REVERSE OSMOSIS

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Module 6
REVERSE OSMOSIS

6.1   Fundamentals of Reverse Osmosis

6.1.1   History of Reverse Osmosis

Reverse osmosis is a modification of the natural process known as osmosis. A French scientist first described the phenomenon of osmosis in 1748. This scientist noted that water spontaneously diffused through a pig bladder membrane into alcohol. Over 200 years later, researchers modified the process of osmosis and discovered and patented the process now known as reverse osmosis. The reverse osmosis process allows the purification of contaminated water by removing dissolved and suspended matter. Reverse osmosis has become a key process technology. Its use in industrial applications has had major advancements since the early 1960s.

Reverse Osmosis (RO) uses a specialized membrane material that is selective about what it allows to pass through, and what it prevents from passing. The RO membranes pass water very easily because water has a small molecular size, but membranes stop many other contaminants from passing through. Only water and small non-ionized (or non-charged) molecules are allowed to pass through. RO has become very popular for water purification applications due to its ability to remove both suspended and dissolved impurities without the need for regenerant chemicals. Reverse Osmosis systems can be found today in a wide range of facilities: kitchens, hospitals, refineries, power plants, semiconductor manufacturing facilities, manned spacecraft, sailboats, etc.

6.1.2   Osmosis and Osmotic Pressure

Reverse Osmosis is a process that separates impurities from water by passing the water through a semipermeable membrane. The semipermeable membrane only allows very small atoms and groups of atoms such as water molecules, small organic molecules, and gases, to go through it. Hydrated ions, or ions that have been dissolved and are therefore surrounded by water molecules, cannot pass through the membrane.

In order to understand **reverse osmosis**, the **osmosis** process needs to be understood. Once osmosis is understood, reverse osmosis can be clearly explained.

6.1.2.1 Osmosis and Its Cause

When two solutions with different dissolved mineral concentrations are separated by a semipermeable membrane, water flows from the less concentrated solution to the more concentrated solution. **Figure 6.1-1** illustrates an apparatus that connects two glass vessels with a membrane located at the point of interface. The water level rises on the more concentrated side of the apparatus. The dilution of the solution with the higher concentration is caused by the process called **osmosis**.
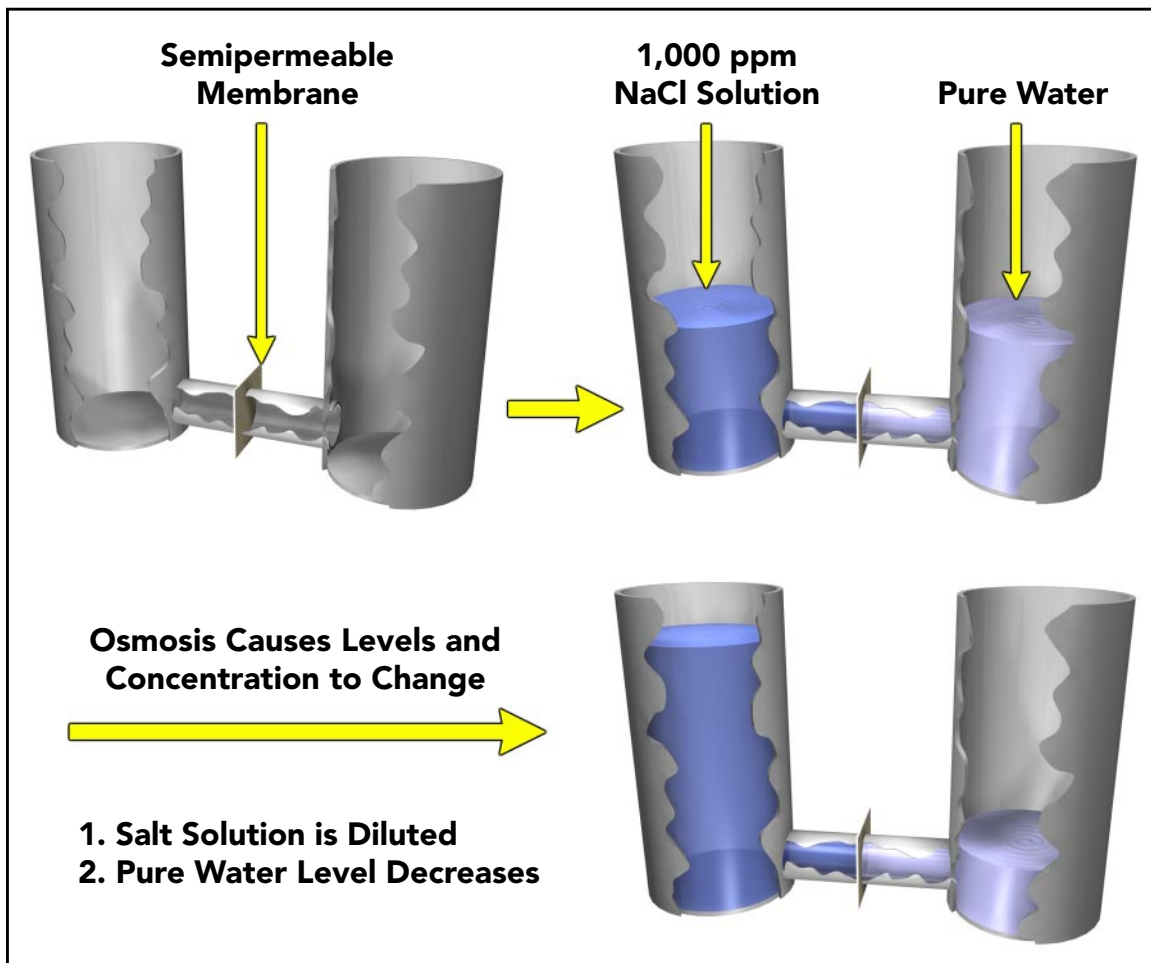

Figure 6.1-1: Apparatus used to Demonstrate Osmosis. Two Glass Vessels with a Semipermeable Membrane Located at their Interface

The simple definition of osmosis is the tendency of a fluid to pass through a somewhat porous membrane until the concentration on both sides is equal. It is better defined as follows:

Osmosis is the migration of water molecules across a membrane caused by the attraction of the dipole moment of water molecules to ions and polar molecules on the other side of a membrane.

Water molecules are attracted to ions on both sides of the membrane. The solution with a higher concentration has a greater number of dissolved ions, therefore, a greater number of water molecules are attracted to that solution. Ions, which are hydrated when in water, tend not to migrate through the membrane to equalize concentrations because of their hydrated size. **Figure 6.1-2** is a graphic illustrating a hydrated ion. Since the large hydrated ions do not migrate through the membrane, there is a net migration of water molecules through the membrane from the lower concentration solution to the side with higher concentration.
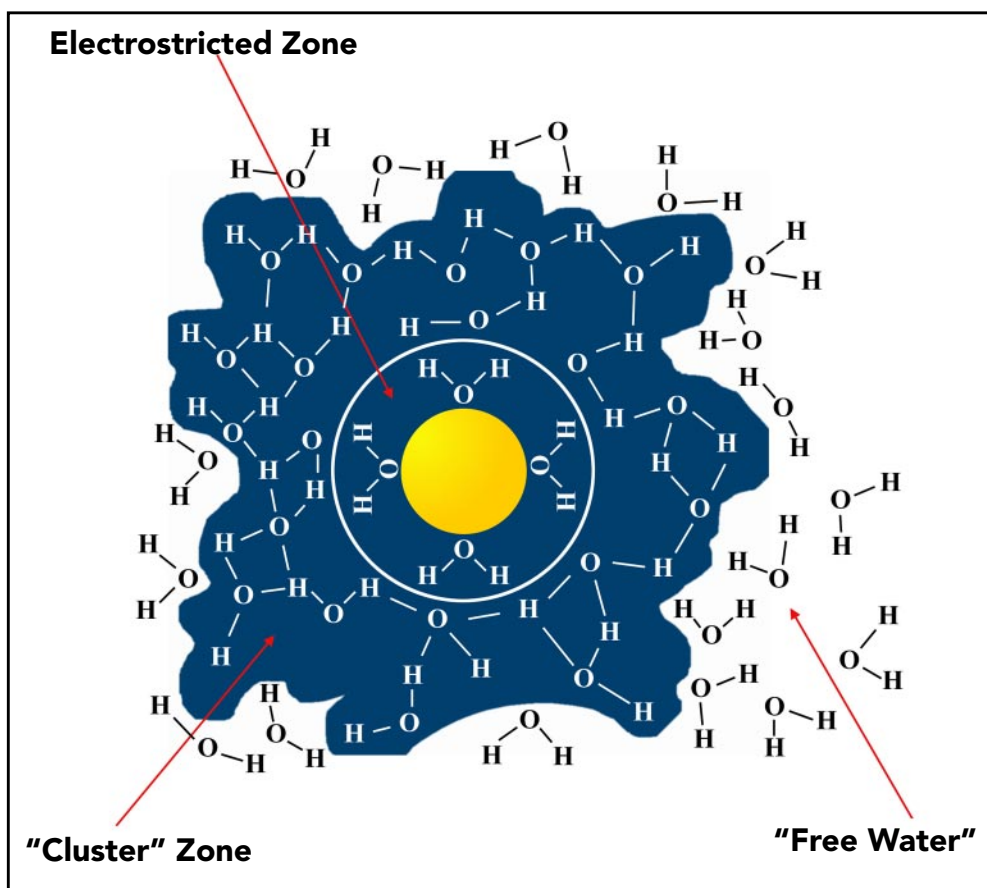
Figure 6.1-2: Hydrated Ion

The result of this migration is that the water level rises on the higher concentration side, and decreases on the lower concentration side.

This force driving molecules from one side of a membrane is called osmotic pressure. The direction of the osmotic pressure is always from the dilute solution to the concentrated solution. Osmotic pressure can be defined as the pressure and potential energy difference that exists between two solutions on either side of a semipermeable membrane.

A rule of thumb for osmosis is that 1 psi of osmotic pressure is caused by every 100 ppm (mg/l) difference in total dissolved solids concentration (TDS). **Figure 6.1-3** shows the osmotic pressures that exist between a 100 ppm TDS solution and a 1,000 ppm TDS solution separated by a semipermeable membrane. The net osmotic pressure for the apparatus in **Figure 6.1-3** is 9 psi towards side B (the concentrated side).
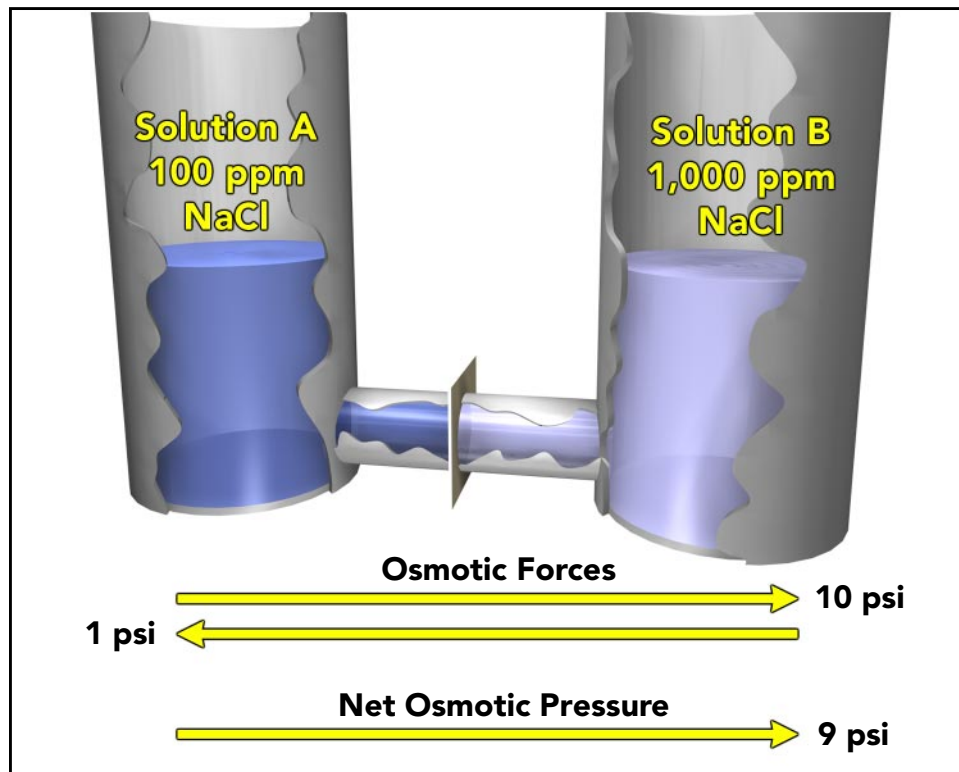
Figure 6.1-3: Osmotic Pressures

One can readily see that osmosis causes water to apparently defy gravity. In the apparatus shown in **Figure 6.1-4**, water rises against gravitational force due to osmotic pressure. If a 100 ppm solution is separated from a 1,000 ppm solution, as shown in **Figure 6.1-4**, to what extent does the level of side A decrease? Does it drain completely?
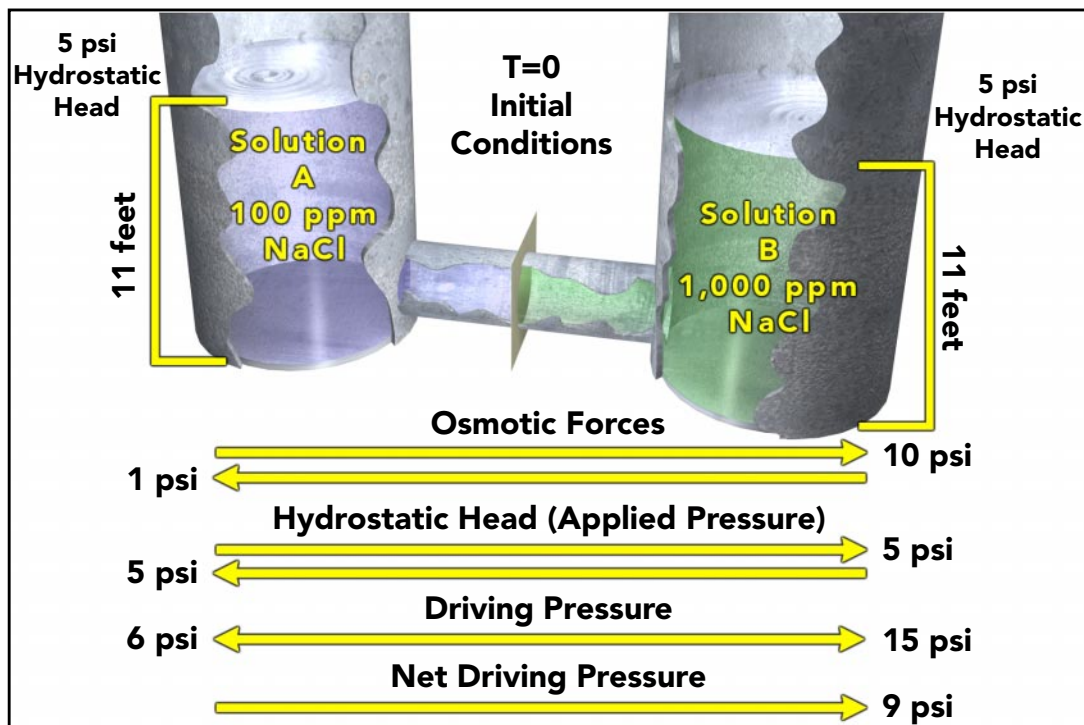
Figure 6.1-4: Starting (T=0) Osmotic and Applied Pressures for 100 ppm and 1,000 ppm Solutions Separated by a Semipermeable Membrane

A system with initial solution concentrations, as shown in **Figure 6.1-4**, reaches equilibrium before all water is transferred from Solution A to Solution B. As the solution level on side A decreases and the solution level on side B increases, a resistance to osmotic flow accumulates due to a difference in hydrostatic head (the pressure exerted by a height of liquid). This differential eventually becomes large enough to stop osmosis. Another contributing factor that causes the system to reach equilibrium is the dilution of the 1,000 ppm solution on the B side which, in turn, reduces the osmotic attraction of solution B.

Listed in **Figure 6.1**-**5** are the conditions under which the system shown in **Figure 6.1**-**4** reaches equilibrium and the forces involved in reaching that equilibrium. Note: the conversion factor used in this example to convert height of water to psi is a rough approximate. The number commonly used is 2.307 feet of water per psi.
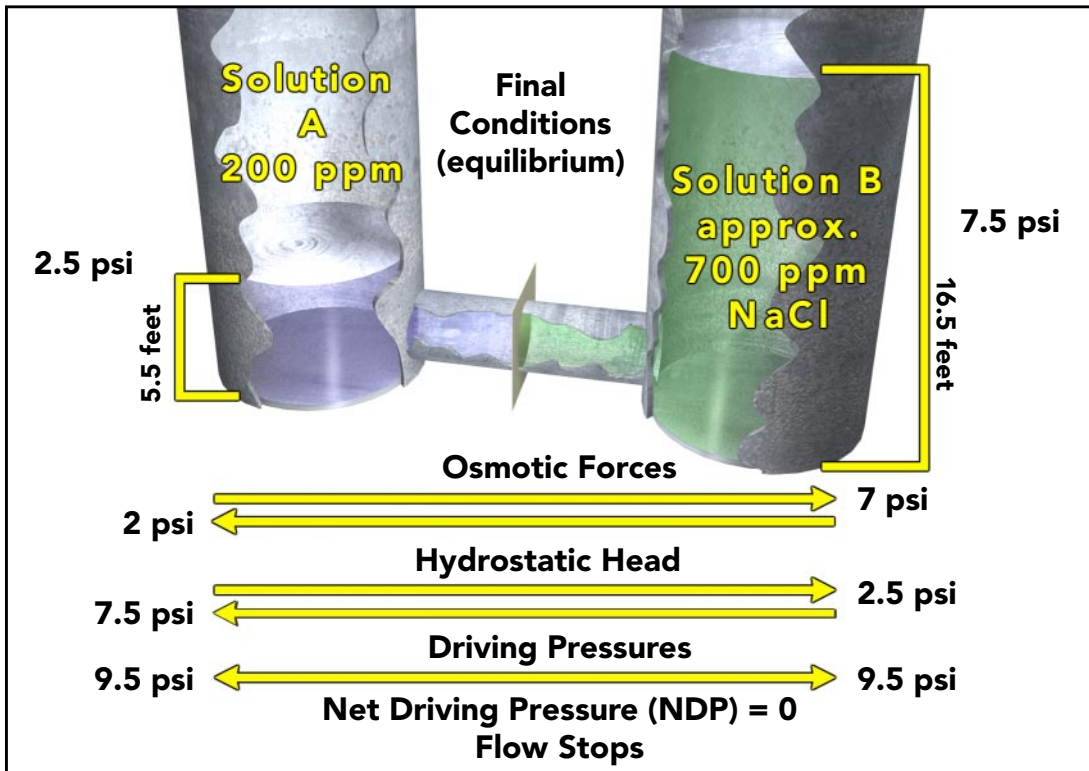
Figure 6.1-5: **Final Equilibrium Conditions.**
Equilibrium is Reached when the NDP goes to Zero

A difference in hydrostatic head due to changing water levels begins to oppose the flow of water driven by differences in osmotic pressure. Eventually water flow across the membrane ceases when the Net Driving Pressure (NDP) becomes zero. The NDP takes into account the net applied pressure of the feedwater and the net osmotic pressure.

6.1.3 Reverse Osmosis

If sufficient pressure is applied to the concentrated solution, we can actually reverse the direction of flow that would normally be caused by osmosis.

Consider the apparatus shown in **Figure 6.1-6**. The net driving pressure is 48 psi towards side B (higher concentration).
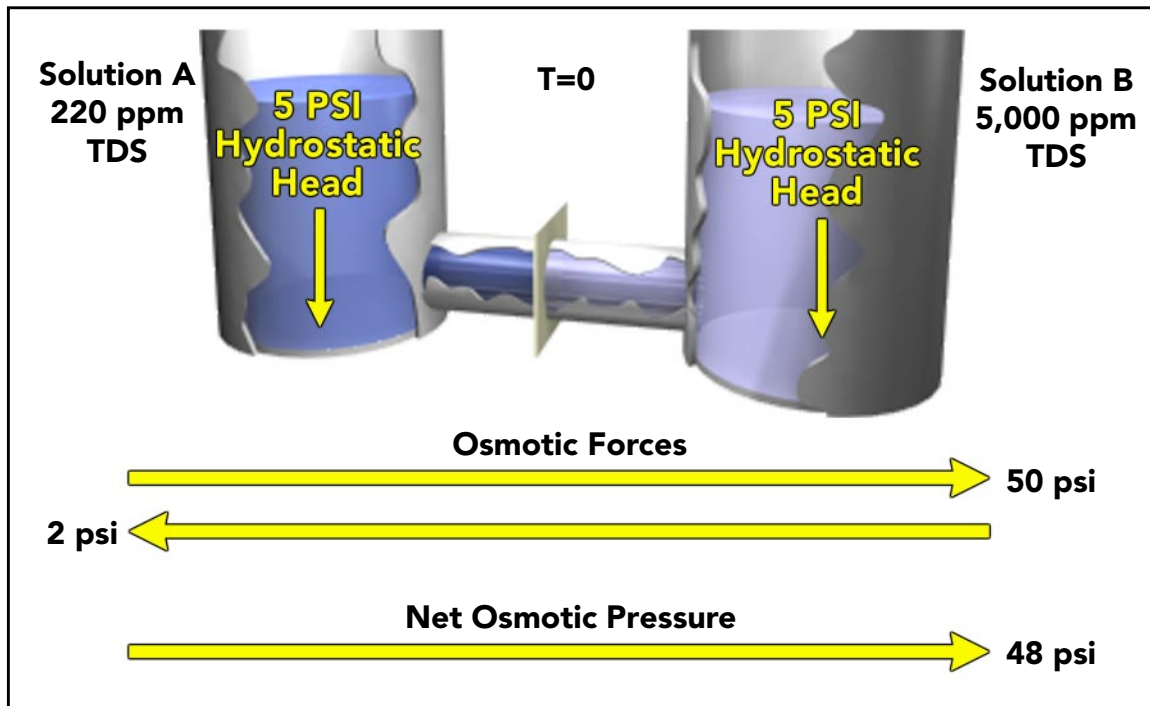
Figure 6.1-6: Initial Conditions for 200 and 5,000 ppm Solutions

If a piston is added to the system to increase the applied pressure on side B by 100 psi, as shown in **Figure 6.1**-7, the net driving pressure is 52 psi in the opposite direction (towards side A). The driving pressure, and therefore the flow of water across the membrane, has been reversed. The water begins flowing toward the solution with the lower concentration. This process is called Reverse Osmosis.
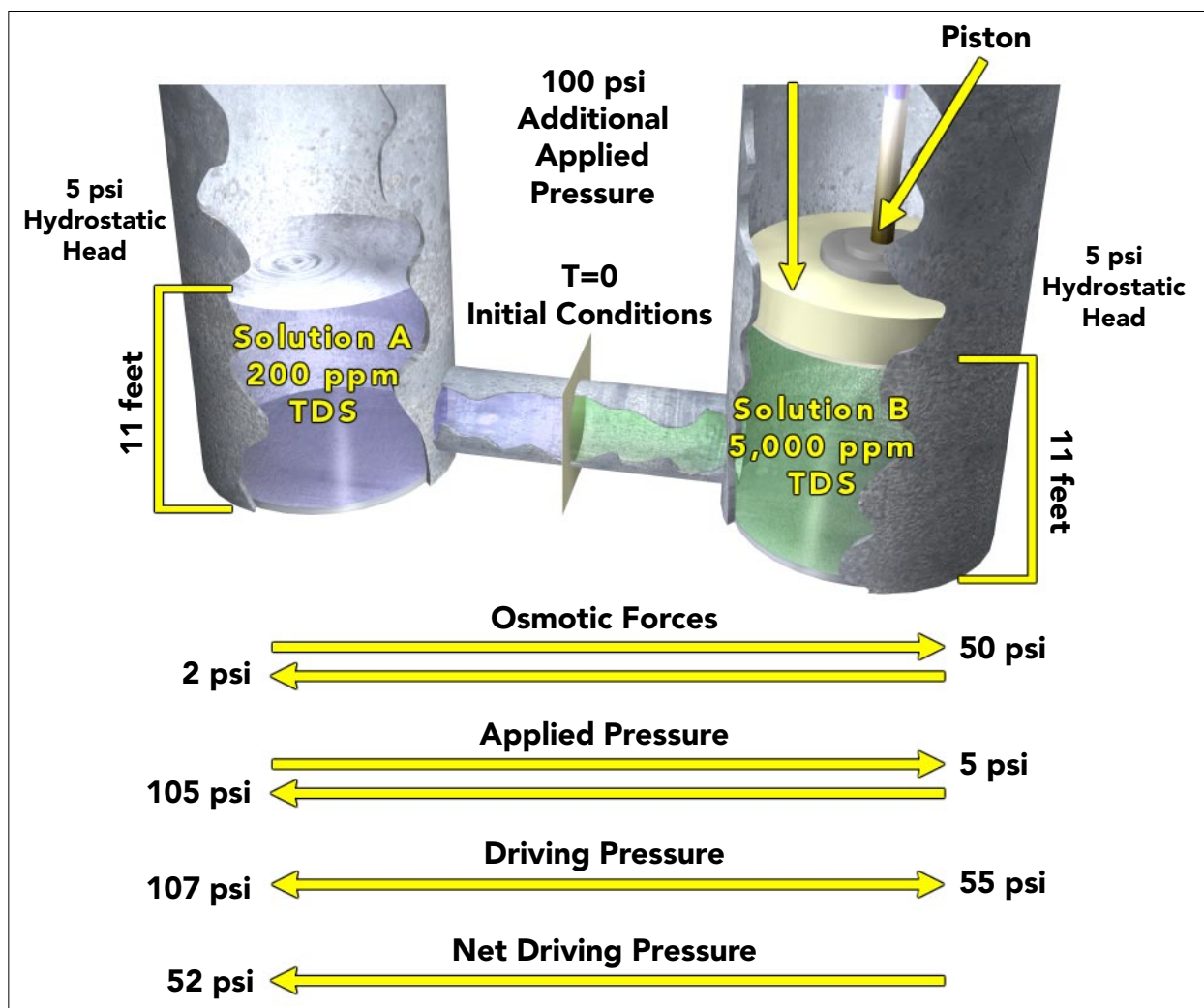
Figure 6.1-7: Reverse Osmosis Occurs When Enough Pressure is Applied to Cause a Positive Net Driving Pressure in the Direction Opposing Osmosis.

Reverse osmosis is a process that forces water molecules to flow against a net osmotic pressure. This is accomplished by applying enough pressure on the high concentration side of a semipermeable membrane to reverse the net migration of water molecules. Thus, with adequate pressure, reverse osmosis can remove purified water from a sample containing higher concentrations of dissolved solids.

At equilibrium, the highly increased concentration on side A eventually causes enough osmotic pressure to stop the net flow of water through the semipermeable membrane, even with 1,009 psi added to side B, as shown in **Figure 6.1-8**.
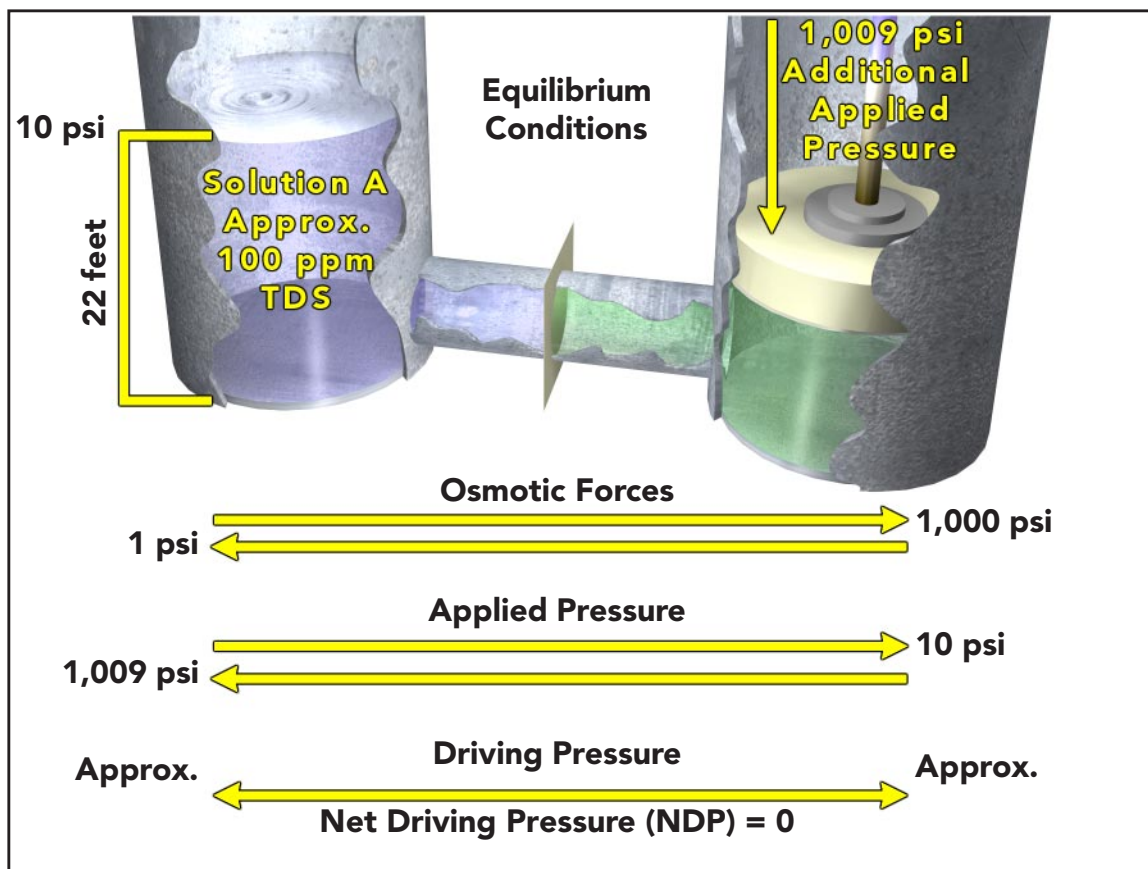
Figure 6.1-8: Equilibrium in a Reverse Osmosis Process

The situation described in **Figure 6.1-8** illustrates the need to remove the concentrated solution (i.e. have a reject flow). 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.

Another very serious challenge for RO operation is scaling due to the high concentrations of minerals that accumulate within RO elements. Concerns about scaling often far outweigh concerns over increased osmotic pressure.

Required flow rates for reverse osmosis system feedwater, reject water, and product water are discussed in subsequent sections. Numerous factors ranging from scaling to the required flow velocities on the feedwater side of an element influence what these flow rates should be for a given system.

6.1.4 Advantages and Disadvantages of Reverse Osmosis

The Reverse Osmosis process has both advantages and disadvantages. These must be weighed when deciding whether to use a Reverse Osmosis system.

Some of the advantages of using an RO system are:

1) RO outperforms any filter on the market (even ultrafiltration) with respect to the size of particles rejected. RO is actually a "molecular filter". Its ability to reject dissolved substances depends on the hydrated size of the molecules or ions in the solution. Non-ionized gases and small organic molecules, which are small as a result of not being hydrated with water molecules, have a poor rejection rate. **Figure 6.1-9** below outlines the different rejection capabilities of RO and other membrane separation methods such as ultrafiltration and conventional filtration.

2) RO removes up to 99.9% of the dissolved impurities in water without using regenerant chemicals.
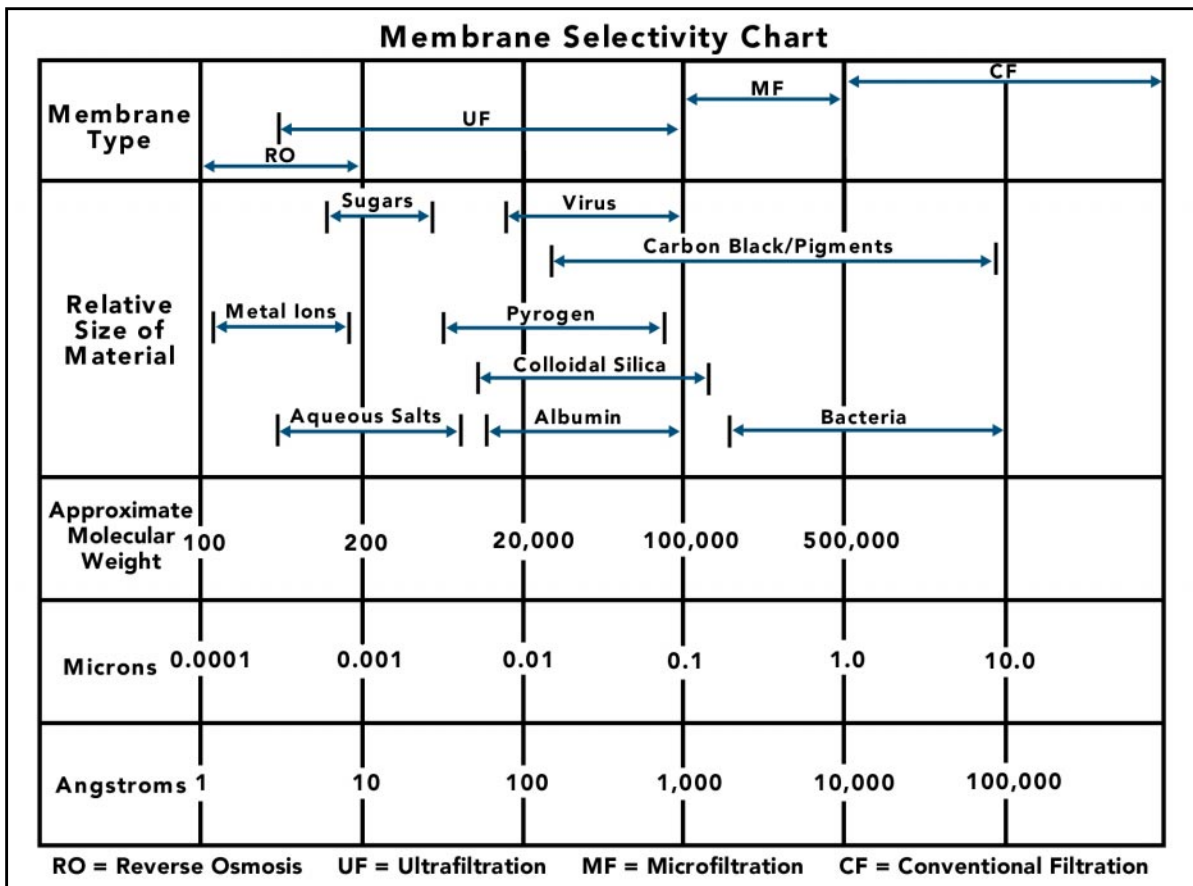
Figure 6.1-9: Filtration Capability Chart

Some of the disadvantages of using an RO system are:

1) The pump requires a significant amount of power to provide the driving pressure for the system.

2) Reverse Osmosis rejects a certain percentage of the feedwater as concentrated waste. Reject quantities typically vary from 15% to 40% of the water processed. This may be more waste water than an ion exchange system generates, depending on the system. In general, the higher the mineral content of the feedwater, the more advantageous RO is.

Figure 6.1-**10**, below, compares various separation processes based on particle or molecular size and the primary factor affecting the separation process.

Primary Factor Affecting Separation	
Size	MICROFILTERS, CLOTH AND FIBER FILTERS, ULTRAFILTRATION, SCREENS, ETC., GEL CHROMATOGRAPHY
Diffusivity	REVERSE OSMOSIS, DIALYSIS, ELECTRODIALYSIS
Ionic Charge	ION EXCHANGE
Vapor Temp Pressure	DISTILLATION/ FREEZE CONCENTRATION
Solubility	SOLVENT EXTRACTION
Surface Activity	FOAM AND BUBBLE FRACTIONATION
Density	ULTRACENTRIFUGES, CENTRIFUGES, LIQUID CYCLONES, GRAVITY SEDIMENTATION

Angstroms	1	10	10^2	10^3	10^4	10^5	10^6	10^7
Microns	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	10^2	10^3

Ionic Range	Macromolecular Range	Micron Particle Range	Fine Particle Range	Coarse Particle Range

Figure 6.1-10: Separation Processes

Osmosis

6.1.5 Membrane and Element Construction

The two primary membrane module configurations used for reverse osmosis applications are hollow fiber and spiral wound. Two other types of membrane configu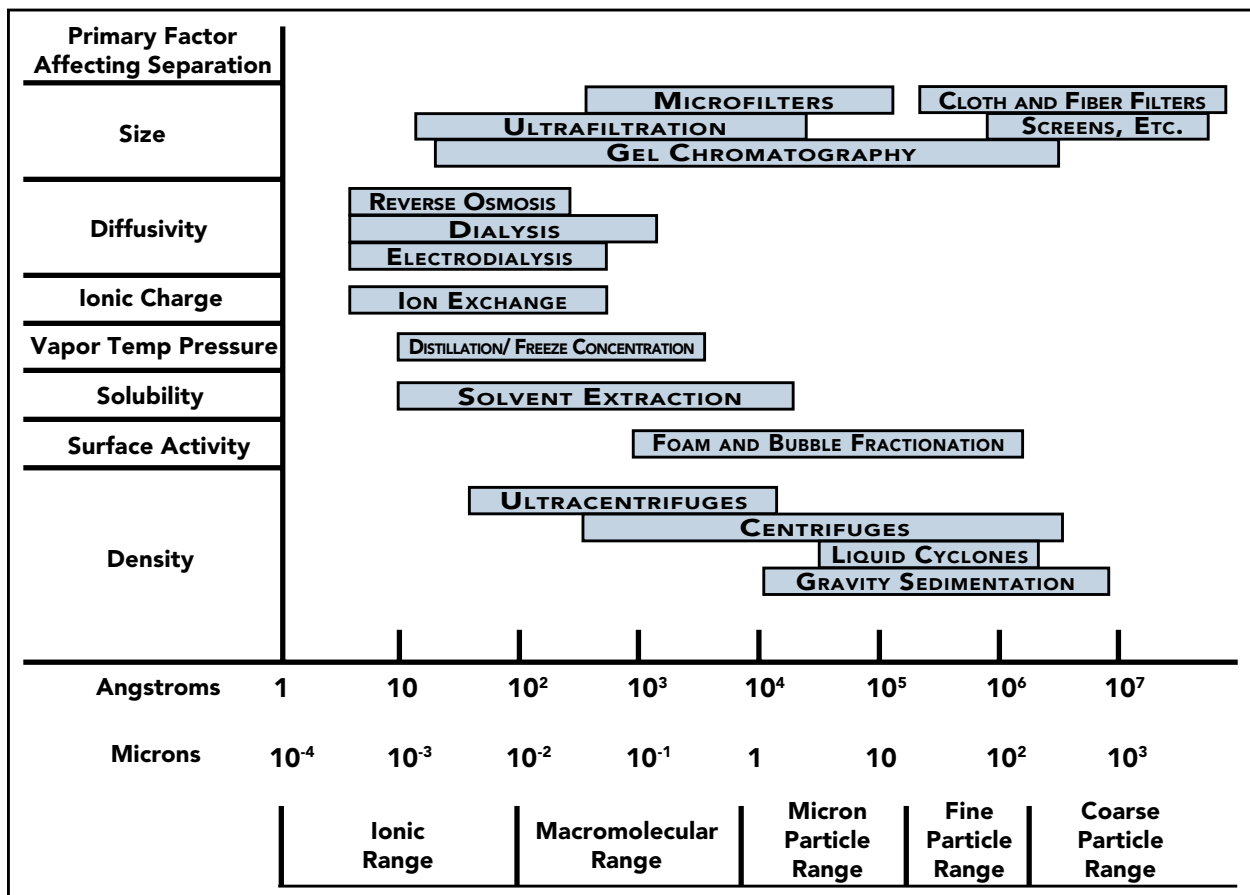rations are tubular and plate and frame. These two have found acceptance in the food and dairy industry and in other special applications, but modules of these configurations have been less frequently used in water treatment applications.

HOLLOW FINE FIBER (HFF) MEMBRANES

This configuration uses membrane in the form of hollow fibers that have been extruded from cellulosic or polymeric material. The fiber is asymmetrical in structure and is as fine as a human hair. It typically measures about 42 micron (0.0016 inch) ID (inner Diameter) and 85 micron (0.0033 inch) OD (Outer Diameter). 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 feedwater 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 that 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 that is approximately 137 cm (54 inches) long and 15 - 30 cm (6 - 12 inches) in diameter. The assembly is called a permeator. The pressurized feedwater 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 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.

Concentration polarization is the ratio of the salt concentration in the membrane boundary layer to the salt concentration in the bulk stream (See **Section 6.1.8-B** for a more thorough discussion). The most common and serious problem resulting from concentration polarization is the increasing tendency for precipitation of sparingly soluble salts and the deposition of particulate matter on the membrane surface. Concentration polarization is worse under conditions of laminar flow. Laminar flow occurs when the velocity is so low that there is no turbulence in the water - the flow moves in "layers" with little or no mixing between layers.

Turbulence helps to mix the concentrated fluid at the membrane surface with the (relatively) dilute fluid in the bulk of the solution. An absence of turbulence allows the concentrated fluid at the membrane surface to become even more concentrated with respect to the bulk stream, causing concentration polarization.

In a hollow fiber module, the permeate water flow per unit area of membrane is relatively low (because of the very high surface area of fibers) and may be laminar; therefore, concentration polarization is high at the membrane surface. Care must be taken to ensure that scaling and fouling of the membrane surface do not occur.

The hollow fiber unit allows a large membrane area per unit volume of permeator, which results in compact systems. Hollow fiber permeators are available for brackish and sea water applications. Brackish water contains dissolved solids below about 15,000 parts per million.

Hollow fine membranes are made of cellulose acetate blends and aramid (a proprietary polyamide type material in an anisotropic form). Hollow fiber membranes require feedwater with a lower concentration of suspended solids compared to the requirements of the spiral wound membranes. This is because of the very close packed fibers and tortuous feed flow inside the hollow fiber membranes. This is one of the reasons that hollow fiber modules are not as popular as spiral wound modules in the water treatment field.

SPIRAL WOUND MEMBRANES

In a spiral wound configuration, two flat sheets of membrane are separated with a permeate collector 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 20 cm (8 inches) in diameter. **Figure 6.1-11** is a graphic representing the design of a spiral wound element.
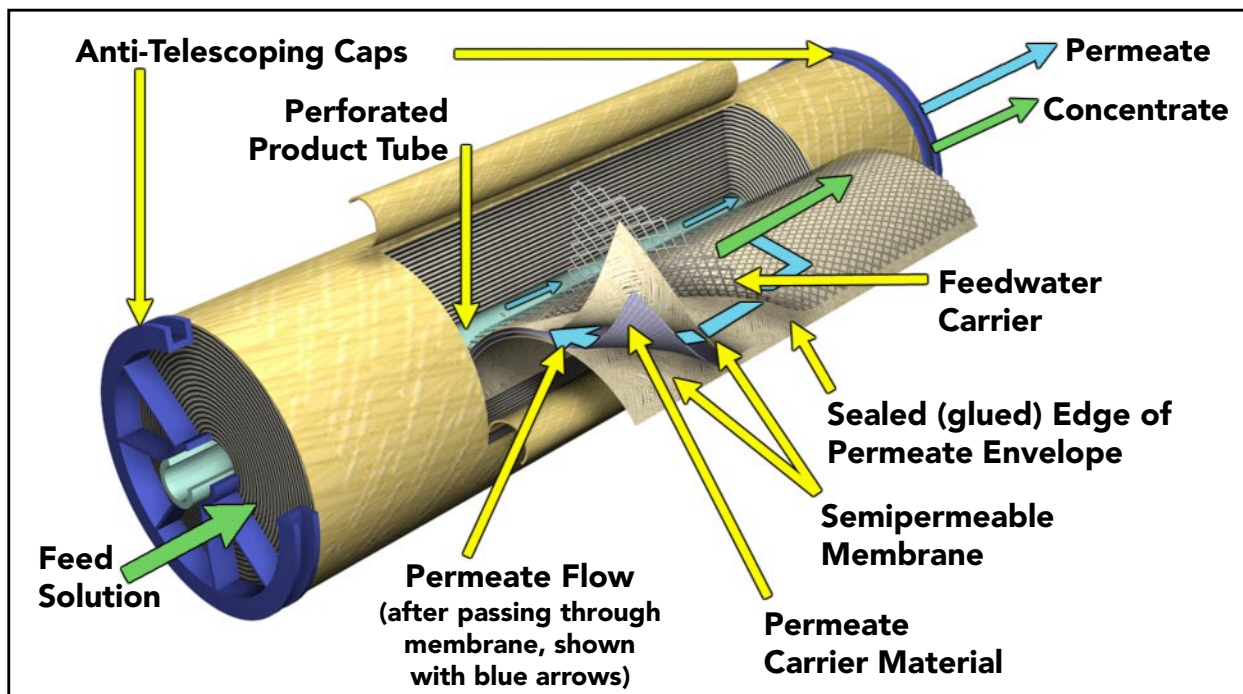
Figure 6.1-11: Spiral Wound Element Cutaway

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.

Recovery is a function of the feed-brine path length. In order to operate at acceptable recoveries, spiral systems are usually staged with three to seven membrane elements connected in series in a pressure tube (or housing).

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 or to feed another tube. Permeate from each element enters the permeate collector tube and exits the tube as a common permeate stream. A single pressure tube with six membrane elements connected in series can be operated at up to 50-percent recovery under normal design conditions.

Each membrane element has a brine (or chevron) seal around the outside of the element at the feed end. The shape of the brine seal is designed to expand when the feedwater pressure pushes against it. When installed correctly, the brine seal prevents the feed/brine stream from bypassing the element. **Figure 6.1-12** is an illustration of a common brine seal.
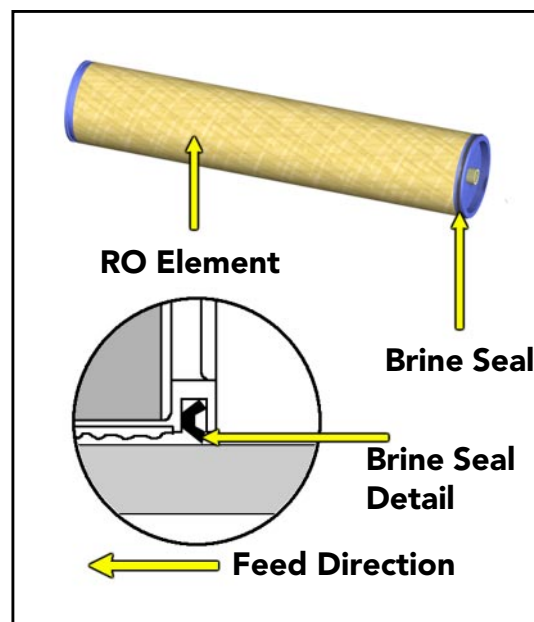
Figure 6.1-12: View of a Brine Seal

Figure 6.1-13 is a simplified representation of a cut-out view of a spiral wound membrane. Shown are the membrane, feedwater carrier, and permeate carrier before they are wrapped around the central permeate or product tube.

Feedwater flows into each element between membrane envelopes, along the feedwater carrier. The feedwater carrier has two main purposes:

1. To separate membrane envelope layers for adequate flow rates.

2. To provide a tortuous path for flow which, in turn, causes turbulence for cleaning along the membrane surface.

Figure 6.1-13: Spiral Wound Multi-Leaf Configuration

6.1.6   Cellulose Acetate vs. Thin Film

The semipermeable membrane used for reverse osmosis systems consists of a thin film of polymeric material cast on a fabric support. The membrane must have high water permeability and a high degree of semipermeability. The rate of water transport must be much higher 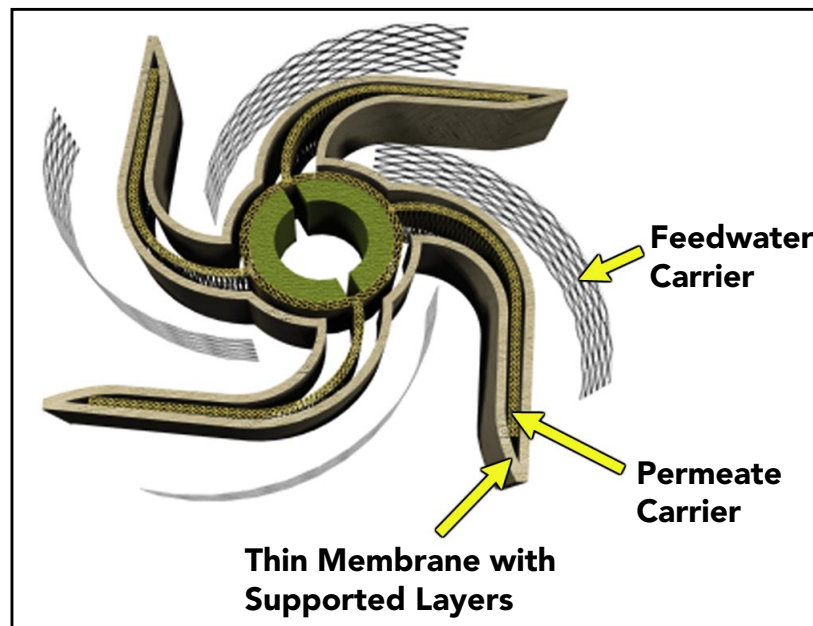than the rate of transport of dissolved ions. The membrane must be stable over a wide range of pH and temperature and have good mechanical integrity. There are two major groups of polymeric materials that can be used to produce satisfactory reverse osmosis membranes: cellulose acetate (CA) and polyamide (PA). 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 1950s by Loeb and Sourirajan, was made from cellulose diacetate. Current CA membrane is usually made from a blend of cellulose diacetate and triacetate. The membrane is formed by casting a thin film of an acetone-based solution of cellulose acetate polymer with swelling additives onto a non-woven polyester fabric.

During casting, the solvent is partially removed by evaporation. After the casting step, the membrane is immersed in 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 the temperature and duration of the annealing step. Water flux is defined as U.S. gallons of permeate produced per square foot of active membrane area per day (GFD). Using the metric system, this definition would be liters of permeate produced per square meter of active area per hour (LMH).

Figure 6.1-14 shows a cellulose acetate (CA) membrane and **Figure 6.1-15** shows a thin film composite membrane.
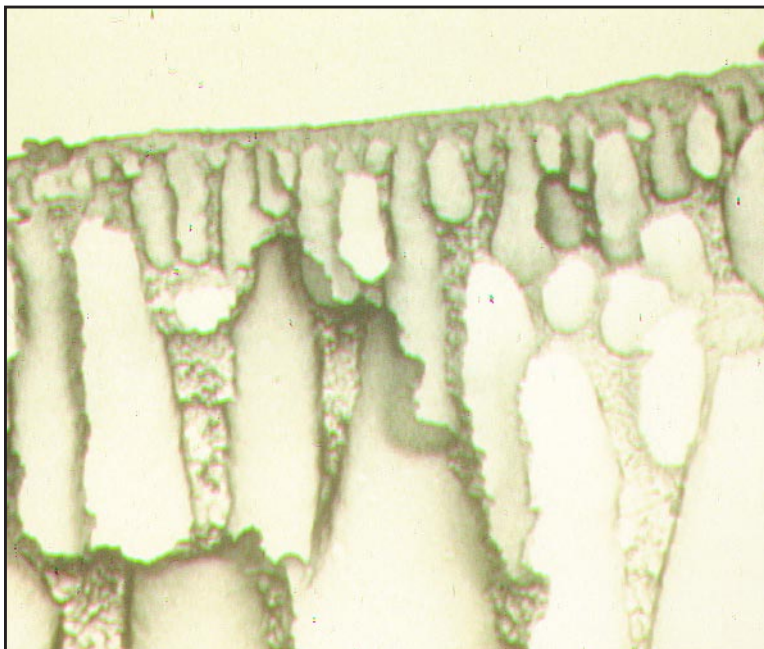
Figure 6.1-14: Cellulose Acetate (CA) Membrane
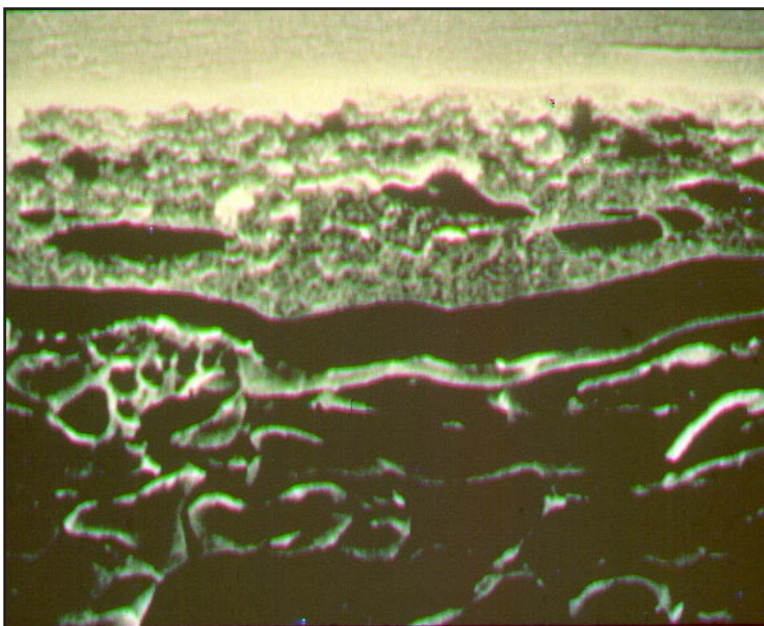
Figure 6.1-15: Thin Film Composite Membrane

Reverse
Osmosis

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; 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 a higher specific water flux (more water per psi of pressure) and lower salt passage (purer permeate water) than that of a cellulose acetate membrane. Polyamide composite membranes are stable over a wider pH range than cellulose acetate membranes. Polyamide membranes, however, 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 usually have a more stable performance (do not foul as quickly) than polyamide membranes in applications where the feedwater has a high fouling potential, such as with municipal effluent and surface water supplies.

6.1.7 Pressure Tube Construction

Spiral wound elements are placed in a structure called a pressure tube. Systems that use 8"x 40" elements typically have 6 elements per pressure tube. The pressure tubes are designed with two connections at each end. One of the connections is located at the center of the end cap and the other is to the side of this center connection. The middle, or center, connection is always the product outlet for vessels containing spiral wound elements. The offset connection on the end cap serves as a feedwater inlet on one side and a concentrate outlet on the other side of the vessel.
Figure 6.1-**16** shows a cutaway of a pressure tube with component pieces identified.

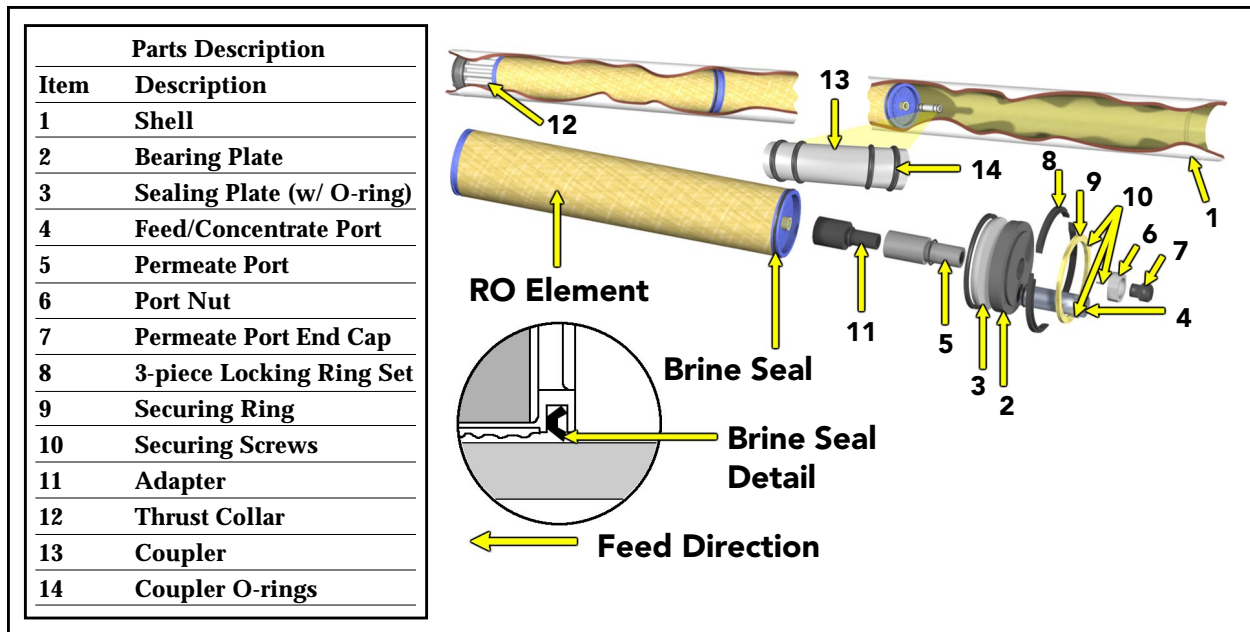| Parts Description	
Item	**Description**
1	Shell
2	Bearing Plate
3	Sealing Plate (w/ O-ring)
4	Feed/Concentrate Port
5	Permeate Port
6	Port Nut
7	Permeate Port End Cap
8	3-piece Locking Ring Set
9	Securing Ring
10	Securing Screws
11	Adapter
12	Thrust Collar
13	Coupler
14	Coupler O-rings

Figure 6.1-16: Pressure Tube Cutaway With Components Identified

6.1.8   Terms and Calculations

A.   Terminology

Specific terms are used to identify certain aspects of the process of reverse osmosis.

As water passes through the RO element, it separates into two flow paths.

1) One flow path contains water that has passed through the semipermeable membrane, removing 90 to 99.9% of the dissolved solids, and virtually all suspended solids. This water is called permeate (water that has permeated the membrane) or product water (water produced by the system). Either term can be used to refer to water that has passed through the membrane.

2) The second flow path is made up of feedwater that remains on the feedwater, or concentrate, side of the membrane. This concentration of the feedwater increases along the flow path, as water molecules pass through the membrane, leaving dissolved and suspended material behind. Water that takes this flow path is called concentrate (feedwater that has become concentrated) or reject (water that is being rejected).

Figure 6.1-17 shows the abbreviated representation of an RO process with the flows labeled.

Reverse Osmosis Terms
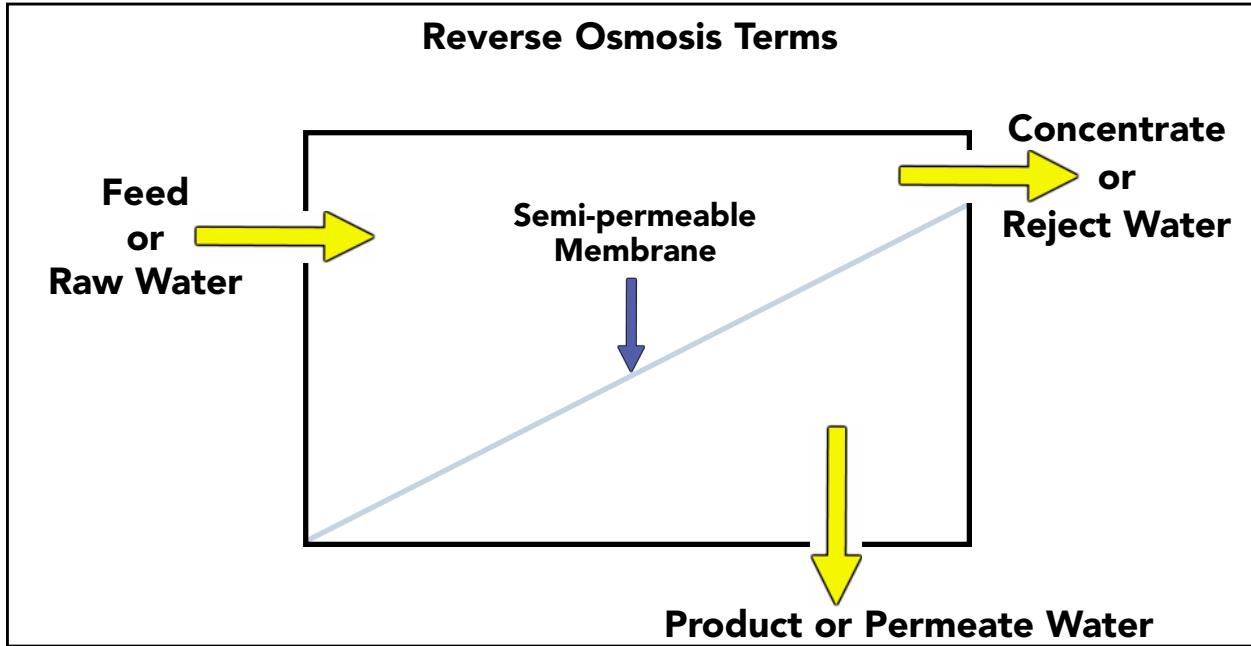
Figure 6.1-17: RO Flow Paths

Figure 6.1-18 below is a more detailed drawing of a pressure tube with six elements. These elements are 40 inches long, by eight inches in diameter. Respective flows are labeled.

Permeate is produced as feedwater passes through each membrane element. As feedwater travels through the pressure vessel, its concentration increases as its volume decreases.
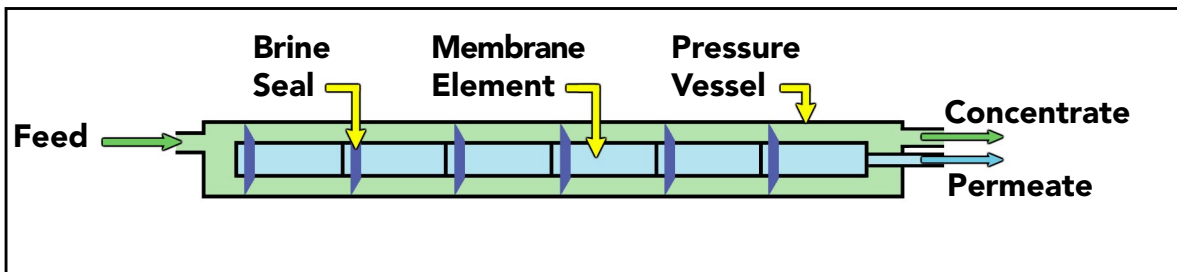

Figure 6.1-18: RO Pressure Vessel With Flow Paths Identified

B. Calculations

There are several terms used in the design of reverse osmosis systems that involve calculations. These calculations are normally performed by the RO membrane manufacturers' design software. The respective terms and equations are described in the following paragraphs.

The osmotic pressure, P_{osm}, of a solution can be determined experimentally by measuring the concentration of dissolved salts in solution, as defined in Equation 1.

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

P_{osm} = osmotic pressure (in psi), T is the temperature (in °C), and $sum(m_i)$ is the sum of the molal concentrations of all constituents in the solution. Molal concentration is the number of moles of a substance per kilogram of water. This should not be confused with molar concentration, which is the number of moles of a substance in a liter of solution. For dilute solutions these are approximately equal. An approximation for P_{osm} can be made by assuming that 100 ppm of Total Dissolved Solids (TDS) has about 1 psi 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 of the membrane reaction suggests that the chemical nature of the membrane is such that it absorbs and passes 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 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.

Qw = (DP - DP$_{osm}$) * Kw * S/d   **(Equation 2)**

Qw is the rate of water flow through the membrane, DP is the hydraulic pressure differential across the membrane, DP$_{osm}$ is the osmotic pressure differential across the membrane, Kw is the membrane permeability coefficient for water, S is the membrane area, and d is the membrane thickness. This equation is often simplified to:

Qw = A * (NDP)   **(Equation 3)**

"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.

FLUX

Flux is a term that describes the amount of water produced per area of membrane per day. Flux is commonly measured as U.S. gallons of water produced per square foot of active membrane area per day (GFD). There is a relationship between the water flux and the rate of fouling on an RO unit. A high flux rate causes the membrane to foul faster. To achieve stable operation, the flux must be below some reasonable cutoff point. Different types of waters have different cutoff points. Typical flux for the main types of water are shown in **Table 6.1**-**1**.

Type of Water	System Operating Water Flux (GFD)
Municipal Wastewater (Sewage)	8-12
Treated River or Canal Waters	8-14
Surface Waters (Lakes/Reservoirs)	8-14
Deep Wells (Low Turbidity)	14-18
RO Permeate Water	20-30
Surface Seawater	7-10
Beach Well Seawater	7-10

Table 6.1-1: General Water Flux Classifications

Once the flux rate is decided and the element area is known, the required number of elements can be calculated using Equation 4.

Number of = **Permeate Flow (US gpm) x 1440 min/day**   **(Equation 4)**
Elements   **Flux (GFD) x Active Membrane Area (Ft²)**

SALT TRANSPORT

The rate of salt flow through the membrane is defined by Equation 5:

Qs = DC * Ks * S/d   **(Equation 5)**

Where Qs is the flow rate of salt through the membrane, Ks is the membrane permeability coefficient for salt, DC 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:

 Qs = B*(DC)   **(Equation 6)**

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

Equations 4 and 5 show that, for a given membrane, the following are true:

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

• The rate of salt flow is proportional to the concentration differential across the membrane and is independent of applied pressure.

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

Cp = Qs/Qw   **(Equation 7)**

 Since water and salt have different mass transfer rates through a given membrane, this creates the phenomena of salt rejection. No membrane is ideal in the sense that it absolutely rejects salts, although the different transport rates create an apparent rejection. Equations 2, 4 and 5 explain important design considerations in RO systems. For example, an increase in operating pressure increases water flow without changing salt flow, 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. It is expressed by Equation 8:

SP = 100% * (Cp/Cfm)   **(Equation 8)**

SP is the salt passage (in %), Cp is the salt concentration in the permeate, and Cfm 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; salt passage increases as applied pressure decreases. This is because a reduction in pressure causes a decrease in permeate flow rate, and 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 the following equation.

SR = 100% - SP   **(Equation 9)**

SR is the salt rejection (in %), and SP is the salt passage as defined in Equation 8. Water and salt have different mass transfer rates through a given membrane, creating 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.

PERMEATE RECOVERY RATE (CONVERSION)

Permeate recovery is another important parameter in the design and operation of RO systems. The recovery, or conversion, rate of feedwater to product (permeate) is defined by Equation 10.

R = 100% * (Qp/Qf)   **(Equation 10)**

Where R is the recovery rate (%), Qp is the product water flow rate, and Qf is the feedwater 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, causing an increase in salt flow rate across the membrane, as indicated by Equation 5.

The increased salt concentration in the feed-brine solution also 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 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. Concentration polarization reduces the actual product water flow rate and salt rejection below theoretical estimates. The effects of concentration polarization are summarized below.

- DP_{osm}, and reduced net driving pressure differential across the membrane $(DP - DP_{osm})$.

- Reduced water flow across membrane (Qw).

- Increased salt flow across membrane (Qs).

- Increased probability of exceeding solubility of sparingly soluble salts at the membrane surface, and the distinct possibility of scaling due to precipitation.

The Concentration Polarization Factor (CPF), or Beta factor, can be defined as the ratio of salt concentration at the membrane surface (Cs) to bulk concentration of salt (Cb).

CPF = Cs/Cb   **(Equation 11)**

An increase in permeate flux increases the delivery rate of ions to the membrane surface and increases Cs. An increase of feed flow rate increases turbulence and reduces the thickness of the high concentration layer near the membrane surface. Therefore, the CPF is directly proportional to permeate flow (Qp), and inversely proportional to average feed flow (Qfavg). This relationship is defined in Equation 12.

CPF = Kp * exp(Qp/Qfavg)   **(Equation 12)**

Kp is a proportionality constant value of which is defined by the geometry of the system.

Using the arithmetic average of feed rate and concentrate flow rate as average feed flow, the CPF can be expressed as a function of the permeate recovery rate of a membrane element (Ri). (Equation 13)

CPF = Kp * exp(2Ri/(2-Ri))   **(Equation 13)**

A Concentration Polarization Factor of 1.2 is the recommended maximum for Hydranautics membrane products, and corresponds to 18% permeate recovery for a 40-inch long membrane element.

6.1.9   Impurities In Water

The nature of a particular impurity dictates how it behaves in a reverse osmosis unit. Impurities in water can be broken into two main categories:

- Dissolved Impurities
- Suspended Colloids and Settleable Impurities

Dissolved Impurities

The dissolved impurities can be further broken into two categories:

- Dissolved Solids or Liquids
- Dissolved Gases

(1)   Dissolved Solids or Liquids

Substances dissolve in water because of the attraction that exists between the dipole moment of water molecules and the charge present on molecules of the substance. When a substance or liquid dissolves, each of its molecules is surrounded by water molecules, or hydrated. Dissolved substances may or may not form charged species in water, but they always have water molecules closely associated with them due to charges and/or polar bonds. **Module 1** provides an explanation of this phenomenon.

Dissolved solids are rejected by reverse osmosis membranes depending on the charge and solvated size of the particular dissolved species.

(2)   Dissolved Gases

Gases that dissolve in water exist as discrete gas molecules or as gas/water reaction products.

Non Water-Reactive Dissolved Gases

Gases that dissolve in water but do not form reaction products are weakly held by water molecules. Their dissolved concentration is dependent upon the partial pressure exerted by the same gas species above the gas/liquid interface. If the partial pressure above the liquid decreases, some of the dissolved gas molecules come out of solution to form small gas pockets (gas bubbles) within the liquid (or they diffuse out of the liquid). **Section 2.8** provides a more detailed discussion of gas solubility.

Dissolved Water-Reactive Gases

Some gases, when dissolved, react with water to form ions.

A water-reactive gas dissolves until the solution becomes saturated with ions formed by the reaction. Once this occurs, the solution can reach saturation with respect to non-reactive gas molecules. If non-reactive gas molecules are removed by degasification, reaction products (ions) recombine to form gas molecules. Carbon dioxide is a water-reactive gas; it reacts with water to form hydrogen and bicarbonate ions. The ions exist in equilibrium with CO_2 molecules in solution. If CO_2 molecules are removed from the solution, more are formed through the recombination of bicarbonate and hydrogen ions. Likewise, if bicarbonate and hydrogen ions are removed from the solution, more will be formed from the reaction of CO_2 and water, to maintain the equilibrium.

During reverse osmosis, carbon dioxide gas passes freely through the membrane, while bicarbonate ions are rejected. This selective permeability changes the ratio of the two species in the feedwater and results in a new equilibrium at a lower pH. The pH drop depends on the rejection of the bicarbonate. A higher rejection of bicarbonate produces a lower pH.

Suspended Colloids and Settleable Impurities

Settleable impurities are generally larger than 10 microns in size, and settle out of water over a period of time. Before the discovery of colloids it was widely believed that suspended solids could be filtered, and dissolved substances could not be. The distinction between dissolved and suspended solids has become difficult to distinguish due to an increased knowledge of colloids.

Almost all particles in water carry a static charge on their surfaces. In most cases this charge is negative. **Suspended colloids** are particles (groups of molecules) so small that they do not settle out of water. Their inability to settle stems from the surface charge just mentioned. Water molecules are attracted to these weak surface charges, which allows the particles to stay suspended indefinitely in solution. Suspended colloids range in size from .001 to 0.1 microns.

The removal of colloidal particles usually requires coagulation to form larger particles which may then be removed by sedimentation and/or filtration.

6.1.10 Fouling and Scaling

Over time, membrane systems can become fouled with a wide range of materials such as colloids, organic matter and biological organisms. Fouling occurs because material in the feedwater that cannot pass through the membrane is forced onto the membrane surface by the flow of the water going through the membrane. If the "cross"flow (water that does not pass through the membrane) is not sufficient (is not turbulent), or if it is prevented from reaching the membrane (by deposits or a mesh spacer), the material from the feedwater is deposited on the membrane surface. Fouling increases with increasing flux rate (the flow of water through the membrane) and with decreasing feed flow (velocity). 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 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. Fouling tends to occur in membranes at the feed end of the system, where the flux rate is highest.

Biological fouling can also occur due to the growth of algae or other biological contaminants in the membrane element. Although this type of fouling is caused by contamination rather than flow problems,the resulting blockage of the membrane is the same.

6.1.11 Scaling

Scaling of the membrane surface occurs due to the precipitation of sparingly soluble salts. As water passes through the membrane, dissolved minerals from the feedwater become concentrated in the reject stream. If the concentrations of minerals in the reject stream exceed their solubility products, crystals will precipitate onto the membrane.

Scaling occurs first in the last elements of an RO system because the feedwater is more concentrated near the end of the process.

The following is a list of some of the types of scale that may occur on the RO system membranes:

- Calcium and Magnesium Carbonates
- Calcium and Magnesium Sulfates
- Metal Oxides
- Silica
- Strontium and Barium Sulfates

6.1.12 Overview of Feedwater Pretreatment

The objective of the feedwater pretreatment process is to improve the quality of the feedwater to the level at which the RO membranes can be reliably operated. Proper pretreatment is critical to the stable operation of an RO system.

Feedwater quality is defined in terms of the concentration of suspended particles and the saturation levels of the sparingly soluble salts. Turbidity and the Silt Density Index (SDI) are common measures of the concentration of suspended solids. Small particles that remain suspended in water are called turbidity. Turbidity is measured by the effect (in terms of scattering and absorption) of the suspended particles on a beam of light passing through the water. Silt Density Index (SDI) measures the ability of a feedwater to foul a membrane filter. Continuous operation of an RO system in which the feedwater has turbidity or SDI values above the design limits may result in significant membrane fouling.

The Langelier Saturation Index (LSI) and the saturation ratio measure the saturation levels of sparingly soluble salts in the concentrate stream.

The LSI provides an indication of 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 to measure the concentration of calcium carbonate in low-salinity potable water.

A saturation ratio is the ratio of the product of the actual concentrations of the ions in the concentrate stream to the theoretical solubility of the salts, at a given temperature and ionic strength. These ratios are applicable mainly to silica and to sparingly soluble sulfates of calcium, barium and strontium. Other potentially scale-forming salts, such as calcium fluoride or calcium phosphate, seldom represent a problem at concentrations found in natural waters.

Depending upon the raw water quality, reverse osmosis pretreatment processes contain some of the following treatment steps:

- Removal of large particles using a coarse strainer
- Chlorine disinfection
- Clarification with or without flocculation
- Clarification and hardness reduction using lime softening
- Removal of suspended particles using media filtration
- Hardness reduction using softeners or weak acid cation exchangers
- pH adjustment
- Addition of scale inhibitor
- Reduction of free chlorine using sodium bisulfite or activated carbon filters
- Sterilization using UV radiation
- Final removal of suspended particles using cartridge filters

When a system is designed, the water to be used as feedwater should be tested and analyzed to provide an adequate feedwater pretreatment for the design. This assures proper and longer operation of the RO system.

6.2 Single Pass RO System

Reverse Osmosis is a process that separates impurities from water by passing the water through a semipermeable membrane. The semipermeable membrane allows only very small atoms and groups of atoms, such as water molecules and non-ionized gases, to pass through. These membranes remove over 99% of all dissolved solids and, essentially perform the complete removal of all particulate matter.

Depending on the requirements for the specific RO System, ancillary equipment is typically required:

- Day tanks and chemical feed pumps to inject antiscalant, sodium bisulfite, acid or caustic
- Cartridge filters to protect the membranes from large particulate matter
- Pumps to pressurize the feed
- Atmospheric tanks for permeate storage
- A Clean-In-Place system (CIP)

6.2.1   Process and Operation Overview

Single pass reverse osmosis systems are designed specifically for a particular application. The number of pressure vessels required per skid varies depending on the quality of the feedwater to be used and the desired quantity and quality of product water.

The RO System is constructed on a rigid skid that accommodates the membrane housings, the high pressure pump (if mounted on the skid), and all required piping, valves, instrumentation, etc.

A reverse osmosis system is a relatively simple unit. Its major components are identified below in **Figure 6.2**-**1**. This example shows a submersible pump feeding a two-stage array with 16 housings in the first stage (the bottom four rows). The feedwater is fed to the first stage through the headers on the right side. The second stage consists of the 8 housings in the top two rows. The concentrate from the first stage is fed to the second stage through the larger header on the left side. The permeate from both stages is collected in the smaller header on the far left.
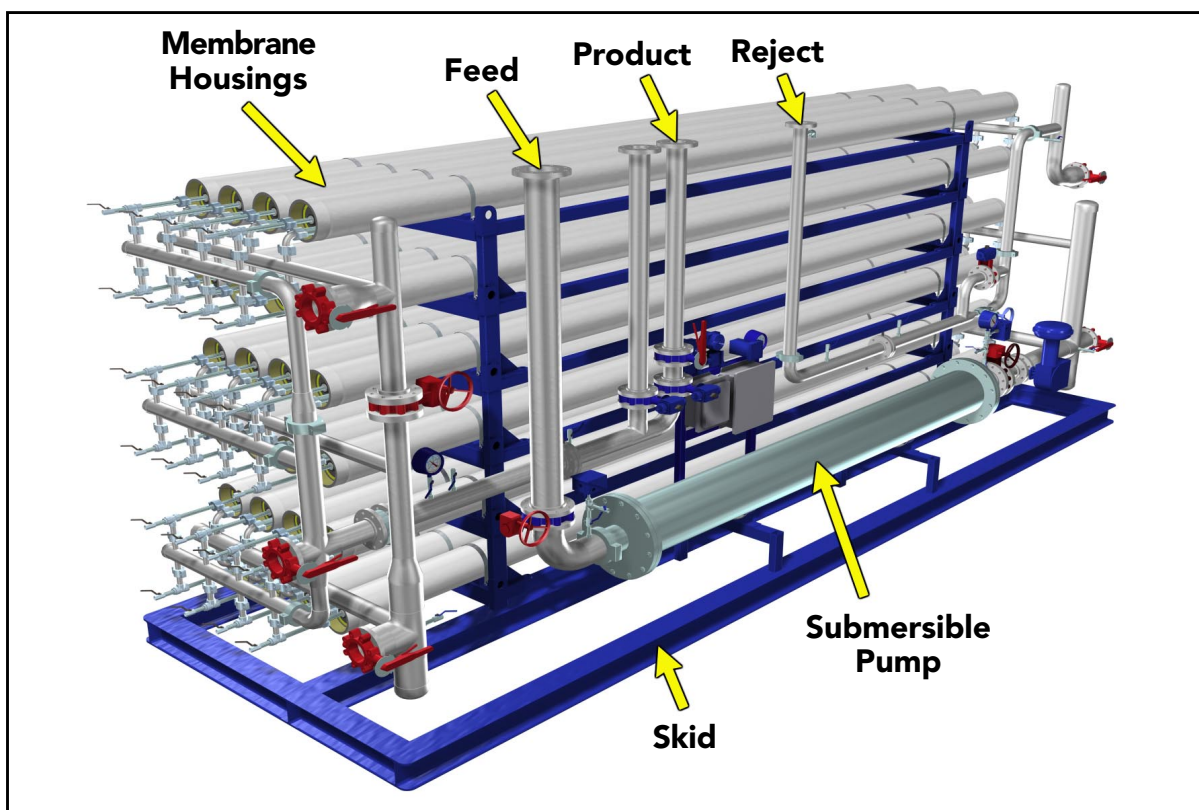

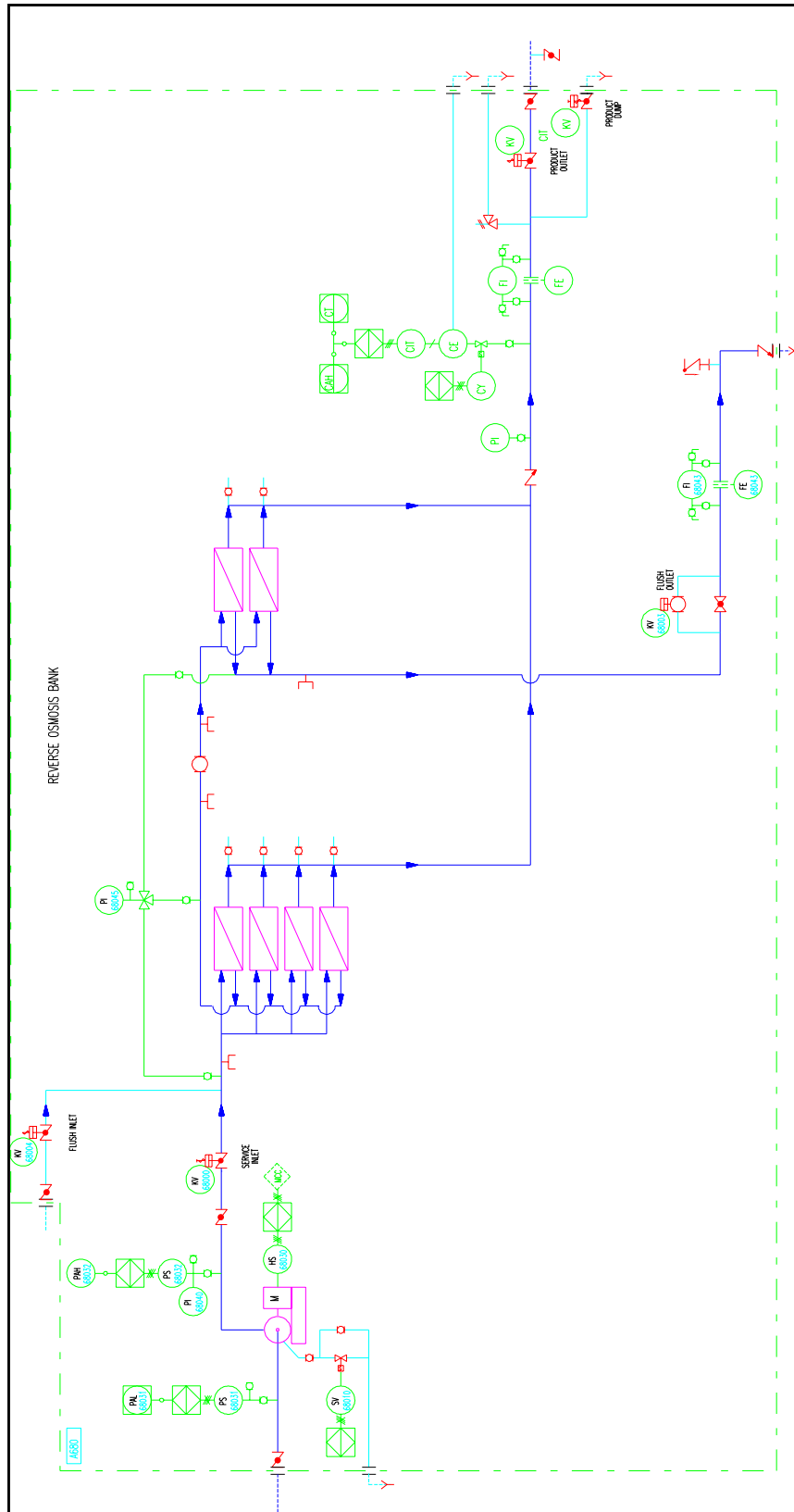**Figure 6.2-1: Typical Single Pass Reverse Osmosis System and Components**

Figure 6.2-2: Single Pass System P&ID

The operation of a Single pass reverse osmosis system is as follows:

1. Feedwater is fed to the reverse osmosis unit at line pressure (typically 20 to 100 psig).
2. The high pressure pump boosts the pressure, which is set to the required operating point by the service (or first stage) inlet valve (or a variable speed drive for the pump).
3. Permeate is sent to drain (if poor quality) or to the service outlet (if acceptable quality).
4. The unwanted feedwater, which is now the concentrate, is directed through a throttling valve that produces the necessary pressure drop in the concentrate stream.

When the system is turned on, the service inlet valve opens and feedwater flows under line pressure. All streams are directed to drain. This removes any air bubbles in the system that might cause water hammer when the pump starts.

When the system is shut down, a flush to waste is performed to flush out the remaining concentrate from the system. Feedwater (or, optionally, a separate clean feed source) is flushed through the elements at line pressure.

This prevents scaling on the membranes from the concentrate stream. After the system is flushed, it remains idle until it is placed in service again.

Figure 6.2-2 (opposite page) shows a P&ID of a typical single pass reverse osmosis system. A summary of the operating modes is shown below in **Table 6.2-1**:

Valves and Pumps	Mode				
	Idle	Preservice Flush	Service to Product	Service to Drain	Flush
Service (1st stage) Inlet	Closed	Open	Open	Open	Open (1)
Product Outlet	Closed	Closed	Open	Closed	Closed
Product Dump Outlet	Open	Open	Closed	Open	Open
*Flush Inlet	Closed	Closed	Closed	Closed	Open
Flush Outlet	Closed	Closed	Closed	Closed	Open
High Pressure Pump	Off	Off	On	On	Off
(*denotes optional valve) (1) Service valve is open unless a flush inlet valve is present.					

Table 6.2-1: Single Pass RO Operating Modes Summary

The RO cleaning operation is strictly manual and does not involve any of the automatic valves or the pump. See **Section 6.4** for a description of the cleaning process.

6.2.2 Equipment and Design

Most of the components on the RO system can be configured to meet specific requirements. The main features and options for common RO systems are discussed in the following subsections.

6.2.2.1 RO Array

The array structure is determined during the design process by the hydraulics of the system. The most common arrangement has six membranes in each pressure vessel. This arrangement recovers as permeate 50% of the water fed to it. For a 75% recovery, two stages are required. When using two stages, 50% of the feed is recovered in the first stage. The remaining 25% is recovered by the second stage, as it yields a 50% recovery on the concentrate from the first stage. The largest number of stages normally used is a three-stage unit. If pressure vessels with fewer than six elements are used the recovery per stage is decreased.

6.2.2.2 RO Housings

The RO housings are the vessels that hold the spiral wound elements. The design selections available for RO housings are:

1. The number of membrane elements per housing. This is normally six elements but can range from three to seven. Smaller housings are used when space constraints preclude the longer housings. A seventh element housing is useful if it is necessary to increase the system recovery marginally.

2. The pressure rating, which depends on the pump deadhead pressure.

3. ASME Code stamp (available if required)

4. Feed Connection types and sizes available are:

    - 1.5" victaulic, end port
    - 1.5" victaulic, side port
    - 2" victaulic, side port
    - 2.5" victaulic, side port

The side port options provide a simpler feed and concentrate header arrangement. Side ports also allow easier element removal from the housing. Larger port sizes may be used to avoid feed and reject headers completely for some applications.

5. Housing color: Colors available for the housings are White or Blue. **Figure 6.2-3** below is a graphic of a typical RO housing.

courtesy of Spaulding Composites

Figure 6.2-3: Typical RO Housing

6.2.2.3 RO Elements

RO Elements contain the semipermeable membranes that remove impurities from the feedwater of an RO system. Two types of membranes available are Spiral Wound Thin Film Composite or Spiral Wound Cellulose Acetate.

The available sizes of elements are:

- 8" diameter X 40" long
- or 8" diameter X 60" long

The 60" elements are only available for certain membrane types. The selection of the membrane is a critical part of the design process. Each membrane has specific compatabilities, rejection characteristics, flow capabilities and pressure requirements. Knowledge of the vendor product line is required in order to make a reasonable choice.

Figure 6.2-4 is a view of a Thin Film Composite membrane and **Figure 6.2-5** is a view of a Cellulose Acetate membrane.
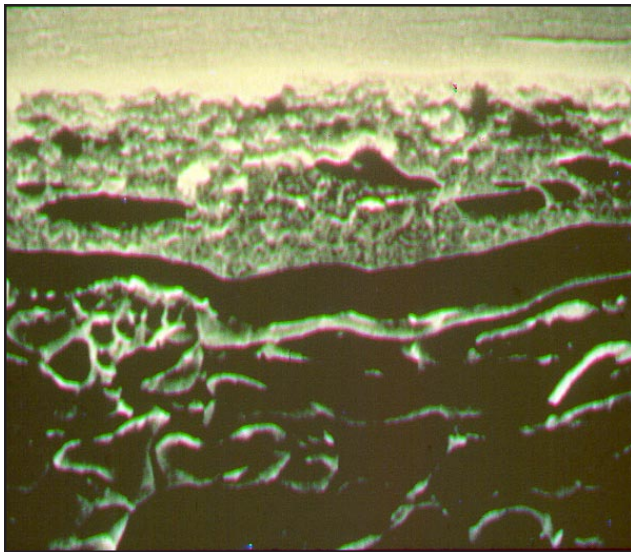

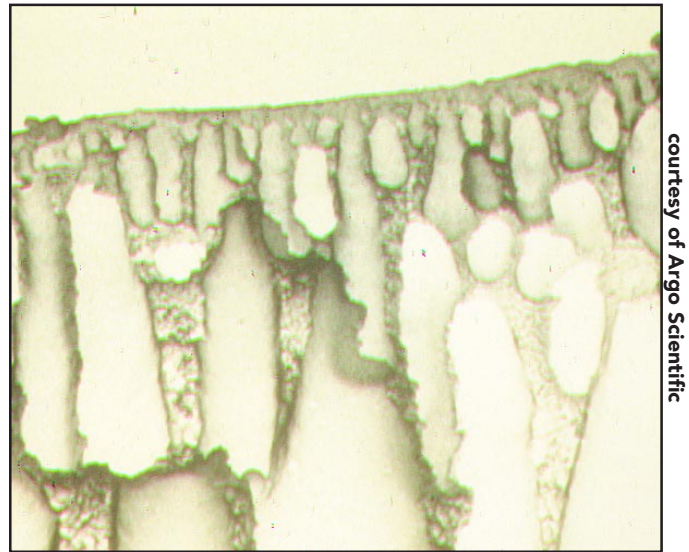**Figure 6.2-4: Thin Film Composite Membrane**

Figure 6.2-5: Cellulose Acetate Membrane

6.2.2.4 Pumps

The RO unit operates at relatively high pressures ranging from 100 to 600 psig (excluding desalination applications). The pressure required can come from pumps separate from the RO unit or from a pump that is part of the RO skid. For more details on pumps, see **Module 9.2** (Ancillary Equipment, Pumps). If a skid-mounted pump is selected, the following describes pump requirements when selecting a pump as part of the RO unit. Note that a skid-mounted pump requires enough pressure on the suction side to prevent cavitation. A separate set of pumps may be required to provide enough pressure to the skid-mounted pump.

Pump choices are:

- Centrifugal: Single-stage centrifugal pumps can be used for lower pressure applications

- Multi-stage centrifugal: for higher pressure requirements (the typical selection)

- Submersible: for higher pressure requirements and extremely quiet operation

The centrifugal and multi-stage centrifugal pumps are provided with NEMA style standard motors. The submersible pump uses a "canned" style water-cooled motor contained in a housing along with the multi-stage pump itself.

The desired flow rate per pump and the desired discharge head in feet of water are supplied by the design of the RO system.

Pump motor selection includes the following choices:

- The size in horsepower (Hp)
- Electrical Service:
  - 460/3/60
  - 575/3/60 (Canadian service)
- Enclosure Type:
  - TEFC
  - Mill & Chem
  - Submersible (for submersible pump only)
- Efficiency: High or Standard (NA for submersible)
- Space Heaters (optional) (NA for submersible)
- Variable Frequency Drive (optional)

6.2.2.5 Skid Paint

The skid paint ensures the protection of all metal surfaces and prevents corrosion on the skid. The types of skid paint available are:

- Epoxy Polyamide Primer & Finish Coat for typical indoor use
- Epoxy Polyamide Primer and Siloxane Finish for outdoor use
- Siloxane Epoxy Primer & Finish Coat for coastal outdoor areas
- Other: (Customer specifies)

6.2.2.6 Piping

There are a few choices for piping used by the RO systems depending on whether the application uses high pressure or low pressure. High-pressure piping is made of 316L Stainless Steel. Low-pressure piping choices are:

- PVC
- Polypropylene
- 316L Stainless Steel

All cleaning connections are provided with victaulic caps for easy connection of the cleaning system hoses.

6.2.2.7 Valves

Valve selection for an RO System covers a number of valves incorporated in the system. **Table 6.2-2** below indicates the valve body type and actuator type recommended for each location.

Service Type	Valve Body Type	Actuator Type
Pump Inlet	Butterfly, Lug, 150# EPDM Lined Cast Iron	Manual
1st Stage Inlet	V-ball, Wafer or Butterfly, Lug, 150# Stainless Steel	Spring-To-Close Pneumatic with travel stop
Product Outlet	Butterfly, Lug, 150# EPDM Lined Cast Iron	Spring-To-Close Pneumatic
Reject Outlet	Globe, 150# Stainless Steel	Manual
Stage Inlet Isolators	Ball or Butterfly, Lug, 150# Stainless Steel	Manual
Product Isolator	Butterfly, Lug, 150# EPDM Lined Cast Iron	Manual
System Flush Inlet	Butterfly, Wafer, 150# EPDM Cast Iron	Spring-To-Close Pneumatic (optional)
System Flush Outlet	Butterfly, Lug, 150# Stainless Steel	Spring-To-Close Pneumatic
Product Dump Outlet	Butterfly, Wafer, 150# EPDM Lined Cast Iron	Spring-To-Open Pneumatic
Cleaning Isolators	Butterfly, Lug, 150# EPDM Lined Cast Iron	Manual (optional)
CIP Fill	Butterfly, Lug, 150# EPDM Lined Cast Iron	Manual

Table 6.2-2: Valve Body and Actuator Recommendations

Diaphragm valves can be used in place of butterfly valves in low-pressure locations.

The product outlet and product dump outlet valves are normally operated from the same solenoid pilot valve so that the effect is that of a three-way valve.

6.2.2.8 Instrumentation

The instrumentation for the RO unit monitors process conditions to ensure proper operation is achieved. Each unit is provided with product and reject flow transmitters so that the system hydraulics can be monitored. A conductivity sensor monitors the product quality. A pressure gauge with a multi-port valve indicates the pressure in and out of every stage. A multi-port valve and one pressure gauge is more accurate than multiple separate gauges.

The following instruments are options available for the Single Pass RO System and may be selected for the Unit Service Inlet or for the Common Header Service inlet feeding all RO banks:

- pH Analyzer (often used in the common header if pH adjustment chemicals are added)

- Pressure Switch (to protect an on-skid pump, if present)

- Pressure Transmitter

- ORP Analyzer (often used in the common header to monitor changes in the oxidizing potential (including chlorine) of the feedwater)

- Temperature Switch (if there is any opportunity for hot water to reach the unit)

- Temperature Transmitter

- Chlorine Analyzer (to enable precise control of chlorine for cellulose acetate membrane based systems)

6.2.3   Application and Design

6.2.3.1 Applications for Reverse Osmosis

Reverse Osmosis can be used for a number of industrial applications that require removal of dissolved solids. It has proven to be a reliable technology capable of handling a broad range of applications.

Reverse Osmosis is generally used as part of the makeup water purification system. Although RO systems can be used for other specialized functions such as wastewater treatment, they are typically used as part of a system that provides demineralized makeup water.

Many configurations are available for makeup water purification systems. The reverse osmosis process is normally used as a roughing demineralizer to remove 95 to 99.9% of the total dissolved solids from the feedwater. Therefore, it is followed by a secondary RO system and even a polishing demineralization system, such as ion exchange, further reverse osmosis (see Double Pass RO discussion in **Section 6.3**) or electrodeionization (see EDI discussion in **Module 8**).

6.2.3.2 Reverse Osmosis Design

The process design of a Reverse Osmosis system involves detailed and involved calculations. However, by using several simple calculations and some rules of thumb, a close approximation can be devised in short order. This approximation can be used to make initial design decisions.

The following are some of the calculations involved in RO design:

- Flux Rate: Flux Rate is a measurement of the gallons (US) of permeate produced per square foot of active membrane area per day (GFD). Using the metric system, flux rate is measured in liters of permeate produced per square meter of active membrane area per hour (LMH). The conversion factor between these two is:

$$\textbf{1.0 GFD = 1.7 LMH}$$

Water Flux values for different types of water are indicated below in **Table 6.2**-**3**.

Type of Water	Water Flux (GFD)
Surface Waters (Lakes/reservoirs/rivers)	8 - 14
Deep Wells (Low Turbidity)	14 - 18
R.O. Permeate Water	20 - 30

Table 6.2-**3: Water Flux Values for Different Types of Water**

The better the water quality, the higher the flux that can be used without causing excessive fouling.

- Number of Elements: When the flux has been set and the element area (a function of the specific membrane selected) is known, the required number of elements can be calculated:

$$\text{Number of elements} = \frac{\text{Permeate Flow (USGPD)}}{\text{Flux (GFD) X Active Membrane Area (Ft}^2)}$$

- Recovery Rate:

$$\text{Recovery (\%)} = \frac{\text{Permeate Flow rate}}{\text{Feed Flow rate}} \text{ X 100\%}$$

For more formulas go to **Section 6.1.8** of this manual.

This rough design can also be used as a starting point for a detailed accurate design using the membrane manufacturers design software. Each of the major membrane manufacturers has a program that performs all of the calculations necessary for a system design. They require varying degrees of knowledge and practice and should not be used without a thorough understanding of the issues and pitfalls that can occur.

The following section discusses the design of an RO System using the RO Design program offered by Hydranautics. Going through the design process using the RO Design Software gives the user a good idea of what information is required when designing a system. See the software documentation for a complete description of all functions and operations in the program.

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. Select the membrane type and the corresponding model number by looking at the manufacturers' membrane charts. Membrane selection depends on the purpose and type of service they will be used for.

2. Calculate the flux rate (GFD) according to expected feedwater quality.

3. 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 = $\dfrac{\text{Permeate Flow (USGPD)}}{\text{Flux (GFD) X Active Membrane Area (Ft}^2)}$

4. Divide the total number of elements by the number of elements per pressure vessel. The number of elements per vessel depends on the desired recovery rate. 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.

6.2.3.3 Reverse Osmosis Design Using Software

In designing an RO system, the basic pieces of information the user needs to know are the characteristics of the feedwater and the amount and quality of permeate required. The feedwater characteristics are recorded in the Analysis window. These characteristics are ion concentrations, pH, temperature, and source of feed (well, surface, etc.). **Figure 6.2-6** below shows the water analysis window.

Figure 6.2-6: Water Analysis Window

In the RO Design window, specifics of the system such as permeate flow, recovery, membrane type, and number of stages are selected. Once the input of data is complete, the user runs the program to determine if the design meets the specified requirements and design constraints for a specific system. The user is then able to redefine the system parameters and proceed through iterations to arrive at an optimized design. If the operator enters a desired pH value, the program automatically calculates the amount of acid to be added.

Options such as the addition of permeate backpressure, booster pumps, recirculation of concentrate, and a permeate desalting pass are also available. Details on each of these are found later in this section.

The following is an explanation of the menu choices available in the design program.

File

Options in the file menu allow for **Saving/Restoring** an entire design, **Printer Setup**, and **Setup** for entering the identification of the user and specifying the type of units to be used. After a design has been created, the user can save the entire configuration as a file with the extension .DES using **Save As**. The design may be reopened using the **Restore** command and choosing the design filename. **Printer Setup** is straightforward for users familiar with Windows. **Setup** allows for identification of the licensee and user, and the specification of default units, U. S. or metric, to be used throughout the program.

The unit options available are shown below in **Table 6.2-4**:

Unit	U.S.	Metric
Pressure	PSI	Bar
Flow	GPM, GPD	m^3/hr, m^3/day
Pump Flow	GPM	m^3/hr, l/min
Flux	GFD	$l/m^2/hr$

Table 6.2-4: Available Unit Options

Analysis

Feedwater analysis records for use in the design of systems are found in analysis files. The default file is "**ANALYSIS**" in the RODESIGN directory. If an analysis file does not exist, the program will create one when a new feedwater analysis is saved. RODESIGN allows the user to create a **New** record, **Retrieve** (open) a record from an existing file, **Save** a new record or an edited record, **Delete** an obsolete record, and **Blend** one feedwater composition with another feedwater composition. Once saved, these feedwater analyses can be re-used and edited for system design at the user's convenience.

NEW

The creation of a **New** record requires the user to input information on the project name and code, feedwater type, pH, temperature, SDI, turbidity, conductivity, H_2S, and Fe concentrations. The user then inputs the concentrations for each ion, and chooses the correct units in the pull down menus beside the concentration value.

While values for project name, SDI, turbidity, conductivity, H_2S, and Fe concentrations can be omitted from the record, it is essential to specify a project code, the type of water from the pull down options, and its pH and temperature. Additionally, as ion concentrations are added to the record, the values are automatically converted to milliequivalents and totaled for the positively and negatively charged ions. Before a feedwater analysis can be used in a design, the total milliequivalent values for the negative and positive ions must be balanced to within 10% of each other.

Before proceeding with a design, it is recommended that the analysis be saved. If the user wants to return to the Analysis window after proceeding from the RO Design window, press the Analysis button in the lower right section of the window.

Reverse
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BLEND

The Blend command is used to combine two or more feed streams into one feed stream. For example, a site has two wells, one concentrated giving a flow rate of 65 GPM, and the other is less brackish at a flow rate of 35 GPM. The user can combine the analysis records for each to determine what the ionic makeup of the resulting stream will be. The procedure is as follows:

1. Choose the Blend command in the Analysis menu.

2. In the dialog box, open the directory and file that contains the feedwater analysis. Choose the desired analysis and either double-click, or click **OK**.

3. Enter the flow rate and press **Enter**.

4. Confirm the units; if other units are desired, click the arrow to open a list. Choose the appropriate units.

5. Click on the up arrow of the **No**. counter box at the upper left side of the window. Choose the file for the next feedwater analysis to be incorporated.

6. Enter the flow rate, and then click **OK** at the upper right side of the window to enter the stream.

7. Continue with steps 6 and 7 until all feed streams are blended.

8. Save the file. The default value is BLEND1. Alternate names can be entered into the project name and code fields. RODESIGN references the record by the code string.

RETRIEVE (open), SAVE, and DELETE

These menu options correspond to the standard windows menu file options. One has the option of saving feedwater analyses to an analysis file. If an analysis file does not exist, RODESIGN will create one. Additionally, one can save permeate and concentrate analyses after running a projection. Use Save after running a projection, and choose either **Permeate** or **Concentrate**. RODESIGN will create a file with the project code **"ROPERM"** or **"ROCONC"** for the permeate and concentrate streams, respectively. To give these files project names, use Retrieve to open the file. Then type in a file name, and save it.

RO DESIGN

Use of this window progresses by filling in the respective fields for the desired recovery and permeate flow rate, and element type. Choice of these factors results in the program giving a "first guess" as to the system size: i.e., number of stages, number of elements per vessel and number of vessels. Values for system flux and for flow of feed and concentrate are calculated. The system configuration is output in the box to the left for clarity. It is important to note that the "first guess" may not be the optimal design.

The user then has the option of altering the system configuration and changing system parameters. Flux decrease and salt passage increase rates can be changed from the default values by typing the desired values in the respective fields. The age of RO elements and an acidified feed pH value can likewise be changed. The feedwater type, acid type, percent acid concentration, and units can be changed by clicking on the scroll bar option arrows next to the respective headings.

Altering the configuration of the pass is done as follows. Stages can be added and deleted from the first pass by clicking on the counter box next to the "Arrays, pass 1" line. As the number increases or decreases, tabs appear or disappear on the upper edge of the specification box. The number on the tab refers to the stage number. Thus by clicking on a tab of a particular number, one can alter the makeup of the particular stage. One can change the element type by clicking on the field for "element type," and then choosing an element from the list. "Elements/vessel" and "vessels" can be changed by entering the desired number and then pressing **Enter**.

In designing, note that when one selects an element in a stage, all other element types in successive stages change to the chosen element type.

One then has the freedom to add options to the design, such as the incorporation of permeate throttling, the addition of an interstage booster pump before the final stage in the pass, or the use of a permeate desalting pass. Permeate blending and concentrate recirculation can also be specified. When one of these options is chosen, the proper value must be entered into the newly formed space provided. To define configuration for the permeate desalting pass, the procedure is the same as for defining the first pass, except that the lower tabs and the counter box below the specification box are used. As with the first pass, the total configuration is output in the box to the left. Note that use of a second pass precludes the use of options for the first pass. If a set of options is needed for the first pass, save the permeate stream in the Analysis menu heading, and then open this feedwater analysis to design the second pass.

A brief description of the options is given below:

Permeate Throttling: This option simulates the presence of permeate backpressure (created either by a valve on that stream or by hydraulic constraints of the system). Clicking on this option will allow the user to type in a given amount of pressure in the field box that appears. The user has the option of simulating permeate backpressure over the first stage or over all stages. Using this option on the first stage can help in flow distribution between stages for high-flow membranes. Use of this option is also viable in optimizing the system when it is discovered that the concentrate osmotic pressure exceeds the concentrate pressure. Application of the permeate backpressure can overcome this problem.

Booster Pump: This option simulates the presence of a booster pump located on the feed side of the last stage. When this option is chosen, the desired pump pressure must be entered in the box that appears. This alternative can be chosen when it is more economical to employ a pump to overcome concentrate osmotic pressure in the last stage than to resort to permeate throttling.

Permeate Blending: This options allows for the blending of the permeate stream with a specified amount of feed. Once this option is chosen, enter the feed flow to be mixed with permeate in the space provided. Running the program gives the concentration of this combined stream.

Concentrate Recirculation: This option allows for part of the concentrate stream to be recycled back to be combined with the feed stream. The recycled stream is introduced on the suction side of the feed pump, and mixed with the "acidified" feedwater. When this option is selected, the amount of the concentrate stream to be recycled must be entered (as a flow value) in the space provided.

Permeate Desalting: Choosing this option adds a second permeate desalting pass that uses the permeate stream from the first pass as its feed. When this option is selected, a set of tabs appears on the lower side of the membrane/vessel specification box along with a counter box for the number of arrays in this new permeate desalting pass. Additionally, a new column of numbers appears next to the initial flow and recovery data for the first pass. The membranes chosen for this second pass are the same as the first pass by default, the recovery is automatically set at 85%, and the corresponding flow is calculated. By reducing the flow of the second pass, blending of first pass permeate with second pass permeate results, and the resulting blended permeate quality is output on the data sheet.

To change the number of arrays, membranes types, or number of vessels, one clicks the tabs and the values in the field boxes the same way as with the first stage, except that the lower tabs are used, and the lower counter box entitled, "Arrays, pass 2" is used.

COMMAND BUTTONS

In the lower right hand corner are the command buttons. One may RUN the design program to determine the projected performance for the given parameters. The screen changes to show the results for each stage, the permeate quality, and the values of saturation limits in the concentrate. If there are problems with the design, such as those described in the last part of the program logic, an error message will appear, or the concentrate osmotic pressure will flash to alert the user that it is too high compared to the concentrate pressure. Design parameters that are outside recommended limits are displayed in red.

Next allows the user to refine the system design parameters. **Print** sends the current screen data to the printer. **Flow diagram** gives a visual representation of the system chosen, and provides meaningful data on the flow, pressure, and salinity of each stream in the design. **Clipboard** copies the screen data to the clipboard for transfer to other applications (such as a word processor), and **Analysis** allows the user to return to the feedwater analysis screen.

TREATMENT

In this section of the program, permeate post-treatment can be projected by specifying the amounts of chemicals to be added to the stream. These chemicals include: $NaOH$, $NaHCO_3$, Na_2CO_3, $Ca(OH)_2$, H_2SO_4, and HCl. Additionally, the concentration of CO_2 in the permeate can be reduced by simulating the use of a degassifier. When the user is finished, screen data may be printed, or copied to another file by using the clipboard.

The composition of the permeate from the RO unit is presented, and values for saturation indices are presented under the composition output. By using the mouse, the user can choose the dosing rate of chemicals found in the lower part of the screen. As the dosing rate of any of the chemicals is changed, the change in ion concentrations and pH of the permeate is reflected in the output. Clicking the **Restore** button resets all of the chemical dosing rates to zero, and restores the original composition of the permeate.

CALCULATION

POWER REQUIREMENTS

Use of this menu will open two windows. The first, **Power Requirements**, enables calculation of the amount of power needed to operate the high pressure pump given flow, pressure, recovery, and pump/motor efficiency data. Flow and pressure are automatically transferred from the RO Design calculations, but the pressure value may be modified if the actual RO feed pump pressure is different. If the user desires, default values for the pump efficiencies can be used by clicking the "default values" box. Input of all the required data will give values for required power, and for the power per volume of water produced.

COSTS

The second window, **Cost**, enables calculation of specific water cost for an RO system based on design parameters. Costs of materials and labor (as % of total budget), and investment/amortization data are entered. Values for permeate capacity, specific power consumption, number of membrane elements, and dosing rates of acid and scale inhibitor are carried over from the RO Design calculations. The costs per volume of water for each major budget category are then calculated.

For both of these screens, the user has the option of printing the data, or copying the data to another program by way of the clipboard.

GRAPHS

Once a projection has been run, the user has the option of creating graphs of performance limits by clicking on the **Graphs** menu. Four tabs appear, which allow feed pressure or permeate salinity to be determined over a range of temperature or recovery. The user selects the tab corresponding to the graph desired, and then inputs the values for upper and lower limits of either temperature or recovery. Limits for temperature are between 5°C and 50°C. Values for recovery are between 5% and 95%, but these limits may need to be modified slightly if the program does not converge. Clicking **Plot** reveals the graph. Once a graph is generated, it may be printed or transferred to the clipboard.

Once the feedwater characteristics have been entered (and saved, if desired), the RO Design window is opened to specify product flow and recovery, membrane type, age and number of stages, as well as rates of flux decline and salt passage increase.

Figure 6.2-7 below is a view of the RO Design window.

Figure 6.2-7: RO Design Window

After the design is run to calculate the product quality and to determine if design limits have been exceeded, the user has the option of returning to the Analysis window, or altering one of the design parameters to optimize performance. From the RO Design window, one may also access a flow diagram with data on the flow, pressure and concentration of each stream.

Two additional windows are available, one to define permeate treatment options and resulting changes in ionic concentrations and pH, and the other to analyze Calculations of cost and power requirements.

Calculation of Product Water Quality

The program calculates the permeate water quality, feed flow, and pressure requirements, as a function of:

- Permeate flow
- Recovery ratio
- Feedwater composition
- Feedwater temperature
- Type and number of membrane elements
- Rate of flux decline
- Rate of salt passage increase

The RO system design window requires the specification of:

- Design recovery, in percent
- Product water, flow in gpd, gpm, m^3/hr or m^3/day
- Element age, typically 0, 1, 3, or 5 years
- % flux decline per year
- % salt passage increase per year
- Number of stages in the array
- Type of membrane or element

The default values of percent flux decline per year and percent salt passage increase, are provided by the program. These values can be accepted, or new values can be entered. These parameters must be specified by the designer in order for the program to calculate meaningful results. The rates of flux decline and salt passage increase should be based on the experience and judgment of the designer and his knowledge of the feedwater and the pretreatment scheme.

The user-defined salt passage increase value defines the percent increase in membrane salt passage per year. This enables the program to determine the system permeate quality at the end of a specified operating period.

The program uses Hydranautics' nominal salt passage data sheet values for RO system design projections with brand new (time = 0) HYDRANAUTICS™ supplied membrane elements. HYDRANAUTICS™ recommends default values of 33% for cellulose acetate membranes and 10% for composite membranes in the absence of other information regarding feedwater type and pretreatment procedure.

The value of the salt passage increase factor is used to calculate permeate salinity.

For example a value of 10% assumes that, after three years of operation, permeate salinity will increase by 30% compared to the initial value. This reflects the common phenomena of membrane degradation due to fouling and exposure of the membrane element to harsh chemicals during cleaning. In RO systems that operate on feedwater of a very high quality and do not require cleaning, membrane performance remains stable. In some cases on such a system, salt passage even decreases over time, i.e., salt rejection increases. However, in most applications, the RO system does require cleaning. For some types of feedwater sources, such as surface water or wastewater, frequent cleaning of the RO system is necessary. It is a good engineering practice to consider the frequency and results of cleaning, and to make provisions for permeate salinity increase in the design of RO systems.

Likewise, the rate of flux decline reflects the tendency of membranes to produce less water over a period of time. This is due to the fouling characteristics of the water. For example, RO permeate as feed will result in less fouling over time than surface or waste water as feed. Thus, the average rate of expected flux decline will be about 2.5% per year for RO permeate feedwater (into the second pass of a double pass unit) and about 7% per year for surface water feed. Other factors governing the rate of flux decline are the effectiveness of pretreatment and the membrane flux rate. Effective elimination of silt or other foulants prior to RO treatment will result in lower flux decline. Exceeding a recommended flux rate will generally cause higher fouling, thus leading to a higher rate of flux decline.

As the default values for salt passage increase and flux decline are good conservative values they should be used unless discussions with membrane experts indicate otherwise.

Membrane Element Choice and Array Sizing

The program allows the designer to select membrane elements for each pass or stage using a scroll window with model numbers and corresponding product performance at standard test conditions common to the industry. Once the program selects the recommended type of element for the parameters entered, the program makes an initial guess as to the size and configuration of the array. With these values given, the total membrane area is defined, and the program can calculate the permeate flux across the membrane. The designer can accept the initial values given by the program, or alter them. After the designer has selected the type of membrane elements, array, and number of elements per pressure tube, and pressed the **Run** button, the program calculates the expected performance of the RO system.

This initial set of results is used for the first calculation of the required feed pressure and system flux, measured in gallons per square foot per day (GFD). The optimization process requires the designer to change the element type and/or the element quantity and array. This is to arrive at a system design that balances the array and quantity of membrane against the feed pressure and beta (b) values (concentration polarization coefficient) consistent with good RO system engineering design and operation.

Computer Algorithm

The program algorithm is an iterative calculation in which the program first estimates a feed pressure to satisfy the desired permeate recovery and then calculates the performance of the first element of the system. The concentrate from the first element becomes the feed to the second element. Then a second calculation of membrane element performance is made, and so on, from element to element through the complete array of the proposed design. The program sums the permeate flow from all elements and compares this value to the target value. Finally, the program adjusts the feed pressure based on this comparison, and returns to the first step. It converges on the feed pressure necessary to achieve the required permeate recovery given the user defined system parameters.

Once the program has converged on a single unique solution, the screen changes to include the concentrations, pressures, and saturation data for the system. Calculations can be repeated with different design parameters or membrane element arrays. At some feedwater conditions and system design parameters, the program may not converge. When this occurs, the program prompts the designer to re-enter (or correct) a variable.

The 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 may or may not be sufficient depending on the specific needs of the user.

A Note of Caution to the Designer

The 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 carefully.

6.2.3.4 Sample RO Design Calculation

When using the RO design program, the first thing needed is a water analysis. A sample of the water to be used as feedwater must be analyzed in order to enter the parameters for the system design.

When the water analysis is available, the fields for the water analysis screen found under the **Analysis** menu, can be filled. Under the **Analysis** menu, select **New** to fill a new water analysis data screen. Once all the fields are filled, the water analysis is complete and it can be saved by clicking on the **Save** button.
Figure 6.2-8 below is a sample of a completed water analysis screen.

Figure 6.2-8: Completed Water Analysis Screen

From this screen, click on the **RO Design** option on the menu bar. This will automatically bring out the RO design screen showing the recommended parameters to be used for the RO system according to the entered values for water analysis. **Figure 6.2-9** below shows an RO design screen sample. In this screen the user may also select if a single pass or double pass system is desired and the number of arrays. For each selection made, the program will automatically indicate the recommended number of elements per vessel, the number of vessels, and the element type.

Figure 6.2-9: RO Design Screen

After all the selections are made, the user clicks on the **Run** button to run the program for RO design. This selection analyzes the entered information and displays another screen that shows **Calculation Results**.

The screen displays the expected permeate quality resulting from the selected design. **Figure 6.2-10** below shows the RO design screen with the calculation results. The user may go back or change designs to see the different results the system will be capable to achieve. This allows the user to select the best system for their needs.
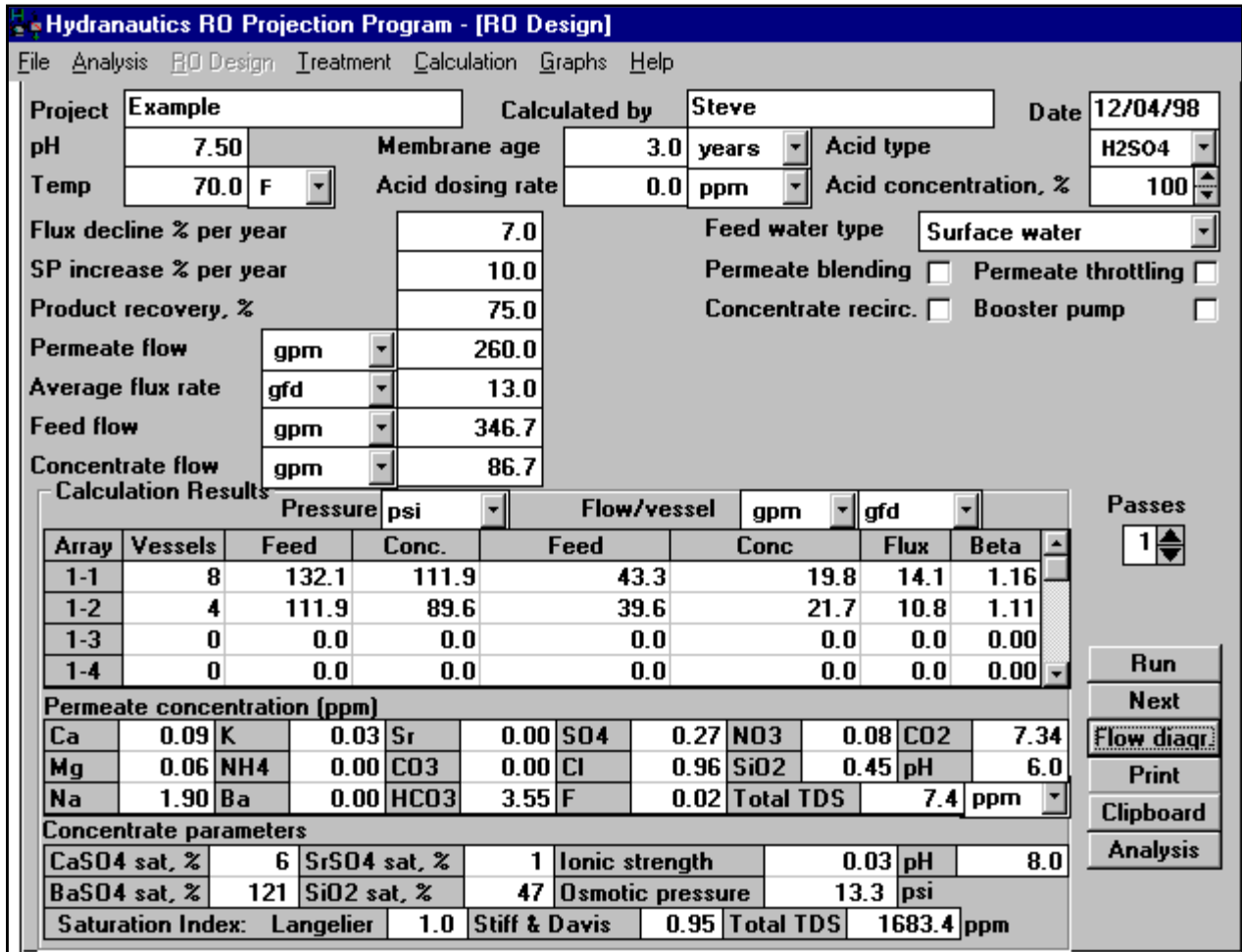

Figure 6.2-10: RO Design Screen with Calculation Results

Once the desired system is found, the user may print the information by clicking on the **Print** button. A flow diagram if the system design can also be viewed and printed by clicking in the **Flow diagr** button seen above on **Figure 6.2-10**.

Figure 6.2-11 below shows a view of the flow diagram for the system designed on **Figure 6.2-10**.
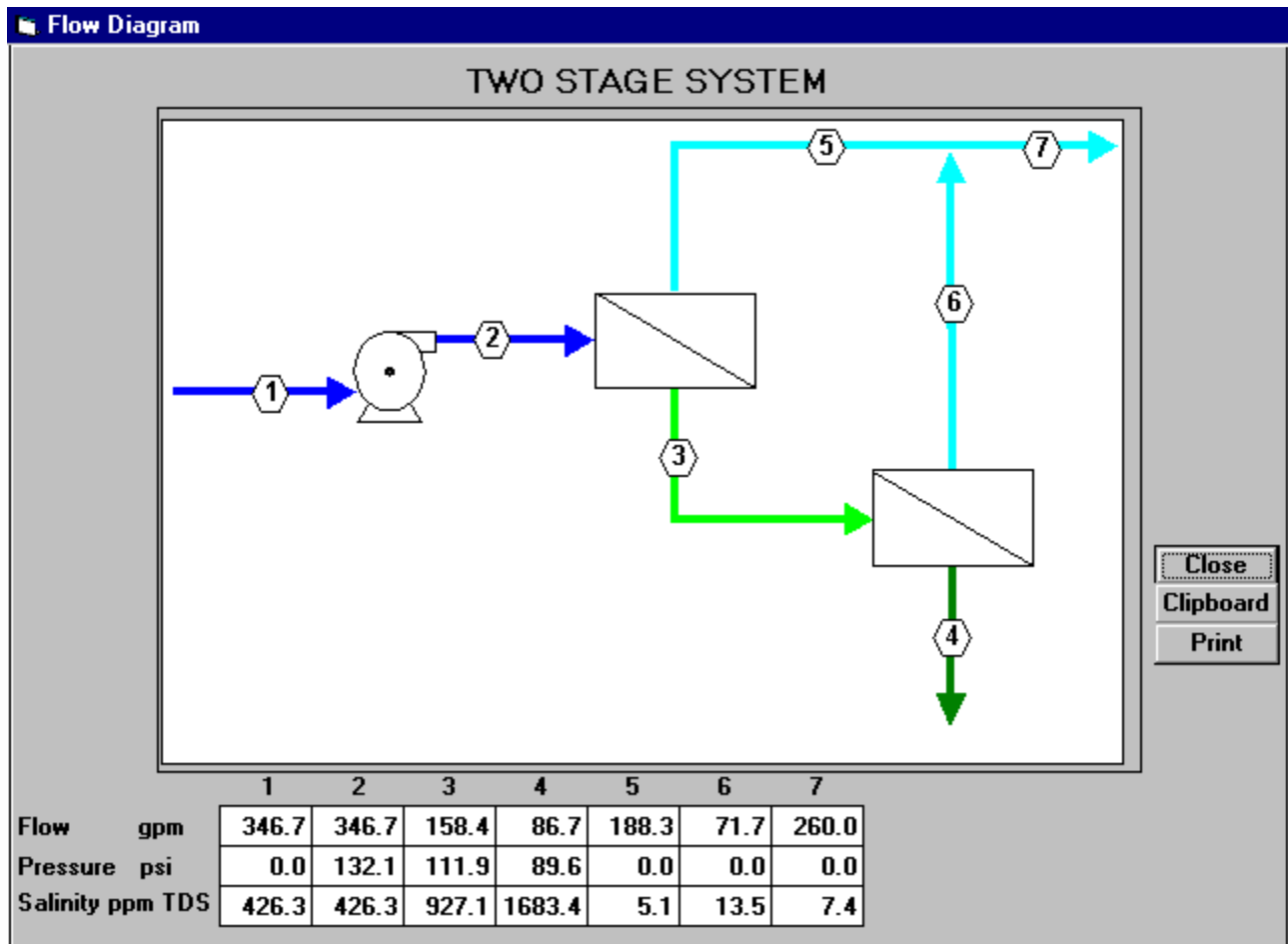

Figure 6.2-11: Flow Diagram Screen

6.3 Double Pass RO System

A double pass reverse osmosis system is actually two single pass reverse osmosis systems. To understand how a single pass system works, refer to **Section 6.2** of this manual. The permeate produced from the first RO system becomes the feedwater for the second RO system. Water permeating through the first RO system membranes is sent to a second RO system. The second RO system removes contaminants that were not removed by the first RO system membranes. Each time water passes through a membrane a very high percentage of the contaminants in the water is removed. Therefore, a second pass through RO membranes results in a very high degree of purification.

A double pass RO system may be advantageous when the feedwater has a high Total Dissolved Solids (TDS). It may also be useful as a replacement for a downstream ion exchange system in situations where highly deionized water is not necessary.

Two single pass RO units can be placed one after another and operated as a double pass RO system. If the RO systems are separated by other equipment such as a tank and pump set, they are considered truly independent. However, the two units can be mounted on the same frame. This is an advantage for systems where the same footprint can be achieved with a combined skid.
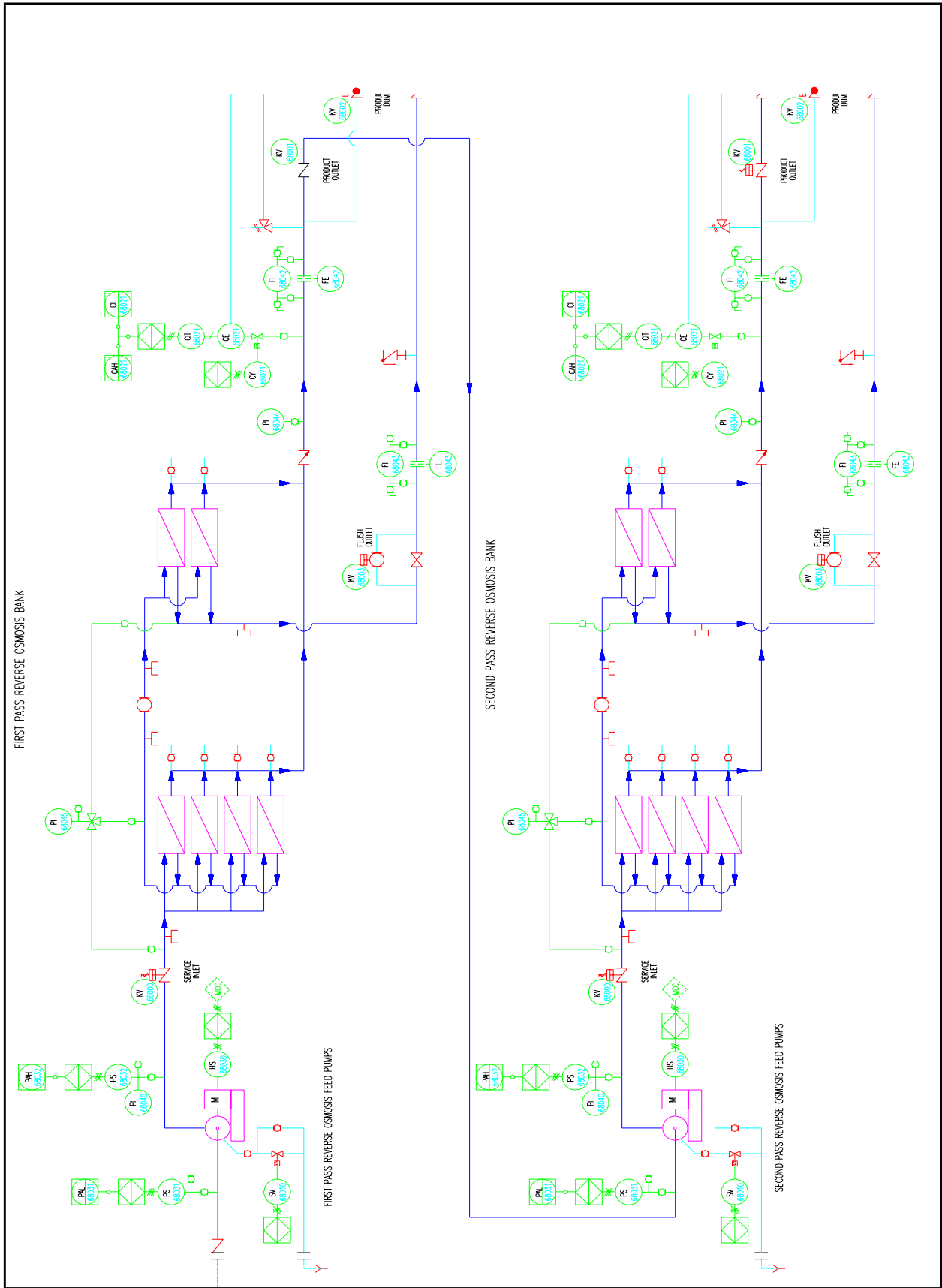
Figure 6.3-1: Double Pass RO System P&ID

Reverse
Osmosis

Figure 6.3-**1** on the opposite page, shows a P&ID of a typical double pass RO system. The following lists possible differences that can be found between the first pass and second pass of a double pass system:

• The second pass concentrate (reject) stream should be returned to feed the first pass unit since the second pass reject is of better quality than the incoming feedwater.

• The first pass does not require an automatic product outlet valve because this function can be performed at the inlet to the second pass.

• The second pass unit does not require an automatic inlet valve because the flow of water is controlled from the first pass.

• A flush system is usually not necessary for the second pass because the water is almost always pure enough to not cause scaling problems.

• The first pass pump can be sized to provide enough pressure for both first and second pass RO units. Depending on the elements selected, the water temperature and the flux rates, the first pass operating pressure may require the use of membrane housings with a higher pressure rating.

• The second pass membranes operate at a higher flux. This is possible because the fouling material in the feedwater has already been removed by the first pass membranes.

Design of the second pass RO system can be done by re-running the membrane manufacturers projection software and using the product water from the first pass as the feed to the second pass. Alternatively, most of the RO projection software packages allow simultaneous calculation of a double pass system.

Note that the conductivity of the product water from a second pass RO unit may not be significantly different from the conductivity of the first pass RO unit feeding it. This is not a reflection of poor ion rejection by the second pass RO. The low pH of the permeate and the presence of carbon dioxide, which is not rejected by RO, account for the majority of the conductivity.

6.4   RO Clean-In-Place System

6.4.1   Process and Operation Overview

Over a period of time, RO membrane elements are subject to fouling by suspended material or scaling by sparingly soluble material that may be present in feedwater. Common examples of such materials are silt, calcium carbonate scale, calcium sulfate scale, metal oxides scale, silica, and organic or biological deposits. **Sections 6.1.10 and 6.1.11** discuss fouling and scaling in deeper detail.

The reverse osmosis clean-in-place (CIP) system is designed to provide cleaning solutions to the RO system arrays. The cleaning solutions are prepared for the specific types of membranes being used and for the foulant or scalant present. The system includes a storage tank to hold cleaning solution, a pump to circulate cleaning solution, and a filter to remove particulate matter that is released by the membranes. **Figure 6.4-1** is a typical view of a reverse osmosis clean-in-place system.
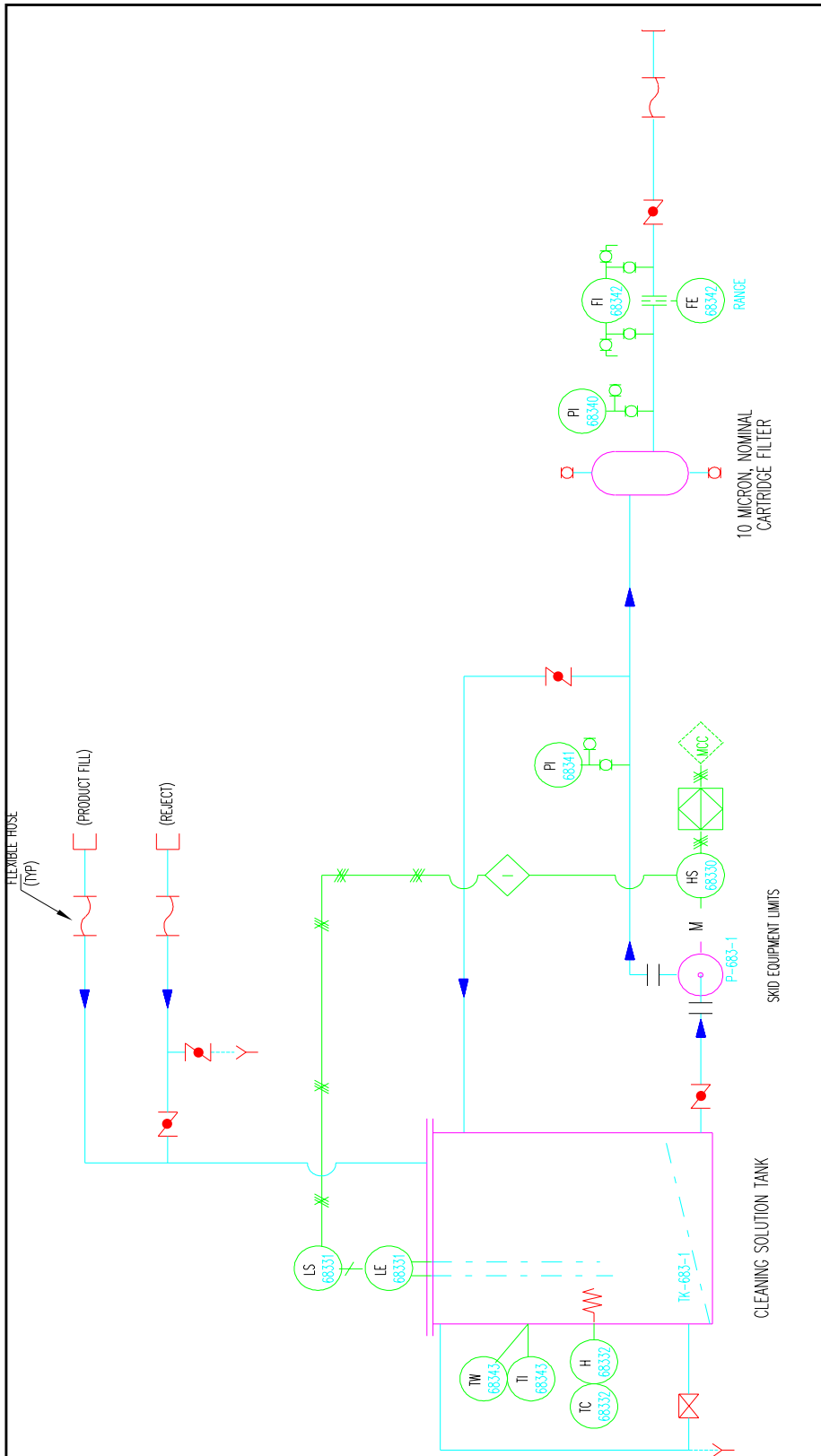

Figure 6.4-1: Typical RO CIP System

Figure 6.4-2: P&ID of a CIP System

The CIP system cleans each stage of the RO units as follows:

1. The CIP system is connected to the appropriate stage of the selected RO unit with flexible hoses.

2. The CIP tank is filled with RO permeate from the RO unit to be cleaned.

3. The operator prepares the cleaning solution in the cleaning solution tank.

4. The pump recirculates the solution to ensure mixing. If required, the solution is also heated at this time. Heat accelerates the process for many cleaning chemicals.

5. The cleaning solution is circulated to the RO system, through the housings, membranes, and other components, then back to the CIP system.

6. Contaminants on the membranes become soluble and are carried back to the CIP tank by the cleaning solution.

7. The cleaning cycle is repeated with any other cleaning chemicals that might be required depending on the system.

8. When one stage is finished, the process is repeated using fresh chemicals on the next stage until all stages are cleaned.

9. After both (or all) stages have been cleaned, the CIP system is rinsed out for future use, and the RO system is operated to rinse out the cleaning solution. Permeate is sent to drain until its conductivity returns to normal.

Figure 6.4-2 is a P&ID of a CIP system. One CIP unit is provided for each site. The unit is designed to be capable of cleaning the array in the system with the largest number of membrane housings in parallel. This assures that the system is capable of cleaning the whole RO unit properly. Stages with fewer housings (second stages or second pass arrays) use the same CIP system, but only part of the cleaning solution is circulated through the membrane array. The amount of cleaning solution is controlled by partially opening the recirculation valve from the pump discharge back to the tank.

6.4.2 Equipment and Design

The RO CIP systems are fairly simple, containing only a storage tank, pump, cartridge filter and required valves, piping and instrumentation. **Figure 6.4-3** shows a CIP system with the major components labeled.
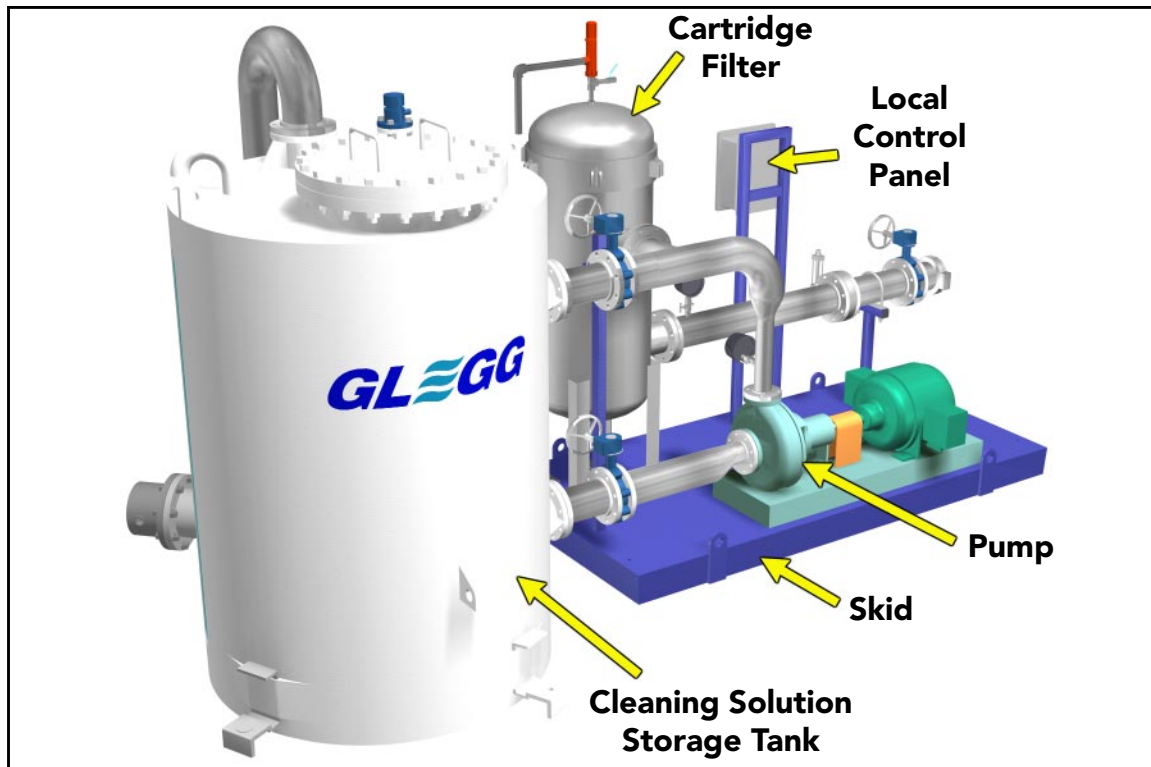

Figure 6.4-3: CIP System with Components Indicated

6.4.2.1 Tank

The storage tank holds the cleaning solution. It is normally manufactured of fiberglass reinforced plastic (FRP). Polyethylene is occasionally used on smaller tanks but may be problematic when an electric heater is installed in the tank. Lined steel or stainless steel tanks could also be used, but these are not economical. Several standard sizes of tanks can typically be used to cover a wide range of applications, since the volume is not critical. The bottom must be designed to drain completely so that spent cleaning chemicals can be completely removed. This is usually accomplished using a sloped bottom.

The tank is often free standing, allowing the skid supporting the rest of the CIP system to be smaller.

Optional Electric Heaters are available for the tank. The heater is sized to provide a reasonable heat-up time for the volume of the particular tank. The electrical service and rating is selected for the location.

CIP systems can also use heat exchangers (steam or hot water) for heating. These tend to have higher capital costs.

6.4.2.2 Pump

The pump is used to circulate the cleaning solution through the system. The flow rate is a function of the maximum number of membrane housings to be cleaned (normally first stage of the largest RO system). The discharge head is usually fixed at a nominal value to ensure sufficient head to overcome pressure losses to the membranes. A high cleaning pressure is detrimental, as it permits the cleaning solution to permeate the membranes. The highest level of cleaning is achieved by supplying an appropriate flow across the membrane surfaces only. A 316 stainless steel pump head is desirable to prevent corrosion by cleaning chemicals.

A redundant pump is not required since the cleaning pump is only used occasionally. Maintenance can be performed during periods when the CIP system is not required.

The pump motor is selected based on the site conditions. See **Section 9.2** for a more detailed discussion of pump motor options.

6.4.2.3 Cartridge Filter

The cartridge filter prevents unwanted particles from entering the RO system and causing damage to the membranes. The housing is often identical to the RO prefilter housings (if one cartridge filter housing is sized to feed one RO unit).

The filter cartridges are usually identical to those used in the RO prefilters. The size rating (in microns) of the filter cartridge is not critical, since its purpose is only to remove larger particles. Any rating between 1 and 50 microns is reasonable; a rating of 5 or 10 microns is typical. Double open end cartridges are used since the service is not demanding.

6.4.2.4 Skid Paint

The skid paint protects metal surfaces from corrosion. The following types of paint are available:

- Epoxy Polyamide Primer & Finish Coat for typical indoor use

- Epoxy Polyamide Primer and Siloxane Finish for typical outdoor use

- Siloxane Epoxy Primer & Finish Coat for outdoor coastal areas

- Custom paint finishes can always be provided

6.4.2.5 Skid Piping

Piping on the CIP skid must be compatible with the cleaning chemicals employed. Any of the non-metallic materials are suitable, and stainless steel is suitable unless hydrochloric acid is left sitting in the system. Three choices of piping are available for the RO CIP System:

- PVC

- Polypropylene

- 316L Stainless Steel

To prevent detergent-type cleaners from foaming in the tank, the return lines must be brought back to a submerged discharge. For this reason, the return lines are normally provided with a down comer into the tank.

6.4.2.6 Valves

All valves on the CIP system are manually actuated. Rubber lined butterfly valves are used, with lug-style construction and either cast or ductile iron bodies. This is not a demanding service for valves and therefore does not justify more expensive options.

6.4.2.7 Instrumentation

Each CIP system is provided with several instruments that enable the operator to set up the proper cleaning conditions.

A temperature switch is provided on the tank to protect the membranes from over-temperature cleaning fluid. The switch is hard-wired to the heater (if present) and the pump.

A pressure indicator is provided on the pump discharge to confirm proper pump operation.

A flow indicator on the line to the RO system allows the operator to set the flow for the size of the array being cleaned.

A level switch on the tank is hard-wired to the pump to prevent operation of the pump if the water level in the tank falls to just above the heater.

6.4.3   Application and Design

6.4.3.1 Application

Every reverse osmosis installation requires a method to clean the membranes of fouling and/or scaling deposits that occur over time.

6.4.3.2 Design

Sizing of the CIP system starts with the array structure of the reverse osmosis system. Each membrane housing requires 40 gpm of cleaning solution flow. If the RO system has a 7:3 array (seven housings in parallel for the first stage and three in parallel for the second stage), the CIP system must be sized to handle the seven housings. The size of the CIP system is determined using the following formula:

Pump flow = max array size x 40 gpm.

The pump is sized to provide approximately 60 psig (about 130 ft TDH) discharge pressure.

The size of the tank is not particularly critical but should be large enough to prevent entrapment of air in the pump suction. Larger tank sizes tend to increase the capital cost of the equipment and the chemical and heating costs. The sizing of the cleaning solution tank has traditionally followed one of several rules of thumb.

A reasonable rule of thumb for sizing the cleaning solution tank is to provide a volume equal to the volume of water in the membrane housings of the first stage of the largest array to be cleaned. Volume allowances are added for the hoses that connect the CIP system to the RO system, along with any volume required to maintain 6 inches of water above an electrical heater in the tank (if present) or to keep the pump flooded.

Approximately 60 gallons of water are required per 6-element housing (10 gallons per 8"x 40"membrane), plus about 100 gallons for hoses. This volume of useable water must reside above the low-level limit of the tank.

Useable volume (gal) = 10 x # of elements in first stage + 100

When an electric heater is used, it is normally mounted about a foot from the bottom of the tank.

The heater is sized to heat the volume of the tank in a reasonable period of time. The contents of the tank are usually heated to a final temperature of 120°F.

Heater size (kW) = volume (gal) x (120 - $T_{initial}$ (°F)) x $\dfrac{0.147 \text{ (kW-min/gal/°F)}}{\text{time (minutes)}}$

The cartridge filter unit is sized for a maximum of 5 gpm for every 10 inches of filter cartridge. The quantity of cartridges used (Qty) depends on the cartridge length and the pump flow rate:

Qty = pump flow (gpm) / 5 gpm / L

L is the cartridge length, and has a value of 3 for 30-inch cartridges and 4 for 40-inch cartridges.

The housing selected must have as many or more cartridges than the quantity calculated using the equation for Qty.

With the above information we can create a sample selection of an RO CIP system. Assume that the RO system has an 8:4 array, 6 elements per housing, the water temperature is 70°F, and the required heating time for the water is 4 hours. In order to calculate the pump flow required to supply the cleaning solution to the RO system, the pump flow formula can be used. With the information supplied on the above paragraph:

Pump flow =8 (max array size) x 40 gpm = 320 gpm

Next, to find out the capacity required for the cleaning solution tank, use the formula for useable volume in gallons. Since the known array is 8:4, we know that there are 8 housings on the first stage. It also known that there are 6 elements per housing. This means that the number of elements in the first stage is 48. Using the formula for usable volume, the following required capacity results:

Usable Volume (gal) = 10 x 48 (# of elements in 1ˢᵗ stage) + 100 = 580 gal

Next, the heater size should be calculated. The heater must be sized to provide sufficient heat to the cleaning solution to supply solution at 120°F. To use the formula, we now that we have 580 gallons, the initial solution temperature is 70°F, and we know we have 4 hours to heat up the solution, which is equal to 240 minutes. Knowing this information, calculate the heater size using the formula:

Heater size (kW) = 580 gal x (120 – 70) x 0.147 / 240 minutes = 17.8 kW

A heater of 18 kW or larger meets the design criteria.

Now the only thing left to calculate is the quantity of cartridge filters needed for this system. Knowing that the pump flow is 320 gpm, and that the L value for the formula is 3 for a 30-inch cartridge and 4 for a 40-inch cartridge, we can figure out how many filters will be needed.

Using 30-inch cartridges:

Qty = 320 / 5 gpm / 3 = 21.33 ((22) 30" cartridges are needed)

Using 40-inch cartridges:

Qty = 320 / 5 gpm / 4 = 16 ((16) 40" cartridges are needed)

6.4.3.3 Cleaning Procedures Requirements

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. The flow should not exceed maximum flow limits for the elements.

To clean an RO system, there are a few basic steps recommended by the manufacturer that should be followed to prevent any damage. It is worthwhile to emphasize the following points that improve cleaning performance and prevent accidental damage:

- The use of chlorine or other strong oxidants on polyamide membranes can cause irreversible damage to the membrane.

- Warm water, 90° F - 100° F (32° C - 37° C), cleans significantly better than lower temperature solutions.

- If the pH of an acid solution increases during recirculation, more acid should be added to return the pH to the target value. 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.

- The 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 after cleaning, to remove cleaning solutions.

- Under severe fouling conditions, it may be necessary to soak the system overnight.