Haward Technology Middle East

Modern Water Desalination Technologies

Handout

June 03-07, 2007
Abu Dhabi, UAE

Course Instructors
Professor Bruce Hendry
Mr. Yehia Mohamed

ISO 9001:2000 Certified

RO Design Help File

What is Reverse Osmosis?

What is Reverse Osmosis?

Reverse Osmosis (RO) is a modern process technology to purify water for a wide range of applications, including semiconductors, food processing, biotechnology, pharmaceuticals, power generation, seawater desalting, and municipal drinking water. From initial experiments conducted in the 1950’s which produced a few drops per hour, the reverse osmosis industry has today resulted in combined world-wide production in excess of 1.7 billion gallons per day. With demand for pure water ever-increasing, the growth of the reverse osmosis industry is poised to continue growing well into the next century.

This section will provide historical background on the development of RO, and introduce the reader to the concepts of osmosis and semi-permeable membranes. An simple illustration to show how RO works to purify water is provided.

Historical Background

Research on Reverse Osmosis began in the 1950’s at the University of Florida where Reid and Breton were able to demonstrate desalination properties of cellulose acetate membrane. Loeb and Sourirajan continued the development of the RO technology with the creation of the first asymmetric cellulose acetate membrane.

Research on these promising developments spawned new and better configurations of RO elements; today the industry produces predominately spiral wound elements, or in some cases, hollow fiber elements. In the early 1980's, research in US Government Labs resulted in the first Composite PolyAmide membrane. This membrane had significantly higher permeate flow and salt rejection than cellulosic membranes. Today, with the introduction of the ESPA3 by Hydranautics, the industry has attained a 20-times increase in flow per pressure over original cellulosic membranes, with an order of magnitude decrease in salt passage.

What is Semi-permeable?

Semi-permeable refers to a membrane that selectively allows certain species to pass through it while retaining others. In actuality, many species will pass through the membrane, but at significantly different rates. In RO, the solvent (water) passes through the membrane at a much faster rate than the dissolved solids (salts). The net effect is that a solute-solvent separation occurs, with pure water being the product. (In some cases, dewatering is desired to concentrate the salts).

What is Osmosis?

Osmosis is a natural process involving the fluid flow of across a semi-permeable membrane barrier. Consider a tank of pure water with a semi-permeable membrane dividing it into two sides. Pure water in contact with both sides of an ideal semi-permeable membrane at equal pressure and temperature has no net flow across the membrane because the chemical potential is equal on both sides.

If a soluble salt is added on one side, the chemical potential of this salt solution is reduced. Osmotic flow from the pure water side across the membrane to the salt solution side will occur until the equilibrium of chemical potential is restored (Figure 1a). In scientific terms, the two sides of the tank have a difference in their “chemical potentials,” and the solution equalizes, by osmosis, its chemical potential throughout the system. Equilibrium occurs when the hydrostatic pressure differential resulting from the volume changes on both sides is equal to the osmotic pressure. The osmotic pressure is a solution property proportional to the salt concentration and independent of the membrane.

Reverse Osmosis

With the tank in Figure 1a, the water moves to the salty side of the membrane until equilibrium is achieved. Application of an external pressure to the salt solution side equal to the osmotic pressure will also cause equilibrium (Figure 1b). Additional pressure will raise the chemical potential of the water in the salt solution and cause a solvent flow to the pure water side, because it now has a lower chemical potential. This phenomenon is called reverse osmosis.

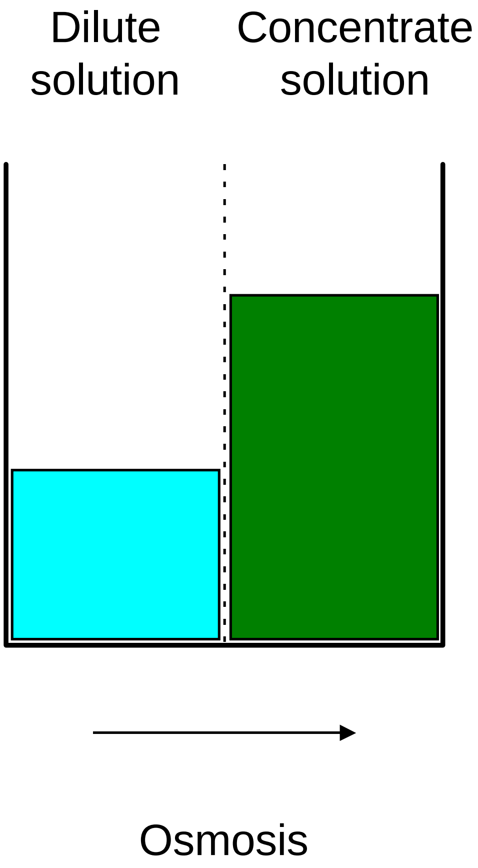


Figure 1a

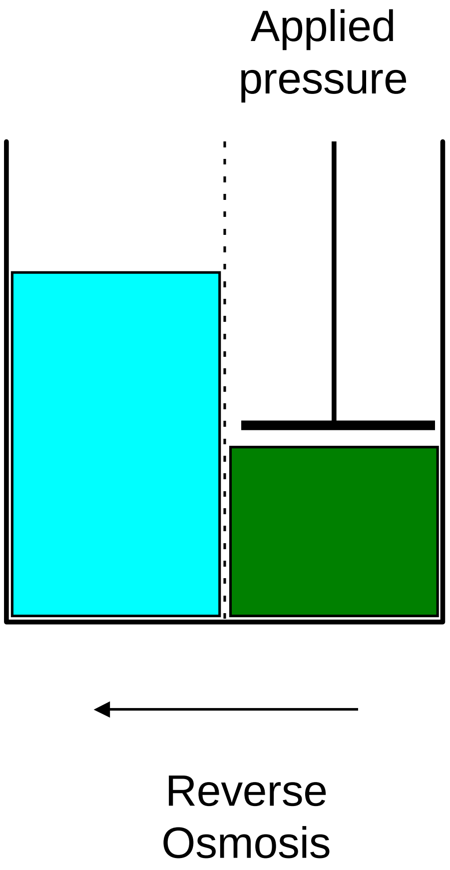


Figure 1b

The driving force of the reverse osmosis process is applied pressure. The amount of energy required for osmotic separation is directly related to the salinity of the solution. Thus, more energy is required to produce the same amount of water from solutions with higher concentrations of salt.

RO Design Help File

Commercial RO Technology

Commercial RO Technology

The semipermeable membrane for reverse osmosis applications consists of a thin film of polymeric material several thousand Angstroms thick cast on a fabric support. The commercial grade membrane must have high water permeability and a high degree of semipermeability; that is, the rate of water transport must be much higher than the rate of transport of dissolved ions. The membrane must be stable over a wide range of pH and temperature, and have good mechanical integrity. The stability of these properties over a period of time at field conditions defines the commercially useful membrane life, which is in the range of 3 to 5 years. There are two major groups of polymeric materials which can be used to produce satisfactory reverse osmosis membranes: Cellulose Acetate (CAB) and Composite Polyamide (CPA). Membrane manufacturing, operating conditions, and performance differ significantly for each group of polymeric material.

CELLULOSE ACETATE MEMBRANE

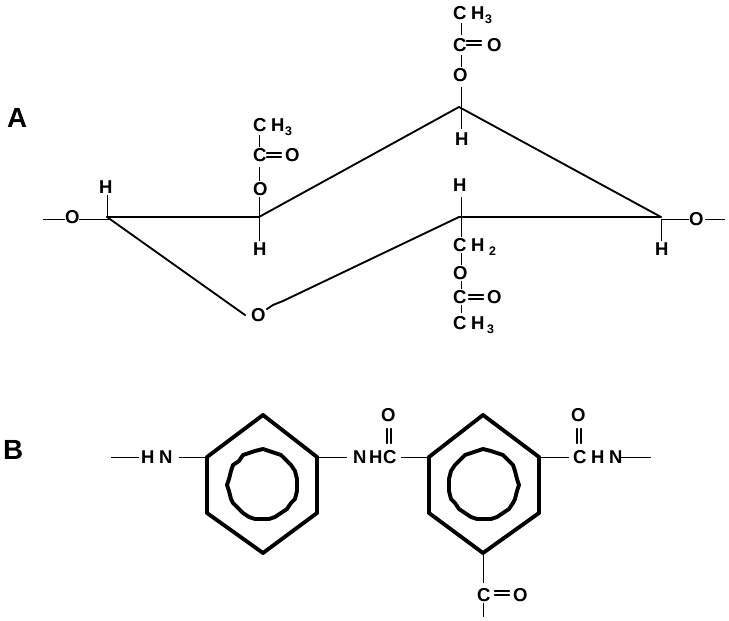
The original cellulose acetate membrane, developed in the late 1950's by Loeb and Sourirajan, was made from cellulose diacetate polymer. Current CA membrane is usually made from a blend of cellulose diacetate and triacetate. The membrane is formed by casting a thin film acetone-based solution of cellulose acetate polymer with swelling additives onto a non-woven polyester fabric. Two additional steps, a cold bath followed by high temperature annealing, complete the casting process.

During casting, the solvent is partially removed by evaporation. After the casting step, the membrane is immersed into a cold water bath which removes the remaining acetone and other leachable compounds. Following the cold bath step, the membrane is annealed in a hot water bath at a temperature of 60 - 90° C. The annealing step improves the semipermeability of the membrane with a decrease of water transport and a significant decrease of salt passage. After processing, the cellulose membrane has an asymmetric structure with a dense surface layer of about 1000 - 2000 A (0.1 - 0.2 micron) which is responsible for the salt rejection property. The rest of the membrane film is spongy and porous and has high water permeability. Salt rejection and water flux of a cellulose acetate membrane can be controlled by variations in temperature and duration of the annealing step.

COMPOSITE POLYAMIDE MEMBRANES

Composite polyamide membranes are manufactured in two distinct steps. First, a polysulfone support layer is cast onto a non-woven polyester fabric. The polysulfone layer is very porous and is not semipermeable; that is it does not have the ability to separate water from dissolved ions. In a second, separate manufacturing step, a semipermeable membrane skin is formed on the polysulfone substrate by interfacial polymerization of monomers containing amine and carboxylic acid chloride functional groups. This manufacturing procedure enables independent optimization of the distinct properties of the membrane support and salt rejecting skin. The resulting composite membrane is characterized by higher specific water flux and lower salt passage than cellulose acetate membranes. Polyamide composite membranes are stable over a wider pH range than cellulose acetate membranes. However, polyamide membranes are susceptible to oxidative degradation by free chlorine, while cellulose acetate membranes can tolerate limited levels of exposure to free chlorine. Compared to a polyamide membrane, the surface of cellulose acetate membrane is smooth and has little surface charge. Because of the neutral surface and tolerance to free chlorine, cellulose acetate membranes will usually have a more stable performance than polyamide membranes in applications where the feed water has a high fouling potential, such as with municipal effluent and surface water supplies.

The structures of cellulose acetate and polyamide polymer are shown respectively as A and B below.



Chemical structure of cellulose triacetate (A) and polyamide (B) membrane material

MEMBRANE MODULE CONFIGURATIONS

The two major membrane module configurations used for reverse osmosis applications are hollow fiber and spiral wound. Two other configurations, tubular and plate and frame, have found good acceptance in the food and dairy industry and in some special applications, but modules of this configuration have been less frequently used in reverse osmosis applications.

HOLLOW FINE FIBER (HFF) MEMBRANES

This configuration uses membrane in the form of hollow fibers which have been extruded from cellulosic or non-cellulosic material. The fiber is asymmetric in structure and is as fine as a human hair, about 42 micron (0.0016 inch) I.D. and 85 micron (0.0033) inch) O.D. Millions of these fibers are formed into a bundle and folded in half to a length of approximately 120 cm (4 ft). A perforated plastic tube, serving as a feed water distributor is inserted in the center and extends the full length of the bundle. The bundle is wrapped and both ends are epoxy sealed to form a sheet-like permeate tube end and a terminal end which prevents the feed stream from bypassing to the brine outlet.

The hollow fiber membrane bundle, 10 cm to 20 cm (4 to 8 inches) in diameter, is contained in a cylindrical housing or shell approximately 137 cm (54 inches) long and 15 - 30 cm (6 - 12 inches) in diameter. The assembly is called a permeator. The pressurized feed water enters the permeator feed end through the center distributor tube, passes through the tube wall, and flows radially around the fiber bundle toward the outer permeator pressure shell. Water permeates through the outside wall of the fibers into the hollow core or fiber bore, through the bore to the tube sheet or product end of the fiber bundle, and exits through the product connection on the feed end of the permeator.

In a hollow fiber module, the permeate water flow per unit area of membrane is low, and therefore, the concentration polarization is not high at the membrane surface. The net result is that hollow fiber units operate in a non-turbulent or laminar flow regime. The HFF membrane must operate above a minimum reject flow to minimize concentration polarization and maintain even flow distribution through the fiber bundle. Typically, a single hollow fiber permeator can be operated at up to 50-percent recovery and meet the minimum reject flow required. The hollow fiber unit allows a large membrane area per unit volume of permeator which results in compact systems. Hollow fiber perimeters are available for brackish and seawater applications.

Membrane materials are cellulose acetate blends and aramid (a proprietary polyamide type material in an anisotropic form). Because of very close packed fibers and tortuous feed flow inside the module, hollow fiber modules require feed water of better quality (lower concentration of suspended solids) than the spiral wound module configuration.

SPIRAL WOUND MEMBRANES

In a spiral wound configuration two flat sheets of membrane are separated with a permeate collector channel material to form a leaf. This assembly is sealed on three sides with the fourth side left open for permeate to exit. A feed/brine spacer material sheet is added to the leaf assembly. A number of these assemblies or leaves are wound around a central plastic permeate tube. This tube is perforated to collect the permeate from the multiple leaf assemblies. The typical industrial spiral wound membrane element is approximately 100 or 150 cm (40 or 60 inches) long and 10 or 20 cm (4 or 8) inches in diameter.

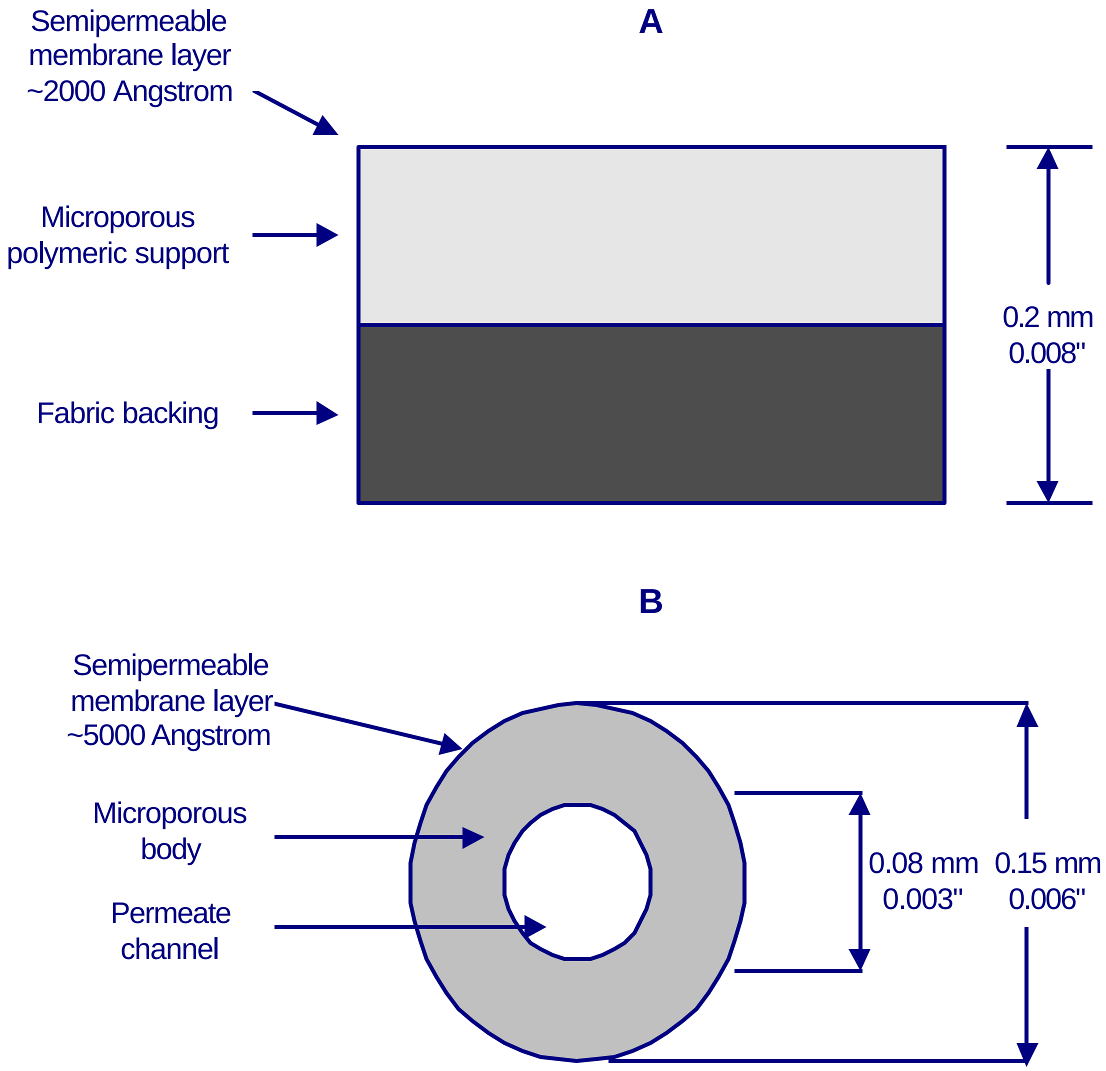
The feed/brine flow through the element is a straight axial path from the feed end to the opposite brine end, running parallel to the membrane surface. The feed channel spacer induces turbulence and reduces concentration polarization. Manufacturers specify brine flow requirements to control concentration polarization by limiting recovery (or conversion) per element to 10 - 20 percent.

Therefore, recovery (or conversion) is a function of the feed-brine path length. In order to operate at acceptable recoveries, spiral systems are usually staged with three to six membrane elements connected in series in a pressure tube. The brine stream from the first element becomes the feed to the following element, and so on for each element within the pressure tube.

The brine stream from the last element exits the pressure tube to waste. The permeate from each element enters the permeate collector tube and exits the vessel as a common permeate stream. A single pressure vessel with four to six membrane elements connected in series can be operated at up to 50-percent recovery under normal design conditions. The brine seal on the element feed end seal carrier prevents the feed/brine stream from bypassing the following element.

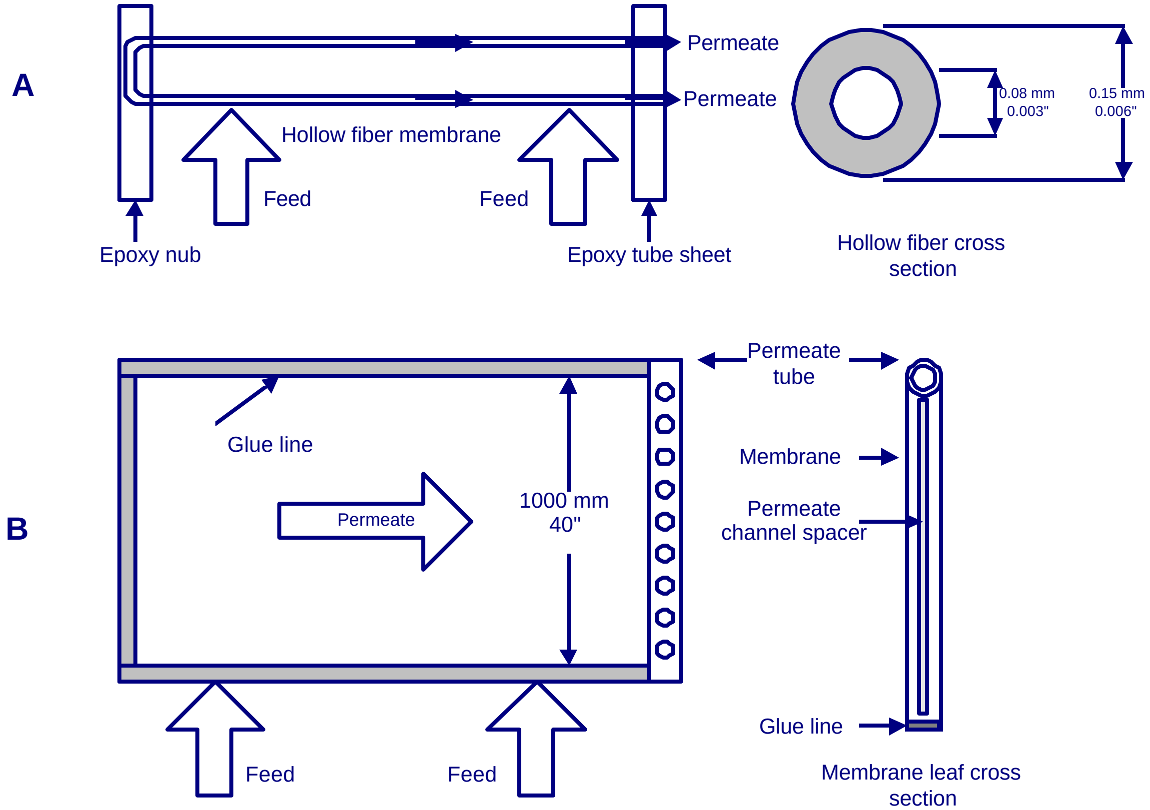
Spiral wound elements are most commonly manufactured with flat sheet membrane of either a cellulose diacetate and triacetate (CA) blend or a thin film composite. A thin film composite membrane consists of a thin active layer of one polymer cast on a thicker supporting layer of a different polymer. The composite membranes usually exhibit higher rejection at lower operating pressures than the cellulose acetate blends. The composite membrane materials may be polyamide, polysulfone, polyurea, or other polymers.

The structure of composite and hollow fiber membrane is shown below.



Cross section of flat (A) and hollow fiber (B) membranes

Corresponding modules configurations are shown below.



Hollow fiber (A) and Spiral wound (B) module configuration

RO Design Help File

RO Water Chemistry

RO Water Chemistry

The material presented in this paper is a glossary of many water related terms used in the water industry. Ionic species, water types, units definition, and concepts are presented in alphabetical order to help the user understand the terms used in the water industry.

Alkalinity: Alkalinity is comprised primarily of carbon dioxide, bicarbonate, carbonate and hydroxides. Naturally occurring alkalinity is the earth's natural buffering system in that small doses of strong acids (e.g. acid rain) react with alkalinity and result in relatively small changes in pH. Carbon dioxide and bicarbonate are in a balance between the pH range of 4.4 and 8.2. At a pH of 4.4 or lower, all alkalinity is in the form of carbon dioxide. At a pH of 8.2, there is no carbon dioxide and all alkalinity is bicarbonate. Bicarbonate and carbonate are in a balance between the pH range of 8.2 and 9.6. At a pH of 9.6, there is no carbon dioxide or bicarbonate and all alkalinity is carbonate. As the pH increases above 9.6, hydroxyl alkalinity due to the presence of the hydroxide ion starts to occur. Most naturally occurring water sources have a pH between 6 and 8.4, so the presence of hydroxides is the result of man-made activity.

Alkalinity, especially by boiler water chemists, can be reported as M-Alkalinity and P-Alkalinity. M-Alkalinity measures the Total Alkalinity in a water in terms of "ppm as calcium carbonate" based on an acid titration to a pH of 4.2 using a Methyl orange indicator endpoint. P-Alkalinity measures the amount of bicarbonate, carbonate and hydroxyl alkalinity based on an acid titration to a pH of 8.2 using a Phenolphthalein pink indicator endpoint.

Aluminum (Al): Aluminum, based on its low solubility, is typically not found in any significant concentrations in well or surface waters. Aluminum, when present in a RO feed water, is typically colloidal in nature (not ionic), and is the result of alum carryover by an on-site or municipal clarifier or lime-softener. Alum (aluminum sulfate) is a popular coagulant that is effective in the absorption and precipitation of naturally occurring, negatively charged colloidal material (e.g. clay and silt) from surface waters. Alum, when introduced into water, disassociates into trivalent aluminum and sulfate. The hydrated aluminum ion reacts with the water to form a number of complex hydrated aluminum hydroxides, which then polymerize and starts absorbing the negatively charged colloids in water.

Fouling by aluminum-based colloid carryover can occur, and the RO designer shoud be alert to levels ranging from 0.1 to 1.0 ppm aluminum in the feed water. Aluminum chemistry is complicated by the fact that it is amphoteric (ie that it can exist in many states). Aluminum at low pH can exist as a positively charged trivalent cation or as an aluminum hydroxide compound. Aluminum at high pH can exist as a negatively charged anionic compound. Typically, the range of least solubility for aluminum compounds is in the pH range of 5.5 to 7.5.

Ammonium (NH_4): A monovalent cation. Ammonium salts are very soluble and do not cause a RO scaling problem. The ammonium ion is the result of very soluble gaseous ammonia (NH_3) being dissolved in water of higher pH. Ammonia ionizes in water at high pH to form the ammonium ion and hydroxide ion. At lower pH the ammonia gas is prevalent and being a gas will not be rejected by a RO (similar to carbon dioxide gas).

Ammonium is typically not found in well water sources, having been converted by bacterial action in soils to the transitory nitrite (NO_2) ion and then oxidized into the more prevalent nitrate ion. Ammonium is found in surface water sources at low levels (up to 1 ppm as the ion), the result of biological activity and the breakdown of organic nitrogen compounds. Surface sources can be contaminated with ammonium from septic systems, animal feed lot runoff, or agricultural field runoff from fields fertilized with ammonia. Ammonium is prevalent in municipal waste facilities with levels up to 20 ppm as the ion in the effluent, the result of high levels of organic nitrogen compound compounds and biological activity. Another source of ammonium is the result of adding ammonia to chlorine to form biocidal chloramines.

Barium (Ba): A divalent cation. The solubility of barium sulfate ($BaSO_4$) is low and can cause a RO scaling problem in the back-end of a RO. Barium sulfate solubility is lower with increasing sulfate levels and decreasing temperatures. Typically, barium can be found in some well waters, with typical concentrations less than 0.05 ppm to 0.2 ppm. It is important that barium be measured with instruments capable of 0.01 ppm (10 ppb) minimum detection levels. With saturation at 100%, super-saturation up to 6000% is typical with an antiscalant.

Bicarbonate (HCO_3): A monovalent anion. The solubility of calcium bicarbonate is low and can cause a RO scaling problem in the back-end of a RO. Calcium bicarbonate solubility is measured using LSI (Langlier Saturation Index) for brackish waters or the Stiff-Davis Index for seawaters, and is lower with increasing temperature and increasing pH. Bicarbonate is one component of alkalinity and its concentration is in a balance with carbon dioxide between the pH range of 4.4 and 8.2, and in a balance with carbonate between the pH range of 8.2 and 9.6.

BOD (Biological Oxygen Demand): BOD is a non-specific test that measures the quantity of "biologically-degradable" organic matter and is reported as "ppm as oxygen". The test measures the quantity of oxygen depletion resulting from the ability of common bacteria to digest organic matter during a 5-day incubation period at 20^{o} C.

Boron (B): Boron can be found in seawater at levels up to 5 ppm and at lower levels in brackish waters where inland seas once existed. Boron is not a foulant, but the removal of boron is an important issue in the electronics industry as it adversely affects the process in some applications. The chemistry of boron is similar to silica in that it exists as the borate monovalent anion $B(OH)_4^-$ at high pH (greater than 10) and as non-ionized boric acid $B(OH)_3$ at lower pH. The rejection of borate is pH dependent, with higher rejection at higher pH levels.

Brackish Water: In the RO field, brackish water can be defined as feed water with low to medium TDS levels (up to 10,000 to 15,000 ppm). It can be treated with a "brackish RO element" designed for 600 psi maximum applied feed pressure.

Calcium (Ca): A divalent cation. Calcium, along with magnesium, is a major component of hardness in brackish water. The solubility of calcium sulfate ($CaSO_4$)(gypsum) is typically limited to 230% with the use of an antiscalant. The solubility of calcium carbonate is typically limited to a LSI (Langlier Saturation Index) value of positive 1.8 to 2.5.

Carbon Dioxide (CO_2): Carbon dioxide is a gas, that when dissolved in water, reacts with the water to form weak carbonic acid (H_2CO_3). If a pure water was completely saturated with carbon dioxide, its concentration would be about 1600 ppm and the pH would be about 4.0. A typical source for carbon dioxide in natural waters is the result of a balance with bicarbonate alkalinity based on the pH of the water. The concentration of carbon dioxide in water is typically indirectly determined by graphical comparison to the bicarbonate concentration and pH. Carbon dioxide and the bicarbonate ion are in a balance between the pH range of 4.4 and 8.2. The alkalinity is all carbon dioxide at pH 4.4 or less, and is all bicarbonate at pH 8.4 or more. The RO design program calculates the carbon dioxide level based on the bicarbonate level and pH of the water. Carbon dioxide, being a gas, is not rejected or concentrated by a RO membrane, therefore its concentration will the same in the feed, permeate and concentrate. Acidifying the RO feed water will lower pH by converting bicarbonate to carbon dioxide.

Carbonate (CO_3): A divalent anion. The solubility of calcium carbonate is low and can cause a RO scaling problem in the back-end of a RO. Calcium carbonate solubility is measured using LSI (Langlier Saturation Index) for brackish waters or SDSI (Stiff-Davis Index) for seawaters and is lower with increasing temperature and increasing pH. Carbonate is one component of alkalinity and its concentration is in a balance with bicarbonate between the pH range of 8.2 and 9.6. At a pH of 9.6 and higher, there is no carbon dioxide or bicarbonate, with all alkalinity being in the carbonate form.

Cations and Anions: Cations are ions with a positive valence state (they are willing to accept electrons) and have the ability to react with anions which are ions with a negative valence state (they have extra electrons to share). The sharing of electrons creates electroneutrality. For example, the calcium ion is a divalent cation and will combine with two monovalent chloride ions to form the electrically neutral salt known as calcium chloride. A balanced water analysis will have the same concentration of cations as anions when reported as “ppm as calcium carbonate” or as meq/l. Silica, a very weak anion, is not used to calculate the ionic balance of cations and anions (though it is used in the calculation of TDS).

Chloride (Cl): A monovalent anion. The solubility of chloride salts is high and does not create a RO scaling problem. Chloride, in seawater, is the prevalent anion. Chloride is the anion used to automatically balance a RO feed water analysis. The recommended upper limit for chloride in potable water by the US EPA and WHO is 250 ppm based on taste issues.

COD (Chemical Oxygen Demand): COD is a non-specific test that measures the quantity of both bio-degradable and non-biodegradable organic matter and is reported as “ppm as oxygen”. The test measures the ability of a hot chromic acid solution to oxidize organic matter.

Color: Color is a non-specific test that measures the relative level of organic compounds in water based on their contribution to adding color and is reported in APHA units relative to the platinum standard.

Conductivity: Conductivity is a measurement of the ability of water to transmit electricity due to the presence of dissolved ions. Absolute pure water with no ions will not conduct an electrical current. Conductivity is measured by a conductivity meter and is reported as micromhos/cm or microSiemens/cm. Conductivity is a convenient method of determining the level of ions in a water but is non-specific in what the ions are. The electrical conductance of ions will vary by ion and will decrease as the concentration of ions increase.

TDS (Total Dissolved Salts) meters utilize conductivity measurements with a conversion factor applied. These conversion factors are a function of the TDS value. Conductivity can also be estimated using individual conversion factors from the reported ion concentrations of a water analysis or by using a single conversion factor based on the sum of the ions (TDS). Carbon dioxide conductivity can be estimated by taking the square root of the ppm concentration and then multiplying by 0.6. The silica ion does not contribute to conductivity. The most accurate conductivity readings for high quality RO permeate are obtained on-site since carbon dioxide levels, being a gas, can vary when exposed to the atmosphere.

Fluoride (F): A monovalent anion. Fluoride is found naturally at low levels in some well waters, but normally its presence is due to injection into municipal water to provide a residual up to 2.5 ppm for the control of dental caries. Fluoride levels in potable waters above 5 ppm can cause mottled and brittle teeth. The rejection of fluoride by a RO membrane is pH dependent. Rejections with polyamide membranes in the basic pH range can be greater than 99% due to fluoride being in the salt form. Rejections in the acidic pH range can drop below 50% due to fluoride being in the acid form.

Grains (per gallon): Ion exchange and boiler water chemists frequently report the concentration of hardness as “Grains per Gallon (as calcium carbonate equivalents)”. One Grain per U.S. Gallon (as calcium carbonate) is equal to 17.1 ppm (as calcium carbonate).

Hydrogen Sulfide (H_2S): Hydrogen sulfide is a gas that causes the noticeable “rotten egg” smell in feed waters, with a threshold odor level of 0.1 ppm and a noticeable offensive odor at 3-5 ppm. Hydrogen sulfide is readily oxidized to elemental sulfur by oxidants (e.g. air, chlorine or potassium permanganate). Sulfur acts as a colloidal foulant and has a history of not being removed well by conventional multimedia filtration. The preferred RO system design suggests leaving the hydrogen sulfide in its gaseous form, let it pass through the RO into the permeate, and then treat the permeate for its removal.

Ionic Strength: The solubility of sparingly soluble salts increases with increasing feed TDS. To account for this effect in calculating the solubility of a salt (e.g. calcium sulfate, barium sulfate, strontium sulfate or SDSI), the Ionic Strength of a water is calculated. The Ionic Strength of each ion is derived by taking the ppm concentration of each ion (as calcium carbonate) and multiplying each monovalent ion by 1 x 10-5 and each divalent ion by 2 x 10-5. Summing the Ionic Strength of each ion then derives the total Ionic Strength of the water.

Iron (Fe): Iron is a water contaminant that takes two major forms. The water-soluble form is known as the ferrous state and has a + 2 valence state. In non-aerated well waters ferrous iron behaves much like calcium or magnesium hardness in that it can be removed by softeners or its precipitation in the back end of the RO system can be controlled by the use of a dispersant chemical in an RO feed water. The water-insoluble form is known as the ferric state and has a + 3 valence state. Typically, RO manufacturers will recommend that combined iron levels be less than 0.05 ppm in the RO feed. If all iron is in the soluble ferrous form, iron levels up to 0.5 ppm in the feed can be tolerated if the pH is less than 7.0 (though an iron dispersant is recommended). The introduction of air into water with soluble ferrous iron will result in the oxidation to insoluble ferric iron.

Soluble iron can be found in deep wells, but can be converted into the more troublesome insoluble iron by the introduction of air by being placed in tanks or by leaky pump seals. Soluble iron can be treated with dispersants or can be removed by iron filters, softeners or lime softening.

Insoluble ferric iron oxides or ferric hydroxides, being colloidal in nature, will foul the front end of the RO system. Sources of insoluble iron are aerated well waters, surface sources, and iron scale from unlined pipe and tanks. Insoluble iron can be removed by iron filters, lime softening, softeners (with limits), ultrafiltration (with limits) and multimedia filtration with polyelectrolyte feed (with limits). Precautions are required with the use of potassium permanganate in manganese greensand iron filters in that potassium permanganate is an oxidant that could damage any polyamide membrane. Precautions are also required with a cationic polyelectrolyte in that they can irreversibly foul a negatively charged polyamide membrane. Corrosion proof vessels and piping (e.g. FRP, PVC or stainless steels) are recommended for all RO systems, RO pretreatment, and distribution piping coming to the RO system.

Iron as foulant will quickly increase RO feed pressure requirements and increase permeate TDS. In some cases, the presence of iron can create a bio-fouling problem by being the energy source for iron-reducing bacteria. Iron-reducing bacteria can cause the formation of a slimy biofilm that can plug the RO feed path.

LSI (Langlier Saturation Index): LSI is a method of reporting the scaling or corrosive potential of low TDS brackish water based on the level of saturation of calcium carbonate. LSI is important to boiler water and municipal plant chemists in determining whether a water is corrosive (has a negative LSI) or will tend to scale calcium carbonate (has a positive LSI). LSI is important to RO chemists as a measurement of the scaling potential for calcium carbonate. The LSI value is calculated by subtracting the calculated pH of saturation of calcium carbonate from the actual feed pH. Calcium carbonate solubility decreases with increasing temperature (as evidenced by the liming of a teakettle), higher pH, higher calcium concentration, and higher alkalinity levels. The LSI value can be lowered by reducing pH by the injection of an acid (typically sulfuric or hydrochloric) into the RO feed water. A recommended target LSI in the RO concentrate is negative 0.2 (which indicates that the concentrate is 0.2 pH units below the point of calcium carbonate saturation). A negative 0.2 LSI allows for pH excursions in actual plant operation. A polymer-based antiscalant can also be used to inhibit the precipitation of calcium carbonate. Some antiscalant suppliers have claimed the efficacy of their product up to a positive LSI value of 2.5 in the RO concentrate (though a more conservative design LSI level is +1.8). Sodium hexametaphosphate, an inorganic antiscalant, was used in the early days of RO but the maximum concentrate LSI was + 0.5 and it had to be made in short-lived batches as the air easily oxidized it.

Magnesium (Mg): A divalent cation. Magnesium can account for about a third of the hardness in a brackish water, but can have a concentration five times higher than calcium in sea water. The solubility of magnesium salts is high and typically does not cause a scaling problem in RO systems.

Manganese (Mn): Manganese is a water contaminant present in both well and surface waters, with levels up to 3 ppm. Manganese, like iron, can be found in organic complexes in surface waters. In oxygen-free water, it is soluble. In the oxidized state, it is insoluble and usually in the form of black manganese dioxide (MnO_2) precipitate. Levels above 0.05 ppm manganese could result in potential fouling in a RO system with aerated RO feed water. Drinking water regulations limit manganese to 0.05 ppm due to its ability to cause black stains. Dispersants used to control iron fouling can be used to help control manganese fouling.

Milli-equivalent (meq/l): A method of reporting the concentration or “equivalent” weight of an ion or substance in a given volume of water is known as milli-equivalents per liter. meq/l is calculated by dividing the mg/l by the equivalent weight of the ion or substance. Reporting the concentration of ions as meq/l is popular by RO chemists for determining whether a water analysis is “balanced” where the sum of the cations equals the sum of the anions.

Milligram per liter (mg/l): (see also ppm). A method of reporting the “actual” concentration (milligrams) of an ion or substance in a given volume of water (liter). For dilute solutions, mg/l and ppm are equivalent. For example, a 1,000 mg/l (ppm) sodium chloride solution would result in a residue of 1,000 mg of NaCl after evaporation of one liter of water. RO chemists use mg/l frequently in the calculation of TDS.

Nitrate (NO_3): A monovalent anion. Nitrate salts are highly soluble and do not cause a RO scaling problem. Nitrate, along with ammonia gas and ammonium, is a nitrogen-based ion whose presence is tied with nature’s nitrogen cycle. The primary sources of nitrogen introduction in a feed water come from decomposing animal and plant waste, septic systems, animal feed lot run-off, or agricultural field run-off from fields fertilized with ammonia. In well water sources, ammonia and ammonium are not found, having been converted to the transitory nitrite ion by certain types of bacteria in soils and then oxidized into the more prevalent nitrate ion.

Frequently, nitrate concentrations are reported as “ppm as nitrogen” in water analysis and not as “ppm as nitrate” as required for RO projections. To convert “ppm as nitrogen” to “ppm as nitrate”, multiply “ppm as nitrogen” by 4.43. The US EPA has set a maximum recommended limit of nitrate at 10 ppm as nitrogen (44.3 ppm as nitrate) for potable drinking water. Nitrates are harmful in that they compete with oxygen for carrying sites in blood hemoglobin. The reduced oxygen content can result in the “blue-baby syndrome” which is why babies and pregnant women are at higher risk to the effects of nitrates.

Osmotic Pressure: The pressure phenomena resulting from the difference of salt concentrations across a RO membrane. Increasing TDS levels result in increased osmotic pressure. The RO feed pump has to generate sufficient pressure to overcome this osmotic pressure before permeate is produced. A rough rule of thumb is that 1,000 ppm TDS equals 11 psi osmotic pressure. A brackish water at 550 ppm TDS produces 5 psi osmotic pressure. A seawater at 35,000 ppm TDS produces 385 psi osmotic pressure.

pH: The pH of the feed water measures the acidity or basicity. A pH of 7.0 is considered neutral. A pH less than 7.0 is acidic. A pH greater than 7.0 basic. To the analytical chemist, pH is a method of expressing hydrogen ion concentration logarithmically with the pH value being the negative logarithm (base 10) of the hydrogen ion concentration. To the water chemist, pH is important in defining the alkalinity equilibrium levels of carbon dioxide, bicarbonate, carbonate and hydroxide ions. The concentrate pH is typically higher than the feed due to the higher concentration of bicarbonate/carbonate ions relative to the concentration of carbon dioxide.

The RODESIGN program allows the user to adjust the pH of the feed water using hydrochloric and sulfuric acid. Lowering the feed pH with acid results in a lower LSI (Langlier Saturation Index) value, which reduces the scaling potential for calcium carbonate. Feed and concentrate (reject) pH can also effect the solubility and fouling potential of silica, aluminum, organics and oil. Variations in feed pH can also affect the rejection of ions. For example, fluoride, boron and silica rejection are lower when the pH becomes more acidic.

Potassium (K): A monovalent cation. It is typically found at much lower concentrations than sodium. The salts of potassium are highly soluble and do not cause a RO scaling problem.

ppb (parts per billion): A method to report the concentration of an ion or substance in a water. The following conversions apply for dilute waters with a specific gravity of 1.0: One ppb is equal to one microgram per liter (ug/L). One ppm is equal to 1,000 ppb.

ppm (parts per million): A method for reporting the concentration of an ion or substance in a water. The following conversions apply for dilute waters with a specific gravity of 1.0: One ppm is equal to one mg/L. One Grain per U.S. Gallon is equal to 17.1 ppm. One Pound per 1,000 U.S. Gallons is equal to 120 ppm. A one per cent solution is equal to 10,000 ppm. One ppm is equal to 1,000 ppb.

ppm as $CaCO_3$: A method of reporting the concentration or "equivalent" weight of an ion or substance in a given volume of water as "ppm as calcium carbonate". Reporting the concentration of ions as "ppm as calcium carbonate" is popular by ion exchange chemists for the calculation of ionic loading of cation or anion resins. It is also popular in determining whether a water analysis is "balanced" where the sum of the cations equals the sum of the anions when the concentration of the ions are reported as calcium carbonate equivalents.

Water chemists use the concept of "equivalency" when balancing cation and anion electroneutrality levels since ions combine in nature based on their valence state and available electrons, not on their "actual" weight. Calcium carbonate was arbitrarily picked because its molecular weight is 100 and its equivalent weight is 50 (MW = 100/charge = 2) since it is divalent (MW = 100/charge = 2). The formula to convert an ion reported as "mg/l as the ion" to "ppm as calcium carbonate" is to multiply "mg/l as the ion" times the ratio of the "equivalent weight of the ion" by the "equivalent weight of calcium carbonate".

As an example, a water with sodium at 100 ppm as calcium carbonate and chloride at 100 ppm as calcium carbonate are in ionic balance since every sodium ion has a corresponding chloride ion. However, sodium concentration at 100 ppm as calcium carbonate is only 47 mg/l of actual substance (since its equivalent weight is 23.0) and 100 ppm of chloride as calcium carbonate is only 71 mg/l of actual substance (since its equivalent weight is 35.5). The calculated TDS of this solution is 118 mg/l.

SDI (Silt Density Index): An empirical test developed for membrane systems to measure the rate of fouling of a 0.45 micron filter pad by the suspended and colloidal particles in a feed water. This test involves the time required to filter a specified volume of feed at a constant 30 psi at time zero and then after 5 minutes, 10 minutes and 15 minutes of continuous filtration. Typical RO element warranties list a maximum SDI of 4.0 at 15 minutes for the feed water. If the SDI test is limited to only 5 or 10 minute readings due to plugging of the filter pad, the user can expect a high level of fouling for the RO. Deep wells typically have SDI's of 3 or less and turbidities less than one with little or no pretreatment. Surface sources typically require pretreatment for removal of colloidal and suspended solids to achieve acceptable SDI and turbidity values.

SDSI (Stiff Davis Saturation Index): SDSI, in similar fashion as LSI, is a method of reporting the scaling or corrosion potential of high TDS seawater based on the level of saturation of calcium carbonate. The primary difference between SDSI for high TDS seawater and LSI for low TDS brackish water is the effect that increasing ionic strength has on increasing solubility.

The solubility of sparingly soluble salts increase with higher TDS and ionic strength, based on the theory that a denser ion population interferes in the formation and/or precipitation of the sparingly soluble salt.

Silica (SiO_2): Silica (silicon dioxide) is a weak anion. The chemistry of silica is relatively complex. In similar fashion as TOC reports the total concentration of organics (as carbon) without detailing what the organic compounds are, silica reports the total concentration of silicon (as silica) without detailing what the silicon compounds are.

The "Total Silica" content of a water is composed of "Reactive Silica" and "Unreactive Silica". Reactive silica (e.g. silicates SiO_4) is dissolved silica that is slightly ionized and has not been polymerized into a long chain. Reactive silica is the form that is best for RO and ion exchange systems. Reactive silica is the form of silica to be used in RO projection programs. Reactive silica, though it has anionic characteristics, is not counted as an anion in terms of balancing a water analysis but it is counted as a part of total TDS.

Unreactive silica is polymerized, or colloidal, silica. It acts more like a solid than a dissolved ion. Silica, in the colloidal form, can be removed by a RO system, but it can cause colloidal fouling of the front-end of the system. Colloidal silica can be measured empirically by the SDI (Silt Density Index) test, but only that portion that is larger than 0.45 micron or larger is retained on the filter pad. Particulate silica compounds (e.g. clays, silts and sand) are usually 1 micron or larger and can be measured using the SDI test. Polymerized silica, which uses silicon dioxide as the building block, exists in nature (e.g. quartzes and agates). Silica, in the polymerized form, also results from exceeding the reactive silica saturation level.

The solubility of reactive silica is typically limited to 200-300% with the use of a silica dispersant. Reactive silica solubility increases with increasing temperature, increases at a pH less than 7.0 or more than 7.8, and decreases in the presence of iron which acts as a catalyst in the polymerization of silica. Silica rejection is pH sensitive, with increasing rejection at a more basic pH as the reactive silica exists more in the salt form than in the acidic form.

Sodium (Na): A monovalent cation. The solubility of sodium salts is high and does not cause a RO scaling problem. Sodium, in seawater, is the prevalent cation. Sodium is the cation used to automatically balance a RO feed water analysis. Dietary sodium levels can range from 2000 mg/l for low-sodium diets to 3500 mg/l for average consumption levels. The US EPA has set a DWEL (Drinking Water Equivalent Limit) of 20 mg/l for potable water but is reevaluating the limit as too low. Daily consumption of 2 liters (0.53 gallons) of water with 100 mg/l of sodium would be only 200 mg. A relatively "hard water" with 10 grains per gallon (171.2 mg/L) of hardness (as calcium carbonate) results in only an additional 79 mg/L of sodium when softened.

Strontium (Sr): A divalent cation. The solubility of strontium sulfate is low and can cause a RO scaling problem in the back-end of a RO. Strontium sulfate solubility is lower with increasing sulfate levels and decreasing temperatures. Typically, strontium can be found in some well waters where lead ores are also present, with typical concentrations less than 15 ppm. With saturation at 100%, super-saturation up to 800% is typical with an antiscalant.

Sulfate (SO_4): A divalent anion. The solubility of calcium, barium and strontium sulfates is low, and these constituents can cause a RO scaling problem in the back-end of a RO. The solubility of these sparingly soluble salts is lower with decreasing temperature. The recommended upper limit for sulfate in potable water is 250 ppm based on taste issues.

TDS (Total Dissolved Solids): TDS, in water treatment, is the inorganic residue left after the filtration of colloidal and suspended solids and then the evaporation of a known volume of water. TDS is reported as ppm or mg/l. TDS, in RO design projections, is determined by calculation using the sum of the cations, anions and silica ions (with the ion reported "as such", not "as calcium carbonate"). Feed or permeate TDS, in RO design projections, can also be estimated by applying a conversion factor to the conductivity of the solution. This factor varies as a function of TDS or composition of ions in the water. TDS can also be determined in the field by use of a TDS meter. TDS meters measure the conductivity of the water and then apply a conversion factor that reports TDS to a known reference solution (e.g. ppm sodium chloride or ppm potassium chloride). The user is cautioned that TDS levels for waters with a mixture of ions and determined from conductivity measurements may not agree with TDS calculated as a sum of the ions. As a rough rule of thumb, one ppm of TDS (when referenced to a NaCl solution) correlates to a conductivity of two micromhos/cm (microSiemens/cm).

Temperature: Temperature is a critical design parameter. It has significant effects on feed pump pressure requirements, hydraulic flux balance between stages, permeate quality, and solubility of sparingly soluble salts. As a rough rule of thumb, every 10-degree Fahrenheit decrease in feed temperature increases the feed pump pressure requirement 15 %.

The hydraulic flux balance between stages (or in other words the amount of permeate produced by each stage) is impacted by temperature. When water temperature increases, the elements located in the front end of the system produce more permeate which results in reduced permeate flow by the elements located at the rear of the system. A better hydraulic flux balance between stages occurs at colder temperatures. At warmer temperatures, salt passage increases due to the increased mobility of the ions through the membrane. Warmer temperatures decrease the solubility of calcium carbonate. Colder temperatures decrease the solubility of calcium sulfate, barium sulfate, strontium sulfate, and silica.

TOC (Total Organic Carbon): TOC, an acronym for Total Organic Carbon or Total Oxidizable Carbon, is a non-specific test that measures the amount of carbon bound in organic material and is reported in units of "ppm as carbon". Since the TOC only measures the amount of carbon in organic matter, the actual weight of the organic mass can be up to 3 times higher in natural surface waters. Organics are compounds that contain carbon (with the exception of carbon dioxide, bicarbonate and carbonate). In water treatment, organics can be classified as naturally occurring or man-made. Naturally occurring organic matter are typically negatively-charged colloids or suspended solids, comprised of tannins, lignin's, water soluble humic acid compounds resulting from the decay of certain vegetative matter, or fulvic acid compounds resulting from the decay of certain vegetative matter. Naturally occurring organic material can be a foulant to RO membranes, particularly the negatively charged composite polyamides. Neutrally charged RO membranes (e.g. neutrally charged composite polyamides and cellulose acetate) are more resistant to organic fouling. A RO will reject organic compounds. Generally, organic compounds with a molecular weight greater than 200 are rejected at levels greater than 99%. The rejection of compounds with molecular weights less than 200 will vary based on molecular weight, shape and ionic charge. As a rough rule of thumb, concentrations of TOC at 3 ppm, BOD at 5 ppm, and COD at 8 ppm in natural water sources may cause organic fouling.

Turbidity: Turbidity is a suspension of fine colloidal particles that do not readily settle out of solution and can result in a "cloudiness". Turbidity is determined by a Nepholometer that measures the relative amount of light able to pass through a solution. Turbidity is reported as NTU (Nephelometric Turbidity Units). Typical RO element warranties list a maximum of 1.0 NTU for the feed water.

RO Design Help File

RO Sizing

RO Sizing

The approximate system size (the number of membrane elements and pressure tubes) required to produce a quantity of product water (permeate) may be determined by the following steps:

a. Select the membrane type and corresponding model number.

b. Select the flux rate (GFD) according to expected feed water quality.

c. Divide the desired plant capacity by the design flux rate and by membrane element surface area (the membrane area is listed in the element specification sheet).

d. Divide total number of elements by the number of elements per pressure vessel. Round result up to the nearest integer.

e. Select the appropriate array to achieve the desired percentage recovery. Increase number of pressure vessels if necessary.

The RODESIGN program displays the recommended pump pressure in addition to the calculated feed pressure. The recommended pump pressure is higher than the feed pressure by 10% of Net Driving Pressure + 3 psi (0.2 bar) for entry loses. This safety margin should usually be sufficient. Alternatively, a safety margin of 10% should be used for system design whenever the fouling rate cannot be predicted. A design should include as a contingency a number of elements 10% higher than calculated by the computer program. Alternatively, the feed pressure should be specified as required for the given product flow with 90% of the calculated membrane elements.

A NOTE OF CAUTION TO THE DESIGNER:

The RODESIGN program only projects RO system performance from a user controlled set of data input and design decisions. The program does not judge whether a system design is realistic or optimized for a given set of conditions. It is the user's responsibility to review and judge the system design based on the anticipated or existing pretreatment, reasonable design guidelines, and experience. The user is strongly recommended to review all RO system designs with the HYDRANAUTICS Technical Support Group or a HYDRANAUTICS Technical Sales Representative.

RO Design Help File

Hydranautics Design Limits

Hydranautics Design Limits.

The Following System Design Limits should be observed when designing a Reverse Osmosis system.

Average flux rates and expected % decrease in flux per year:

Water Type	SDI	Flux	% Flux Decline/year
Surface water	(SDI 2 - 4)	8 - 14 GFD	7.3 - 9.9
Well water	(SDI < 2)	14 - 18 GFD	4.4 - 7.3
RO Permeate	(SDI < 1)	20 - 30 GFD	2.3 - 4.4

Expected % Salt Passage Increase per year:

MembraneType	Abbreviation	% SP Increase/year
Cellulosic membrane	CAB1, CAB2, CAB3	17 - 33
Composite Membrane		
Brackish, Low Pressure	ESPA1, ESPA2, ESPA3	3 -- 17
Brackish, High Rejection	CPA2, CPA3, CPA4	3 -- 17
Low Fouling	LFC1, LFC2	3 -- 17
Seawater	SWC1, SWC2, SWC3	3 -- 17
Softening, PolyVinyl Deriv.	PVD1, ESNA1, ESNA2	3 -- 17

Maximum Feed Flow and Minimum Concentrate Flow Rates per Vessel:

Membrane Diameter (in)	Max (GPM)	Max (m^3/hr)	Min (GPM)	Min (m^3/hr)
4	16	3.6	3	0.7
6	30	8.8	7	1.6
8	75	17.0	12	2.7
8.5	85	19.3	14	3.2

Saturation Limits for Sparingly Soluble Salts in the Concentrate:

Salt	Saturation %
$CaSO_4$	230
$SrSO_4$	800
$BaSO_4$	6000
SiO_2	100

Limits of Saturation Indices:

Condition*	LSI Value
LSI and SDSI without scale inhibitor	$\leq$ -0.2
LSI & SDSI with SHMP	$\leq$ 0.5
LSI & SDSI with organic scale inhibitor	$\leq$ 1.8

* Langelier and Stiff & Davis Saturation Indices

RO Design Help File

Terms and Equations of Reverse Osmosis

Terms and Equations of Reverse Osmosis

There is a set of terms and equations used to define the parameters governing transport across a membrane. This paper presents the concepts of Reverse Osmosis and the equations used to describe them.

OSMOTIC PRESSURE

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

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

where P_{osm} = osmotic pressure (in psi), T is the temperature (in °C), and $\Sigma(m_i)$ is the sum of molal concentration of all constituents in a solution. An approximation for P_{osm} may be made by assuming that 1000 ppm of Total Dissolved Solids (TDS) equals about 11 psi (0.76 bar) of osmotic pressure.

The mechanism of water and salt separation by reverse osmosis is not fully understood. Current scientific thinking suggests two transport models: porosity and diffusion. That is, transport of water through the membrane may be through physical pores present in the membrane (porosity), or by diffusion from one bonding site to another within the membrane. The theory suggests that the chemical nature of the membrane is such that it will absorb and pass water preferentially to dissolved salts at the solid/liquid interface. This may occur by weak chemical bonding of the water to the membrane surface or by dissolution of the water within the membrane structure. Either way, a salt concentration gradient is formed across the solid/liquid interface. The chemical and physical nature of the membrane determines its ability to allow for preferential transport of solvent (water) over solute (salt ions).

WATER TRANSPORT

The rate of water passage through a semipermeable membrane is defined in Equation 2.

$Q_w = (\Delta P - \Delta P_{osm}) * K_w * S/d$ (2)

where Q_w is the rate of water flow through the membrane, ΔP is the hydraulic pressure differential across the membrane, ΔP_{osm} is the osmotic pressure differential across the membrane, K_w is the membrane permeability coefficient for water, S is the membrane area, and d is the membrane thickness. This equation is often simplified to:

$Q_w = A * (NDP)$ (3)

Where A represents a unique constant for each membrane material type, and NDP is the net driving pressure or net driving force for the mass transfer of water across the membrane.

SALT TRANSPORT

The rate of salt flow through the membrane is defined by Equation 4:

$Q_s = \Delta C * K_s * S/d$ (4)

where Q_s is the flow rate of salt through the membrane, K_s is the membrane permeability coefficient for salt, delC is the salt concentration differential across the membrane, S is the membrane area, and d is the membrane thickness. This equation is often simplified to:

$Q_s = B*(\Delta C)$ (5)

Where B represents a unique constant for each membrane type, and ΔC is the driving force for the mass transfer of salts.

Equations 4 and 5 show that for a given membrane:

a) Rate of water flow through a membrane is proportional to net driving pressure differential (NDP) across the membrane.

b) Rate of salt flow is proportional to the concentration differential across the membrane and is independent of applied pressure.

Salinity of the permeate, C_p, depends on the relative rates of water and salt transport through reverse osmosis membrane:

$C_p = Q_s/Q_w$ (6)

The fact that water and salt have different mass transfer rates through a given membrane creates the phenomena of salt rejection. No membrane is ideal in the sense that it absolutely rejects salts; rather the different transport rates create an apparent rejection. The equations 2, 4 and 5 explain important design considerations in RO systems. For example, an increase in operating pressure will increase water flow without changing salt flow, thus resulting in lower permeate salinity.

SALT PASSAGE

Salt passage is defined as the ratio of concentration of salt on the permeate side of the membrane relative to the average feed concentration. Mathematically, it is expressed in Eq. 7:

$SP = 100\% * (C_p/C_{fm})$ (7)

where SP is the salt passage (in %), C_p is the salt concentration in the permeate, and C_{fm} is the mean salt concentration in feed stream.

Applying the fundamental equations of water flow and salt flow illustrates some of the basic principles of RO membranes. For example, salt passage is an inverse function of pressure; that is, the salt passage increases as applied pressure decreases. This is because reduced pressure decreases permeate flow rate, and hence, dilution of salt (the salt flows at a constant rate through the membrane as its rate of flow is independent of pressure).

SALT REJECTION

Salt rejection is the opposite of salt passage, and is defined by Equation 8.

$SR = 100\% - SP$ (8)

where SR is the salt rejection (in %), and SP is the salt passage as defined in Equation 7.

PERMEATE RECOVERY RATE (CONVERSION)

Permeate recovery is another important parameter in the design and operation of RO systems. Recovery or conversion rate of feed water to product (permeate) is defined by Equation 9.

$R = 100\% * (Q_p/Q_f)$ (9)

where R is recovery rate (in %), Q_p is the product water flow rate, and Q_f is the feed water flow rate. The recovery rate affects salt passage and product flow. As the recovery rate increases, the salt concentration on the feed-brine side of the membrane increases, which causes an increase in salt flow rate across the membrane as indicated by Equation 5. Also, a higher salt concentration in the feed-brine solution increases the osmotic pressure, reducing the NDP and consequently reducing the product water flow rate according to Equation 2.

CONCENTRATION POLARIZATION

As water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration exceeds the salt concentration in the bulk solution. This increase of salt concentration is called concentration polarization. The effect of concentration polarization is to reduce actual product water flow rate and salt rejection versus theoretical estimates. The effects of concentration polarization are as follows:

1. Greater osmotic pressure at the membrane surface than in the bulk feed solution, ΔP_{osm}, and reduced Net Driving Pressure differential across the membrane ($\Delta P - \Delta P_{osm}$).

2. Reduced water flow across membrane (Q_w).

3. Increased salt flow across membrane (Q_s).

4. Increased probability of exceeding solubility of sparingly soluble salts at the membrane surface, and the distinct possibility of precipitation causing membrane scaling.

The Concentration Polarization Factor (CPF) can be defined as a ratio of salt concentration at the membrane surface (C_s) to bulk concentration (C_b).

$CPF = C_s/C_b$ (10)

An increase in permeate flux will increase the delivery rate of ions to the membrane surface and increase C_s. An increase of feed flow increases turbulence and reduces the thickness of the high concentration layer near the membrane surface. Therefore, the CPF is directly proportional to permeate flow (Q_p), and inversely proportional to average feed flow (Q_{favg}).

$$CPF = K_p * \exp(Q_p / Q_{favg}) \qquad (11)$$

Where K_p is a proportionality constant depending on system geometry.

Using the arithmetic average of feed and concentrate flow as average feed flow, the CPF can be expressed as a function of the permeate recovery rate a of membrane element (R_i).

$$CPF = K_p * \exp(2R_i/(2-R_i)) \qquad (12)$$

The value of the Concentration Polarization Factor of 1.20, which is the recommended Hydranautics limit, corresponds to 18% permeate recovery for a 40" long membrane element.

RO Design Help File

Pretreatment

Pretreatment

MEMBRANE FOULING CONSIDERATIONS

The feed water, depending on its source, may contain various concentrations of suspended solids and dissolved matter. Suspended solids may consist of inorganic particles, colloids and biological debris such as microorganisms and algae. Dissolved matter may consists of highly soluble salts, such as chlorides, and sparingly soluble salts, such as carbonates, sulfates, and silica. During the RO process, the volume of feed water decreases, and the concentration of suspended particles and dissolved ions increases. Suspended particles may settle on the membrane surface, thus blocking feed channels and increasing friction losses (pressure drop) across the system. Sparingly soluble salts may precipitate from the concentrate stream, create scale on the membrane surface, and result in lower water permeability through the RO membranes (flux decline). This process of formation of a deposited layer on a membrane surface is called membrane fouling and results in performance decline of the RO system. The objective of the feed water pretreatment process is to improve the quality of the feed water to the level which would result in reliable operation of the RO membranes.

The quality of the feed water is defined in terms of concentration of suspended particles and saturation levels of the sparingly soluble salts. The common indicators of suspended particles used in the RO industry are turbidity and Silt Density Index (SDI). The maximum limits are: turbidity of 1 NTU and SDI of 4. Continuous operation of an RO system with feed water which has turbidity or SDI values near the limits of these values may result in significant membrane fouling. For long-term, reliable operation of the RO unit, the average values of turbidity and SDI in the feed water should not exceed 0.5 NTU and 2.5 SDI units, respectively.

The indicators of saturation levels of sparingly soluble salts in the concentrate stream are the Langelier Saturation Index (LSI) and the saturation ratios. The LSI provides an indication of the calcium carbonate saturation. Negative values of LSI indicate that the water is aggressive and that it will have a tendency to dissolve calcium carbonate. Positive values of LSI indicate the possibility of calcium carbonate precipitation. The LSI was originally developed by Langelier for potable water of a low salinity. For high salinity water encountered in RO applications, the LSI is an approximate indicator only. The saturation ratio is the ratio of the product of the actual concentration of the ions in the concentrate stream to the theoretical solubilities of the salts at a given conditions of temperature and ionic strength. These ratios are applicable mainly to sparingly soluble sulfates of calcium, barium and strontium. Silica could be also a potential scale forming constituent. Other potential scale forming salts, such as calcium fluoride or phosphate which may be present in RO feed, seldom represent a problem.

Depending on the raw water quality, the pretreatment process may consists of all or some of the following treatment steps:

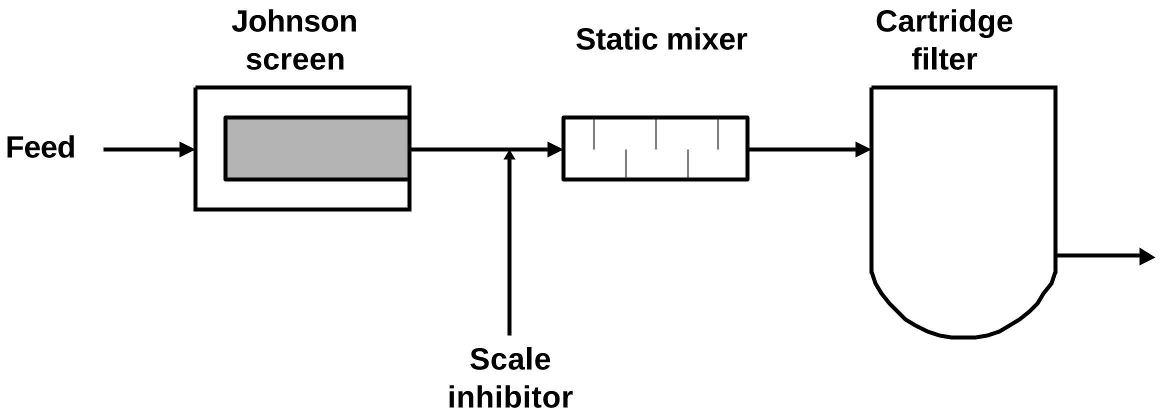
- Removal of large particles using a coarse strainer.
- Water disinfection with chlorine.
- Clarification with or without flocculation.
- Clarification and hardness reduction using lime treatment.
- Media filtration.
- Reduction of alkalinity by pH adjustment.
- Addition of scale inhibitor.
- Reduction of free chlorine using sodium bisulfite or activated carbon filters.
- Water sterilization using UV radiation.
- Final removal of suspended particles using cartridge filters.

The initial removal of large particles from the feed water is accomplished using mesh strainers or traveling screens. Mesh strainers are used in well water supply systems to stop and remove sand particles which may be pumped from the well. Traveling screens are used mainly for surface water sources, which typically have large concentrations of biological debris.

It is common practice to disinfect surface feed water in order to control biological activity. Biological activity in a well water is usually very low, and in majority of cases, well water does not require chlorination. In some cases, chlorination is used to oxidize iron and manganese in the well water before filtration. Well water containing hydrogen sulfide should not be chlorinated or exposed to air. In presence of an oxidant, the sulfide ion can oxidize to elemental sulfur which eventually may plug membrane elements.

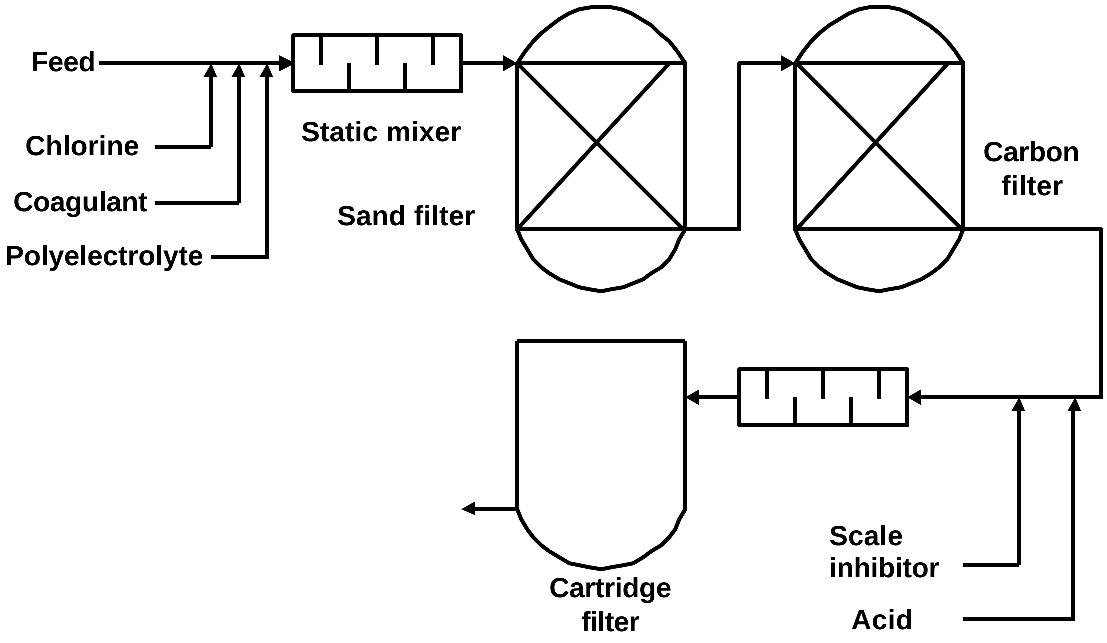
Settling of surface water in a detention tank results in some reduction of suspended particles. Addition of flocculants, such as iron or aluminum salts, results in formation of corresponding hydroxides; these hydroxides neutralize surface charges of colloidal particles, aggregate, and adsorb to floating particles before settling at the lower part of the clarifier. To increase the size and strength of the flock, a long chain organic polymer can be added to the water to bind flock particles together. Use of lime results in increase of pH, formation of calcium carbonate and magnesium hydroxide particles. Lime clarification results in reduction of hardness and alkalinity, and the clarification of treated water.

Well water usually contains low concentrations of suspended particles, due to the filtration effect of the aquifer. The pretreatment of well water is usually limited to screening of sand, addition of scale inhibitor to the feed water, and cartridge filtration.



Pretreatment system for well water source

Surface water may contain various concentrations of suspended particles, which are either of inorganic or biological origin. Surface water usually requires disinfection to control biological activity and removal of suspended particles by media filtration. The efficiency of filtration process can be increased by adding filtration aids, such as flocculants and organic polymers. Some surface water may contain high concentrations of dissolved organics. Those can be removed by passing feed water through an activated carbon filter. Depending on composition of the water, acidification and addition scale inhibitor may be required. The flow diagram of pretreatment system for surface water is shown below.



Pretreatment system for surface water source

Cartridge filters, almost universally used in all RO systems prior to the high pressure pump, serve as the final barrier to water born particles. The nominal rating commonly used in RO applications is in the range of 5 - 15 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.

Recently, new pretreatment equipment has been introduced to the RO market. It consists of backwashable capillary microfiltration and ultrafiltration membrane modules. This new equipment can operate reliably at a very high recovery rates and low feed pressure. The new capillary systems can provide better feed water quality than a number of conventional filtration steps operating in series. The cost of this new equipment is still very high compared to the cost of an RO unit.

RO Design Help File

Flow Configuration

Flow Configuration

There are several flow configurations for RO that allow the user to get the most out of the system. This paper will cover a few of the techniques used in RO design to optimize system performance.

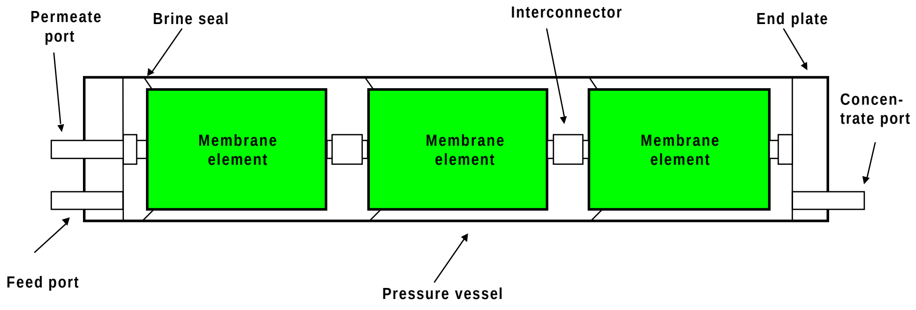
These techniques include the use of concentrate staging and concentrate recirculation to increase recovery, permeate staging to attain ultrapure standards of separation, and permate throttling and interstage boosting to manipulate the flow distribution between stages.

SYSTEM COMPONENTS

RO systems consist of the following basic components:

- Feed water supply unit
- Pretreatment system
- High pressure pumping unit
- Membrane element assembly unit
- Instrumentation and control system
- Permeate treatment and storage unit
- Cleaning unit

The membrane assembly unit (RO block) consists of a stand supporting the pressure vessels, interconnecting piping, and feed, permeate and concentrate manifolds. Membrane elements are installed in the pressure vessels. The pressure vessel has permeate ports on each end, located in center of the end plate, and feed and concentrate ports, located on the opposite ends of the vessel. Each pressure vessel may contain from one to seven membrane elements connected in series.



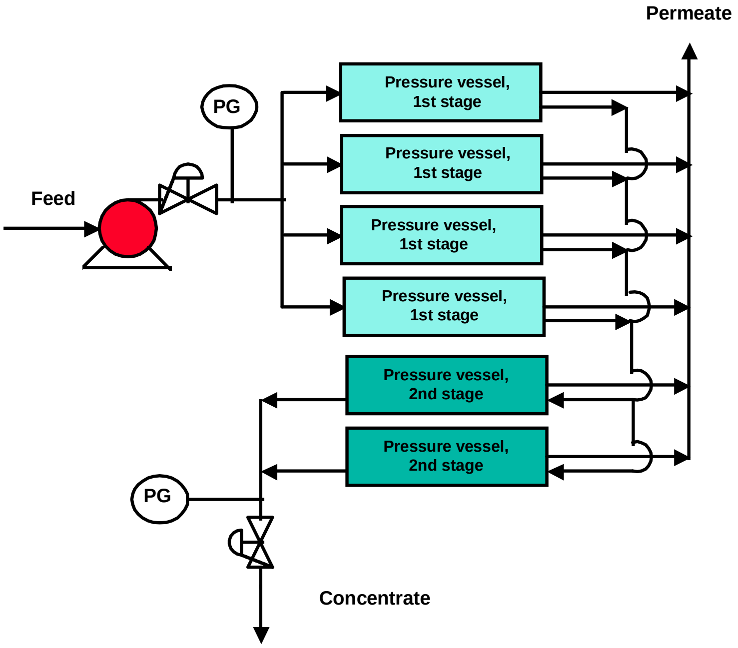
Pressure vessel with three membrane elements

As shown above, the permeate tube of the first and the last element is connected to the end plates of the pressure vessel. Permeate tubes of elements in the pressure vessel are connected to each other using interconnectors. On one side of each membrane element there is a brine seal, which closes the passage between outside rim of the element and inside wall of the pressure vessel. This seal prevents feed water from bypassing the membrane module, and forces it to flow through the feed channels of the element.

As feed water flows through each subsequent membrane element, part of the feed volume is removed as permeate. The salt concentration of the remaining feed water increases along the pressure vessel. Permeate tubes conduct the permeate from all connected elements. The collected permeate has the lowest salinity at the feed end of the pressure vessel, and increases gradually in the direction of the concentrate flow.

CONCENTRATE STAGING and PYRAMID DESIGN

A system is divided into groups of pressure vessels, called concentrate stages. In each stage pressure vessels are connected in parallel, with respect to the direction of the feed/concentrate flow. The number of pressure vessels in each subsequent stage decreases in the direction of the feed flow, usually in the ratio of 2:1, as shown below.



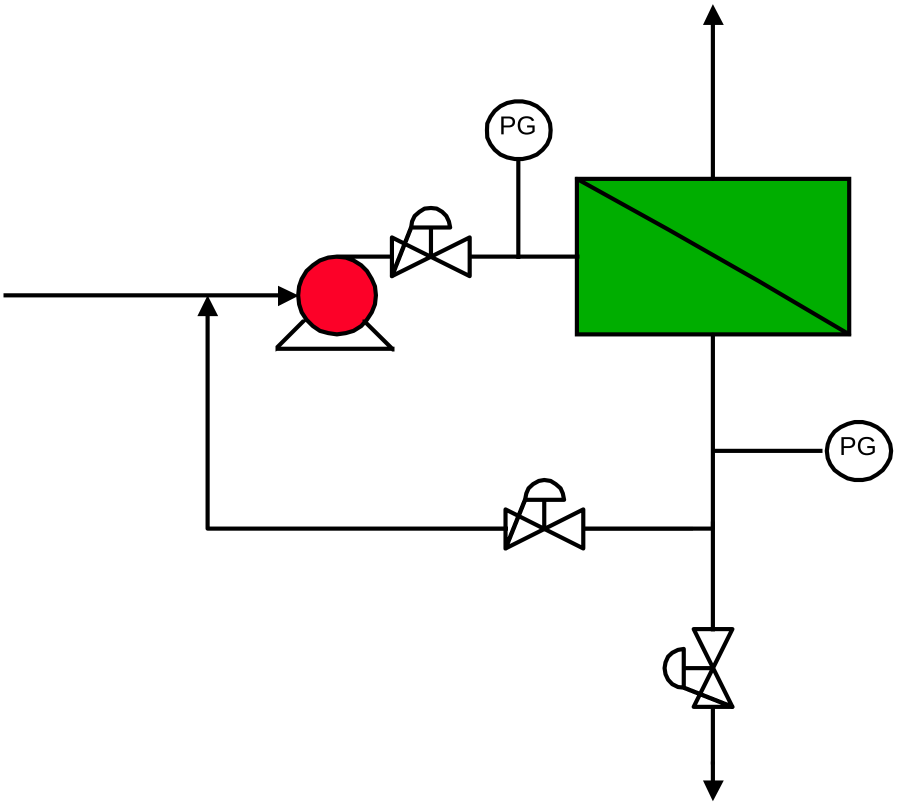
Flow diagram of a two stage RO system

Thus, one can visualise that the flow of feed water through the pressure vessels of a system resembles a pyramid structure: a high volume of feed water flows in at the base of pyramid, and a relatively small volume of concentrate leaves at the top. The decreasing number of parallel pressure vessels from stage to stage compensates for the decreasing volume of feed flow, which is continuously being partially converted to permeate. The permeate of all pressure vessels in each stage, is combined together into a common permeate manifold.

The objective of the taper configuration of pressure vessels is to maintain a similar feed/concentrate flow rate per vessel through the length of the system and to maintain feed/concentrate flow within the limits specified for a given type of membrane element. Very high flow through a pressure vessel will result in a high pressure drop and possible structural damage of the element. Very low flow will not provide sufficient turbulence, and may result in excessive salt concentration at the membrane surface. For a given RO unit, the number of concentrate stages will depend on the permeate recovery ratio and the number of membrane elements per pressure vessel. In order to avoid excessive concentration polarization at the membrane surface, the recovery rate per individual membrane element should not exceed 18%. It is common engineering practice to design brackish RO systems so that the average recovery rate per 40 inch long membrane element will be about 9%. Accordingly, the number of concentrate stages for an RO unit having 6 elements per pressure vessel would be two for recovery rates over 60%, and three for recovery rates over 75%. With pressure vessels containing seven elements, a two stage configuration would be sufficient for recovery rates up to 85%.

CONCENTRATE RECIRCULATION

The simplest membrane element assembly consists of one pressure vessel, containing one membrane element. Such a configuration, used in a very small systems, can operate at a limited permeate recovery ratio, usually about 15%. In order to increase the overall system recovery ratio and still maintain an acceptable concentrate flow, a part of the concentrate stream is returned to the suction of the high pressure pump. The concentrate recycling configuration, shown below, is used mainly in a very small RO units. An advantage of such a design is the compact size of the RO unit. The disadvantage of concentrate recirculation design is related to the need for a larger feed pump to handle higher feed flow. Accordingly, the power consumption is relatively higher than that required in a multistage configuration. Due to blending of the feed with the concentrate stream, the average feed salinity is increased. Therefore, both the feed pressure and the permeate salinity are higher as well.

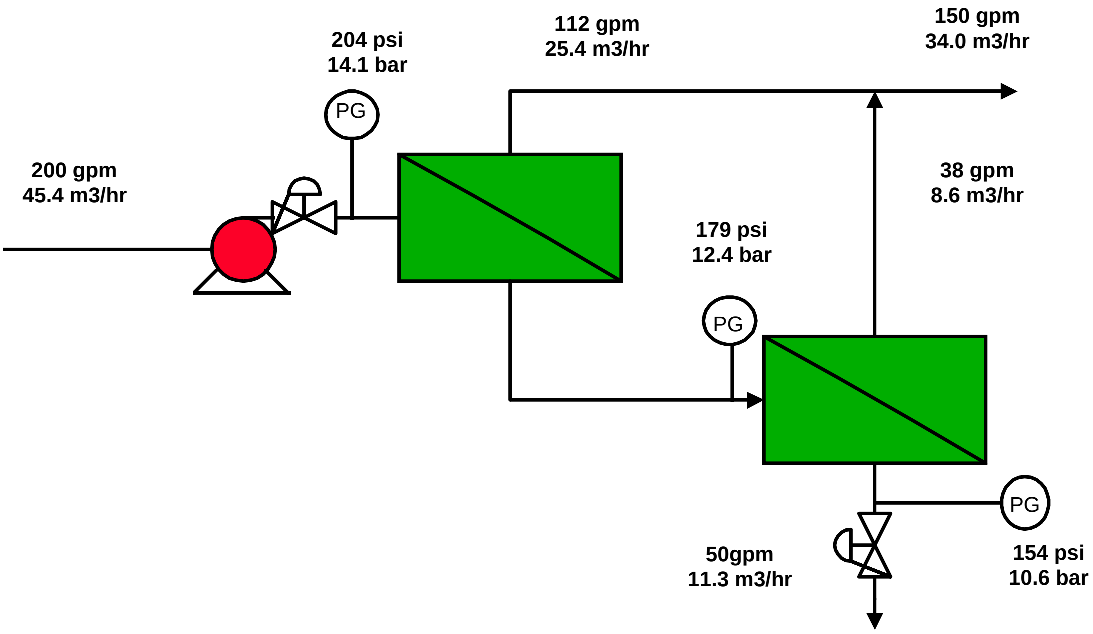


Flow diagram of a single stage RO unit with concentrate recirculation

CONCENTRATE STAGING

A commercial RO unit usually consists of single pump and a multistage array of pressure vessels. A simplified block diagram of a two stage RO unit is shown on the next page.

The concentrate from the first stage becomes the feed to the second stage; this is what is meant by the term "concentrate staging." The flows and pressures in the multistage unit are controlled with the feed and concentrate valves. The feed valve, after the high pressure pump, controls feed flow to the unit. The concentrate valve, at the outlet of RO block, controls the feed pressure.

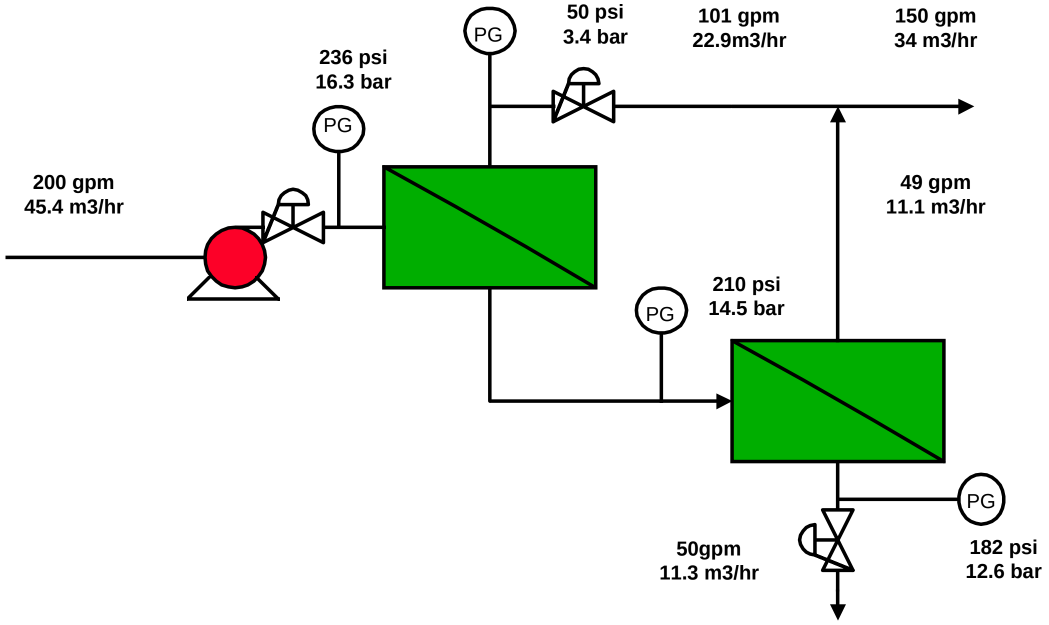


Flow diagram of a two stage RO system

FLOW DISTRIBUTION

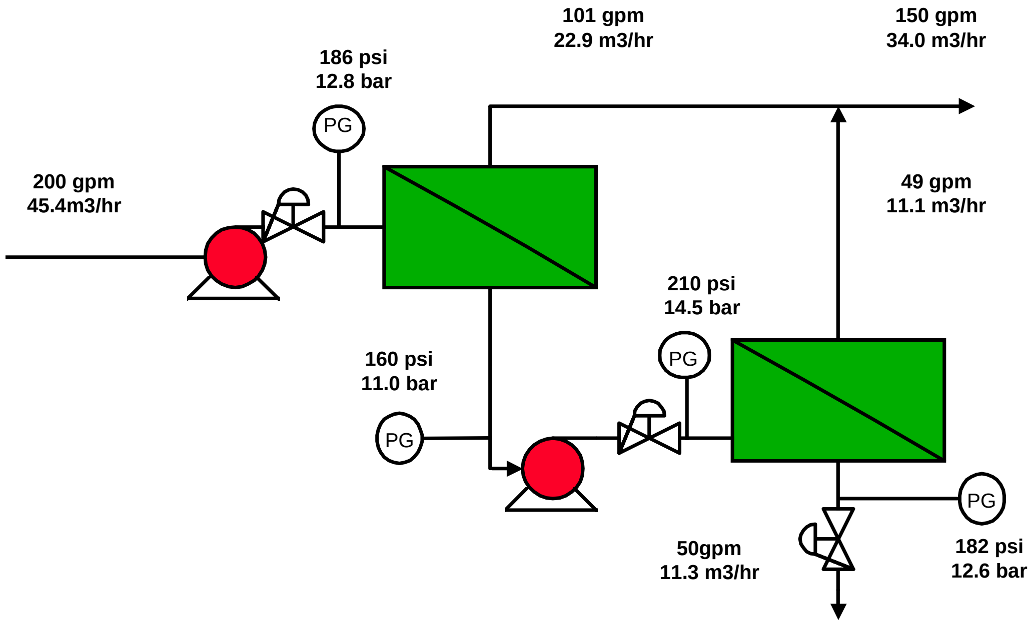
In some cases it is necessary to equilibrate permeate flow between stages i.e. decrease permeate flow from the first stage and increase permeate flow from the last stage. This can be accomplished in one of two design configurations. One solution is to install a valve on the permeate line from the first stage, as shown.

By throttling this valve, permeate back pressure will increase, reducing net driving pressure and reducing permeate flux from the first stage. The differential permeate flux is produced from the second stage by operating the RO unit at a higher feed pressure.



Flow diagram of a two stage RO system with permeate throttling

The other solution is to install a booster pump on the concentrate line between the first and the second stage, as diagrammed below. The booster pump will increase feed pressure to the second stage resulting in higher permeate flow. The advantage of the permeate throttling design is simplicity of the RO unit and low capital cost. However, this design results in additional power losses due to permeate throttling and higher power consumption. The interstage pump design requires modification of the interstage manifold and an additional pumping unit. The investment cost is higher than in the first design, but the power consumption is lower.



Flow diagram of a two stage RO system with interstage pump

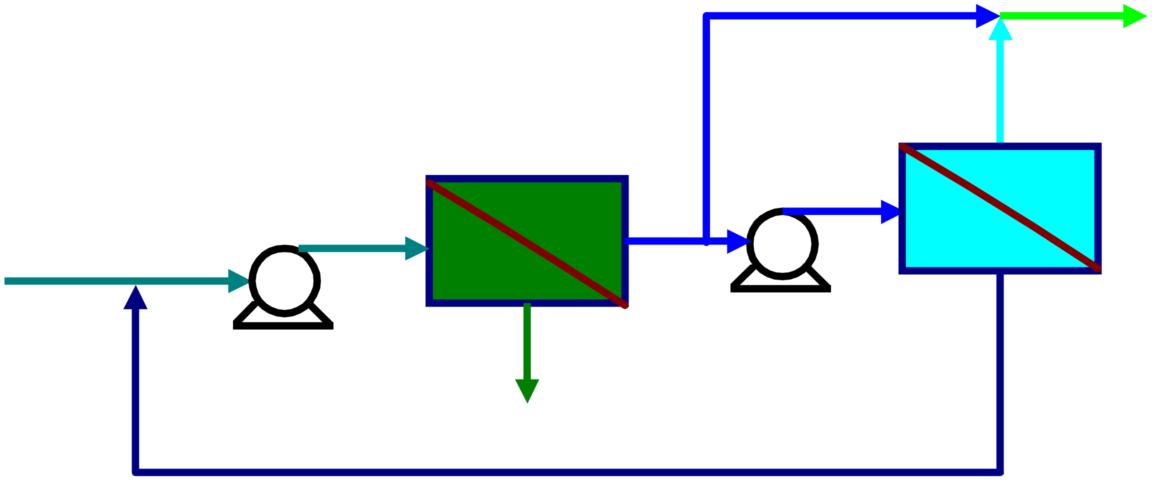
PERMEATE STAGING

For some applications, the single pass RO system may not be capable of producing permeate water of a required salinity. Such conditions may be encountered in two types of RO applications:

- Seawater RO systems, which operate on a very high salinity feed water, at high recovery ratio and/or at high feed water temperature.
- Brackish RO applications which require very low salinity permeate such supply of makeup water for pressure boilers or production of rinse water for microelectronics applications.

To achieve an additional reduction in permeate salinity, the permeate water produced in the first pass is desalted again in a second RO system. This configuration is called a two pass design, or "permeate staging." Depending on quality requirements, all or part of the first pass permeate volume is desalted again in the second pass system. The system configuration is known as a complete or partial two pass system depending on whether all of the permeate is fed to the second pass or not.

The first pass permeate is a very clean water. It contains very low concentrations of suspended particles and dissolved salts; therefore, it does not require any significant pretreatment. The second pass system can operate at a relatively high average permeate flux and high recovery rate. The common design parameters for the second pass RO unit are average flux rate of 20 gfd and recovery rate of 85% - 90%. In a two pass system, the permeate from the first pass flows through a storage tank or is fed directly to the suction of the second pass high pressure pump. There are number of possible configuration of the two pass RO units. One configuration, which is a partial two pass system, shown here, splits the permeate from the first pass into two streams.



Flow diagram of a partial two pass RO system

One stream is processed by the second pass unit, and is then combined with the unprocessed part of the permeate from the first pass. Provided that the partial second pass system can produce the required permeate quality, this configuration results in smaller capital and operating costs, as well as higher combined permeate recovery rate (utilization of the feed water), compared to a complete two pass system.

It is a common procedure in a two pass systems to return concentrate from the second pass unit to the suction of the high pressure pump of the first pass unit. The dissolved salts concentration in the concentrate from the second pass is usually lower the concentration of the feed to the first pass unit. Therefore, blending feed water with the second pass concentrate reduces slightly the salinity of the feed, and increases the overall utilization of the feed water.

RO Design Help File

What is Membrane Performance Normalization?

What Is Membrane Performance Normalization?

The majority of Reverse Osmosis (RO) systems normally will operate under fairly steady conditions over long periods of time if operating parameters remain constant. Fouling does not occur, and membrane damage is avoided. Unfortunately, operating parameters (e.g. temperature, feed TDS, permeate flow, recovery) do change, and fouling of the membrane and element feed path can occur. Normalization is a technique that allows the user to compare operation at a specific set of conditions to a reference set of conditions. This allows the user to determine whether changes in flow or rejection are caused by fouling, dmamge to the membrane, or are just due to different operating conditions.

Hydranautics offers a Windows based normalization program: RODATA. This program can be downloaded from the "Designing" page.

Normalization Equations

Normalized Flow

Net Driving Pressure (NDP) and temperature influence the permeability of the membrane to water. NDP is a function of the applied pressure, pressure drop, osmotic pressure, and permeate pressure of the system. As NDP increases, the membrane will produce more water. Likewise, as temperature increases, the membrane becomes more permeable, and flow increases. A Temperature Correction Factor (TCF) correlates change in flow to change in temperature. By multiplying the given flow by ratios of initial and specified values of both the NDP and Temperature Correction Factor (TCF), the normalized flow is found.

Equation 1 gives the formula for general normalized flow.

$$Q_N = Q_t \times (NDP_r/NDP_t) \times (TCF_r/TCF_t) \qquad (1)$$

Where:

Q_N = Normalized flow rate (vol/t) at time t
Q_t = Actual flow rate (vol/t) at time t
NDP_r = Net Driving Pressure at reference point (units of pressure)
NDP_t = Net Driving Pressure at time t (units of pressure)
TCF_r = TCF for temperature at referenced conditions (no units)
TCF_t = TCF for temperature at time t (no units)

Equation 2 gives the formula for Net Driving Pressure. All units are pressure units such as psi, kPa, bar.

$$NDP = P_f - ½*\Delta P_{fb} - P_{osm} - P_p \qquad (2)$$

Where:

P_f = Feed Pressure
ΔP_{fb} = Pressure drop between the feed and brine streams
P_{osm} = Osmotic pressure
P_p = Permeate pressure

Osmotic pressure is further expanded in equation 3.

$$P_{osm} = CF_{lm} * C_f * 11/1000 * K_{p\text{-}cond} \qquad (3)$$

Where:

CF_{lm} = Log mean concentration factor. (no units)
C_f = Feed conductivity (µS-cm)
$K_{p\text{-}cond}$ = conversion factor, conductivity to pressure. This constant is a function of the TDS of the sample.

The log mean concentration factor can be further expanded as shown in Equation 4.

$$CF_{lm} = \ln [1/(1-R)] / R \qquad (4)$$

Where R is recovery, expressed as a decimal.

$$R = Q_p/Q_f \text{ , Permeate Flow divided by Feed Flow.} \qquad (5)$$

Finally, the Temperature Correction Factor is given by equation 6.

$$TCF = \exp \{ K * [1/(273\,^\circ K + t) – 1/298\,^\circ K] \} \qquad (6)$$

Where t is degrees Celsius, and K = 2700 °K for composite membrane.

Normalized Salt Passage

The salt passage of a system can be normalized by the following equation:

$$\%SP_n = (EPF_a/EPF_n) * (STCF_n/STCF_a) * \% SP_a \qquad (7)$$

Where:

$\%SP_n$ = Percent Salt Passage normalized to standard conditions
$\%SP_a$ = Percent Salt Passage at actual conditions
EPF_n = Element Permeate Flow rate at standard conditions
EPF_a = Element Permeate Flow rate at actual conditions
$STCF_n$ = Salt Transport Temperature Correction Factor at standard conditions
$STCF_a$ = Salt Transport Temperature Correction Factor at actual conditions

Actual Salt Passage is given by equation (8):

$$\%SP_a = C_p/C_{fb} \qquad (8)$$

Where

C_p = Permeate concentration, ppm
C_{fb} = Feed-Brine concentration, ppm,
which equals the feed concentration, in ppm, multiplied by the log mean average of the recovery, (equation 4)
= $C_f * CF_{lm}$

Element permeate flow at standard conditions is unique to the element, and is provided by the manufacturer. Element permeate flow at actual conditions is dependent on the system.

The Salt Transport Temperature Correction Factor is provided by the element manufacturer. If the factor is unavailable, substitute the TCF (equation 6).

Changes in Apparent Membrane Performance

Changes in operating parameters will have a normal effect on membrane performance. These influences can either result in an apparent reduction of permeate flow or quality. This section will enumerate those effects that normally affect membrane performance.

Loss of Flow:

The following changes in operating parameters will decrease the actual permeate flow of a system:

- A decrease in feed water temperature with no change in feed pump pressure.
- A decrease in RO feed pressure by throttling down the feed valve.
- An increase in permeate back pressure with no change in feed pump pressure.
- An increase in the feed TDS (or conductivity) since this increases the osmotic pressure that has to be overcome to permeate water through the membrane.
- An increase in the system recovery rate. This increases the average feed/concentrate TDS which then increases the osmotic pressure.
- Fouling of the membrane surface.
- Fouling of the feed spacer that results in an increase of feed-to-concentrate pressure drop (delta P) which starves the back-end of the system of net driving pressure (NDP) to produce permeate water.

Loss of Water Quality:

The following changes in operating parameters will result in actual lower quality permeate water, as indicated by an increase in permeate TDS as ppm or conductivity:

- An increase in feed water temperature with the system adjusted to maintain the same permeate flow (or flux).
- A decrease in the system permeate flow, which reduces the water flux, and results in less permeate water to dilute the amount of salts that have passed through the membrane.
- An increase in the feed TDS (or conductivity) since the RO will always reject a set percentage of the salts.

- An increase in the system recovery rate since this increases the average feed/concentrate TDS of the system.
- Fouling of the membrane surface.
- Damaged o-rings seals.
- Damage to the membrane surface (such as exposure to chlorine) which allows more salts to pass.

Use of the normalization program thus “factors out” the effects of changing feed pressure, concentration, and temperature. Factors related to fouling, degradation, or systemic factors (ie, blown o-rings) are thus more clearly discerned.

Normalized data that is graphed will show not only the instantaneous condition of the RO system at any given time, but also shows the detailed operating history. These graphs can be a useful tool for troubleshooting.

Normalization data

The normalized data graphs presented in the Hydranautics RODATA Normalization program are:

- **Normalized Salt Passage vs. Time**: This graph plots the normalized per cent salt passage of the system relative to the System Reference Data at start-up.

- **Normalized Permeate Flow vs Time**: This graph plots the normalized permeate flow in gpm or m^3/hr, relative to the System Reference Data at start-up.

- **Salt Transport Coefficient vs. Time**: This graph plots Salt Transport Coefficient (STC) for “membrane technophiles”. The importance of this number is that it measures the efficiency of the membrane in how fast it allows the passage of salts. The value is reported as m/sec (meters per second). This number allows the comparison of membranes from site to site, independent of what the on-site operating conditions are. This number will be affected by changes in the ionic makeup of the feed water. For example, an increase in divalent ions (like hardness or sulfate) will result in a lower Salt Transport Coefficient.

- **Water Transport Coefficient vs. Time**: This graph plots the Water Transport Coefficient (WTC) for "membrane technophiles". The importance of this number is that it measures the efficiency of the membrane in how fast it allows the passage of water. The value is reported as m/sec-kPa (meters per second per kilopascal. This number allows the comparison of membranes from site-to-site, independent of what the on-site operating conditions are.

- **Normalized Delta P vs. Time**: This graph plots the normalized feed-to-concentrate pressure drop in PSI or Bar relative to the System Reference Data at start-up. The normalized Delta P value reflects adjustments to pressure drop due to varying feed and concentrate flows.

RO Design Help File

Cleaning

Cleaning

Over time, membrane systems can become fouled with any of a number of foulants such as colloids, organic matter, metallic scales, and biological constituents. (See Pretreatment). These materials can build up on the membrane surface and in the feed brine channel. If left uncorrected, the accumulation of these foulants can cause a severe loss of performance in the system: pressure requirements increase to maintain flow, pressure drops increase, and salt rejection can suffer. If the system is not cleaned and the system continues to build up foulants, the elements may "telescope," or shear internally, causing the integrity of the membrane surface to be compromised and rendering the membrane irreversibly damaged.

This section will cover several points related to cleaning. The first part will concern itself with data collection and symptoms of membrane fouling. The second part will define the components of a cleaning system and provide guidelines for building and operating a cleaning skid. Finally, directions and guidelines for performing a cleaning will be given; the reader is encouraged to double click on topics related to specific procedures for cleaning specific membrane elements.

DATA Monitoring

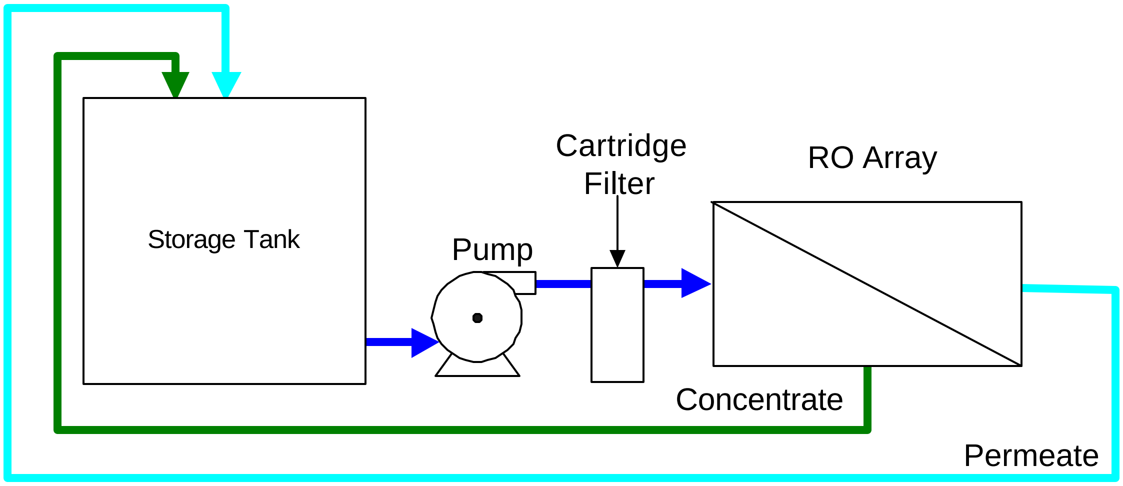
Good monitoring of the performance of a system can alert the user to possible fouling before the situation becomes severe. The practice of entering operational data several times a week into a normalization program can provide the means to track performance over time. Symptoms of fouling would include one or all of the following conditions:

- Normalized water flow has decreased by 10-15% from start-up (reference) conditions.
- Delta P, or pressure drop over a stage or the system, has increased by 10-15%.
- Salt rejection has decreased (ie permeate TDS has increased) significantly over time.

Note that it is important to use normalized data. Normalized data corrects for temperature effects on system performance. For instance, if the temperature drops, it is expected to require more pressure to achieve the same flow. Loss of flow due solely to a reduction in temperature does not mean the system is fouled.

Cleaning System Specifications

The following diagram gives the basic parts of an RO cleaning skid. Cleaning solution is pumped from a storage tank through a cartridge filter to the RO array. Solution is then recycled back to the tank. The volume of solution should be adequate to fill the volume of the vessels, filters and piping. The diagram below shows no instrumentation, however, it may be adviseable to add a low level switch to the tank to prevent the pump from running dry. Additionally, a temperature controller and heater/cooler unit may be added to maintain solution at the optimum temperature range.



Volume requirements:

To figure the volume of solution required for a system consisting of six 8" vessels with six elements per vessel and 40 feet of 4 inch pipe (3.82 " ID), figure the volume of the vessels and add it to the volume of the piping to obtain the total volume. For example:

Volume of the vessels:

The calculation is made where Vv is the volume of one vessel, Pi = 3.14, and R is the radius of the vessel or pipe. US units are given on the left, SI units on the right

Vv = Pi*(R*R)*length

= 3.14 * (4in * 4in) * 20ft / (144 in2/ft2)	= 3.14*(.10m*.10m)*6.1m
= 6.98 ft3	= 0.196 m^3
= 6.98 ft3 * 7.48 gal/ ft^3	
= 52 gal/vessel	= 196 liters/vessel

Total vessel volume = 6 vessels * 52.2 gal/vessel = 313.2 gal
= 6 vessels * 196 liters/vessel = 1176 liters

Volume of piping:

Vp = Pi* (R*R) * length
= 3.14 * (1.91in*1.91in) *40 ft/(144 in2/ ft2) = 3.14*(.049m*.049m)*12.2m
= 3.18 ft3 = 0.09 m^3
= 3.18 ft3 * 7.48 gal / ft^3
= 23.8 gal = 90 liters

Total required volume = 313.2 gal + 23.8 gal = 337 gal
= 1176 liters + 90 liters = 1266 liters

The tank for this system should hold a minimum of 340 gallons or 1270 liters of cleaning solution.

Materials/components:

Materials for the skid should be the following:

Tank:	Fiberglass reinforced plasitc (FRP) or polypropylene.
Piping:	PVC schedule 80 or Nylon reinforced flex hose.
Victaulics:	Stainless Steel
Valves:	Stainless Steel
Pump	Stainless Steel or Non-metallic composite polyesters.

Pump should be a centrifugal type able to attain the flows and pressures listed in table 1of the next section. Cartridge filters should be 5 micron rating string wound modules. Valves should be installed appropriately to control flow. Tank should have a removable cover. All components should be able to withstand extremes in pH, temperatures up to 113 F (45 C), and electrical sources/switches should be protected and well grounded.

Cleaning Procedures

Generally, low pH solutions are used to clean metallic scales while alkaline solutions are used to clean biological and organic fouling. Relatively high flow (governed by the size of the element) with low pressure is recommended. (Do not, however, exceed maximum flow limits for the elements). Table 1 provides guidelines for pressures and flows per vessel for a range of element diameters.

Table 1: Pressures and Flows for Elements

Element diameter inches (cm)	Feed Pressure psi (bar)	Feed Flow/vessel GPM (lpm)
2.5 (6.4)	20-60 (1.4-4.1)	3-5 (11-20)
4 (10.1)	20-60 (1.4-4.1)	8-10 (30-40)
6 (15.2)	20-60 (1.4-4.1)	16-20 (60-75)
8 (20.2)	20-60 (1.4-4.1)	30-40 (115-150)

To clean a system, follow these six basic steps:

1. Prepare the cleaning solution per the instructions found in the appropriate TSB.
2. Displace the solution in the vessels either by flushing with permeate water or by pumping cleaning solution at a low pressure and low flow. To prevent dilution of the cleaning solution, the process water can be dumped to drain until the cleaning solution has filled the vessels.
3. Recycle the solution through the elements and back to the tank.
4. Soak the elements for 1 hour. (For heavy fouling, overnight soaking may be required).
5. Recycle at the flow rates listed in Table 1 for an hour. The turbulence created in this high flow regime will help to displace the foulants from the membrane. Do not exceed 10 psi pressure drop per element; if the pressure drop is too great, reduce the flow.
6. Flush the system with clean permeate water or pre-filtered raw water.

List of TSB's

TSB 100: RO Membrane Foulants and Their Removal from Cellulose Acetate Blend (CAB) RO Membrane

TSB 102: RO Membrane Foulants and Their Removal from Polyvinyl Derivative (PVD) RO Membrane Elements

TSB 107: RO Membrane Foulants and Their Removal from Composite Polyamide (ESPA, ESNA, CPA, LFC, and SWC) RO Membrane Elements

TSB 111: Cleaning Procedure for Ultrafiltration Membranes used for Oily Water Separations

TSB 112: Cleaning Procedure for Ultrafiltration Membranes used for E-Coat Paint Applications

In general, the steps and solutions listed in the above TSB's are similiar. However, it is worthwhile emphasizing the following points:

- Use of chlorine or other strong oxidants on polyamide membranes can cause irreversible damage to the membrane.
- Warm water, ie 90 F - 100 F (32 C - 37 C), gives significantly better cleaning than lower temperature solutions.
- If the pH of an acid solution increases during recirculation, add more acid to return the pH back to the target value. What is occurring is that acid is being consumed as it dissolves inorganic scale.
- Do not use sulfuric acid for low pH solutions as this creates a risk of creating sulfate scale.

- Permeate water is preferred for mixing solutions.
- Use of filtered tap water for high pH solutions can result in carbonate fouling if the water is hard.
- Flush the membranes with permeate water following cleaning to remove the cleaning solutions.
- Under severe fouling conditions, it may be necessary to soak overnight.

Storage TSB’s

If elements are to be out of service for more than 24 hours, please refer to the following TSB's for storage instructions:

TSB 101: General Storage Procedures for Cellulose Acetate Blend (CAB) RO Membrane Elements

TSB 108: General Storage Procedures for Composite Polyamide (ESPA, ESNA, CPA, LFC, and SWC) and Polyvinyl Derivative (PVD) RO Membrane Elements

RO Design Help File

Troubleshooting Your RO

Troubleshooting Your RO

Summary: There can be many reasons why a RO system suffers a loss in performance, and is unable to produce the proper quantity and/or quality of permeate water. Similar to a doctor attempting to make a diagnosis, you must identify as many symptoms as possible before you can derive an educated guess as to what the disease is.

INTRODUCTION

The focus of this paper is how to troubleshoot a RO system on-site. Many of the techniques assume the equipment has been designed with instrumentation and sampling points to allow troubleshooting and for on-site cleanings, which is common for "industrial quality" systems, but not necessarily for "residential or light commercial" equipment. The capital cost for small RO to include troubleshooting instruments and sample valves is prohibitive for their market niches, relative to the minimal cost of replacing RO elements on a more frequent basis. As RO systems reach a certain size (say 15 gpm or larger), the cost of replacing RO elements on a frequent basis becomes prohibitive versus the initial capital cost of adding instruments, sample valves and on-site cleaning equipment.

HOW TO AVOID TROUBLE

The best way to stay out of trouble with a RO system is to avoid it initially. A few RO design tips are:

- Design the RO system with access to a complete water analysis. If there are seasonal variations (which are common for surface sources) or varying sources (which are common with municipal sources), get all the analyses you can and be sure they are recent.

- Perform 15 minute SDI (Silt Density Index) tests. This on-site testing helps to determine the potential for colloidal silt fouling. Refer to TSB113.
- Invest in the appropriate pretreatment. If you want to sleep well at night, make sure the system design has adequate pretreatment to the RO.
- Design the RO system flux rate conservatively, especially if the potential for fouling exists. A RO with a clean well water source can be designed more aggressively than one for a surface water source. A reduced rate of permeate water flow for a given area of membrane reduces the convective deposition of foulants at the membrane surface. Fluxes for surface waters should range from 8 to 14 gfd (gallons per square foot of membrane area per day) and 14 to 18 gfd for well sources.
- Design the RO recovery rate conservatively. A conservative per cent recovery of the feed water minimizes the concentration of foulants.
- Maximize the cross flow velocity in the elements. A conservative design maximizes the cross-flow velocity of the feed and concentrate streams. A higher cross-flow velocity reduces the concentration of salts and foulants at the membrane surface by increasing their diffusion back into bulk feed stream above the membrane surface.
- Select the right membrane for the application. Sometimes a neutrally charged CAB (cellulose acetate blend) or LFC (Low Fouling Composite) RO element is a better choice than a negatively charged CPA (Composite PolyAmide) RO element for difficult surface or waste water sources.

IDENTIFYING A PROBLEM

Verify that you really have RO system fouling. Changes in system operating parameters do have an effect on performance. For instance, an increase in feed TDS (total dissolved solids) will increase feed pressure requirements by approximately 1 psig for every 100 ppm TDS increase due to increased osmotic pressure and it will also increase permeate conductivity since the RO will always reject a fixed percentage of the salts. A 10^{o} F increase in feed water temperature will decrease the feed pump pressure requirement by 15%. An increase in the per cent recovery of the system will increase the reject TDS which in turn will increase permeate conductivity. (Concentrate TDS due to concentration of the feed water is 2 times higher at 50% recovery, 4 times higher at 75% recovery and 10 times higher at 90% recovery). Finally, a reduction in the permeate flow will result in higher conductivity if the same recovery is maintained because the passage of salts through the membrane is independent of the passage of water through the membrane, which results in less permeate water to dilute the salts that have passed through.

It is recommended that you “normalize” your logged operating data to determine if you have a problem with your system. “Normalization” computer programs, such as RODATA, graphically represent normalized permeate flow, per cent salt rejection and feed-to-reject pressure drop. These normalized parameters are calculated by comparing a particular day’s operations to the first day of operation. Adjustments are made for changes in major operating variables such as temperature, feed TDS, recovery, and pressures. In this way, performance declines unrelated to operating parameters can be identified and treated.

Questions to ask yourself…

Loss in performance is generally divided into two categories: loss of flow, and loss of rejection. The following lists of questions help to identify possible root causes for either of these problems.

Loss of Flow

Attributable to fouling, these questions can help pinpoint the problem. Certain foulants impact the front end of the system while others impact the back end of the system. Use the RO Troubleshooting Matrix (at the end of this document) to help determine the nature of the foulant.

- Did you shut down the RO system properly? In some instances, the reject water from the Service operation should be flushed out of the system upon shutdown. If not, inorganic foulants can precipitate onto the surface of the membrane. The best flush water source is RO permeate.
- Did you store the RO system properly? Improperly stored systems (especially under warm conditions) can produce a severe biofilm problem. (Refer to TSB’s 101, 103, 108, and 110 for more information).
- If you acidify to lower feed pH or add scale inhibitor (SI) for the control of calcium carbonate (lime) scale, are you meeting your target pH or SI concentration? If not, you may need to do an acid clean. (TSB’s 100, 102, 107)

- Has your pressure drop between the feed and reject lines increased greater than 15%? Increasing pressure drop indicates that fouling of the feed path and a restriction of flow over the membrane surface is occurring. Monitoring pressure drops across stages gives you the advantage of determining if the fouling is limited to a particular stage, which can help identify the potential foulant.
- In seawater systems, are you flushing with permeate water at shut-down? Flushing removes high concentrations of ions that could precipitate out of solution. At a minimum, feedwater can be used, but it is recommended to use permeate water for the flush.
- Are the cartridge filters fouling? Inspect the RO feed cartridge filter for foulants as this is relatively easy.

Loss of Rejection

Loss of rejection displays itself as a higher permeate conductivity. It may be due either to fouling, degradation of the membrane surface, or an o-ring leak. The following questions can help you pinpoint the source of this problem. Verify that the permeate conductivity has not increased greater than 15%.

- Do all the vessels in a stage have nearly the same conductivity permeate? Measure permeate quality by stage and by pressure vessel if possible. One vessel having a significantly higher permeate conductivity probably has a faulty o-ring, a disconnect, or a damaged membrane. (See TSB's related to vessel shimming (TSB 109) and vessel probing (TSB 114) to determine the point of the leak).
- Have your composite membranes been exposed to chlorine or any other strong oxidant? The exposure may have damaged the membranes.
- Have your cellulose acetate (CAB) membranes been exposed to pH extremes? The exposure may have damaged the membranes. Likely causes of pH extremes are faulty metering pumps, acid tanks that have gone dry, loss of prime to the metering pump, or flushing/storage in non-acidified water.
- Is the instrumentation accurate? Verify that all of your instruments are calibrated properly.

- Do the elements look discolored or damaged? Inspect the RO elements for foulants or physical damage.
- How do the actual conductivity and temperature of the feedwater compare to the design criteria? If the actual feedwater has higher TDS or is warmer than the design, this may account for the discrepancy. Sample and obtain detailed water analyses of the RO feed, concentrate and permeate. Compare the results of the analyses to the RO design projections of the element manufacturer.
- Can there be times when the permeate pressure exceeds the feed pressure? If the permeate is pumped to an elevated position, and there are no check valves on the permeate lines, at shut down, the permeate pressure can exceed the feed pressure. This can cause the membrane envelopes to expand and rupture.
- Are your o-rings in good condition? O-rings can flatten or crack with age. The result is that leaks can develop. Replacement of o-rings periodically is a good, cost-effective preventive maintenance step. Alternatively, vessels may be probed (TSB 114) to find faulty o-rings.

IF you still think there is a problem…

- Once you have ruled out any mechanical failures as the source of your RO problem, then you need to determine what your suspected foulant or foulants are and perform a cleaning or series of cleanings.
- The cleaning solution can be collected and analyzed for the foulants removed, color change or pH change. The effectiveness of the cleaning can be verified by placing the RO back into Service.
- If you don't know what your foulants are and don't want to experiment on site as to what cleaning solution(s) are required and what the proper cleaning procedures should be, their are companies who specialize in the supply of proprietary cleaning chemicals and off-site evaluations of RO elements. These services can be invaluable, especially the first time around in cleaning a RO.
- If all else fails in determining what fouled the RO element, a destructive autopsy can be performed. The RO element is cut open and unrolled with analytical tests run on the membrane and the foulant to determine the problem.

Hydranautics can perform analytical testing of foulants at our labs, as well as perform Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray analysis to help determine the cause of fouling. TSB 116, Returned Goods Authorization (RGA) Procedure, provides a list of services and costs.

Summary

This list of questions should help in troubleshooting most RO problems. Attached is a table to help determine some of the most common problems from the given systems.

If further assistance is required, contact the Technical Service Group at Hydranautics by e:mail or at 1-800-CPA-PURE (1-800-272-7873)

RO Troubleshooting Matrix

Possible Cause	Possible Location	Normalized Pressure Drop	Normalized Permeate Flow	Normalized Salt Passage
Metal Oxide	**1st stage**	**Normal to Increased**	**Decreased**	**Normal to Increased**
Colloidal Fouling	**1st stage**	**Normal to Increased**	**Decreased**	**Normal to Increased**
Scaling	**Last stage**	**Increased**	**Decreased**	**Increased**
Biological Fouling	**Any stage**	**Normal to Increased**	**Decreased**	**Normal to Increased**
Organic Fouling	**All stages**	**Normal**	**Decreased**	**Decreased or Increased**
Oxidant (e.g. Cl_2)	**1st stage most severe**	**Normal to Decreased**	**Increased**	**Increased**
Abrasion (carbon, silt)	**1st stage most severe**	**Normal**	**Increased**	**Increased**
O-ring or glue leaks	**Random**	**Normal to decreased**	**Normal to Increased**	**Increased**
Recovery too high	**All stages**	**Decreased**	**Normal to Decreased**	**Increased**

Haward Technology Middle East

Modern Water Desalination Technologies

Volume: 2

June 03-07, 2007
Abu Dhabi, UAE

ISO 9001:2000 Certified

Course Instructors
Professor Bruce Hendry
Mr. Yehia Mohamed

To the Participant

The Course Notes are intended as an aid in following lectures and for review in conjunction with your own notes; however they are not intended to be a complete textbook. If you spot any inaccuracy, kindly report it by completing this form and dispatching it to the following address, so that we can take the necessary action to rectify the matter.

Haward Technology Middle East
P.O. Box 26070
Abu Dhabi, UAE

Tel.:+971 2 4488301
Fax: +971 2 4488302
Email: info@haward.org

Name	
Address	
E-mail	
Course Title	
Course Date	
Course Location	
Description of Inaccuracy	

Disclaimer

The information contained in these course notes has been compiled from various sources and is believed to be reliable and to represent the best current knowledge and opinion relative to the subject.

Haward Technology offers no warranty, guarantee or representation as to its absolute correctness or sufficiency.

Haward Technology has no responsibility in connection therewith; nor should it be assumed that all acceptable safety and regulatory measures are contained herein, or that other or additional information may be required under particular or exceptional circumstances.

COURSE OVERVIEW PE540

Modern Water Desalination Technologies

Course Title

Modern Water Desalination Technologies

Course Date / Venue

June 03-07, 2007/Corniche Room 105, Millennium Hotel, Abu Dhabi, UAE

Course Reference

PE540

Course Duration/Credits

Five days / 3.0 CEUs

Course Description

Water desalination technologies play a crucial role in socio-economic development in a number of countries in the world. Desalinated water is an essential and often the sole, source of fresh water in several of these countries, and rising living standards and high population growth are likely to render desalination a viable option for many areas of the world. Fresh water is rapidly becoming a scarce resource in many countries around the world. Modern desalination technologies, applied to seawater and brackish water, offer effective alternatives in a variety of circumstances. For some countries in the world particularly in Gulf States they are on the most aird part of the globe and characterized by some of the world's highest population growth rates, would benefit greatly from the adaptation, further development and wider dissemination of desalination technologies.

Large-scale thermal desalination technologies have been in use since the 1950s. The larger desalination plants have provided fresh water supplies for drinking municipal use and agricultural development, particularly in the Gulf States. In the past, high capital costs and heavy energy consumption generally translated into excessive desalinated water costs. However, advances in technology have helped to drastically reduce capital and running costs as well as energy requirements, rendering desalination more viable an option than ever before.

This course is essentially aimed at outlining trends in modern desalination technologies and highlighting the options offered by recent technological advances. The course covers available technologies, proposed design improvements and market potential in the near future. Through case studies, some of their more salient features are examined. Energy demands for both current processes and the newer innovations will be discussed. The course will cover both major processes in water desalination, the thermal and the membrane separation.

Course Objectives

Upon the successful completion of the course, participants will be able to have the knowledge on the following topics:

- Thermal Desalination Processes
- Membrane Separation Processes
- Desalination Economics
- Strategic Issues In Desalination Technology Capacity Building
- Renewable Energy Desalination Technologies
- Recent Trends and Expected Future Developments in Water
- Desalination Technologies

Training Methodology

This interactive training course includes the following training methodologies as a percentage of total tuition hours:-

50%	Lectures
30%	Courses, Group Work & Practical Exercises
20%	Videos & Software

Who Should Attend

This course is aimed at engineers, scientists and technologists involved in the planning, management and operation of water desalination technology and also for manufacturers, consultants, designers, researchers and water personnel.

Course Certificate

Haward Technology certificate will be issued to all attendees completing minimum of 75% of the total tuition hours of the course.

Course Accreditation

Haward Technology's courses/workshops/seminars meet the professional certification and continuing education requirements for participants seeking Continuing Education Units (CEUs) in accordance with the rules & regulations of the International Association for Continuing Education & Training (IACET). IACET is an International authority that evaluate programs according to strict, research-based criteria and guidelines. The CEU is an internationally accepted uniform unit of measurement in qualified courses of continuing education.

Haward Technology Middle East will award **3.0 CEUs** (Continuing Education Units) for participants who completed the total tuition hours of this program. One CEU is equivalent to ten Professional Development Hours (PDHs) or ten contact hours of the participation in and completion of Haward Technology programs. A permanent record of a participant's involvement and awarding of CEU will be maintained by Haward Technology. Haward Technology will provide a copy of the participant's CEU Transcript of Records upon request.

Course Fee

US $ 3,250 per Delegate. This rate includes Participant's Pack (Folder, Manual, Hand-outs, etc.), buffet lunch, coffee/tea on arrival, morning & afternoon of each day.

Accommodation

Accommodation is not included in course fees. However, any accommodation required can be arranged by Haward Technology at the time of booking.

Course Instructors

(1) Professor Bruce Hendry MSc. BSc. (UK) has **36 years** of **extensive practical** and **academic experience** in **Water Treatment Technology.** He is currently the **Professor** of **Water Desalination** at **Cape Peninsula University.** He gives **lectures** to both **undergraduates** and **postgraduates** on the **subject** of **Desalination** of **Water Resources & Effluents** with **Recovery** of **Chemical Values, Electro-membrane Processes: Saline Waste Electrolysis & Electrodialysis, Biotechnology Applications** of **Membranes & Adsorptive Materials, Innovative Water & Waste Treatment** as well as **Reuse Applications, Minerals Industry Technology Applications** including **Ion Exchange, Fluidized Beds, Sedimentation** and **Membrane Equipment.**

Professor Hendry started his **industrial career** as a **Laboratory Technician** on **Water Analysis** at the **Department of Water Affairs**. Through **hard work** he became the **Senior Officer** of **Water Treatment Quality** and **Pollution Control**. He was **consistently promoted** to **Senior Engineer** for **Water Treatment Plant Design** and **Operation**. Finally, he became the **Lead Engineer** for **Sea Water Desalination Process** including **research, pilot plant planning, construction** and **overall desalination plant operation**. Then he worked for **BINTECH** as the **Development Manager** of **Desalination Tubular Reverse Osmosis manufacture** and **applications**. He became a **Consultant** on **Water & Wastewater Treatment** and later on **founded** his own **business**, **Solutions Technology Ltd**. **specializing** in **Desalination Process** and **Water Treatment.**

Professor Hendry has presented **numerous papers** such as **Desalination Technologies—Outlook, Challenges & Opportunities, Membrane Filtration of Seawater, Continuous Countercurrent Ion Exchange for Desalination & Other Brackish Water, Chemical Recovery and Recycling of Water, A New Ion Exchange Process for Treatment of Hard Waters & Acid Mine Drainage Water**, and many more.

Professor Hendry is an **active member** of **prestigious associations** like the **Water Institute** and **SA Institution of Chemical Engineers.**

AND,

(2) Mr. Yehia Mohamed has some **20 years** of **broad experience** in **various water** and **wastewater treatment process utilities** and **facilities** including **Commissioning, Start-up** and **Operation** of **Desalination Plants** using **RO Units, Potable Water Treatment Plants, Sewage Waste Water Biological Treatment Plants (Aerobic & Anaerobic), Chlorination Plants, Industrial Waste Water Treatment Plants, Demineralization Plants** (using **ion exchange resins**), **High & Low Pressure Boilers, Pre-treatment (Iron Removing) & Filtration Plants, De-oiling/De-sanding and Magnetic Contamination Removing Plants.** He is an expert in the application of **American Petroleum Standard** as well as **HSE regulations.** He is currently the **Operations Manager** of **American Engineering.** His main area of responsibility lies on the **commissioning, start-up** and **pre-operation** of **B.W. RO Plant, Sewage Treatment Plant (STP), Deionizer Unit** and **Iron Removal & Filtration Plant.**

Mr. Mohamed started his successful career with the **Electricity Authority** where he was first an **Operation Shift Engineer** for **Water Treatment Facilities.** Through **merits** he became the **Start-up & Operation Engineer,** and he **continuously** got **promoted** to the post of **Operation Shift Leader.** During this time, his **skills** were **honed** on the **overall technical processing** necessary for the **start-up** and **operation** of **Raw Water Pre-treatments & Potable Water Production Plants, Chlorination Plants, Demineralization**

Plants, Industrial Waste Treatment Plants, Sewage Water Treatment Plants, High Pressure Boilers Water Conditioning/Lay Up and **Boiler Pre/Post Operation Chemical Cleaning Process.** Then he worked for the **Sheikh Zayed City Potable Water Treatment Plant** through his company **Lurgi Bamag GmbH** first as the **Process Start-up & Operation Shift Leader**, then later on, as the **Operations Manager.** He **extensively worked** on **Flash Mixers, Vortex Chambers, Tube Settler Clarifiers, Chemical Injection System, Chlorination Plant, Changeable Level Sand Filters** complete with **backwashing system** and **Treated/Irrigation Water Storage** as well as **Distribution Pumping Station.** Then he transferred to **CIMI_MONTUBI** where he was at first employed as **Process Supervisor** and was **elevated** to the **position** of **Process Commissioning Supervisor.** He also worked for **Degremont** as the **Operation Superintendent & Assistant Training Manager** for the **Gabal EL-Asfar Waste Water Treatment Plant.** He was **responsible** for the **commissioning, start-up** and **operation** of **RO Plant and Potable Water Compact Unit (UCD), Pre-treatment Units (grease/sand removal), Primary Sedimentation Tanks, Aerobic/Anaerobic Biological Treatment including primary & secondary digesters, Sludge Thickening Plants (gravity thickeners & dissolved air flotation), mechanical dewatering using belt press filters** and **fire fighting pumping stations.**

Mr. Mohamed has a **Bachelor's degree** in **Chemical Engineering**

Course Program

Day 1: Sunday, 03rd of June 2007

0730 – 0800	Registration & Coffee
0800 – 0815	Welcome & Introduction
0815 – 0930	**Thermal Desalination** - Water Resources, Composition and Measuring Scales - Classification, Historical Development and Market Status
0930 – 0945	Break
0945 – 1045	**Thermal Desalination (cont'd)** - Flash Desalination Processes - MSF Flashing Stage
1045 – 1100	Break
1100 – 1230	**Thermal Desalination (cont'd)** - Single Effect Evaporation - Single Effect Mechanical Vapor Compression
1230 – 1330	Lunch
1330 – 1500	**Thermal Desalination (cont'd)** - Multiple Effect Evaporation
1500	End of Day One

Day 2: Monday, 04th of June 2007

0730 – 0900	**Thermal Desalination (cont'd)** - Multiple Effect Evaporation with Vapor Compression
0900 – 0915	Break
0915 – 1045	**Thermal Desalination (cont'd)** - Energy
1045 – 1100	Break
1100 – 1230	**Thermal Desalination (cont'd)** - Fouling and Scaling
1230 – 1330	Lunch

1330 – 1500	**Thermal Desalination (cont'd)** • Trends in Desalination
1500	End of Day Two

Day 3: Tuesday, 05th of June 2007

0730 – 0900	**RO Membrane Desalination** • Basic Principles of MF and UF
0900 – 0915	Break
0915 – 1045	**RO Membrane Desalination (cont'd)** • Fouling of UF and MF Systems
1045 – 1100	Break
1100 – 1230	**RO Membrane Desalination (cont'd)** • Cleaning of MF and UF systems
1230 – 1330	Lunch
1330 – 1500	**RO Membrane Desalination (cont'd)** • Basic principles of Reverse Osmosis Technology
1500	End of Day Three

Day 4: Wednesday, 06th of June 2007

0730 – 0900	**RO Membrane Desalination (cont'd)** • Design of Reverse Osmosis Systems
0900 – 0915	Break
0915 – 1045	**RO Membrane Desalination (cont'd)** • Overview RO and NF Membranes
1045 – 1100	Break
1100 – 1230	**RO Membrane Desalination (cont'd)** • Fouling in RO and NF systems
1230 – 1330	Lunch
1330 – 1500	**RO Membrane Desalination (cont'd)** • Pretreatment for RO and NF systems
1500	End of Day Four

Day 5: Thursday, 07th of June 2007

0730 – 0900	**RO Membrane Desalination (cont'd)** • Postreatment for RO and NF systems
0900 – 0915	Break
0915 – 1045	**RO Membrane Desalination (cont'd)** • Concentrate disposal in Brackish and SWRO
1045 – 1100	Break
1100 – 1230	**RO Membrane Desalination (cont'd)** • Comparison of membrane and distillation
1230 – 1330	Lunch
1330 – 1445	**Summary and Open Forum**
1445 – 1500	Presentation of Certificates
1500	End of Course

Course Coordinator

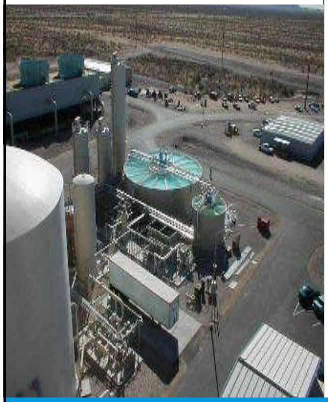
Janeth Recacho, Tel: +971-2-44 88 301, Fax: +971-2-44 88 302, Email: janeth@haward.org

Haward Technology Middle East

PIONEERS IN TECHNOLOGY TRANSFER

Modern Water Desalination Technologies

Professor Bruce Hendry
Mr. Yehia Mohamed



Technology Solutions: Membrane Filtration and Reverse Osmosis

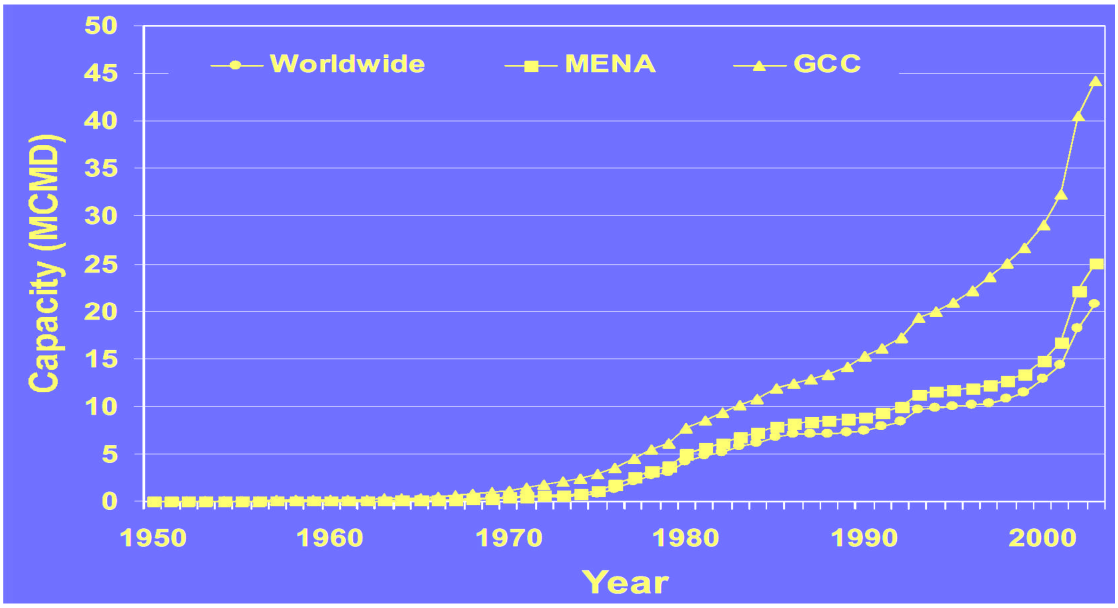
Presentation Format

- Introduction
- Thermal processes (Review)
- Membrane processes
- Membrane Filtration Processes: MF, UF
- Nanofiltration (NF) and Reverse Osmosis (RO)
- Electrodialysis (ED) and Electrodialysis Reversal (EDR)
- Conclusions

Introduction

- Desalination, mainly started in 1960 with 5000 m^3/day, presently more than $33x10^6$ m^3/day.
- More than 133 countries have desalination plants.
- Has become the main source of potable water in the GCC states and many islands worldwide
- Prices have fallen from US$ 4.0/m^3 to less than US$ 1.0/m3 - Recent projects $0.5/$m^3$

Cumulative capacity of Desalinating Plants (Contracted)

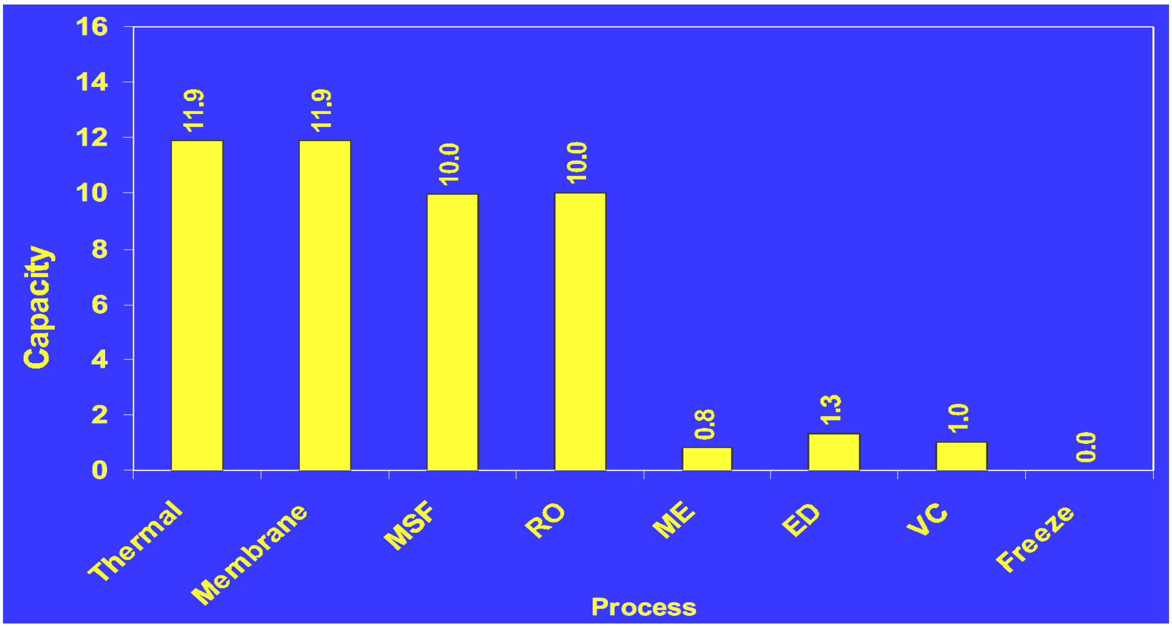


Desalination Technologies

Classification	Process	Energy Required
Thermal = Distillation (Phase Change, liquid → Vapor)	1. Multi-Stage Flash Evaporation (MSF) 2. Multiple Effect Evaporation (MEE) 3. Vapor Compression (MVC)	Electrical + Heat Electrical + Heat Electrical, Heat + Electrical
Membrane (no phase change)	1. Reverse Osmosis (RO) 2. Nanofiltration (NF) 3. Electrodialysis, ED 4. Electrodialysis Reversal (EDR)	Electrical

Modern Water Desalination Technologies

Desalination Processes (Capacity in Mm^3/day)



Thermal Processes (MSF, MED, VC)

- Generally,
  - Can produce high purity water that can be used directly in industrial processes without further treatment
  - Can be coupled to power plants, thus reduce the high energy requirement
  - Do not require sophisticated pretreatment
  - More durable and require less maintenance
- But they are
  - Energy Intensive
  - Require high investment

Membrane Separation Process

- Synthetic membranes were first introduced in modern separation process in the 1960s.
- They began to play an increasingly important role in the water desalination in 1980s.
- Membrane separation has become the main source of potable water worldwide.
- Prices have fallen from US$ 4.0/m^3 to less than US$ 1.0/m3 - Recent projects $0.5/m^3.

Synthetic Membrane Filtration

- Membrane-based processes in commercial use for water treatment include:

- Micro filtration (MF) pore size 0.05 to 10 μ.
- Ultra filtration (UF) pore size10 to 1000 Å.
- Nano filtration (NF) pore size 2 to 80 Å.
- Reverse Osmosis (RO) pore size 1 to 70 Å.

Reminder;

- 1 Micron (μ) = 10 000 Angstrom (Å).
- 1 Bar = 100 Kilopascal.

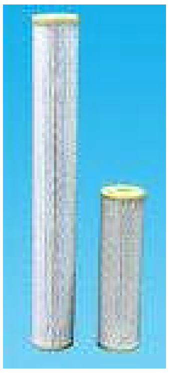
Micro Filtration and Ultra Filtration

Basic principles of MF & UF

- The principle difference between the membrane separation processes lies on the size of the entities, ions, molecules and suspended particles that are retained or allowed to pass in typical separation processes.
- Particle separation in the MF & UF essentially involves the use of a sieving mechanism (membrane) that allows particles smaller than its pours but retain the larger ones.
- MF and UF processes are commonly utilized to remove suspended solids.

Micro Filtration (MF)

- In the MF separation process (pore size 0.05 to 10 μ, microns) under 140 to 200 KPa operating pressure; Bacteria, viruses, larger colloidal particles, precipitates and coagulates will be removed.
- MF alternative traditional water treatment methods are; Oxidation (O_3 or Cl_2) ⟶ (coagulation /sedimentation) then sand-bed filtration.
- MF is useful not only in pretreatment (RO input flow), but also for polishing (remove fine resin particles) the ion exchange units output stream.



Micro Filtration (MF)

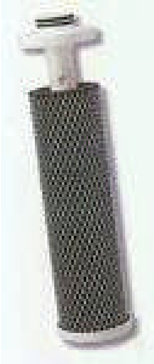
- MF membranes have larger pore size than the other membranes. As a result, the permeate flux is higher compared with the other types of membranes.
- Generally, MF is capable of removing colloids, bacteria and large organic molecules yielding a much better quality permeate when compared with the conventional separation process such as sedimentation and/ or flotation then filtration.

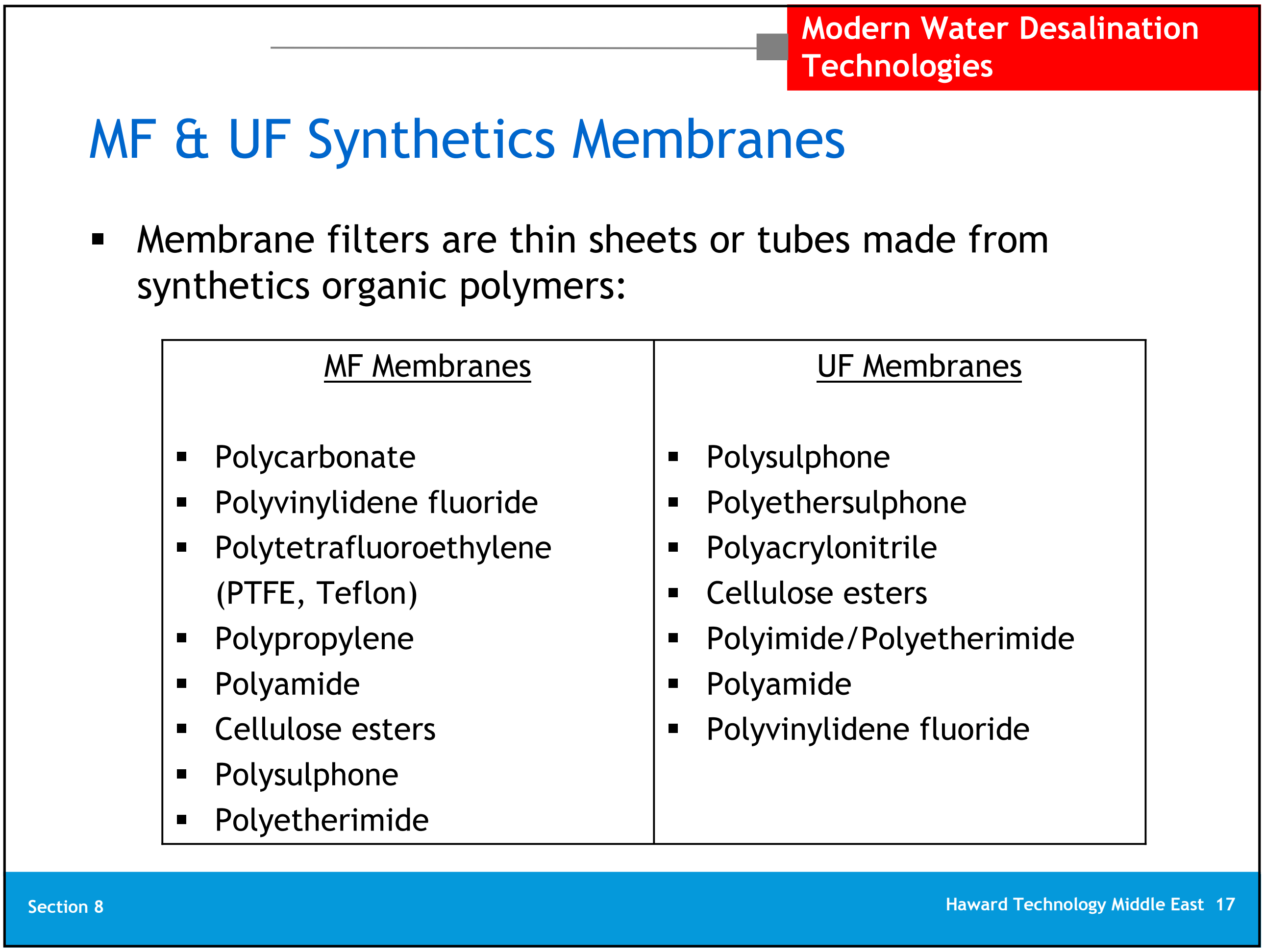
Ultra Filtration UF

- In the UF separation process (pore size 10 to 1000 Å, Angstrom) under 200 to 300 KPa operating pressure; Color, higher molecular weight proteins and higher weight dissolved organic molecules will be removed.
- UF alternative traditional water treatment methods are; Oxidation (O_3 or Cl_2) → (coagulation /sedimentation) → sand-bed filtration then active carbon treatment.
- UF is used in situations where it's essential to retrieve good quality water for reuse in industrial processes.

Ultra Filtration UF

- Metals may be retrieved from electroplating and photographic processing water streams.
- In the pharmaceutical industry, UF is used to harvest enzymes and other products from the biotechnology processes.
- Another important use for UF in water treatment is in removing harmful organic substances (products owing to interaction of pesticide and disinfectants with large liable molecules) from food industry water streams.





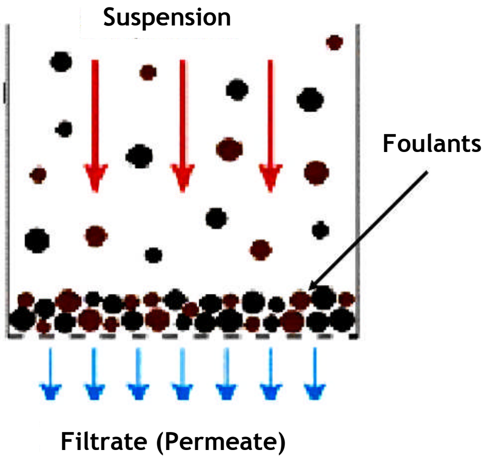
MF & UF Synthetics Membranes

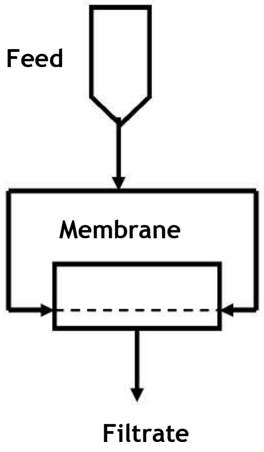
- Membrane filters are thin sheets or tubes made from synthetics organic polymers:

MF Membranes	UF Membranes
▪ Polycarbonate	▪ Polysulphone
▪ Polyvinylidene fluoride	▪ Polyethersulphone
▪ Polytetrafluoroethylene (PTFE, Teflon)	▪ Polyacrylonitrile
▪ Polypropylene	▪ Cellulose esters
▪ Polyamide	▪ Polyimide/Polyetherimide
▪ Cellulose esters	▪ Polyamide
▪ Polysulphone	▪ Polyvinylidene fluoride
▪ Polyetherimide	

Mode of Operation MF & UF

- Dead end filtration - All feedwater is forced to flow through the membranes





MF & UF Membranes Processes

	MF	UF
Membrane type	Symmetric/asymmetric porous	Asymmetric
Membrane thick	10-150 μm	150
Pore sizes	0.05-10 μm	0.001-0.1
Driving forces	Pressure (<2bar)/ vacuum	Pressure (<3bar)
Separation principle	Sieving mechanism	Sieving
Membrane material	Polymeric	Polymeric

Most Famous Applications of MF & UF

- Disinfection of surface water & ground water (combined with chlorination)
- Production of industrial water from surface water (removal of suspended & colloidal matter)
- Pre-treatment of feed water for NF & RO systems (usually combined with chlorination)
- The most famous uses are for drinking water treatment or for pretreatment before RO to remove turbidity, suspended solids, virus, color, and some organic material.

Most Famous Applications of MF & UF

Examples of micro filtration applications are:

- Cold sterilization of beverages and pharmaceuticals
- Clearing of fruit juice
- Separation of bacteria from water (biological wastewater treatment)
- Effluent treatment polishing
- Separation of oil/ water emulsions
- Pre-treatment of water for nano filtration or RO

Industrial Spiral Wound System

Most Famous Applications of MF & UF

Examples of fields where ultra filtration is applied are:

- The dairy industry (milk, cheese)
- The food industry (proteins)
- The metal industry (oil/ water emulsions separation, paint treatment)
- The textile industry

Sanitary Ceramic Systems

Fouling of MF & UF systems

Fouling of Membranes Systems

- Fouling is caused by the trapping of material within the pores or on the surface of the membranes.
- Fouling rates are effected by many factors including membrane porosity, pore size distribution, surface roughness and physiochemical properties (size and charge of the treated solution including colloids and suspended solids).
- Five types of membrane fouling have been identified for pressure-driven systems.

Common Foulants & Scalants in Feed Water

Foulants	Scalants
▪ Suspended matter	▪ Silica
▪ Colloidal matter	▪ Calcium carbonate
▪ Organic matter	▪ Calcium Sulfate
▪ Metals (Fe^{2+}/Mn^{2-})	▪ Calcium fluoride
▪ Bacteria &	▪ Barium sulfate
▪ Biodegradable products	▪ Phosphate salts
↓	↓
MF. UF. NF. RO	Mainly **NF. RO**

Membrane Fouling Types

1. Membrane scaling
2. Fouling by metal oxides
3. Plugging by particulates
4. Colloidal fouling
5. Biological fouling

Membrane Fouling by Scaling

- Membrane scaling is caused by the precipitation of partially soluble saturated salts (calcium carbonate / sulfate / fluoride, barium sulphate and phosphate salts) originally present in feed water.
- This type is very rare at MF and/or UF. Why?

Membrane Fouling by Metal Oxides

- Manganese and Iron oxides are insoluble and will deposit on the membrane surface, which will lead to a drastic reduction in the filtration performance.
- For MF & UF it can considered as Colloidal fouling.

Membrane Fouling, Particles Plugging

- Plugging occurs when membrane pores trap larger particles.
- This is the most famous reason to dispose the MF and/or UF specially when you reach 200 KPa as a differential pressure.

Membrane Fouling, Colloidal Fouling

- Colloidal fouling is caused by the entrapment of colloids on the membrane surface.
- Colloids found in the feed water derive mainly from clays, Iron originating from pipes corrosion.
- Other colloidal fouling agents may come from soap and detergent-based entities as well as proteins and organic matter.
- The level of colloidal loading may be minimized using co-precipitation (Al (III), Fe (III) or Si (IV) hydroxide or polymers then filtration.
- Choosing the water intake source is very effective in colloidal load reducing.

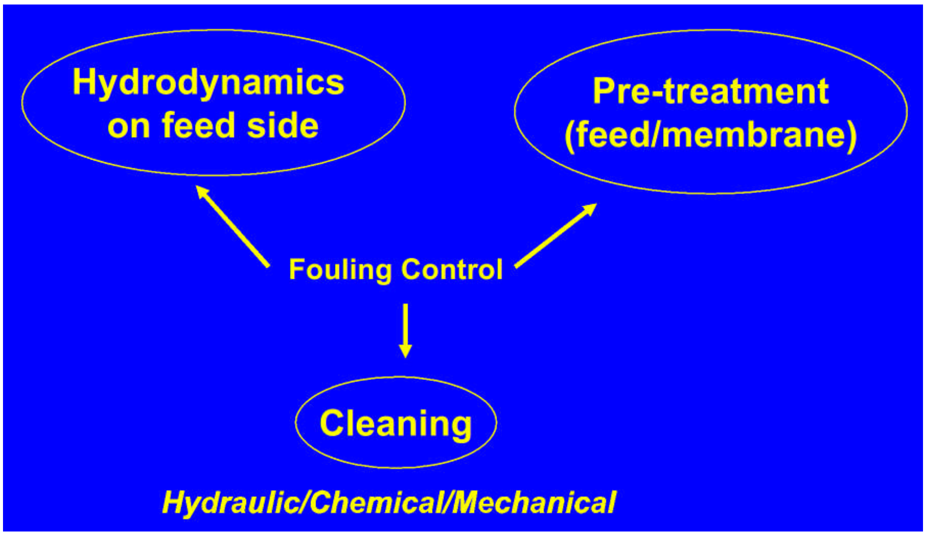
Membrane Fouling, Biological Fouling

- Live or dead micro-organisms are responsible for biological fouling.
- When live microbes are present in feed water, they may form colonies on membranes, eventually leading to pore plugging and destruction of the membrane structural integrity.
- To protect the membranes systems from biological fouling, chlorination followed by sand filtration then de-chlorination or UV radiation should be used.

Membrane Fouling & Scaling Effects

- Fouling and scaling may result in:
  - Increasing energy consumption
  - Lowering recovery
  - Increasing cleaning frequency
  - Deteriorating product quality
  - Shortening membrane lifetime

Fouling Control

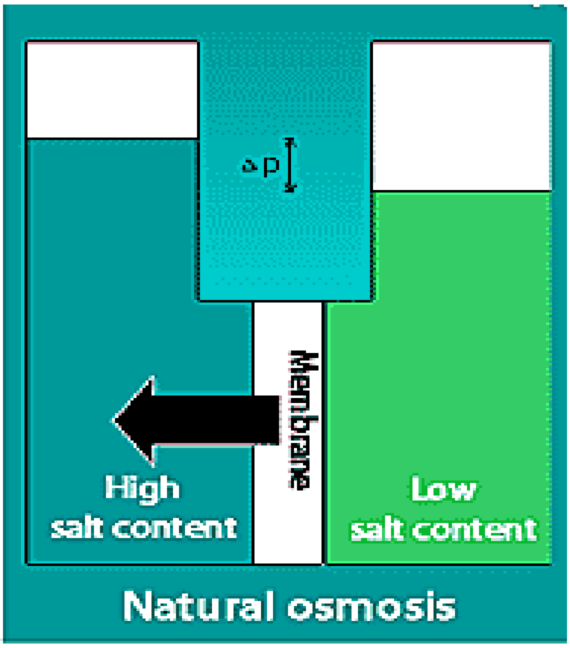


Cleaning of MF & UF systems

- Keeping the membrane clean extends its life and efficiency.
- As a rule, the membrane elements should be cleaned whenever we get 10 to 15 % drops in the product water flow rate and increase in the membrane in / out differential pressure.
- For MF & UF membranes, hydraulic cleaning (backwashing) may be used to prevent physical fouling by removing internally deposited particles.
- However it can't remove the cake build up in dead-end systems.

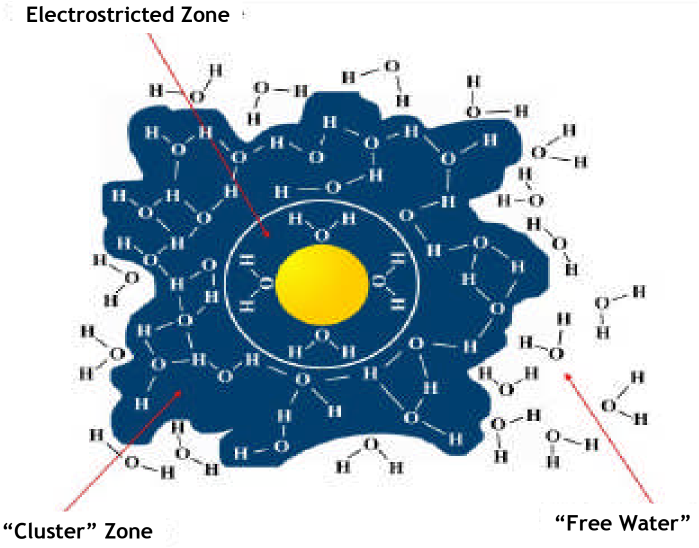
Basic Principles of Reverse Osmosis Membrane Desalination Technology

Principles of Natural Osmoses



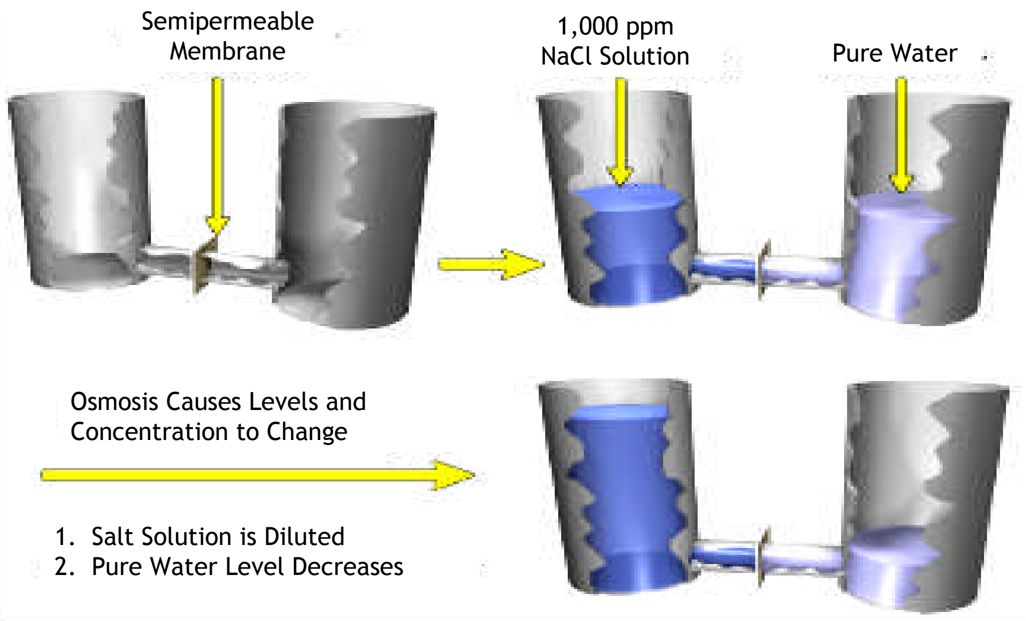
1. Osmosis is a purely natural process.
2. Fluids with a low salt content will always try to mix with fluids with a high salt content until the salt content of the two fluids is the same.
3. If the two fluids are separated by a semi - permeable membrane, the fluid with the low salt content will permeate (go through) the membrane until the salt content is the same at both sides of the membrane.
4. The level difference of the two fluids is called the osmotic pressure.

Principles Of Natural Osmoses, (continued)



- Water molecules is attracted to ions on both sides of the membrane.
- So, a greater number of water molecules are attracted to the higher concentration side.
- Hydrated ions size prevent them from migration to the diluted side.

Principles of Natural Osmoses, (Continued)



Semipermeable Membrane

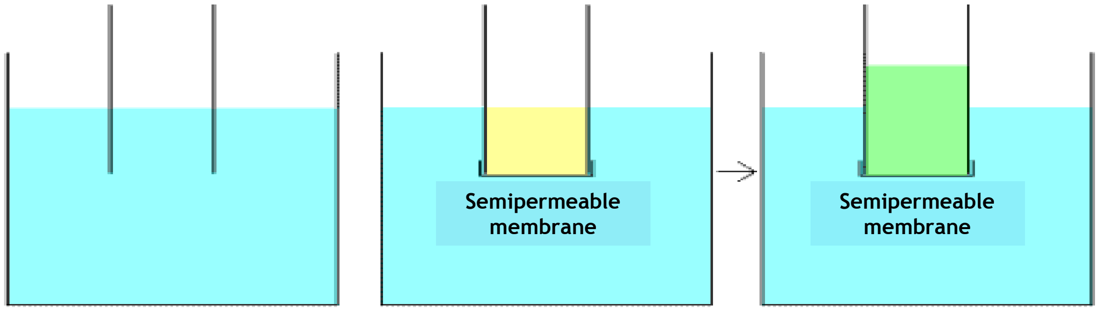
1,000 ppm NaCl Solution

Pure Water

Osmosis Causes Levels and Concentration to Change

1. Salt Solution is Diluted
2. Pure Water Level Decreases

Principles of Natural Osmoses, (Continued)



Imagine a beaker which is filled with water and has a tube that has been half-submerged in the water.

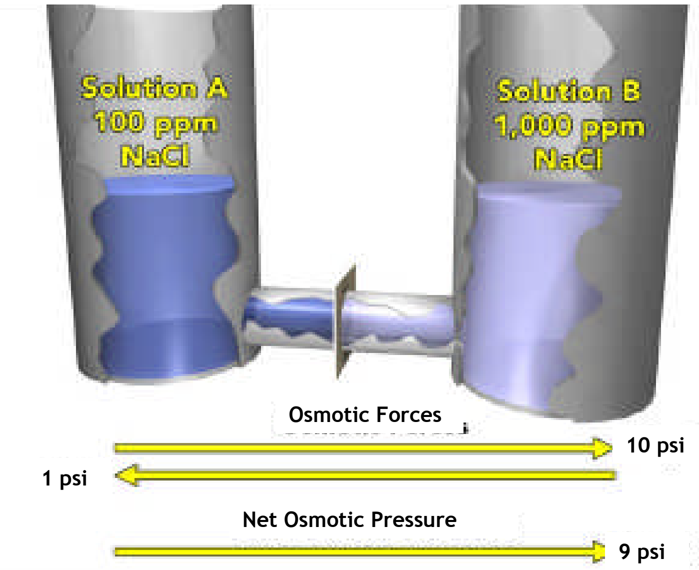
As expected, the water level in the tube and the beaker will be the same.

If we used a sealed end tube (using semi-permeable membrane) has been partially - filled with a salty solution.

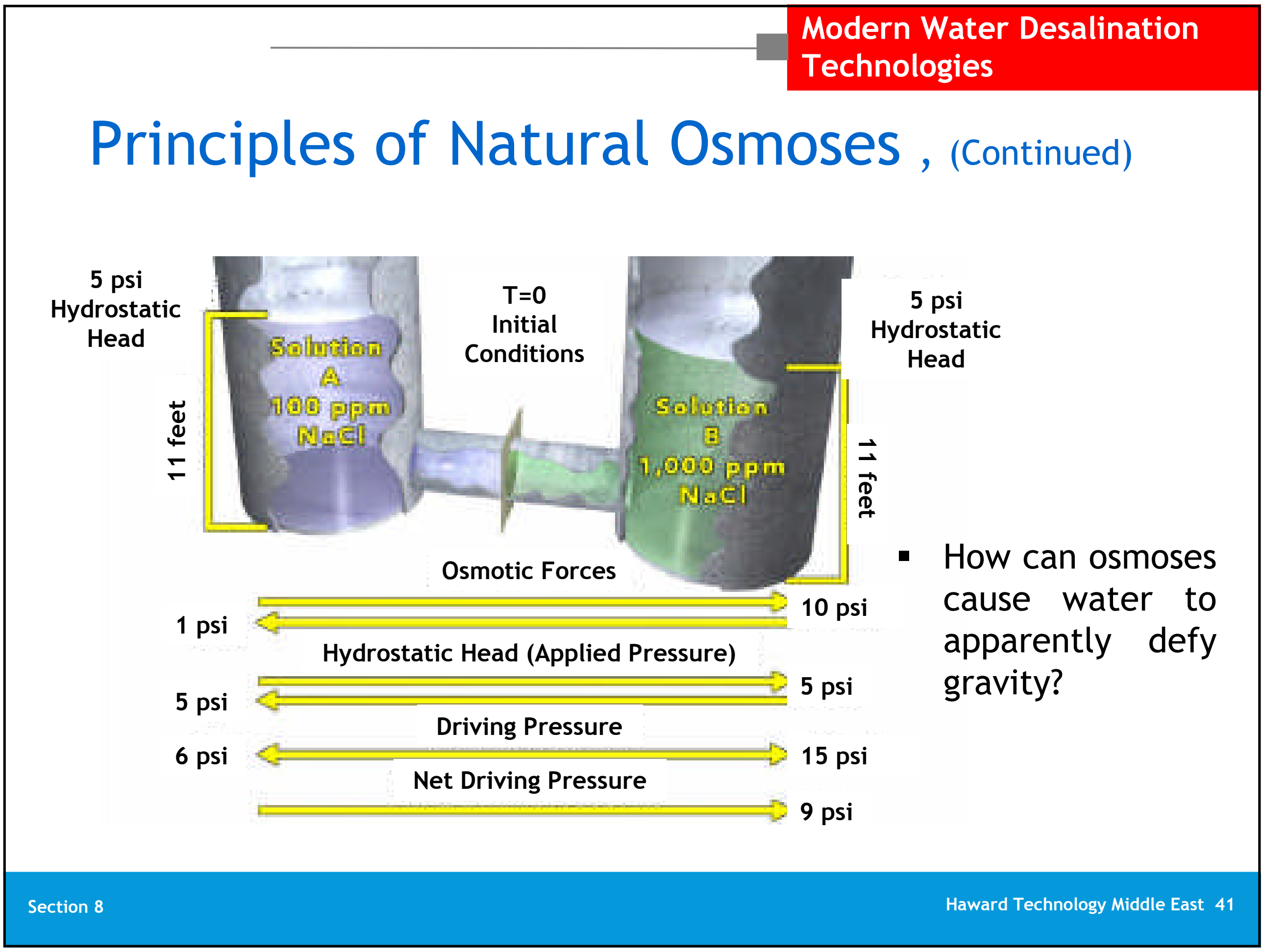
Initially, the level inside and outside the tube will be the same

Over time, something unexpected happens -- the water in the tube actually rises. The rise is attributed to "osmotic pressure."

Principles of Natural Osmoses, (Continued)



- The force driving the molecules from one side to the other is called the osmotic pressure.
- 1 psi of osmotic pressure is caused by every 100 ppm difference in TDS.



Principles of Natural Osmoses , (Continued)

5 psi
Hydrostatic
Head

T=0
Initial
Conditions

5 psi
Hydrostatic
Head

Osmotic Forces

1 psi

10 psi

Hydrostatic Head (Applied Pressure)

5 psi

5 psi

Driving Pressure

6 psi

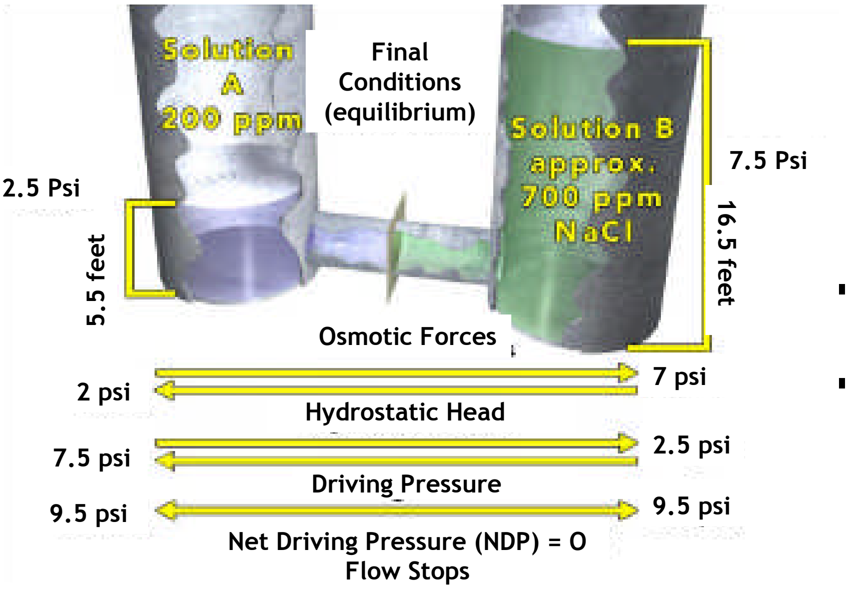
15 psi

Net Driving Pressure

9 psi

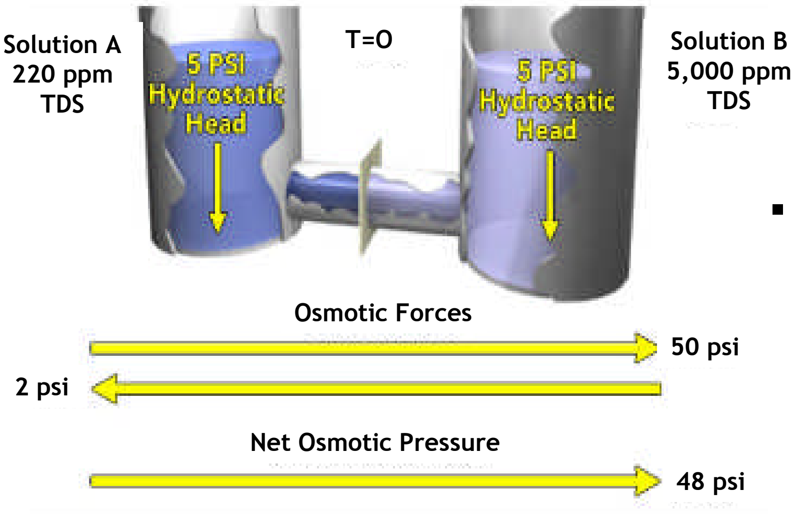
- How can osmoses cause water to apparently defy gravity?

Principles of Natural Osmoses, (Continued)



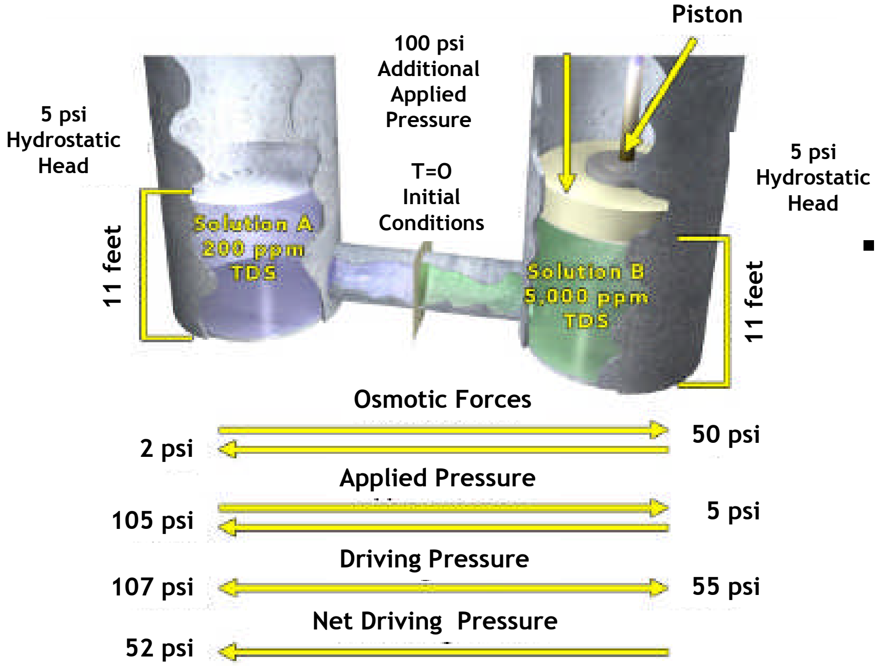
- Final equilibrium condition
- Equilibrium is reached when the NDP goes to zero.

Principles of Reverse Osmosis, (Continued)



- We can reverse the natural osmosis phenomena by applying a higher pressure on the high salt concentration side.

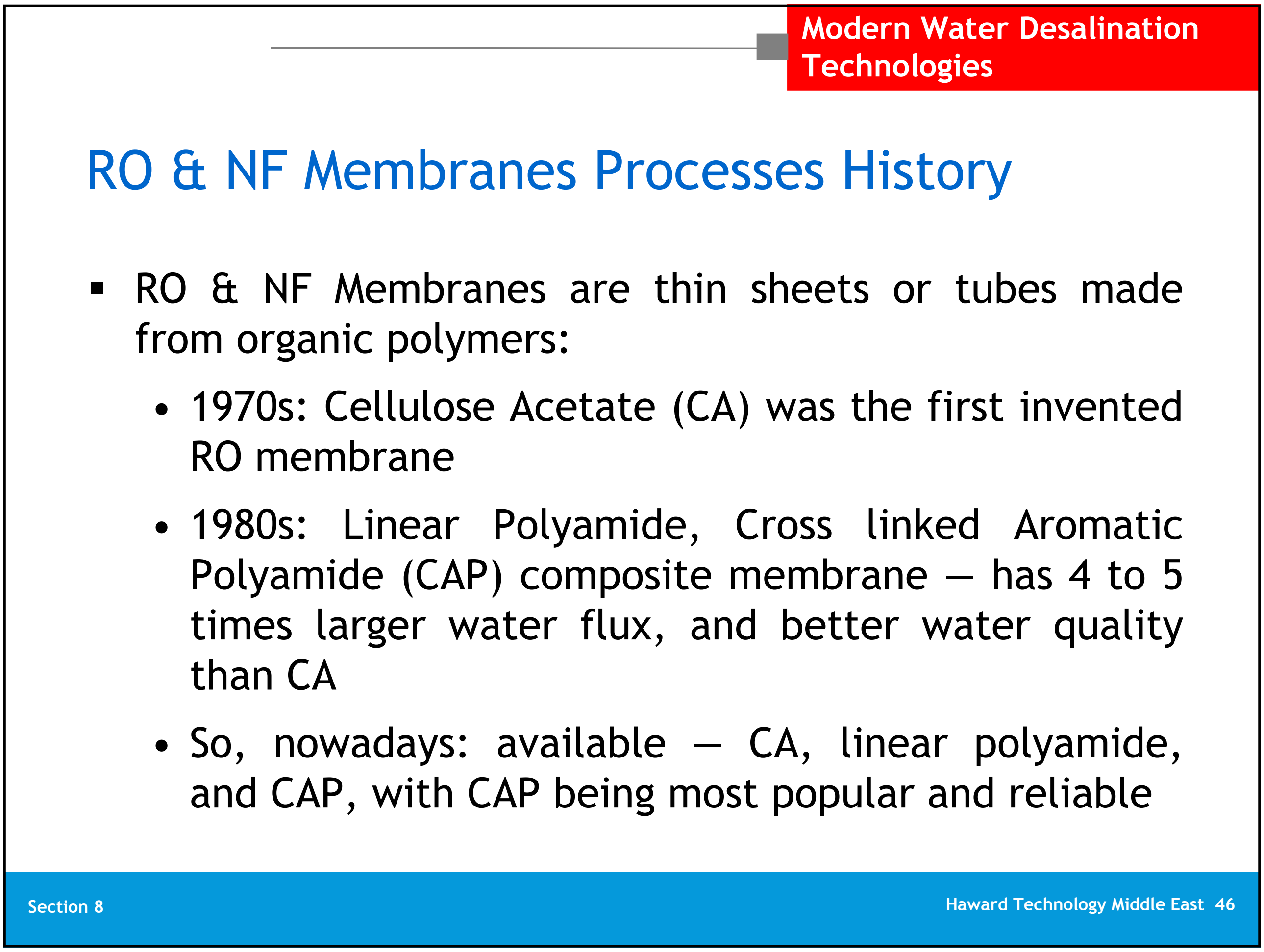
Principles of Reverse Osmosis, (continued)



- RO occur when we apply enough pressure to cause +ve net driving pressure against osmoses.

Basic Principles Of Reverse Osmosis, conclusions

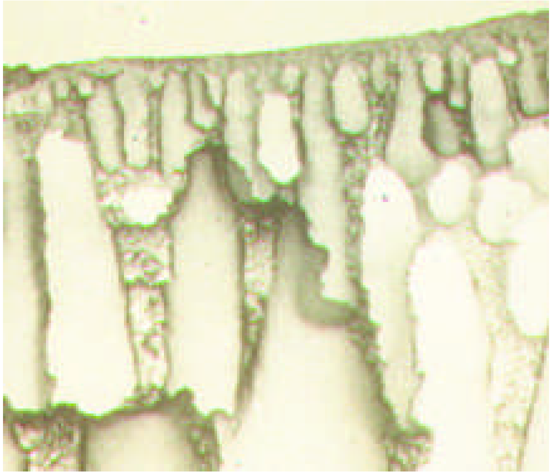
- Reverse osmoses is a process that forces water molecules to flow against a net osmotic pressure.
- With adequate pressure, reverse osmoses can remove purified water from a sample containing higher concentrations of dissolved solids.
- Any solution, no matter how dilute, eventually concentrates enough to shut down a reverse osmosis system unless there is reject flow and corresponding makeup (dilution flow) for the concentrate side.
- Osmotic forces can accumulate to tremendous pressures if a solution continues to increase in TDS.



RO & NF Membranes Processes History

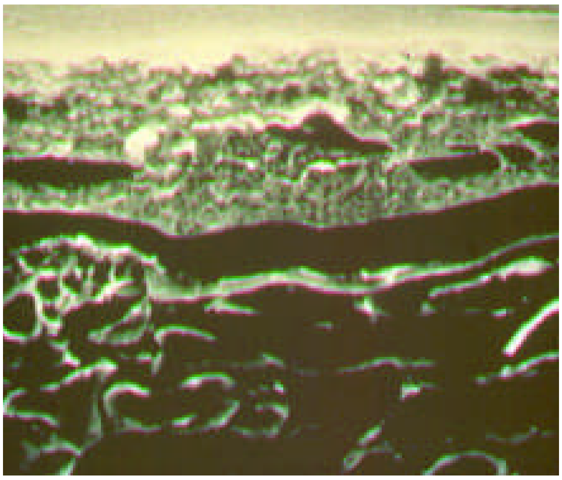
- RO & NF Membranes are thin sheets or tubes made from organic polymers:
  - 1970s: Cellulose Acetate (CA) was the first invented RO membrane
  - 1980s: Linear Polyamide, Cross linked Aromatic Polyamide (CAP) composite membrane – has 4 to 5 times larger water flux, and better water quality than CA
  - So, nowadays: available – CA, linear polyamide, and CAP, with CAP being most popular and reliable

Cellulose Acetate (CA) Membrane



- CA membrane has an asymmetric structure responsible for the salt rejection probably and high water permeability.

Composite Aromatic Polyamide (CAP) Membrane



- CAP membrane is characterized by a higher specific water flux (more water per psi of pressure) and lower salt passage (purer permeate water) than that of (CA) membrane.

Membrane Module Configurations

Tubular

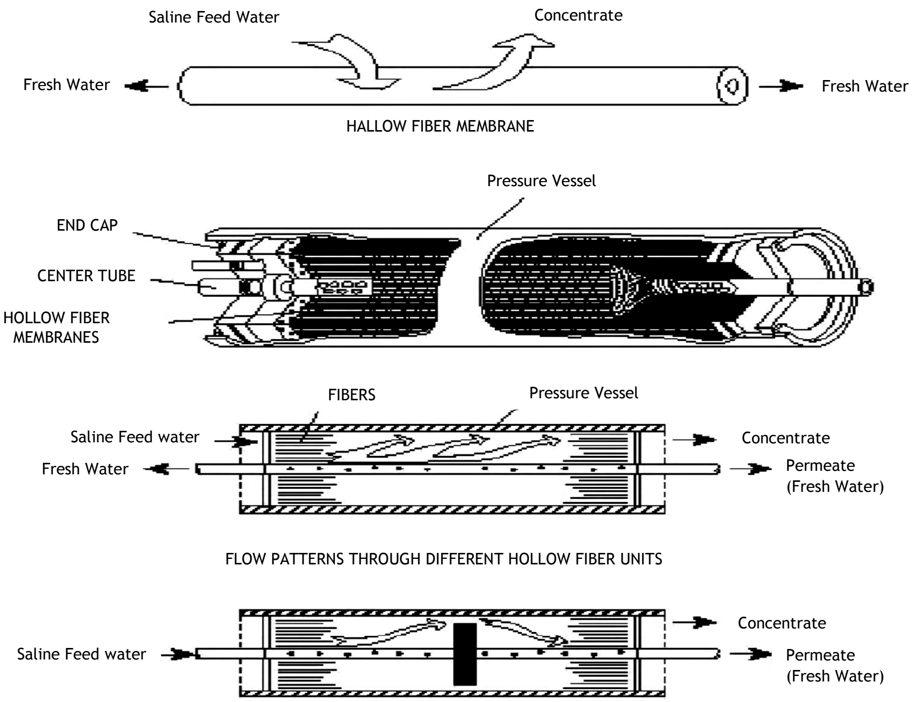
- Hollow fiber
- Spiral wound

Plate and frame

- For RO mainly
  - « Hollow fibers (but require feed water of better quality than spiral wound)
  - « Spiral wound

See RO Membranes In Commercial

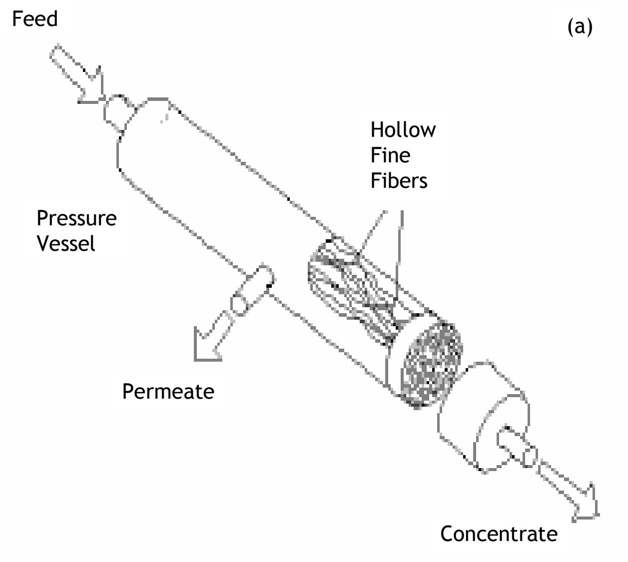
Hollow Fiber RO Membrane



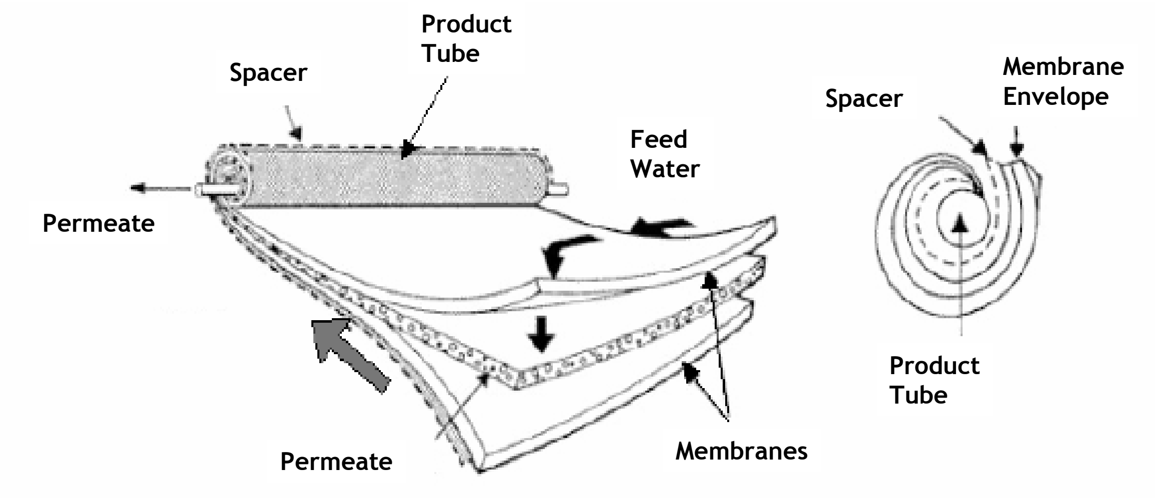
FLOW PATTERNS THROUGH DIFFERENT HOLLOW FIBER UNITS

Hollow fiber RO membrane

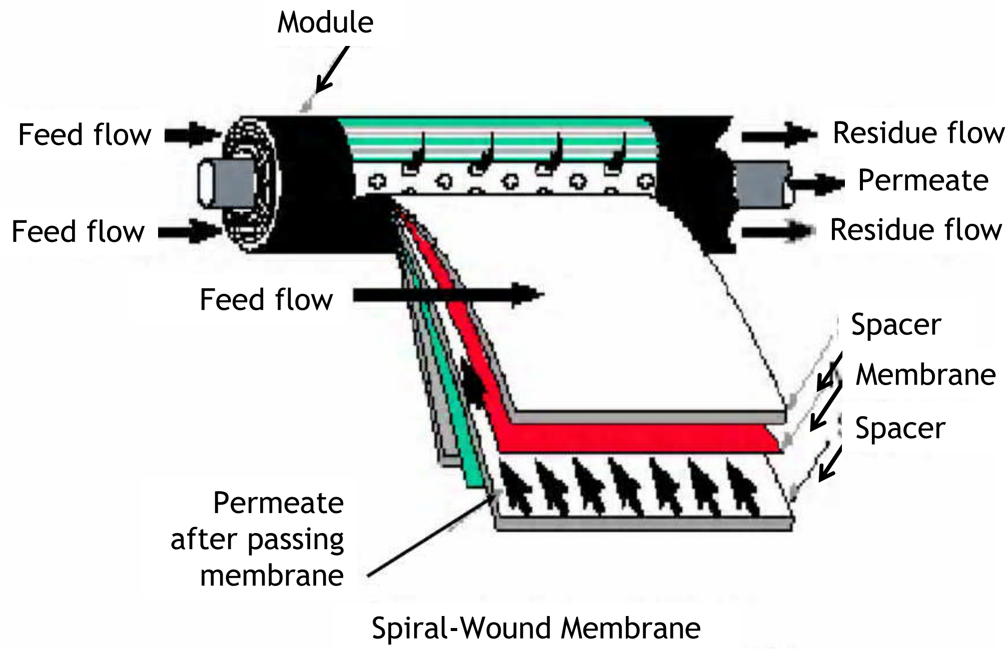
- Old design process.
- Commercial name is the permeator.
- It needs a relatively higher operating pressure
- Most of the permeator types has been upgraded to the spiral wound type.



Spiral Wound RO Membrane

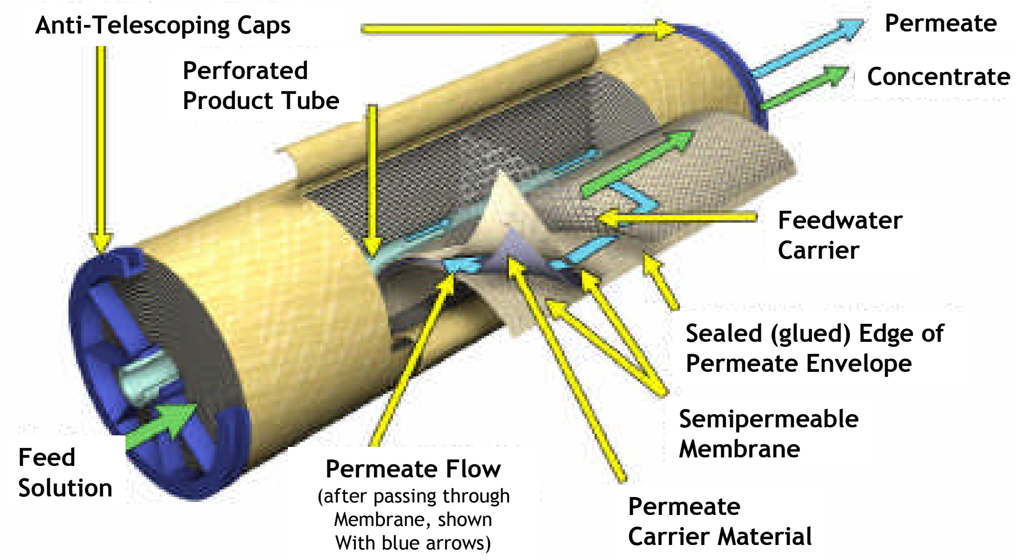


Spiral Wound RO Membrane

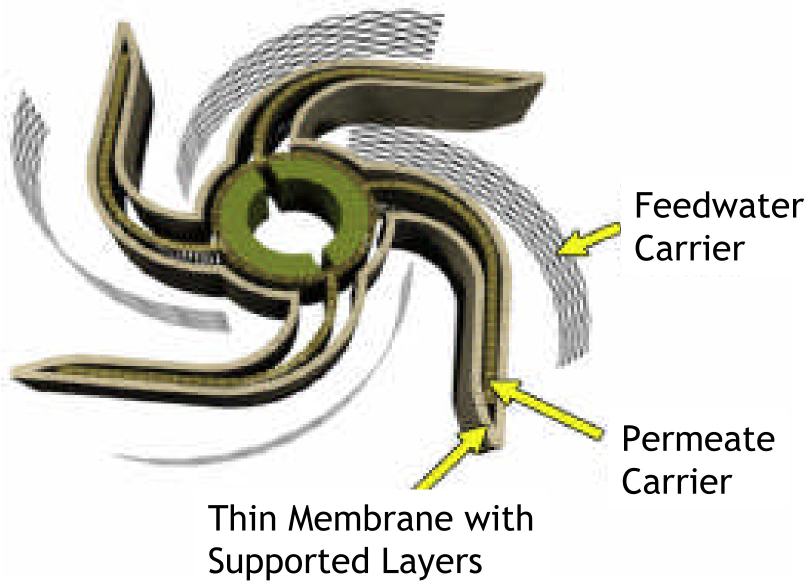


Spiral-Wound Membrane

Spiral Wound Membrane Element

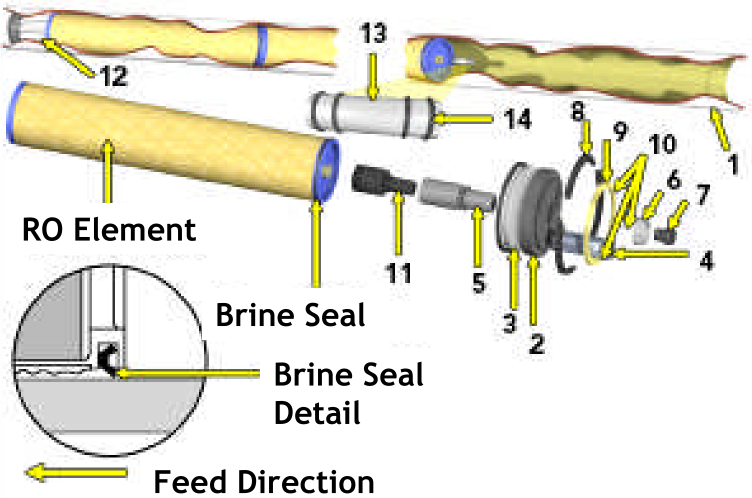


Cut-out view of Spiral Wound Membrane Element

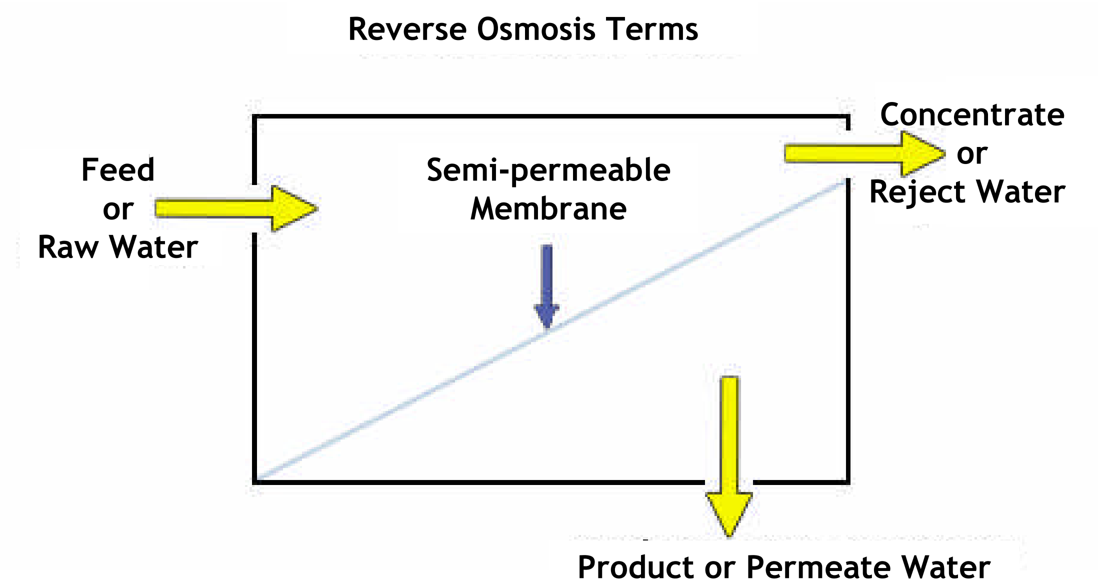


RO Pressure Tube Construction

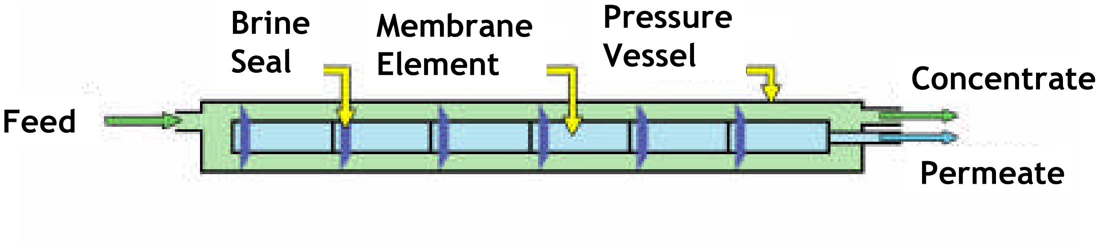
Parts Description	
Item	Description
1	Shell
2	Bearing Plate
3	Sealing Plate (w/O-ring)
4	Feed/Concentrate Port
5	Permeate Port
6	Port Nut
7	Permeate Port End Cap
8	3-piece Locking Ring Set
9	Securing Ring
10	Securing Screws
11	Adapter
12	Thrust Collar
13	Coupler
14	Coupler O-rings



RO Flow Path

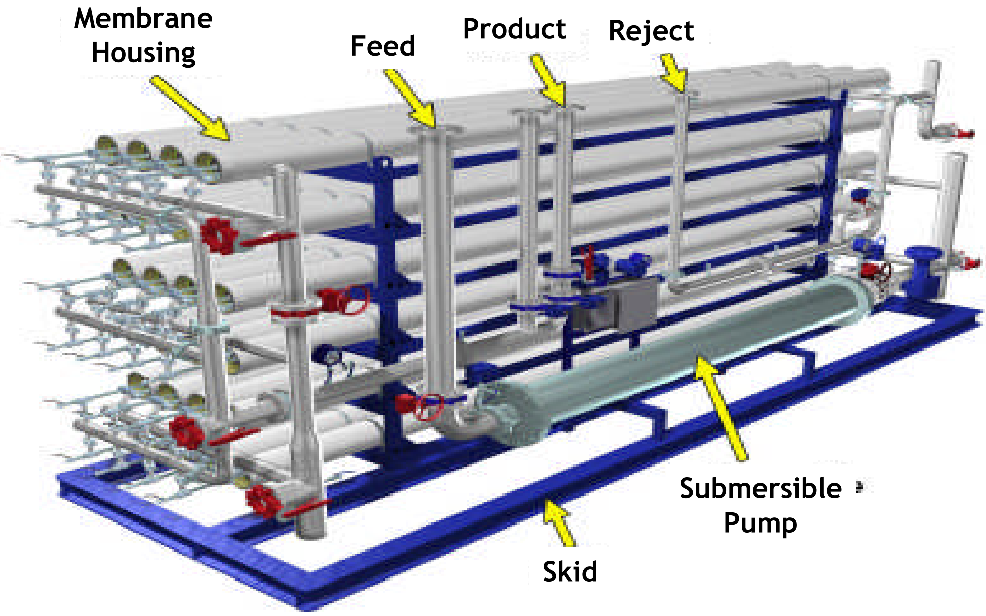

Reverse Osmosis Terms
Feed
or
Raw Water
Semi-permeable
Membrane
Concentrate
or
Reject Water
Product or Permeate Water

RO Pressure Vessel with a flow Path Identified



Typical RO Membrane Pressure Vessel

Typical RO system and components



Design of
Reverse Osmoses

RO Design Steps

- The approximate system size (the number of membrane elements and pressure tubes) required to produce a quantity of product water (permeate) may be determined by the following steps:

1. Membrane selection, select the membrane type and the corresponding model number by looking at the manufacturers' membrane charts.
2. Flux rate calculation according to expected feedwater quality.

RO Design Steps (continued)

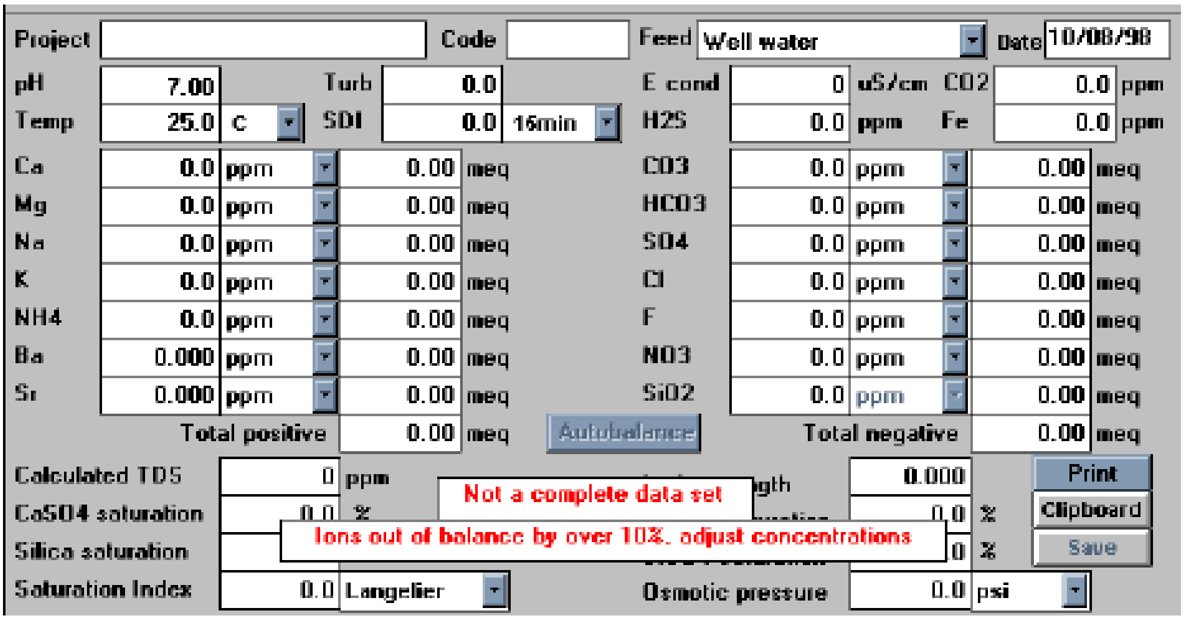
3. No. of element calculation.

- Divide the desired plant capacity by the design flux rate and by the membrane element surface area (the membrane area is listed in the element specification sheet) to get the Number of Elements.
- Number of Elements = Permeate Flow (USGPD)/ Flux (GFD) X Active Membrane Area (Ft2)

RO Design Steps (continued)

4. No. of pressure vessel calculation.
    - Divide the total number of elements by the number of elements per pressure vessel.
    - Round the result up to the nearest integer.
5. Select the appropriate array to achieve the desired percent recovery. Increase the number of pressure vessels if necessary.

RO Design Using Software



Project		Code		Feed	Well water	Date	10/08/98	
pH	7.00	Turb	0.0	E cond	0	uS/cm	CO2	0.0 ppm
Temp	25.0 C	SDI	0.0 16min	H2S	0.0	ppm	Fe	0.0 ppm

Ca	0.0 ppm	0.00	meq	CO3	0.0 ppm	0.00	meq
Mg	0.0 ppm	0.00	meq	HCO3	0.0 ppm	0.00	meq
Na	0.0 ppm	0.00	meq	SO4	0.0 ppm	0.00	meq
K	0.0 ppm	0.00	meq	Cl	0.0 ppm	0.00	meq
NH4	0.0 ppm	0.00	meq	F	0.0 ppm	0.00	meq
Ba	0.000 ppm	0.00	meq	NO3	0.0 ppm	0.00	meq
Sr	0.000 ppm	0.00	meq	SiO2	0.0 ppm	0.00	meq
Total positive		0.00	meq	Total negative		0.00	meq

Calculated TDS	0	ppm	gth	0.000
CaSO4 saturation	0.0	%		0.0 %
Silica saturation				0 %
Saturation Index	0.0	Langelier	Osmotic pressure	0.0 psi

Not a complete data set

Ions out of balance by over 10%, adjust concentrations

Performance Parameters In RO

- The RO process is defined in terms of certain variables, including the following:
  1. Osmotic and operating pressure.
  2. Salt rejection.
  3. Permeate recovery.

Design Parameters Effecting Performance

The performance of membrane elements operating in a reverse osmosis system is affected by:

- Feed water composition, temperature, pressure, and permeate recovery ratio.
- Membrane compaction and fouling also affect membrane performance.
- Performance at a given set of system operating parameters can be calculated from nominal membrane performance at reference test conditions.

Design Parameters Effecting Performance (continued)

1. Feed water salinity;
   - As long as different feed water compositions will not require a change in the system recovery ratio, changing feed water composition will affect only the required feed pressure and permeate water salinity.
   - If the different contains soluble salts higher than in the design feed water, then the recovery ratio may have to be reduced to avoid the possibility of precipitation of scale from the concentrate stream.

Design Parameters Effecting Performance (continued)

2. Feed Pressure;

- Over operating time, the feed pressure is adjusted to compensate for fluctuation of feed water temperature, salinity and permeate flux decline due to fouling or compaction of the membrane.
- It is noted that the specific flux of the membrane will decline by about 20% in three years.
- The pump has to be designed to provide feed pressure corresponding to the initial membrane performance and to compensate for expected flux decline.

Design Parameters Effecting Performance (continued)

3. Feed water Temperature;

- Change in feed water temperature results in the change in the rate of the relative flux rate.
- Because permeate flux is maintained constant, permeate salinity changes accordingly to the temperature fluctuations.
- Higher feed water temperature will also result in a higher compaction rate.

Design Parameters Effecting Performance (continued)

4. Permeate recovery ratio;

- Recovery ratio affects system performance, i.e. permeate salinity and feed pressure, by determining the average feed salinity.
- Because recovery rate strongly affects process economics, there is a tendency to design operation of RO systems at the highest practical value.

Design Parameters Effecting Performance (continued)

5. Membrane compaction and fouling;
    - Exposure of membranes to high pressure (during initial operating period) result in compaction, which will decreases the rate of diffusion of water and dissolved constituents through the membrane.
    - As a result of compaction, higher pressure has to be applied to maintained the design permeate flow.
    - In parallel, a lower rate of salt diffusion will result in lower permeate salinity.
    - In the initial stages of membrane fouling, performance changes are similar to those caused by the compaction process.

Overview
RO & NF membranes

Hyperfiltration (RO & NF) Processes

- Hyper filtration is the term often used to refer to NF and RO process because both allow the separation of dissolved ions from feed water streams.
- The main difference is that NF membranes possess lower rejection levels for small mono valent ions.
- NF membrane will allow entities in the size range 8 - 80 Å to pass, while RO membranes allow only entities in the range 1 – 15 Å to filter throw.

Synthetic Membrane Filtration reminder

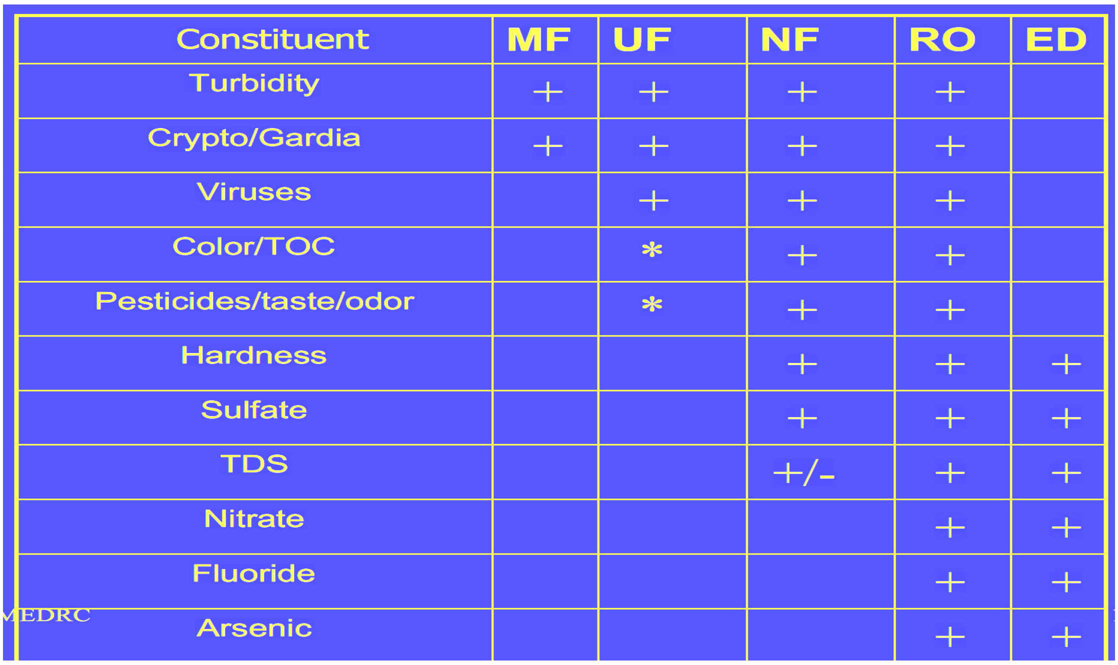
Membrane-based processes in commercial use for water treatment include:

- Micro filtration (MF) pore size 0.05 to 10 µ.
- Ultra filtration (UF) pore size10 to 1000 Å.
- Nano filtration (NF) pore size 2 to 80 Å.
- Reverse Osmosis (RO) pore size 1 to 70 Å.

Reminder;

- 1 Micron (µ) = 10 000 Angstrom (Å).
- 1 Bar = 100 Kilopascal.

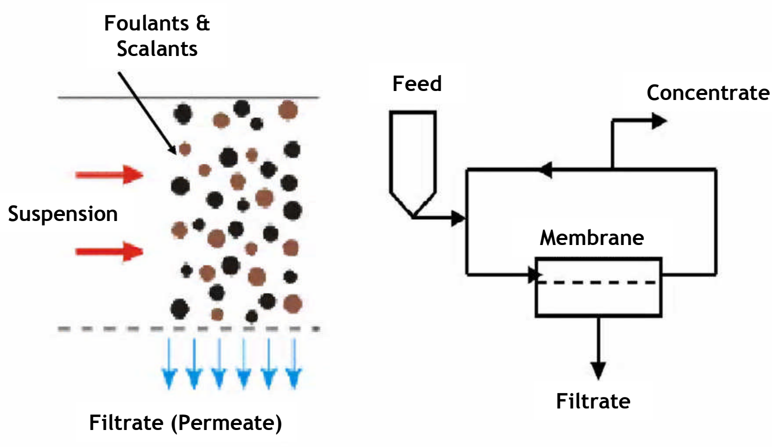
Applications of Membrane Processes



Constituent	MF	UF	NF	RO	ED
Turbidity	+	+	+	+	
Crypto/Gardia	+	+	+	+	
Viruses		+	+	+	
Color/TOC		*	+	+	
Pesticides/taste/odor		*	+	+	
Hardness			+	+	+
Sulfate			+	+	+
TDS			+/-	+	+
Nitrate				+	+
Fluoride				+	+
Arsenic				+	+

Mode of Operation NF&RQ

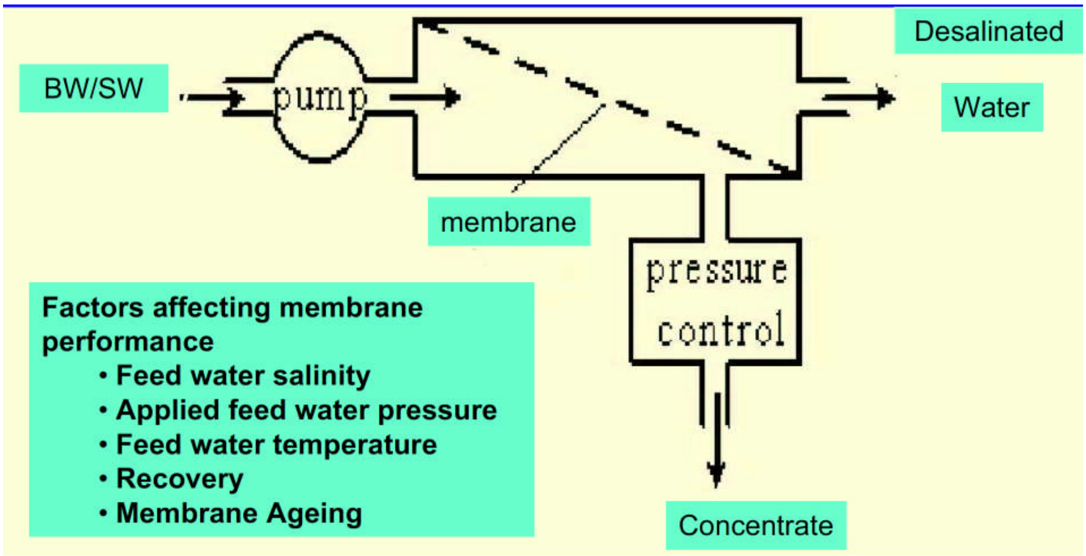
- Cross flow: Tangential flow is created. Part of the feedwater is rejected



NF/RO Processes

- NF/RO system is made of the following components:
  - Feed water supply unit.
  - Pretreatment system (to keep membrane surface clean)
  - High-pressure pump (15-25 bar for BWRO, 54-80 bar for SWRO)
  - Membrane assembly (pressure vessel and membrane elements)
  - Instrumentation and
  - Post-treatment unit
  - Cleaning unit

NF/RO Processes



Factors affecting membrane performance

- **Feed water salinity**
- **Applied feed water pressure**
- **Feed water temperature**
- **Recovery**
- **Membrane Ageing**

Fouling
in RO & UF systems

Fouling of membranes systems

- Fouling is caused by the trapping of material within the pores or on the surface of the membranes.
- Fouling rates are effected by many factors include membrane porosity, pore size distribution, surface roughness and physiochemical properties (size and charge of the treated solution including colloids and suspended solids).
- Five types of membrane fouling have been identified for pressure-driven systems.

Common Foulants & Scalants in Feed water

Foulants	Scalants
▪ Suspended matter	▪ Silica
▪ Colloidal matter	▪ Calcium carbonate
▪ Organic matter	▪ Calcium Sulfate
▪ Metals (Fe^{2+}/Mn^{2-})	▪ Calcium fluoride
▪ Bacteria &	▪ Barium sulfate
▪ Biodegradable products	▪ Phosphate salts
↓	↓
MF. UF. NF. RO	Mainly **NF. RO**

Membrane fouling types

1. Membrane scaling.
2. Fouling by metal oxides.
3. Plugging by particulates
4. Colloidal fouling.
5. Biological fouling.

Membrane fouling by scaling

- Membrane scaling is caused by the precipitation of partially soluble saturated salts (calcium carbonate / sulfate / fluoride, barium sulphate and phosphate salts) originally present in feed water.
- This type is very rare at MF and/or UF. Why?
- This type is very dangerous for RO membranes specially at the reject (concentrated) side.
- Feed stream PH adjustment (to be 5.5 to 6.0) will prevent calcium scaling.
- Water softening chemical can be used to control the sulfate scaling.
- In general, early detection of scaling cause will effect the remedial action.

Membrane fouling by metal oxides

- Manganese and Iron oxides are insoluble and will deposit on the membrane surface, which will lead to a drastically reduce in the filtration performance.
- For MF & UF it can considered as Colloidal fouling.
- This is very dangerous fouling for RO and/or NF membrane in case of Mg and/or Fe presence in the feed water with an oxidation possibilities inside the membranes fiber itself.
- Oxidation followed by precipitation, clarification or filtration is the preferred method to overcome the metal oxides fouling.
- Sometimes aeration followed by filtration is better specially when the groundwater supplies are used.

Membrane fouling particles plugging

- Plugging occurs when membrane pores trap larger particles.
- This is the most famous reason to dispose the MF and/or UF specially when you reach 200 KPa as a differential pressure.
- To protect the RO & NF membrane you should use MF and/or UF membrane just before the high pressurization step.

Membrane fouling, colloidal fouling

- Colloidal fouling is caused by the entrapment of colloids on the membrane surface.
- Colloids found in the feed water derive mainly from clays, Iron originating from pipes corrosion.
- Other colloidal fouling agents may come from soap and detergent-based entities as well as proteins and organic matter.
- The level of colloidal loading may be minimized using co-precipitation (Al (III), Fe (III) or Si (IV) hydroxide or polymers then filtration.
- Choosing the water intake source is very effective in colloidal load reducing.

Membrane fouling, colloidal fouling (continued)

- The tolerance of different RO membrane systems to colloidal contamination varies.
- A spiral wound membrane can tolerate colloidal loadings with the SDI values up to 5.0, while the hollofiber membrane systems are capable of dealing with maximum SDI in the range of 3.0 or lower.

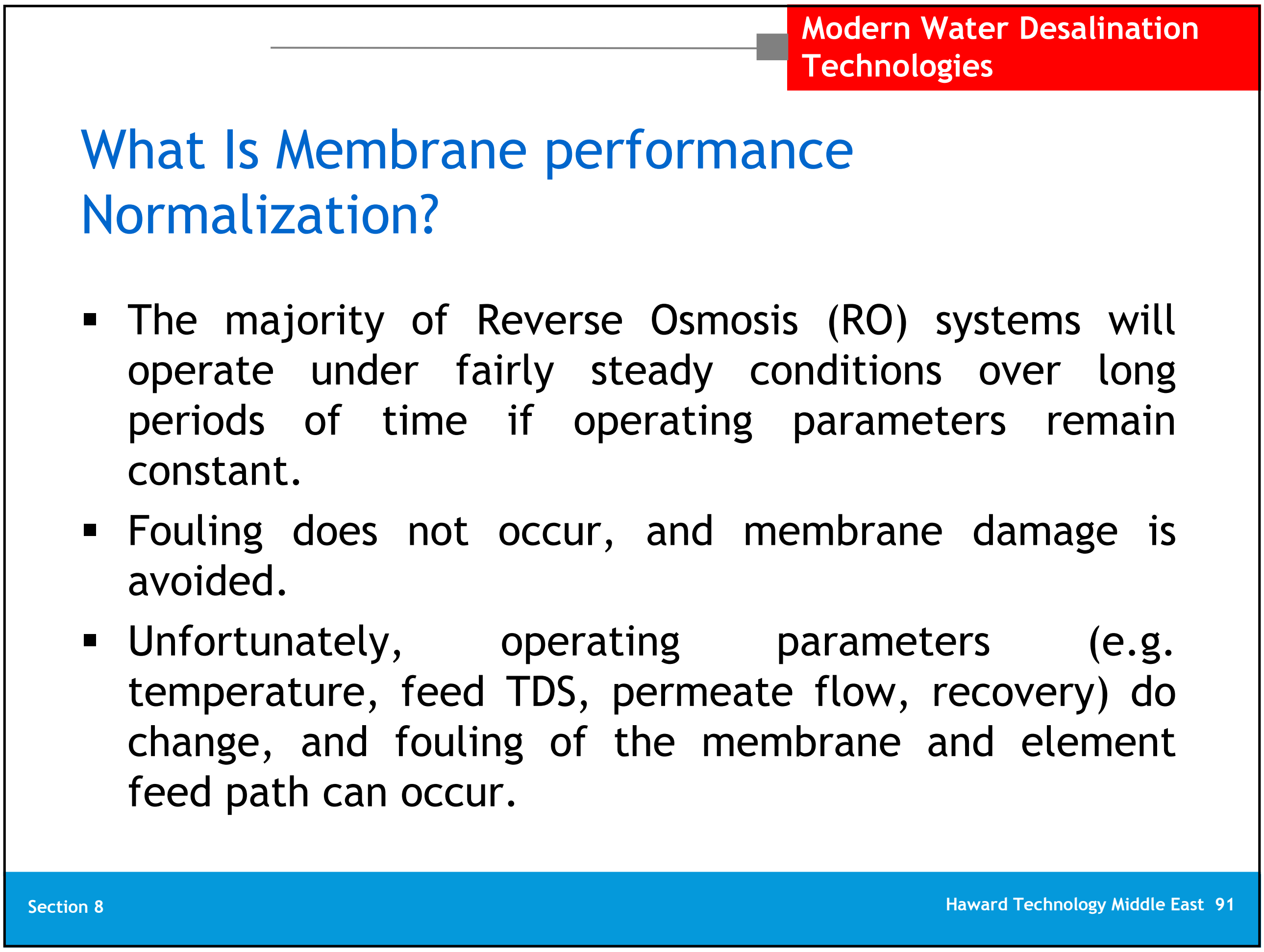
Reminder,

- SDI = Silt Density Index = $P_{30}/T = (1 - T1 / Tf) * (100)/T$
- Where; P_{30} is SDI filter-paper % pluggage at feed pressure 30 psig.
  T is the total test time in minutes (usually 15 min.).
  T_i is the initial time (sec.)required to obtain sample.
  T_f is the time required to obtain sample after 15 minutes.

Membrane fouling, biological fouling

- Live or dead micro-organisms are responsible for biological fouling.
- When live microbes are presenting feed water, they may form colonies on membranes, eventually leading to pore plugging and destruction of the membrane structural integrity.
- To protect the membranes systems from biological fouling, Chlorination follower by sand filtration then de-chlorination or UV radiation should be used.

Membrane Performance Normalization



What Is Membrane performance Normalization?

- The majority of Reverse Osmosis (RO) systems will operate under fairly steady conditions over long periods of time if operating parameters remain constant.
- Fouling does not occur, and membrane damage is avoided.
- Unfortunately, operating parameters (e.g. temperature, feed TDS, permeate flow, recovery) do change, and fouling of the membrane and element feed path can occur.

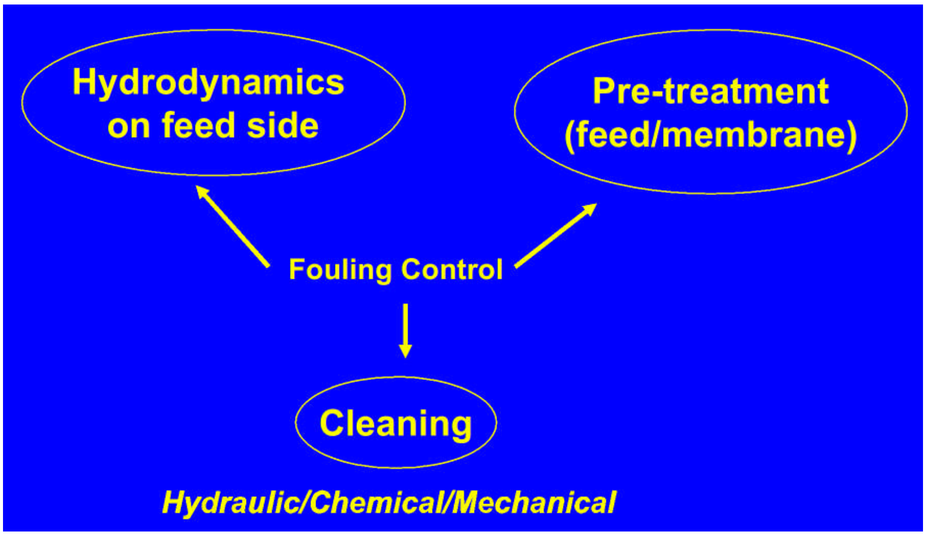
Membrane performance Normalization?

- Normalization is a technique that allows the user to compare operation at a specific set of conditions to a reference set of conditions. This allows the user to determine whether changes in flow or rejection are caused by fouling, damage to the membrane, or are just due to different operating conditions.
- Membranes manufacturers offer a normalization programs which will help in determining the cause of flow changing.

Membrane fouling & scaling effects

- Fouling and scaling may result in:
  - Increasing energy consumption
  - Lowering recovery
  - Increasing cleaning frequency
  - Deteriorating product quality
  - Shortening membrane lifetime

Fouling Control



Hydrodynamics on feed side

Pre-treatment (feed/membrane)

Fouling Control

Cleaning

Hydraulic/Chemical/Mechanical

See RO Membrane
Cleaning File

RO cleaning in place (CIP) sysem

NF/RO Processes, pre treatment

- How to reduce the rate of fouling /scaling in RO & NF?
  - Pretreatment;
    - Sedimentation, rapid sand filtration.
    - Micro-/ultra filtration.
    - Softening.
  - Operate membrane at lower flux.
  - Addition of anti Scalants (for $CaSO_4$, etc.).
  - Addition of add (for $CaCO_3$).
  - Addition of chlorine (should be followed by de-chlorination after filtration).
  - Reducing concentration polarization by increasing the rejected water flow (Safe flow changing).

RO Processes

Post treatment

Treatment of product water from RO plant to be suitable for transportation via pipes and for drinking, involves (Stabilization of product water, pH adjustment, chlorination)

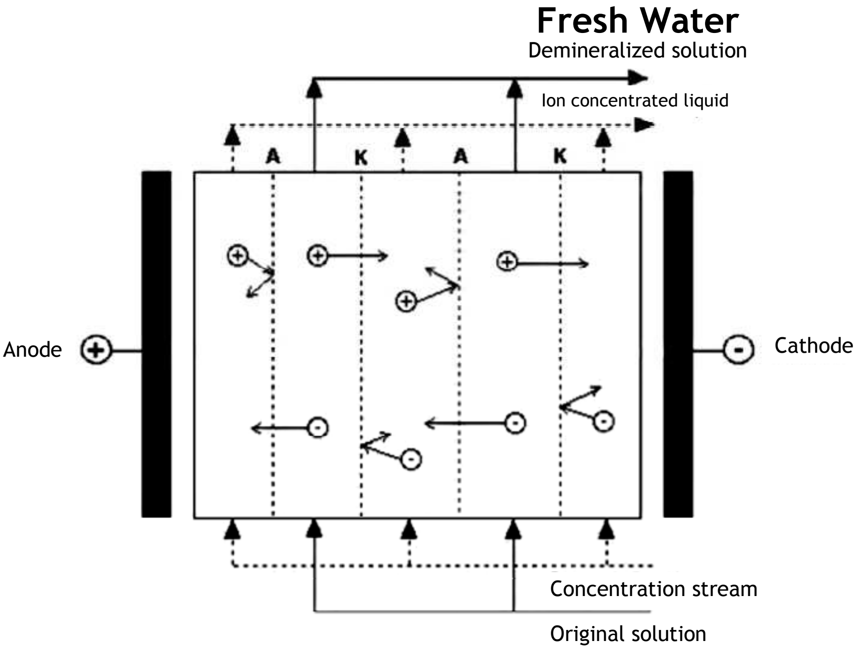
- To ensure the safety from microbiological
- To protect against microbiological growth in the distribution system
- To minimize corrosivity against pipe materials, e.g.
  - Copper - Copper alloys – iron
  - Asbestos cement, concrete, cement lining

Electrodialysis

- Introduced in the early 1960s
- Treats brackish water only
- High recovery
- Able to cope with suspended solids, but materials that may harm the membranes or clog the narrow channels in the cell must be removed (via pretreatment)
- Low chemical usage
- Unaffected by non-ionic substances such as silica

Electrodialysis

- ED Unit is made up of the following basic components:
  - Pretreatment
  - Membrane stack
  - Low-pressure circulating pump
  - Power supply for direct current (a rectifier)
  - Post treatment **(stabilizing the product water before distribution, may consist of removing gases such as H2S and adjusting the pH)**



Fresh Water

Demineralized solution

Ion concentrated liquid

Anode

Cathode

Concentration stream

Original solution

A anion exchange membrane, permeable to onions
K cation exchange membrane, permeable to cations

Electrodialysis Reversal

- Introduced in the early 1970s
- Same principles as ED, except brine and product channels are identical in construction
- At intervals the polarity of the electrodes is reversed, and the flows simultaneously switched **(the product channel becomes the brine and the product channel becomes the brine)**
- Flushing for 1 or 2 minutes
- The reversal process is useful in flushing scales, slimes, other deposits in the cells
- Because of Flushing, less pretreatment chemicals and minimize membrane fouling

Conclusions

- MF and UF are gaining popularity as alternative to conventional treatment method, prices are falling close to conventional
- NF is gaining popularity as a softening process to treat hard water or as pretreatment to RO
- Developments in membrane, Energy Recovery Devices, and anti-scalants are making desalination by RO cheaper and cheaper.