spacer thickness (mil)	Permeate flow rate gpd (m^3/d)	Stabilized salt rejection (%)	Minimum salt rejection (%)
BW30-400	98650	400 (37)	28	10,500 (40)	99.5%	99.0%

1. Permeate flow and salt rejection based on the following standard conditions: 2,000 ppm NaCl, 225 psi (15.5 bar), 77°F (25°C), pH 8 and 15% recovery.
2. Flow rates for individual elements may vary but will be no more than 15% below the value shown.
3. Sales specifications may vary as design revisions take place.
4. Active area guaranteed +/-3%. Active area as stated by Dow is not comparable to nominal membrane area often stated by some manufacturers. Measurement method described in Form No. 609-00434.

Figure 1



Dow supplies coupler part number 313198 with each element. Each coupler includes two 3-912 EPR o-rings (Dow FilmTec part number 151705).

Product	Dimensions – inches (mm) A	B	C
BW30-400	40.0 (1,016)	1.125 ID (29)	7.9 (201)

1. Refer to Dow FilmTec Design Guidelines for multiple-element applications and recommended element recovery rates for various feed sources. 1 inch = 25.4 mm
2. Element to fit nominal 8.0-inch (203 mm) I.D. pressure vessel.

Operating Limits

• Membrane Type	Polyamide Thin-Film Composite
• Maximum Operating Temperature[a]	113°F (45°C)
• Maximum Operating Pressure	600 psig (41 bar)
• Maximum Pressure Drop	15 psig (1.0 bar)
• pH Range, Continuous Operation[a]	2 - 11
• pH Range, Short-Term Cleaning (30 min.)[b]	1 - 13
• Maximum Feed Flow	85 gpm (19 m^3/hr)
• Maximum Feed Silt Density Index	SDI 5
• Free Chlorine Tolerance[c]	< 0.1 ppm

[a] Maximum temperature for continuous operation above pH 10 is 95°F (35°C).

[b] Refer to Cleaning Guidelines in specification sheet 609-23010.

[c] Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure. Since oxidation damage is not covered under warranty, Dow recommends removing residual free chlorine by pretreatment prior to membrane exposure. Please refer to technical bulletin 609-22010 for more information.

Important Information

Proper start-up of reverse osmosis water treatment systems is essential to prepare the membranes for operating service and to prevent membrane damage due to overfeeding or hydraulic shock. Following the proper start-up sequence also helps ensure that system operating parameters conform to design specifications so that system water quality and productivity goals can be achieved.

Before initiating system start-up procedures, membrane pretreatment, loading of the membrane elements, instrument calibration and other system checks should be completed.

Please refer to the application information literature entitled “Start-Up Sequence” (Form No. 609-02077) for more information.

Operation Guidelines

Avoid any abrupt pressure or cross-flow variations on the spiral elements during start-up, shutdown, cleaning or other sequences to prevent possible membrane damage. During start-up, a gradual change from a standstill to operating state is recommended as follows:

- Feed pressure should be increased gradually over a 30-60 second time frame.
- Cross-flow velocity at set operating point should be achieved gradually over 15-20 seconds.
- Permeate obtained from first hour of operation should be discarded.

General Information

- Keep elements moist at all times after initial wetting.
- If operating limits and guidelines given in this bulletin are not strictly followed, the DOW™ FILMTEC™ Reverse Osmosis and Nanofiltration Three-Year Prorated Limited Warranty (Form No. 609-35010) will be null and void.
- To prevent biological growth during prolonged system shutdowns, it is recommended that membrane elements be immersed in a preservative solution.
- The customer is fully responsible for the effects of incompatible chemicals and lubricants on elements.
- Maximum pressure drop across an entire pressure vessel (housing) is 50 psi (3.4 bar).
- Avoid static permeate-side backpressure at all times.

Regulatory Note

These membranes may be subject to drinking water application restrictions in some countries: please check the application status before use and sale.

DOW FILMTEC™ Membranes
For more information about DOW FILMTEC membranes, call the Dow Water & Process Solutions business:

North America:	1-800-447-4369
Latin America:	(+55) 11-5188-9222
Europe:	(+32) 3-450-2240
Pacific:	+60 3 7958 3392

www.dowwaterandprocess.com

Notice: The use of this product in and of itself does not necessarily guarantee the removal of cysts and pathogens from water. Effective cyst and pathogen reduction is dependent on the complete system design and on the operation and maintenance of the system.

APPENDIX 2 – Product information of SWC4+ and SWC5 membranes

NITTO DENKO HYDRANAUTICS

Membrane Element SWC4+ 8040

Performance:	Permeate Flow:	6,500 gpd (24.6 m^3/d)
	Salt Rejection:	99.8 % (99.7 % minimum)
	Boron Rejection (Typical):	93.0%[†]

Type	Configuration:	Spiral Wound
	Membrane Polymer:	Composite Polyamide
	Membrane Active Area:	400 ft^2 (37.1m^2)

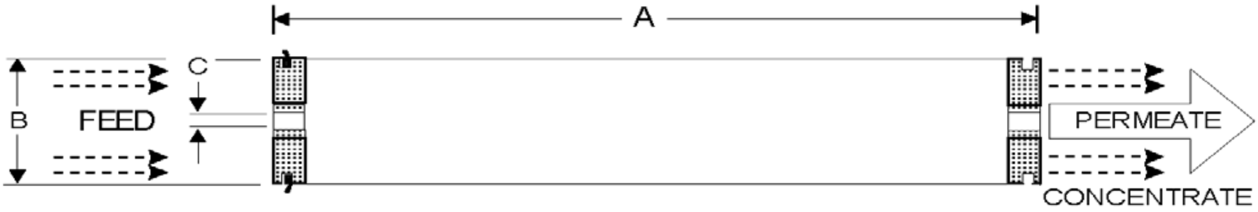
Application Data*	Maximum Applied Pressure:	1200 psig (8.27 MPa)
	Maximum Chlorine Concentration:	< 0.1 PPM
	Maximum Operating Temperature:	113 °F (45 °C)
	pH Range, Continuous (Cleaning):	2-11 (1-13)*
	Maximum Feedwater Turbidity:	1.0 NTU
	Maximum Feedwater SDI (15 mins):	5.0
	Maximum Feed Flow:	75 GPM (17.0 m^3/h)
	Minimum Ratio of Concentrate to Permeate Flow for any Element:	5:1
	Maximum Pressure Drop for Each Element:	10 psi

* The limitations shown here are for general use. For specific projects, operating at more conservative values may ensure the best performance and longest life of the membrane. See Hydranautics Technical Bulletins for more detail on operation limits, cleaning pH, and cleaning temperatures.

Test Conditions

The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:

32,000 ppm NaCl
800 psi (5.5 MPa) Applied Pressure
77 °F (25 °C) Operating Temperature
10% Permeate Recovery
6.5 - 7.0 pH Range



A, inches (mm)	B, inches (mm)	C, inches (mm)	Weight, lbs. (kg)
40.0 (1016)	7.89 (200)	1.125 (28.6)	36 (16.4)

Notice: Permeate flow for individual elements may vary + or - 15 percent. Membrane active area may vary +/-4%. All membrane elements are supplied with a brine seal, interconnector, and o-rings. Elements are vacuum sealed in a polyethylene bag containing less than 1.0% sodium meta-bisulfite solution, and then packaged in a cardboard box.

[†] When tested at standard test conditions with 5.0ppm Boron in feed solution.

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NITTO DENKO

HYDRANAUTICS
www.membranes.com
A Nitto Denko Company

Membrane Element SWC5

Performance:	Permeate Flow:	9,000 gpd (34.1 m^3/d)
	Salt Rejection:	99.8 % (99.7 % minimum)
	Boron Rejection (Typical):	92.0%†

Type	Configuration:	Spiral Wound
	Membrane Polymer:	Composite Polyamide
	Membrane Active Area:	400 ft^2 (37.1m^2)

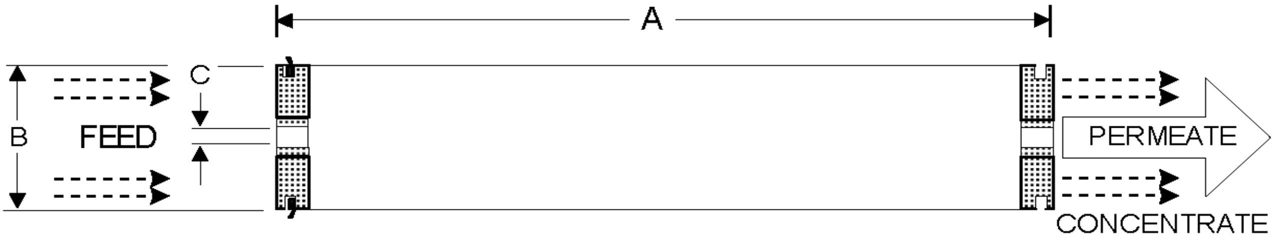
Application Data*	Maximum Applied Pressure:	1200 psig (8.27 MPa)
	Maximum Chlorine Concentration:	< 0.1 PPM
	Maximum Operating Temperature:	113 °F (45 °C)
	pH Range, Continuous (Cleaning):	2-11 (1-13)*
	Maximum Feedwater Turbidity:	1.0 NTU
	Maximum Feedwater SDI (15 mins):	5.0
	Maximum Feed Flow:	75 GPM (17.0 m^3/h)
	Minimum Ratio of Concentrate to Permeate Flow for any Element:	5:1
	Maximum Pressure Drop for Each Element:	10 psi

* The limitations shown here are for general use. For specific projects, operating at more conservative values may ensure the best performance and longest life of the membrane. See Hydranautics Technical Bulletins for more detail on operation limits, cleaning pH, and cleaning temperatures.

Test Conditions

The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:

32,000 ppm NaCl
800 psi (5.5 MPa) Applied Pressure
77 °F (25 °C) Operating Temperature
10% Permeate Recovery
6.5 - 7.0 pH Range



A, inches (mm)	B, inches (mm)	C, inches (mm)	Weight, lbs. (kg)
40.0 (1016)	7.89 (200)	1.125 (28.6)	36 (16.4)

Notice: Permeate flow for individual elements may vary + or - 15 percent. Membrane active area may vary +/-4%. All membrane elements are supplied with a brine seal, interconnector, and o-rings. Elements are vacuum sealed in a polyethylene bag containing less than 1.0% sodium meta-bisulfite solution, and then packaged in a cardboard box.

† When tested at standard test conditions with 5.0ppm Boron in feed solution.

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