Treatment of Variable Water Sources: Adaptations for a Flexible Desalination System[1]

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Abstract

There are a number of locations where a utility would want to be able to treat multiple sources of water with one treatment system. Those that the Bureau of Reclamation (Reclamation) has come across recently are:

- The Texas Gulf Coast where brackish surface or groundwater is available for much of the year but only seawater is available during dry seasons;
- South central California where the character of the irrigation drainage water changes with the intensity of irrigation;
- Inland desert areas where the composition of brackish surface and groundwater is significantly different when augmented with storm water.

Reclamation assisted the US Office of Naval Research in development and demonstration of the Expeditionary Unit Water Purifier system which can produce 378 m^3/day (100,000 gal/day) of potable water from any liquid source water up to 60 g/L TDS under 35°C. The system was tested under the Environmental Technology Validation (ETV) program overseen by NSF International for the US Environmental Protection Agency (EPA). Test water sources were seawater, turbid surface water, and tertiary wastewater. As a complete system, it performed well with each source. It was only capable of 50% recovery of water however. Because of this, the system has been turned down for potential emergency applications due to the excessive loss of water. This issue occurring at the same time as the three situations mentioned above prompted a proposal to design a flexible system that could be adapted to achieve high water recovery when the feed source allows while still maintaining the capability of recovering energy when the remaining concentrate pressure allows.

Background

Location of a desalination plant is determined by the need for and availability of additional water supply as well as an adequate space and power supply; capacity is determined by the expected demand for water. However, the design of a desalting plant process is typically based on the composition of the feed water. In the ideal case the designer knows the average composition, including concentrations of minor species, and the seasonal variation of the various components.

But what if the feed source varies widely in composition? There are at least three ways to tackle the problem:

1) Design for the most extreme case and take the inherent inefficiencies the rest of the year,

2) Design for the case that meet the needs most of the time and make do during the extreme events, or

3) Design a flexible system with materials and capabilities to accommodate the extreme events while operating efficiently during the moderate conditions.

For this study we will examine the issue starting with the type of membrane: a seawater membrane system that occasionally is used for brackish water; and a brackish water membrane that is used for seawater. Examples of such systems are in the literature. An example of the first case is the Expeditionary Unit Water Purifier (EUWP), designed to treat any source up to 60 gr/L seawater up to 50°C to fresh surface water. The Long Beach, CA two stage Nanofiltration system is an example of the second case, except that the Long Beach facility is not envisioned to treat anything but seawater.

Brackish System Treating Seawater

The Long Beach seawater nanofiltration system is advertized as a low-pressure, economic option for seawater desalination. The membranes are not true nanofiltration since they are capable of greater than 90% rejection of sodium chloride. Permeate from the first stage is fed to a second permeate pass to produce potable water. Concentrate from the second pass is returned to the first stage feed. The overall recovery using this method is 33%.

Seawater System Treating Brackish Sources

The EUWP was developed by the Office of Naval Research EUWP team which included the US Army Tank Automotive Command, Naval Sea Systems Command, Naval Facilities Engineering Service Center, and the Bureau o f Reclamation. The objective was to design a high productivity mobile system that fits in two 1CC ISO containers (20 ft long, 8 ft high, 8 ft wide) weighing 15,500 lbs each. The system uses ultrafiltration pretreatment, with the option of chemical coagulation, followed by reverse osmosis with an Energy Recovery Inc. pressure exchanger to pressurize one third of the system.

The system was evaluated on seawater, brackish municipal wastewater, and fresh surface water using the Environmental Protection Agency's Environmental Technology Validation (ETV) program. The system worked well operating both systems together, but the 50% recovery limitation for the brackish wastewater was not an acceptable process for the water poor desert area hosting the test. Opportunities have arisen since the unit was completed for emergency response missions but the waste of 50% of the water was deemed unacceptable. The system needed the flexibility to operate on brackish water at a higher recovery rate.

Flexible system

These two examples provide clues to the design options for a flexible system. Certainly, with a few plumbing alterations both low recovery, energy efficient seawater systems could be converted to produce potable water from a brackish source while increasing recovery and maintaining energy efficiency due to higher water production with similar energy demand. Before plunging into design options a review of the design basis for recovery, energy efficiency, and permeate quality are examined.

Recovery

The recovery of a membrane desalination system is controlled by the number of modules in the system. One standard sized module can recovery about 10% of the feed water to that module. Pressure at that point in the system must be high enough to overcome the osmotic pressure of the mixed feed and concentrate at that point as well as the hydraulic resistance of the membrane and the module itself.

Membrane specifications include a minimum concentrate flow from each module that is the minimum necessary to wash concentrated salts from the feed channel. Therefore each module in a vessel subtracts energy in the form of reduced feed flow and reduced pressure. At some point there is no longer enough energy to allow the reverse osmosis process to occur. That is why most systems have only six or seven modules in a vessel. A rule of thumb is that one stage is capable of no more than 50% recovery of permeate.

If the salinity of the concentrate is low enough that there is still enough hydraulic pressure to overcome the osmotic pressure and other resistances, then a second stage can be used to attain another 50% for 75% overall recovery. The number of vessels in the second concentrate stage is typically one half that of the first stage so that the feed flow is equivalent to the first stage.

In seawater systems the osmotic pressure of the first stage concentrate is too high to gain further permeate without a pressure boost. It is more economical to just stop at 40-50% recovery in seawater reverse osmosis and to recover the pressure left in the concentrate to help pressurize the feed.

The Long Beach seawater NF process would have a very low recovery if they did not return the concentrate from the second permeate stage to the feed water. The first stage recovers 50% of the water as permeate which needs to be re-pressurized before the second stage where 50% is retained as concentrate, but much lower in salinity than seawater so that, once the process in running at steady state, the feed water is diluted, can be more productive at lower pressure, and the overall recovery is 33% rather than 25% - a different way of reducing energy consumption.

Energy Efficiency

Energy efficiency is obtained in RO systems either by using the energy remaining in the concentrate stream to desalt more water or ease the burden on the high pressure pump or by using thinner, high productivity, low pressure, membranes while accepting a lower rejection of salts. Long Beach Water (Covelli, 2004) claims their low pressure nanofiltration membrane process uses 20-30% less energy than “traditional” seawater RO, but does not define “traditional”. The Affordable Desalination Collaborative has demonstrated high pressure RO desalination with pretreatment at 2.75 – 2.98 kWh/m^3 (10.4 – 11.3 kWh/kgal) with 50% water recovery (MacHarg, Seacord, & Sessions, 2008). Their 2008 analysis includes pretreatment and as a result the most affordable operating point is shifted to higher recovery than their earlier findings. This is because the energy for the pretreatment process has less impact on the total energy use if more of the pretreated water is recovered. Pretreatment is not included in the Long Beach estimate of energy savings.

Permeate Quality

The permeate, or product water quality is a function of the feed water quality, membrane selectivity, and rate of recovery. Seawater membranes have a very low salt passage rate, or high salt rejection rate, so that the permeate from a 50% recovery system treating seawater will have less than 500 mg/L dissolved salts. If brackish water membranes, with less than 99.2% rejection are used with seawater, the permeate will not meet drinking water standards and a second pass for will be needed just as is done with the Long Beach process, resulting in a lower overall recovery. Conversely, if Seawater membranes are used to treat brackish water at only 50% recovery, then the permeate will have very low dissolved solids and will require further treatment for stabilization or blending with another source of water. But, if the feed water composition allows for a higher recovery and the system can be configured to achieve a higher recovery, the permeate may not be just fine. This is the balance we are seeking in the following analysis of flexible feed water RO systems.

Brackish Water System

Two places where high variability in a brackish source water are found are in southern Texas near where the Rio Grande meets, or used to meet, the sea and also in Panoche, CA where irrigation drainage ranges from mildly brackish to one half seawater concentration. Production of the proposed systems is one million gallons per day with recovery ranging from 40% for seawater to 70% or more for the brackish source. Stabilized product quality must be no more 500 mg/L dissolved solids.

Ultrafiltration is assumed for pretreatment. Projections were developed using Hydranautics’ IMSDesign program, version 2008. Various configurations were evaluated, first to explore the variability available in operation and arrangement within the limitations published for the membrane elements, then to determine how the flow would be changed to use the same membrane equipment to treat two different waters.

Basis of Conceptual Design

As much of the equipment as possible must be used for both treatment configurations. Pretreatment is assumed to be ultrafiltration adequate to produce sufficient RO feed water with less than 0.1 NTU and less than 3.0 Silt Density Index to attain the desired RO system productivity. Recovery of the RO system is the highest attainable with antiscalants to ensure long term operational stability. A form of energy recovery is used if the feed pressure is sufficient.

Composition of Feed Waters

Seawater was taken as standard seawater with Total Dissolved Solids (TDS) of 34,500 mg/L. Brackish water is expected to vary in composition with an average of 2500 mg/L TDS. For all calculations, the following water will be used as feed. This is an admittedly a made-up composition, but relative values of different ions are characteristic of natural waters. This composition has a slightly positive Langelier Index and characteristic ratios of various scaling compounds. It is also water that is likely to scale membrane surfaces as the reject becomes more concentrated. It is thus, by design, a challenging water to desalt

Product Properties

- Product Flow: The initial basis will be one million gallons per day (MGD). That done, the range over which this plant can be operated while staying within the manufacturer's requirements for element operation will be determined.

- Recovery: Design recovery as product will be 40 to 50% for seawater and 70% or more for brackish water depending on the composition of the water.

- Product Composition: The desired product quality is approximately 350 mg/L TDS to allow addition of sufficient chemicals like calcium hydroxide and carbon dioxide to produce a stabilized product with a finished TDS less than 500 mg/L.

Table 1. Water Compositions used in system design.

Ion	Formula	Seawater Concentration, mg/L	Brackish Water Concentration, mg/L
Chloride	Cl^-	18,980	675
Sodium	Na^+	10,556	325
Sulfate	SO_4^{2-}	2,649	725
Magnesium	Mg^{2+}	1,262	146
Calcium	Ca^{2+}	400	275
Potassium	K^+	380	4
Bicarbonate	HCO_3^-	140	350
Strontium	Sr^{2+}	13	0.05
Barium	Ba^{2+}		0.004
Bromide	Br^-	65	
Boron	B	4.8	
Silica	SiO_2		22
Others		≤ 1	

Plant Characteristics

- Plant Layout: Various layouts and stagings were investigated including the two pass nanofiltration system developed by Long Beach Water Department.
- Element size: The desalting equipment will be configured around spiral wound elements, 8 inch nominal diameter and 40 inches length. We will keep an eye open for the possible use of 16 inch diameter elements depending on the acceptance of this development by the engineering community and availability of equipment.
- Element age: Performance of RO elements was taken at an average age of 3 years.
- Operating Fraction: The plant will be designed for an operating fraction of 95%.
- Flexibility: The dominant concern in designing this plant is that flexibility should be obtained at reasonable cost. One must recognize that an increase in flexibility is always accompanied by an increase in cost.
- Operating Limits: The design program used incorporates the following operation limits. These limits were respected in the interest of having a well-operating plant.
    - Maximum feed flow rate (at inlet element) — 75 gpm (283.9 lpm)
    - Minimum concentrate flow rate (at tail end element) — 12 gpm (113.6 lpm).
    - Concentration polarization factor, β[2] — < 1.2
    - Langelier Saturation Index in brackish concentrate — < 1.8[3]
    - Stiff & Davis Index in seawater concentrate — < ~0.75
- Pretreatment

To simplify the study, a microfiltration system was selected for pretreatment of the water. This selection also acknowledges that design and operation of a conventional clarification and media filtration pretreatment system is affected by composition of the feedwater, which is expected to be highly variable not only as one shifts from one type of feedwater to the other but also from season to season with the same type of feedwater.

Plant Layouts

A number of elements in parallel are typically shown in a block as follows:

[2] This is the calculated ratio of the concentration at the membrane surface to the concentration of the bulk stream.
[3] If the concentration factor exceeds 100% or the LSI is positive, use of a scaling inhibitor is required.

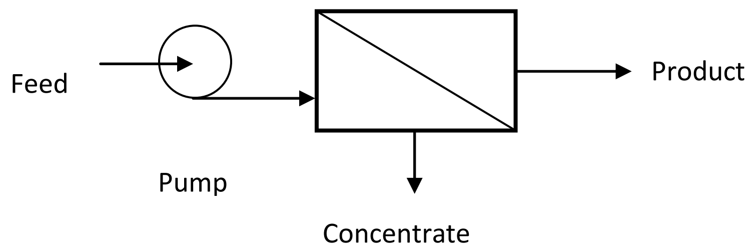

Figure 1. Layout Diagram of Elements in a Block

When the number of elements in series necessary to obtain a certain recovery exceeds about 5 to 7, the elements are typically staged in the following manner to keep the flow in the last elements at a reasonable velocity.

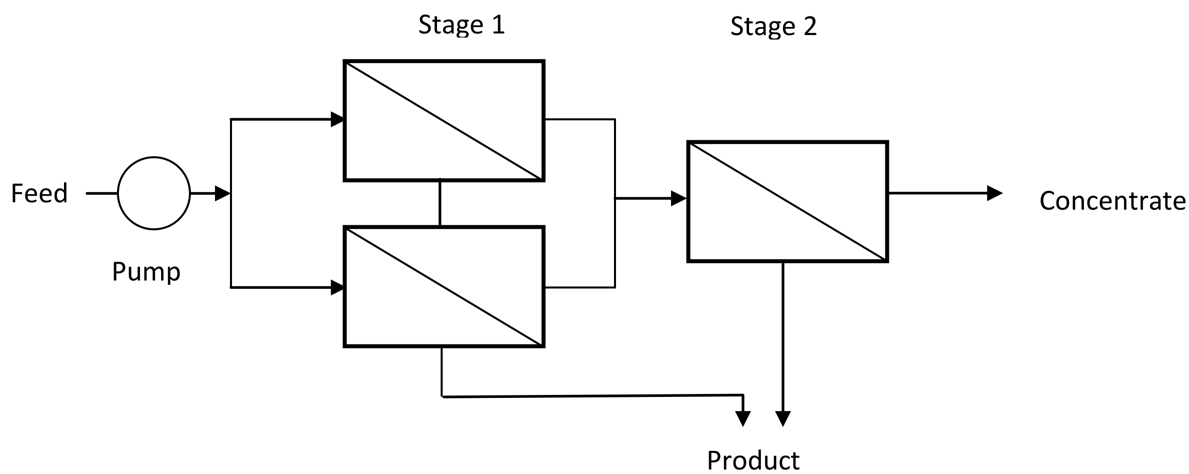

Figure 2. Layout Diagram of Elements in 2/1 Staging

If one pass through the membrane does not cause sufficient reduction in salinity, a second pass may be necessary. The second pass requires use of a second pump.

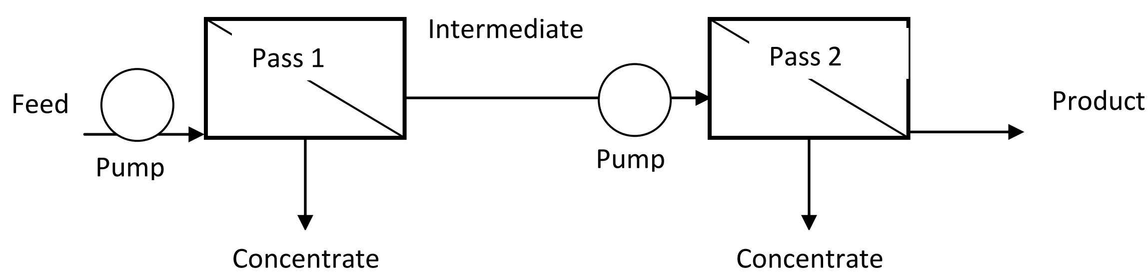

Figure 3. Layout Diagram of Elements in Two Passes

Procedure

The procedure used Hydranautics' IMSDesign program, version 2008. The brackish water and seawater compositions indicated in Section 3 above were entered. Various configurations were evaluated, first to explore the variability available in operation and arrangement within the limitations published for the membrane elements, then to determine how the flow would be changed to use the same membrane equipment to treat the two different waters.

Results

Variation of Flow

To determine the variability of operation of a unit, several units configured in different manners but using the same membrane element, ESPA1, the same number of elements, 240, and the same feed water, brackish, were calculated at different flow conditions. Nominal capacity of each unit was the same, 1 MGD. Because of the way the program is organized, the recovery was held constant and different product rates were input. The change in product rate causes the feed rate to change. Operation of three unit configurations was calculated with the result shown in figures 4 and 5.

Table 2. System configurations examined.

Configuration	Elements per Vessel	Number of Vessels in Stage 1	Number of Vessels in Stage 2	Number of Vessels in Stage 3
I	6	26	14	–
II	5	32	16	–
III	4	26	20	14

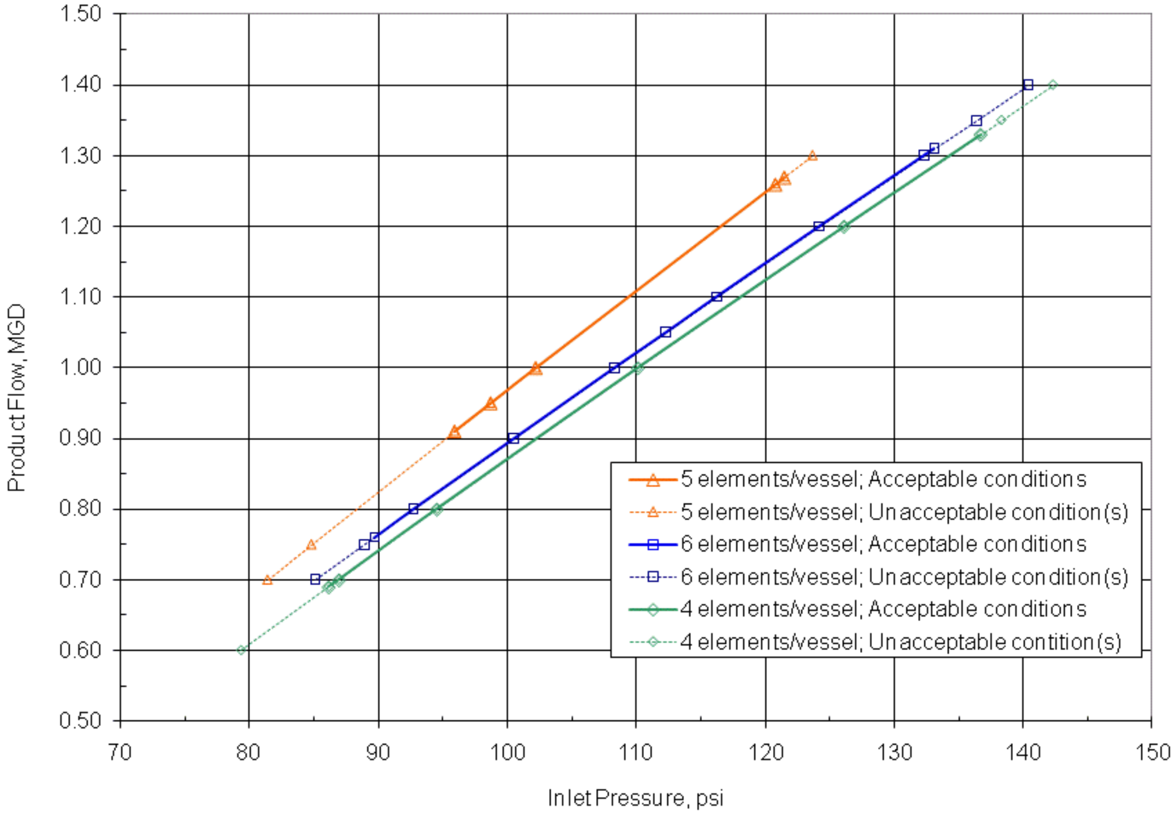

Figure 4. Relationship between Product Flow and Inlet Pressure

In figures 4 and 5, each hollow character shows the calculated operation of a unit. The relationship between product flow and pressure is linear (correlation coefficient for each line is 0.9999), but with a non-zero intercept. Dashed extensions of each line represent operation when one or more parameter lies outside the recommended conditions. Generally, the upper lines represent better productivity, that is more product from the same elements at the same pressure, however, the differences are modest.

A feature that affects flexibility of operation is the range of feed flows, or product flows, over which the desalting unit can operate. This range relates to velocities of feed/brine stream in an element. The maximum, which occurs at the entrance to the first element in a vessel, is set by what can cause physical damage to the element called "telescoping." The minimum occurs at the reject end of the last element in the vessel where excessive concentration polarization occurs. These two values set the range over which a configuration can operate. Generally, the more elements in a vessel, the narrower this operating range will be. The configuration with 4 elements per vessel gives the widest such range, with a ratio of maximum to minimum flow of 1.93. The 6 element/vessel unit was next with 1.72 and the 5 element/vessel unit had a ratio of 1.4.

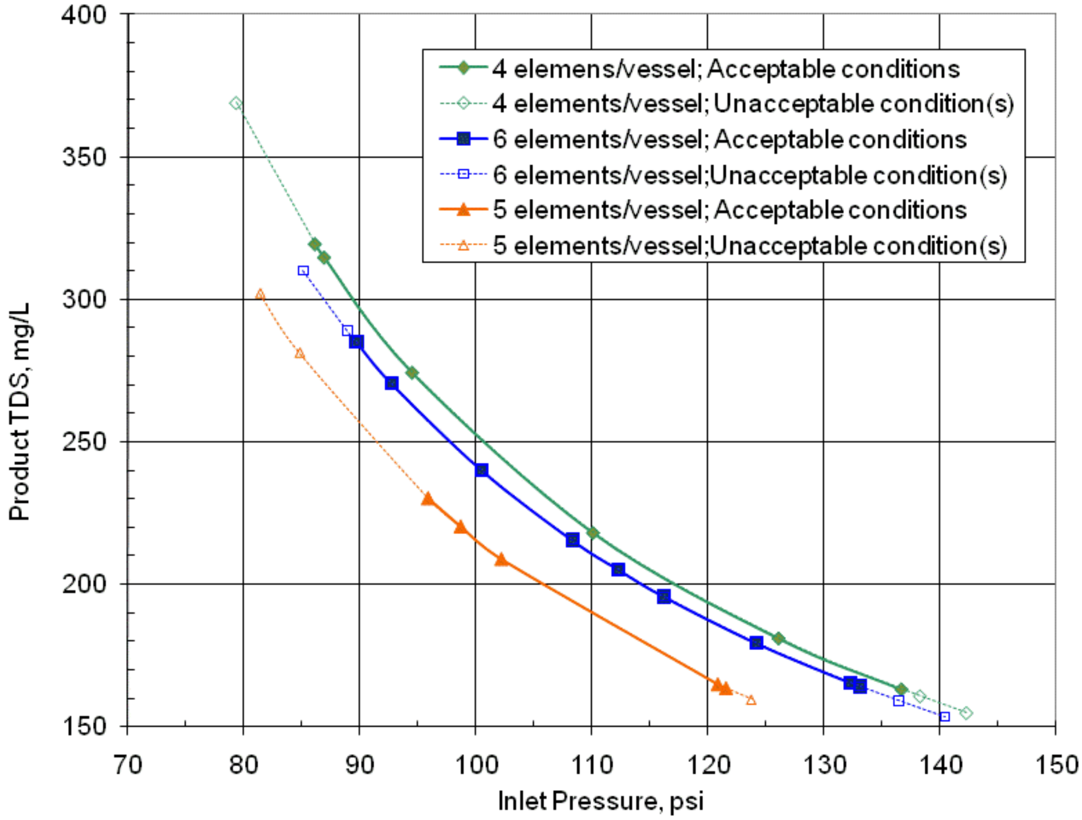

Figure 5. Dependency of Product Salinity on Inlet Pressure

Operating at different fluxes and driving pressures affects the product salinity. Generally if the product salinity is below a certain value, say 350 mg/L, this constitutes only a collateral benefit. If there is a plan to blend product with another stream or with water not desalinated, this benefit can be tangible.

Variation of Type of Feed Water

The real purpose of this study was to determine if a plant could treat alternatively brackish water and seawater. If a modest reconfiguration is permissible, the answer is "yes."

An arrangement of elements and vessels that would meet the requirements for a flexible plant was determined as shown in figure 6. This may not be optimal, but it appears satisfactory. It meets the requirements that product quality is satisfactory, i.e., product TDS is below 350 mg/L; all membrane equipment is used for both types of water; and for the design conditions, no design constraint stated by the manufacturer is violated.

All membranes are contained in 8-inch diameter 6-element vessels. The brackish water plant consists of two stages with 26 vessels in the first stage and 14 vessels in the second. The first stage elements are ESPA2, a fairly high rejection thin-film composite membrane. The elements in the second stage are ESPA1, a similar element with slightly lower rejection. The feed pressure is 122 psi and the product TDS is 137 mg/L. The product flow is 1 MGD.

The seawater configuration, shown in figure 7, consists of a first pass with 26 vessels (the same as the first stage of the brackish configuration). There is a two stage second pass, each stage containing 7 vessels. The feed pressure is 596 psi in the first pass and 130 psi in the second pass. The product TDS is 158 mg/L. The product flow is 0.42 MGD.

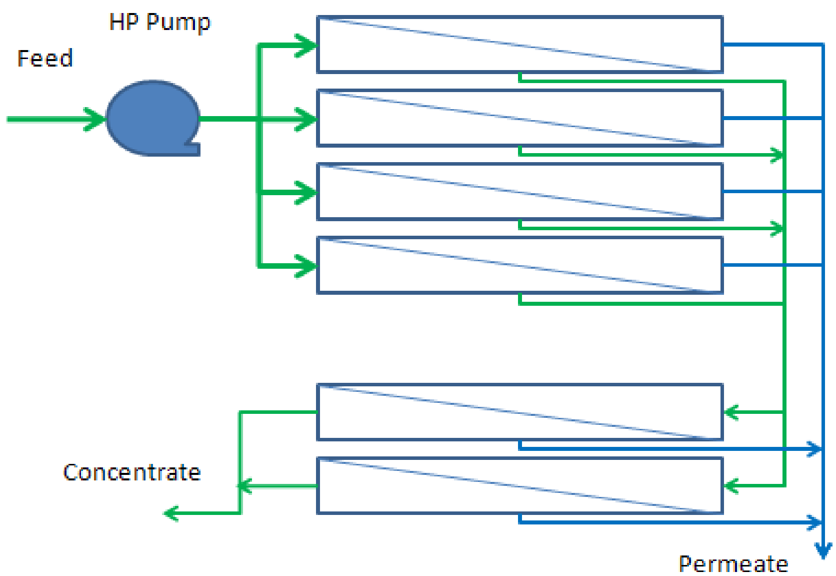

Figure 6. Flow Diagram for Unit in Brackish Water Operation

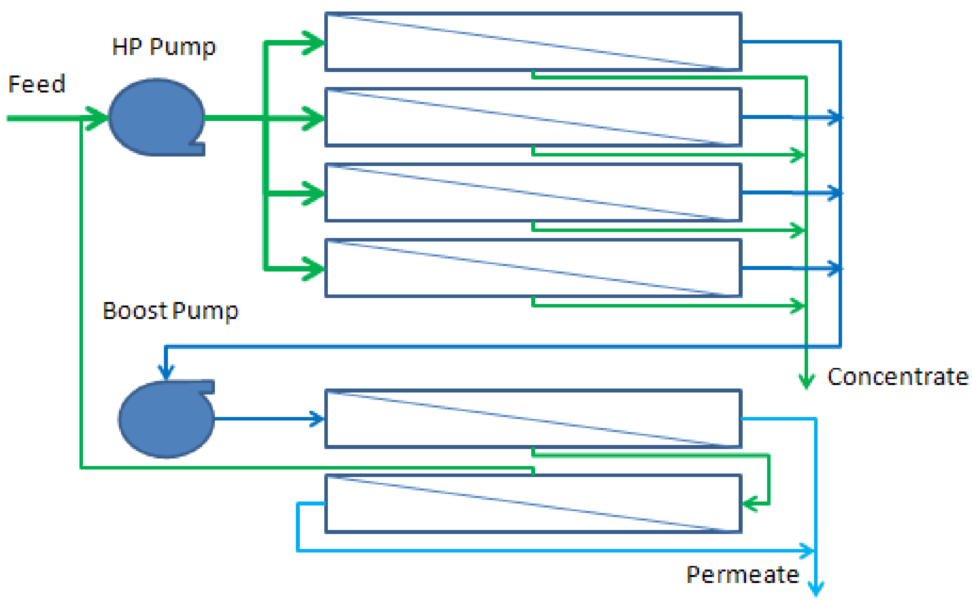

Figure 7. Flow Diagram for Unit in Seawater Operation

A reasonable structure for the membrane portion of the plant would be racks 7 vessels high and two vessels wide. The first 26 vessels would fit on two such racks with two empty spaces. Connections from the vessels would be made to vertical manifolds. The 14 vessels (second stage for brackish, second pass for sea water) would fit on a third rack. Piping for the two modes of operation is shown diagrammatically below. In this sketch, connections near the edge of the vessel are to the feed-reject channel, connections at the center are to the product water pipe.

The changeover from one mode of operation to the other requires only a modest amount of rerouting of flows. Since the changes are almost all in the low pressure, low salinity portion of the plant, most of these changes can be made with valves. The one exception is at the point marked “reject” in the seawater diagram. The change required at this point is best made with blind flanges to avoid leakage of concentrated reject into the product stream. A clever piping specialist can lay out the piping to minimize the work required for changeover. Figure 8 shows the manner in which the piping can be valved to permit changeover from one mode of operation to the other. The reject stream exits the system at different places depending on the mode of operation.

Operation in the two different modes will require a flexible pumping system. Brackish water operation feed needs 1000 gpm at 122 psi. Seawater operation requires lower flow at substantially higher pressure: 836 gpm at 600 psi, as well as 350 gpm at 130 psi. Since the pressure for the second pass for the seawater plant is essentially the same as the feed pressure for the brackish water plant, part of the pump system can be used in both modes.

Printouts from the design program at attached in Appendix A. These give details of the operating parameters and the composition of flow streams in the two modes of operation.

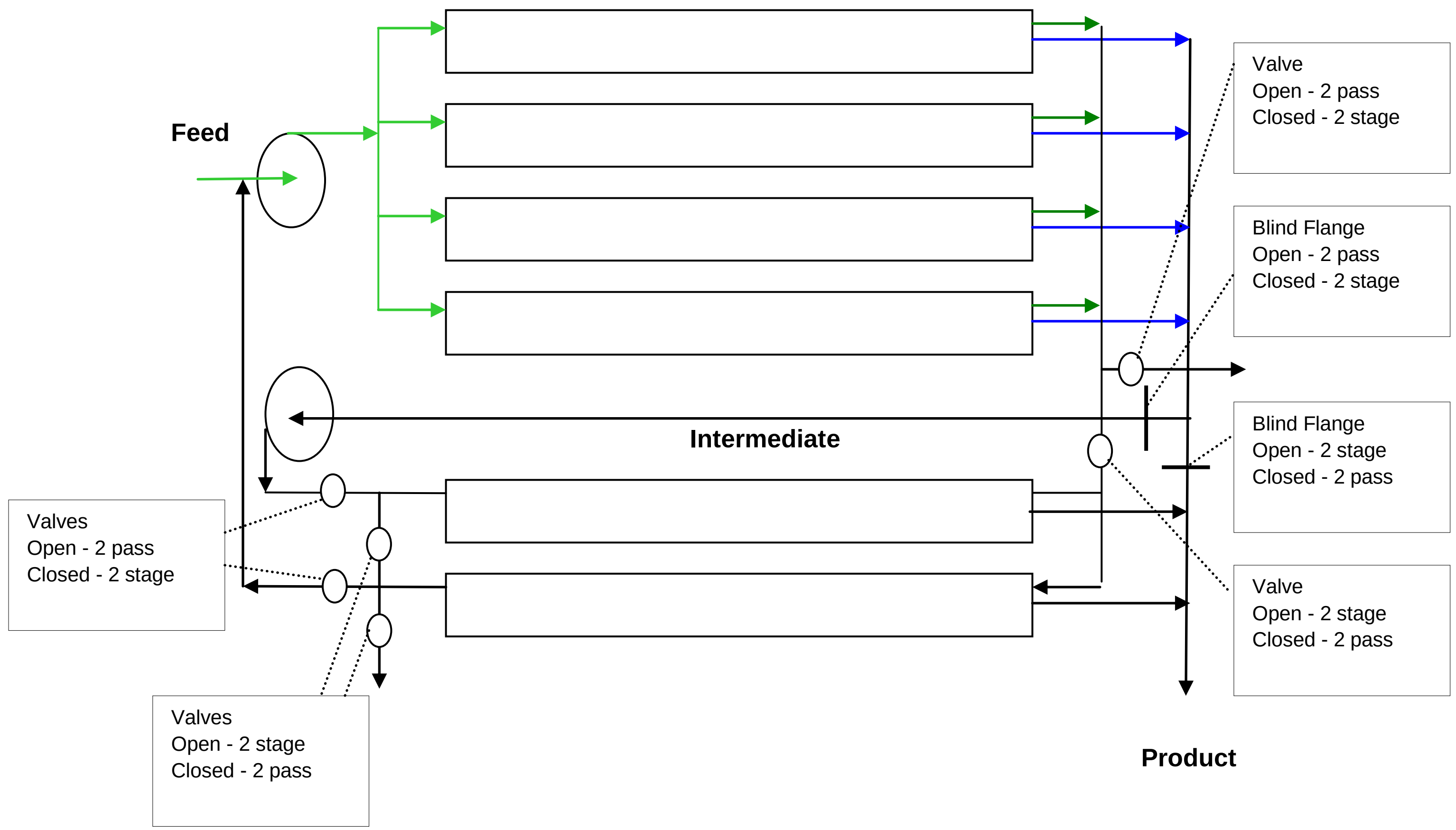

Figure 8. Flow Diagram Indicating Changeover between Modes of Operation

Sea Water System

The alternative scenario for a flexible desalination system is one that is mainly for seawater. The Expeditionary Unit Water Purifier is used as an example. The system does have an optional second pass in the case that highly toxic compounds are present that may not be completely rejected in one pass. However, this scenario uses only the first pass of the system which is composed of two parallel split vessels of eight 8x40" elements each, pressurized with a 100 HP diesel driven positive displacement pump. Concentrate pressure from these two vessels is used via an ERI pressure exchanger to pressurize feed for an identical third vessel. Each vessel has a series of three types of elements arranged to distribute productivity more evenly among the eight elements. Table 3 lists the order, model number, and specified properties of the three types. The arrangement was chosen to maximize water production from the fewest number of vessels due to space and weight restrictions for transportability of the equipment.

Table 3. EUWP Seawater RO element arrangement.

Order	Model Number	Area (m^2)	Productivity (m^3/d)	Salt Rejection
1-2	SW30XLE-400i	37	34	99.7
3-4	SW30HRLE-400i	37	28	99.75
5-8	SW30HR-380	35	23	99.7

The EUWP was evaluated under the NSF International and US EPA's ETV program with brackish municipal wastewater and with seawater in this configuration, achieving approximately 50% recovery in both cases. Representative flows, pressures, and conductivity for these tests are presented in table 4. . Average RO system energy use for the brackish water evaluation was 1 kWH/m^3 or 3.8 kWH/kgal. To determine how well the program RO System Analysis for FilmTec membranes (ROSA v6.1.5) agrees with actual performance using seawater and brackish water, the EUWP was modeled in two parts: three stages of two vessels filled as described in table 3; and in the second part three stages of one vessel each filled in the same manner. Since the pump for the second part is driven completely by the concentrate pressure of the first part, only the energy from the first part is considered necessary. Feed flow, pressures, and recovery were selected to match the actual performance. Table 5 lists the ROSA v6.1.5 simulation results.

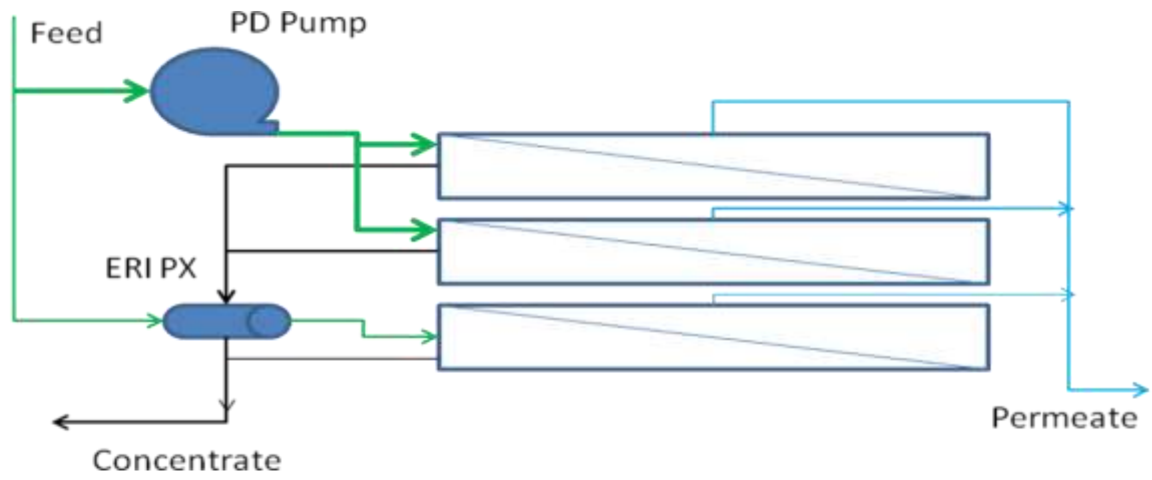

Figure 8. EUWP Stage 1 Seawater Configuration.

Table 4. Operating data for EUWP treating seawater and municipal wastewater (Flow in L/min, pressure in bar).

	Feed			Permeate			Concentrate		
	Flow	TDS	Pres	Flow	TDS	Pres	Flow	TDS	Pres
Seawater HP Array	430	32,627 mg/L	65	212	240 mg/L	1.4	218	N/A	62.8
Seawater PX Array	250		63	95		1.4	155		59
Brackish HP Array	408	1720 µS/cm	20	185	9 µS/cm	1.4	223	3640 µS/cm	14
Brackish PX Array	148		14	61		1.5	87		9.6

Table 5. FilmTec Corp. ROSA v6.1.5 Simulation of EUWP with Seawater and Brackish Water.

	Feed			Permeate			Concentrate		
	Flow	TDS	Pres	Flow	TDS	Pres	Flow	TDS	Pres
Seawater HP Array	439	32,627 mg/L	66	171	215 mg/L	1.5	232	N/A	62
Seawater PX Array	194		61	88		1.5	105		58
Brackish HP Array	428	1720 µS/cm	21	215	5 µS/cm	1.5	212	3640 µS/cm	18
Brackish PX Array	178		14	69		1.5	109		11.6

The projected power requirement for the seawater scenario is 3.4 kWh/m^3 (13 kWh/kgal) and 1.1 KWh/m^3 (4.3 KWh/kgal) for the brackish water scenario. The actual power consumption for the system treating brackish water was 1 KWh/m^3 (3.8 kWh/kgal) for the RO system plus 1.6 kWh/m^3 (6 kWh/kgal) for UF pretreatment at 50% water recovery which includes transfer and product pumping. Obviously Rosa does not include pretreatment or transfer pumping but it is fairly close for RO alone energy consumption.

Next the same system was simulated in the Rosa program using brackish water feed from the Brownsville Public Water Utility's Southmost Regional Water Authority desalination plant in southern Texas at 75% recovery using the PX vessel as a second stage for the HP array. The system was modeled in one part with six stages: the first three with two vessels, the same as the HP Array used previously; and the second three with one vessel the same as for the PX array. Results for this analysis are presented in table 6.

Table 6. FilmTec Corp. ROSA v6.1.5 Simulation of EUWP with Brackish Water, 75% recovery (flow in L/min, pressure in bar).

	Feed			Permeate			Concentrate		
	Flow	TDS	Pres	Flow	TDS	Pres	Flow	TDS	Pres
Brackish HP Array	439	2928 mg/L	29.3	238	6.4 mg/L	1.5	200	6527 mg/L	25.9
Brackish 2nd Stage	200	6527 mg/L	25.5	89	16 mg/L	1.5	111	9108 mg/L	22

The energy requirement for this design is estimated at 1.38 kWh/m^3 (5.23 kWh/kgal). There were no design warnings that came with this analysis, though barium and strontium sulfate, calcium fluoride and silica concentrations are over their solubility limits. Antiscalant is used at the facility now which also operates at 75% recovery.

The PX array of the EUWP can easily be converted to a second stage by replacing the high pressure entrance to and exit from the PX with a straight connecting pipe to divert the first stage concentrate past the PX directly to the PX array. Figure 9 shows the pressure exchanger on the EUWP with a drawing of the pipe that would be required.

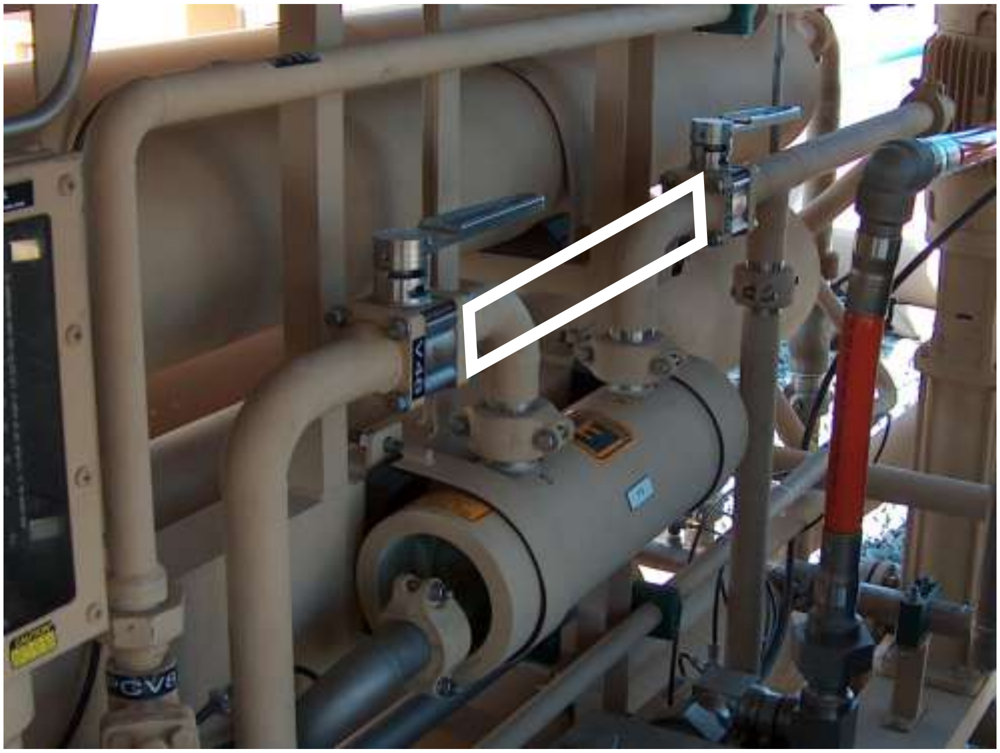

Figure 9. EUWP pressure exchanger indicating by pass piping needed to convert to two stage system.

Conclusions

Two methods of obtaining flexibility in a reverse osmosis system have been described one using a brackish water system, constructed with the proper materials, and another starting with a seawater system. In both cases all of the membrane vessels were used for treating seawater at 50% recovery and brackish water at 75% recovery. In the brackish water system an additional boost pump is added when treating seawater while in the seawater system the pressure exchanger is bypassed to allow concentrate from the first stage to enter the second stage.

References

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