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Brine recovery at industrial RO plants: Conceptual process design studies

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ABSTRACT

Reverse osmosis (RO) and nanofiltration (NF) membrane plants used for brackish water (total dissolved solids (TDS) = 500–10,000 ppm) desalination and industrial water (TDS = 100–500 ppm) purification generate large quantities of concentrated brine that is a disposal problem, especially, when the plants are located inland. Increasingly, industrial plants are required to generate minimal liquid discharge in order to obtain plant operating licenses from their local governments. Because of high costs of disposing brine, and the need to reclaim and conserve water, primary RO (PRO) reject water is sometimes polished with a brine RO (BRO) system to recover additional potable water and reduce the volume of brine stream. Such PRO + BRO hybrid systems can achieve overall product water recoveries (OPWR) of up to 90%. However, OPWR $\geq$ 95% are required. Several alternate NF and RO process flow designs were developed using membrane manufacturers' performance projections software deploying reject data from industrial PRO plants varying in flow rates between 30 and 300 m^3/h. The design data show that for brine streams of low to medium brackish water quality, OPWR $\geq$ 95% is achieved with minimal chemical pre-treatment (acidification and anti-scalant addition). In addition, the process utilises state-of-the-art membrane technologies, does not generate solid waste, has a small foot-print and is easy to scale-up.

Keywords: Desalination; RO reject; High recovery; NF; Brine disposal

1. Introduction

The production and supply of potable water and the disposal of wastewater are among the major challenges of the 21st century. Inadequate supply of potable water, coupled with increasing water demand in developing countries due to rapid population growth and industrialisation are among the major reasons for the worsening water situation [1]. Water pollution from industrial, agricultural and other human activity is also polluting natural water sources. It is, therefore, vitally important to optimise potable water treatment and supply to communities, especially in developing countries where water is often contaminated and water shortages perennially acute.

Reverse osmosis (RO) membrane plants are used extensively for brackish water (total dissolved solids (TDS) = 1000–10,000 ppm) desalination and industrial water (TDS = 100–1000 ppm) purification. Typically, these plants operate at 75% product water recovery (or simply recovery) so that 25% of feed water is wasted as concentrated brine. For example, in the state of Texas, USA, brine wastewater is generated at 40,000 m^3/day from 100 brackish water desalination plants producing 160,000 m^3/day potable water. Similarly, a mid-size 100 m^3/h industrial water treatment RO plant typically generates 600 m^3/day of high salinity concentrated reject. The large quantities of concentrated brine generated is a disposal problem especially when the plants are located inland [2,3]. High disposal

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Table 1
Conventional pre-treatment methods for RO systems

Problem	Primary pretreatment	Purpose	Limitations
Ca/Mg bicarbonate	IX softening	Removes; replaces Ca/Mg by Na which has a soluble bicarbonate	High TDS causes slip max. 800 ppm; too expensive at greater than 9000 m^3/day
	Lime softening	Removes: precipitates as $CaCO_3$ and $Mg(OH)_2$	Not suitable for less than 5000 m^3/day
	Acid addition	Removes: replaces the bicarbonate with the more soluble chloride or sulfate.	Difficulty and cost of obtaining acid
Ca Sulfate scale	IX softening	See above	
Silica scale	Raising temperature	Stabilises: increases solubility	Cost of heat
	Lime softening	Removes: brings down some of the silica with the $CaCO_3$ and $Mg(OH)_2$	Not suitable for less than 5000 m^3/day
Colloids	Coagulation and filtration	Removes: causes the colloids to form larger particles which can be filtered out	
	IX softening	Stabilises: discourages coagulation as the solution is concentrated and the colloids are rejected by the RO membrane	Not suitable for high TDS waters where slip through the softener causes more than 5 ppm total hardness in the softened water

costs, in turn, have an adverse affect on the economic operation of industrial plants where RO systems are deployed. Common methods of brine disposal include deep well injection, surface discharge, or sanitary sewers. Because of high disposal costs, and the need to reuse and conserve water, RO reject concentrate (brine) is being increasingly processed to recover additional potable water. In order to achieve higher recoveries, therefore, alternate processes are required, and are discussed in this paper.

2. Background

2.1. RO membrane systems operating constraints

The operating range of RO membrane systems used for brackish water desalination and industrial water purification is 65–80% recovery based on membrane manufacturer's design guidelines and depending on RO feed water quality (e.g. TDS, pH, temperature, hardness, alkalinity, silica) and RO feed water treatment (e.g. softening, pH to <7.0, anti-scalant addition). Higher recoveries are constrained by the solubility limits of sparingly soluble salts as the feed/brine water gets concentrated in the feed channel (e.g. the salts get concentrated by a factor of 4 at 75% recovery and 10 times at 90% recovery). Once the solubility limit of a salt, e.g. barium sulfate, which has very low solubility, is exceeded, it precipitates out resulting in membrane scaling and eventually fouling that in turn reduces membrane product water flow rate [4]. Typical conventional pre-treatment methods are given in Table 1.

Eventually, sooner rather than later, the RO system has to be shutdown to clean the membranes to restore membrane productivity and performance to minimum acceptable levels noting that its original value is almost never restored. Since the membrane surface is quite fragile, membrane cleaning must be as infrequent as possible to protect it from chemical damage and to ensure the membrane element lasts at least 3 years. Thus, the only feasible method for increasing the overall product water recovery of an RO system is by the purification of the reject/brine wastewater.

2.2. Brine recovery RO membrane systems

The simplest method of purifying the reject/brine stream is with a brine RO (BRO) unit operating at recoveries of 50–70% as shown in Fig. 1. Such streams are generally high in hardness, alkalinity and silica. Because of these constraints, higher recoveries are not possible as discussed earlier. Typically, the brine recovery RO (BRO) unit product water is blended with the primary RO (PRO) feed water. Alternately, if the BRO product water quality is acceptable, it can be blended with the PRO product water. Hence, the

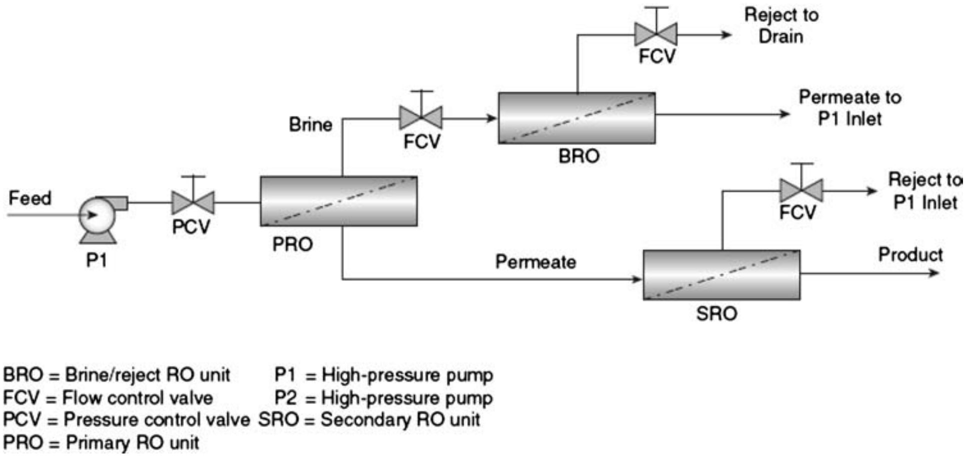

Fig. 1. Process flow schematic of a high recovery RO system. Note, SRO in this case stands for second-pass RO system for further purifying the first-pass RO permeate.

maximum overall product recovery achievable with a dual RO membrane system [PRO + BRO] is <90%.

2.3. Softening systems

In order to achieve recoveries ≥95%, alternate processes have been investigated such as softening the PRO reject stream with lime and sodium hydroxide to raise the pH to 11, thereby, reducing hardness and silica ion concentration [5]. The softened and clarified water is then polished by an RO unit. However, such processes generate large quantities of solid waste, essentially transferring a liquid waste disposal problem to a solid waste disposal problem. Alternate processes include pre-treating the PRO feed water with ion exchange and acid followed by degasification, and then adding caustic soda to raise the pH to 10–11 to increase silica solubility [6]. Such processes are well suited for very high hardness and silica concentrations even though they generate liquid chemical waste solutions.

Recent industrial applications include treating wastewaters with high concentrations of silica and hardness from cooling tower blow-down. Treatment of these wastewaters requires addition of magnesium chloride and/or lime and soda ash to raise the pH to 11 to reduce hardness and silica prior to polishing with an RO unit. Alternately, a cross-flow MF system replaces a conventional lime softening clarifier and multimedia filter to produce feed water of higher quality for RO polishing as shown in Fig. 2 [7]. Overall product water recoveries of 95–97% can be achieved. The lime/soda ash sludge is dewatered in a filter press and disposed off as 35% solid waste. Alternately, caustic soda is used instead of lime; caustic treatment reduces the sludge by 50% and is easier to handle but is more expensive.

2.4. Brine recovery NF–RO membrane systems

Nanofiltration (NF) membranes are sometimes referred to as ''loose'' RO membranes with the average 'pore size' of NF membranes roughly twice that of RO membranes. Thus NF systems operate at lower pressure but produce higher flux than RO systems. The NF membrane is usually negatively charged so that anion repulsion is the primary determinant of solute rejection. The rejection of divalent ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}) is >98% as compared to <50% rejection of monovalent ions (Na^+, Cl^-). Hence, low pressure NF is often used for water softening and seawater pre-treatment. It is also less susceptible to fouling [8]. Indeed, the largest application of NF is in water softening; it is a more attractive alternate to lime-softening and ion exchange softening because not only is it a reliable process, it does not require chemicals for regeneration, and minimises waste. NF separation is a continuous process and is independent of plant capacity (throughput) and feed water hardness unlike ion exchange. It reduces both the hardness and the total dissolved solids to a much greater degree than lime softening. Various brine NF–RO integrated membrane designs for achieving high recoveries are evaluated in this paper.

3. Design basics

3.1. RO/NF membrane performance parameters

The performance of RO and NF membrane processes is typically determined by two key parameters, recovery and rejection defined below:

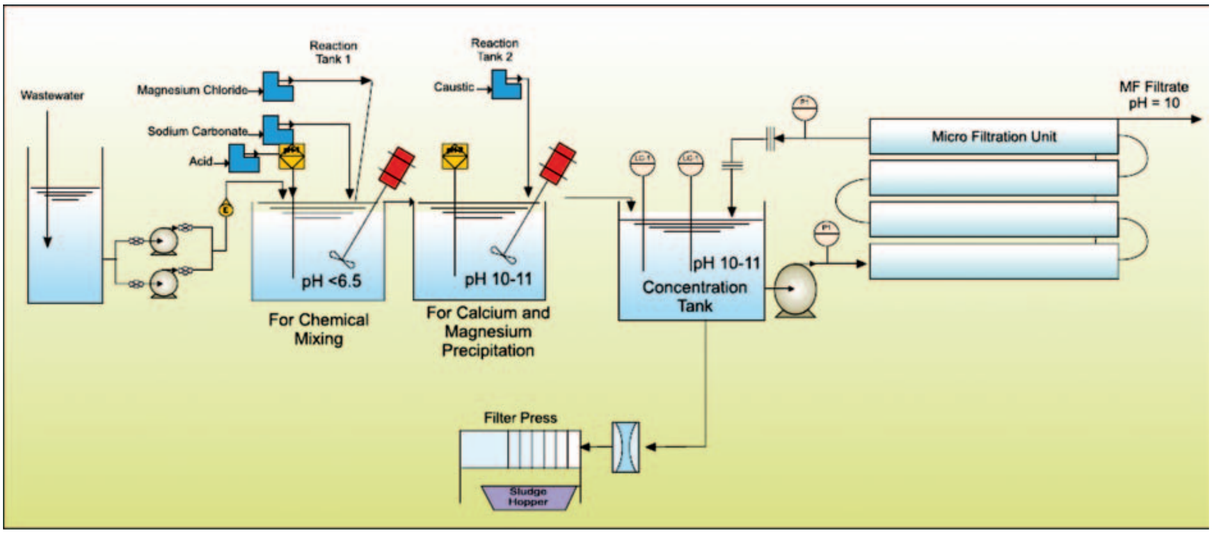

Fig. 2. Process flow schematic of a brine recovery process with feed water softening followed by cross-flow microfiltration. RO treatment of MF filtrate is not shown.

$$\%\ \text{Recovery},\ \text{PWR} = \frac{\text{Product flow rate}}{\text{Feed rate}} \times 100$$

$$\%\ \text{Rejection},\ R = \frac{\text{Feed solute concentration} - \text{product solute concentration}}{\text{Feed solute concentration}} \times 100$$

Another useful expression for membrane rejection is [9]

$$\%R = [1 - (\rho.B)/A(\Delta p - \Delta\pi)] \times 100$$

where, ρ is the density of water, g/cm^3, B is the salt permeability constant, A is the membrane permeability constant, $\triangle p$ is the pressure difference across the membrane and $\triangle\pi$ is the osmotic pressure differential across the membrane. The value of A is in the range of 3 (10^{-3}) – 6 (10^{-5}) m^3/m^2 h bar for RO membranes and higher for looser NF membranes [3 (10^{-3}) – 2 (10^{-2}) m^3/m^2 h bar]. The value of B is in the range of 5 (10^{-3}) – 1 (10^{-4}) m^3/m^2 h for RO membranes with NaCl as the solute [10].

In addition, flux data is normalised for feed temperature and pressure using the following equation [4]:

$$J_S = J_M(\Delta P_S/\Delta P_M) \times (1.024)\exp(T_S - T_M)$$

where J_S and J_M are permeate flux at standard and measured conditions; $\triangle P_S$ and $\triangle P_M$ are membrane net differential pressure across the feed inlet and reject outlet at standard and measured conditions; and T_S and T_M are fluid temperature at standard and measured conditions.

The amount of product water (permeate) recovered is generally dependent on: (a) total area of membrane within each vessel; (b) membrane pressure supplied by the high pressure pump(s); (c) reject flow rate; and (d) feed water quality [4]. The recovery in each element is controlled by the concentration of rejected species due to the solubility limits of sparingly soluble salts of calcium, magnesium, barium, strontium and silica in the brine stream. When the product recovery is 50%, the salt concentration in the reject stream is doubled, whereas the salt concentration increases fourfold when the recovery is 75%. Hence, RO plants are operated below the design recovery point. The scaling potential is usually the highest in the last elements of the final stage. Calcium carbonate scaling is easy to control by adding acid to lower the Langelier Saturation Index (LSI), by softening the water to remove calcium and/or by adding an anti-scalant. Silica is a function of pH and temperature. It is most soluble at pH < 6.0 and >9.0. $CaSo_4$, $BaSo_4$ and $SrSo_4$ are relatively independent of pH.

3.2. Brine membrane system design conditions

The brine recovery system membrane processes were modelled using Hydranautics Membrane Solutions Design Software v. 2007 and Dow/Film-Tec ROSA software 6.1 for the four feed water cases with brine TDS between 1300 and 6600 ppm (Table 1). The performance projection data were based on the feed water temperature of 18 °C (65 °F), and performance

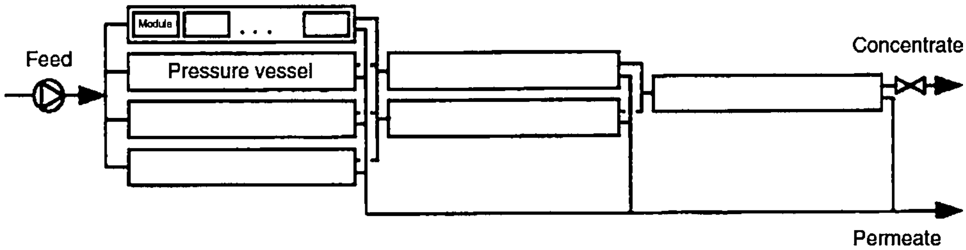

Fig. 3. A typical RO/NF three-stage membrane array. The tapered configuration has four pressure vessels in stage 1, two in stage 2 and one in stage 3.

after 3 years service run time. The membranes were polyamide thin-film composite (TFC) elements. The spiral-wound membrane elements were either 40 cm diameter × 100 cm long or 20 cm diameter × 100 cm long, 3–6 mounted in series in pressure vessels as shown in Fig. 3. Feed water treatment included anti-scalant addition and pH adjustment with acid to 6.5–6.8 to maintain the LSI < 1.8. Based on membrane manufacturer's recommendations, the saturation limits with anti-scalants are as follows: $BaSO_4$ = 6000%, $SrSO_4$ = 800% and $CaSO_4$ = 230%. Silica solubility can be up to 300 ppm in the presence of a dendrimer anti-scalant (Professional Water Technologies, Vista, California).

4. Process design and performance Data

4.1. Brine recovery membrane system design – low TDS water

The design for Cases IA–IE was based on the following conditions and the brine water data from an industrial site given in Table 2:

- PRO feed water flow rate = 400 gpm (90.9 m^3/h).
- PRO product water recovery = 75%.
- PRO reject (brine) flow rate = 100 gpm (22.7 m^3/h).
- Reject hardness = 825 mg/L as $CaCO_3$.
- Reject alkalinity = 450 mg/L as $CaCO_3$.

The design data for Hydranautics RO and NF membrane are summarised in Table 3. Process flow schemes with flow and dissolved solids mass balances are shown in Fig. 4–9. The membrane rejection data for each sub-system is included in Table 3.

Case IA, Table 3. This is the simplest scheme as shown in Fig. 4 where the PRO reject flows to the BRO unit at 100 gpm (22.7 m^3/h). BRO1 is a single-stage array (3:0) with three parallel pressure vessels. The membrane elements were 40 cm diameter ESPA1. The maximum recovery achievable is 50% resulting in an overall recovery of 87.5% (350 gpm/400 gpm).

The overall recovery increases to 92.5% (370 gpm/400 gpm) when the BRO unit recovery is 70%. This is achieved when a portion (20%) of the BRO2 reject is recycled to the feed side (*Case IB, Table 3*) as shown in Fig. 5. Reject recycle provides additional fluid flow above the membrane, thereby reducing concentration polarisation and making higher recoveries feasible. BRO2 is a two-stage array (3:2) similar to the tapered array shown in Fig. 3. The membrane elements were 40 cm diameter ESPA2+. In each case the BRO product water is blended with PRO product water.

In order to increase product water recovery from 90–92% to $\geq$95%, it is virtually necessary to use a combination of RO and NF membranes in the brine

Table 2
PRO concentrate water analysis*

Item	Case No.			
	Case I + (mg/L)	Case II (mg/L)	Case III (mg/L)	Case IV (mg/L)
Ca	220	316	654	638
Mg	67	83	214	203
Na	28	225	51	1335
K	1.4	16	14	8
Ba	0.01	0	0	0
Sr	0.8	0	0	0
CO_3	1.0	2.6	2.3	2.1
HCO_3	554	702	1424	966
SO_4	360	224	472	808
Cl	30.9	587	809	2611
F	0.4	0	0	0
NO_3	15.6	0	0	19
B	0.01	0	0	0
SiO_2	16	46	61	60
TDS	1295	2200	3640	6650
pH	8.2	7.5	7.7	7.5
CO_2	–	26	150	91
PRO TDS**	332	563	945	1705
PRO pH**	7.5	7.0	7.1	7.0
PRO TDS#	5	15	28	42

*PRO reject (BRO system feed) at 75% recovery.
**PRO feed water.
#PRO permeate.
+Well water.

Table 3
Brine recovery system design summary – low TDS water

Case @	Recovery system	Sub-system product flow (gpm)	Sub-system rec. (%)	Brine system rec. (%)	Overall rec.* (%)	Salt rejection (%)	Total pump power (Kw)	Energy consumption** (kWh/m^3)
IA	BRO1	50	50	50	87.5	95.7	7	0.62
IB	BRO2	70	70	70	92.5	97.1	8	0.48
IC	NF1+		70			79.1		
	SRO1	63	90			97.4		
	&	+		79	95		18	1.0
	NF2+	16	50			84.8		
	SRO2		72			96.9		
ID	NF1+		70			79.1		
	NF2+	76	50			85.8		
	SRO1	+	89	84	96	97.1	21	1.1
	&	8						
	SRO3		35			93.9		
IE	SRO4+		50			98.7		
	NF3	84	68	84	96	81.9	11	0.57

Notes: The membrane system designs were modelled using Hydranautics Membrane Solutions Design Software v.2007.
@For feed water analysis, refer to Table 2. For all flow rates and mass balances, refer to Figs. 4–9. PRO feed flow rate = 400 gpm; PRO permeate flow rate = 300 gpm; PRO brine flow rate = 100 gpm. 1 m^3/h = 4.4 gpm.
*Overall recovery = PRO recovery (75%) + brine system recovery.
**(kW÷gpm) × (4.4 gpm÷m^3/h).
Average flux = 10–12 gfd (17–20 L/m^2 h).

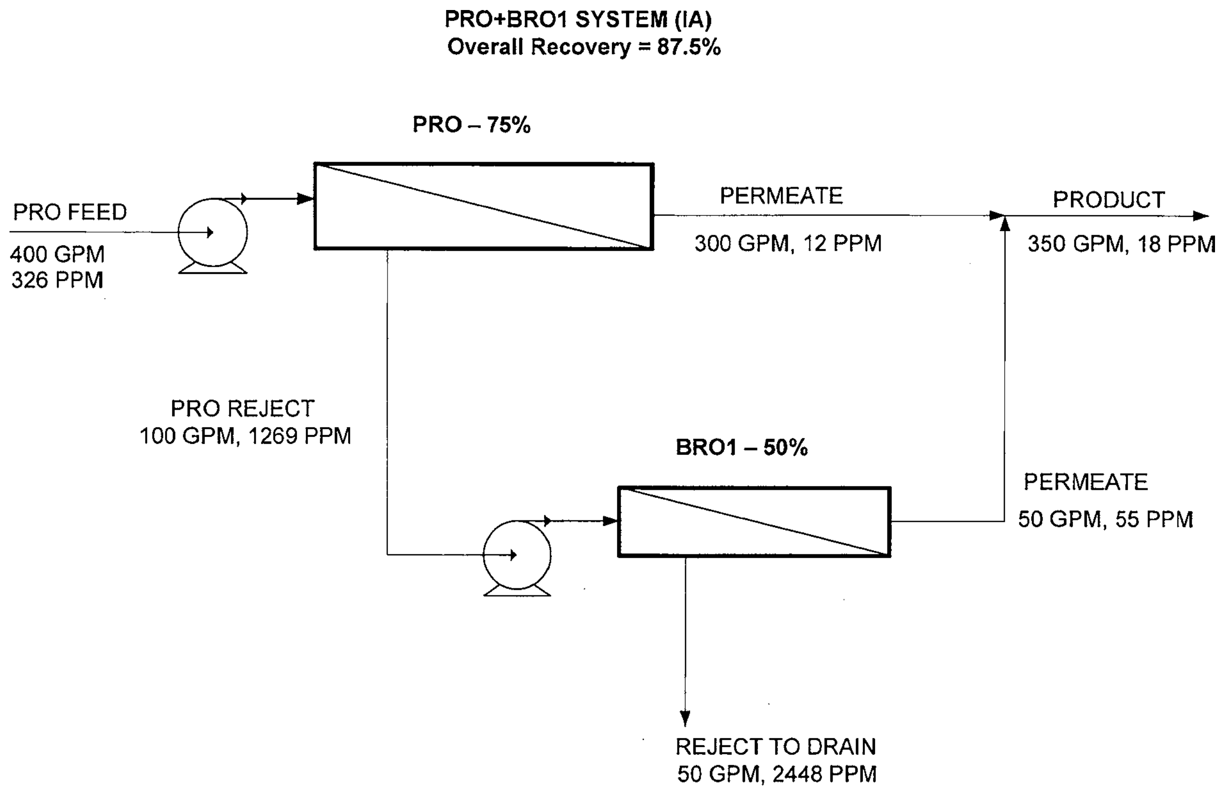

Fig. 4. Process flow diagram of a brine recovery system – Case IA. PRO recovery = 75%, BRO recovery = 50% and overall recovery = 87.5%.

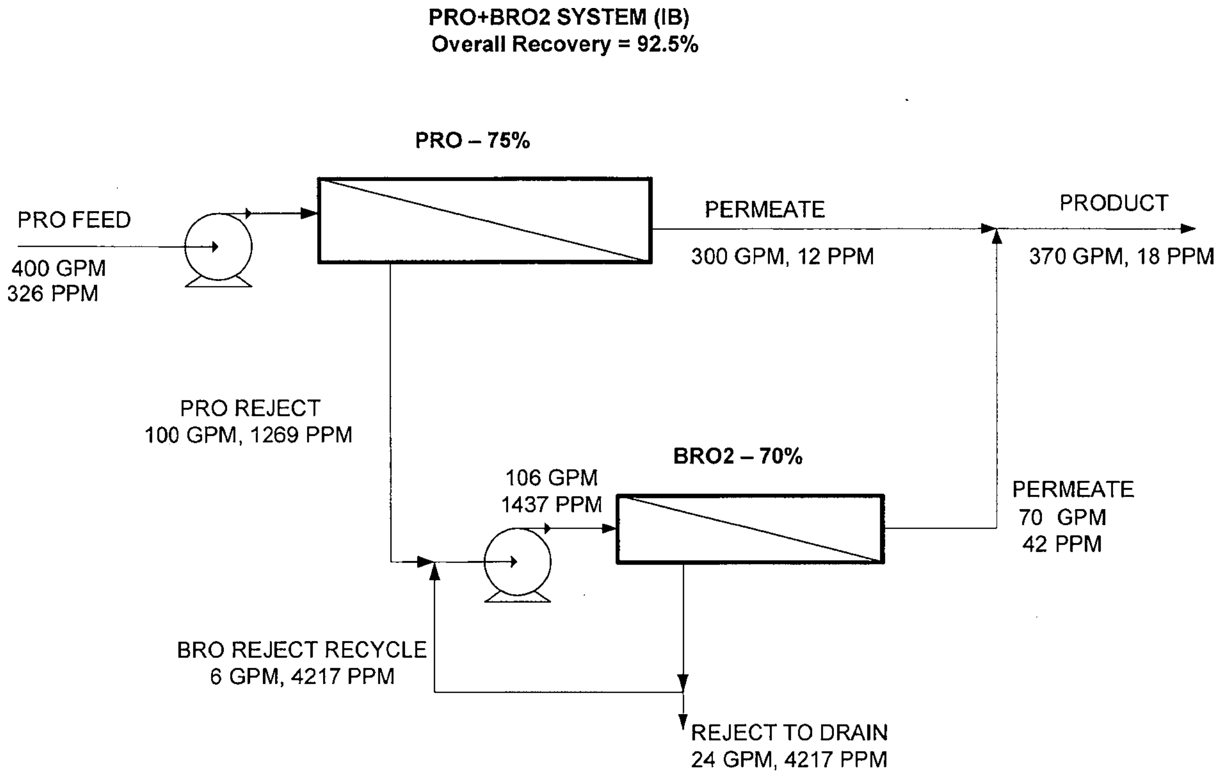

Fig. 5. Process flow diagram of a brine recovery system with reject recycle – Case IB. PRO recovery = 75%, BRO recovery = 70% and overall recovery = 92.5%.

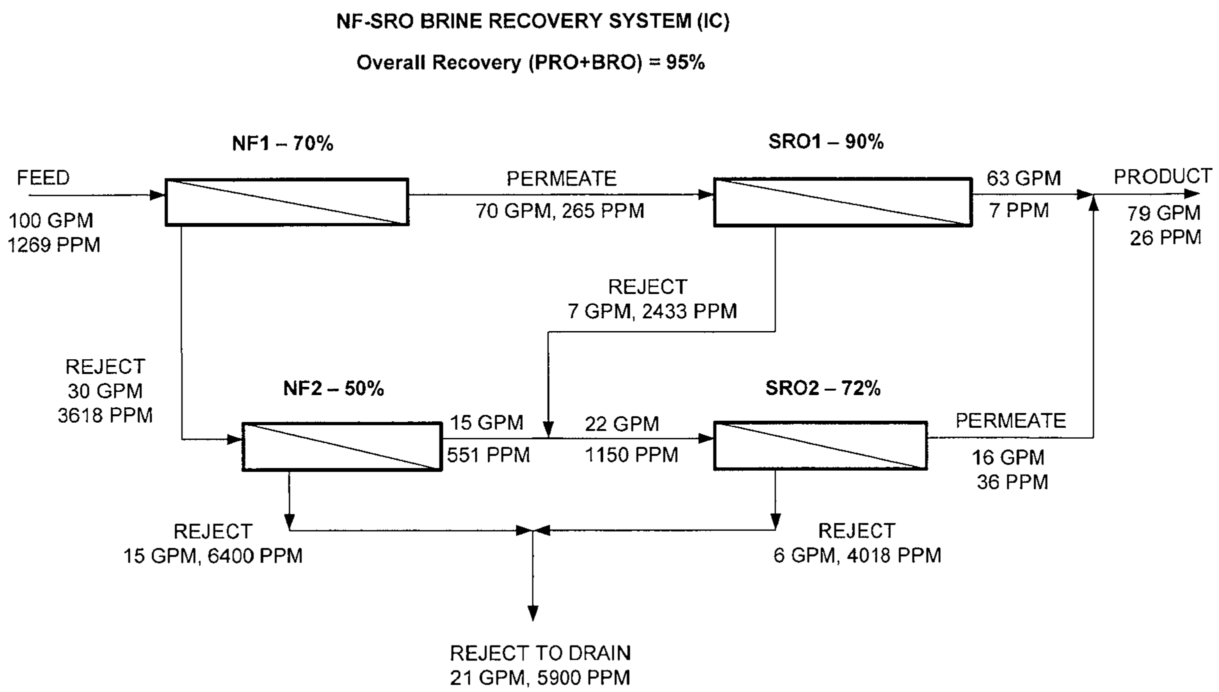

Fig. 6. Process flow diagram of a high recovery NF–SRO brine recovery system – Case IC. PRO recovery = 75%, BRO recovery = 79% and overall recovery = 95%.

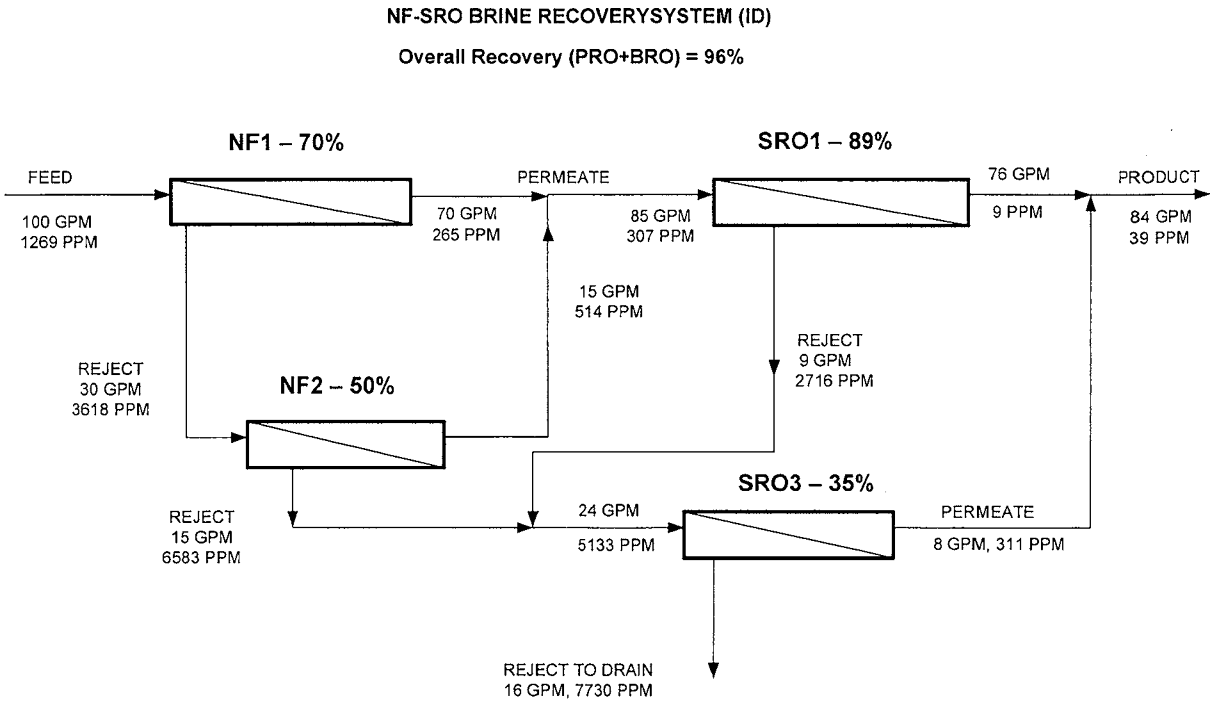

Fig. 7. Process flow diagram of a high recovery NF–SRO brine recovery system – Case ID. PRO recovery = 75%, BRO recovery = 84% and overall recovery = 96%.

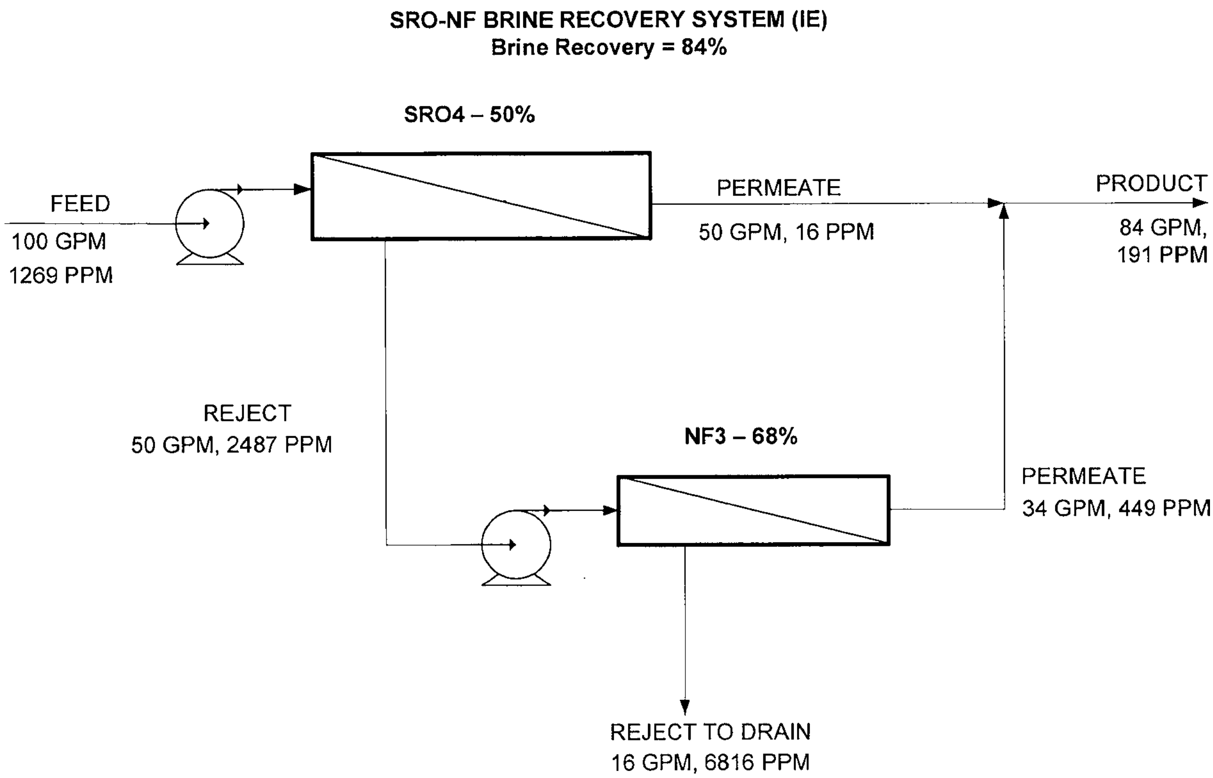

Fig. 8. Process flow diagram of a simplified high recovery SRO–NF system – Case IE. BRO recovery = 84%.

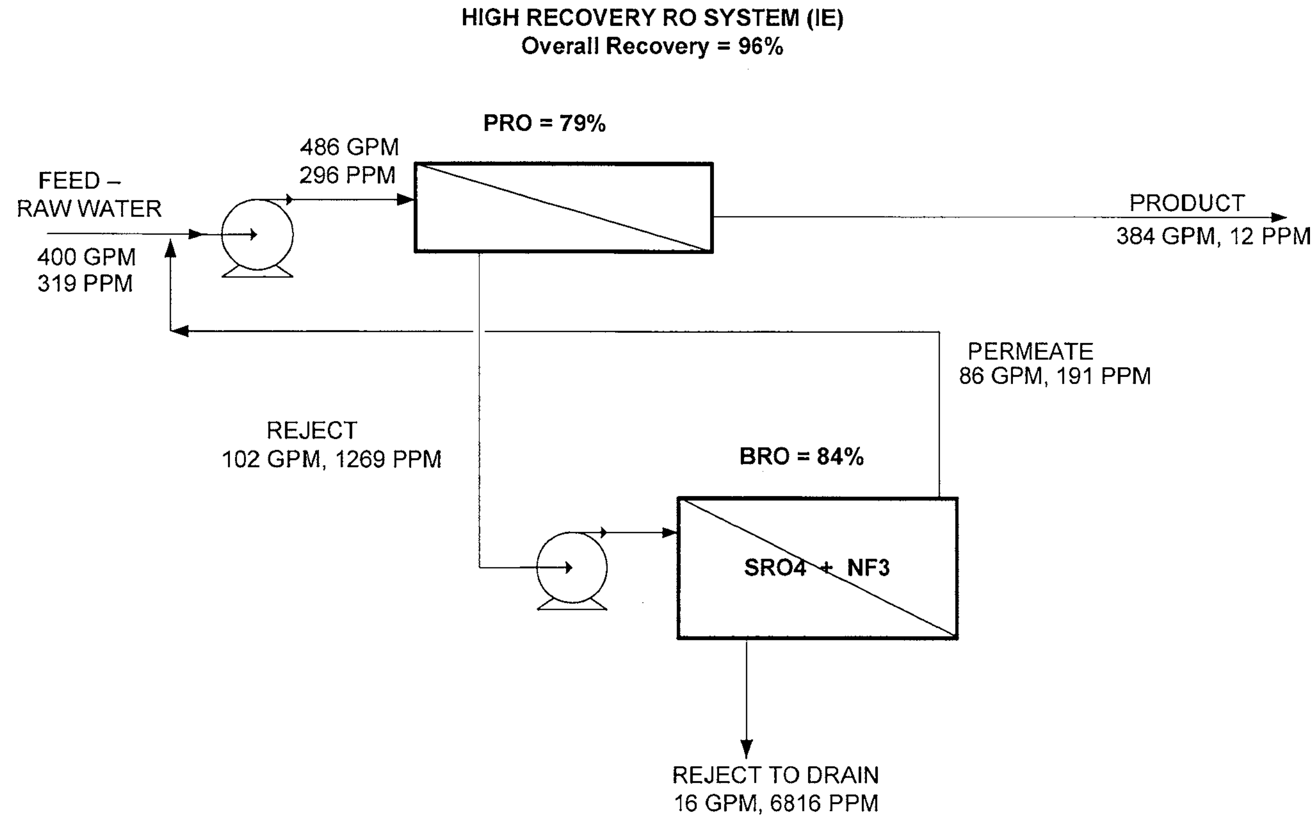

Fig. 9. Process flow diagram of a simplified high recovery RO plant – Case IE. PRO recovery = 79%, BRO recovery = 84% and overall recovery = 96%.

recovery system. Several combinations of RO and NF membrane schemes were analysed, and the most promising cases are summarised in Table 3. The mass balances are given in Figs. 6–9.

Case IC, Table 3. The data in Fig. 6 is a combination of two double-pass NF/RO integrated units wherein the permeate from NF1 is purified in SRO1, and the permeate from NF2 is combined with the reject from SRO1, and purified in SRO2. This combination achieves a recovery of 79% for the BRO system, and an overall recovery of 95% (379 gpm/400 gpm). The product water recoveries for NF1, SRO1, NF2 and SRO2 were 70%, 90%, 50% and 72%, respectively. The NF1, SRO1, NF2 and SRO2 units were either single-stage or multi-stage arrays, i.e. 3:2, 6:3:2, 5:0 and 2:2, respectively. The membrane elements, respectively, were 40 cm diameter ESNA1-LF, 20 cm diameter ESPA1-4040, 20 cm diameter ESNA1-LF-4S, and 20 cm diameter CPA2-4040. ES stands for energy saving whereas CPA is the standard TFC membrane.

Case ID, Table 3. The data in Fig. 7 is also a combination of multiple NF/RO integrated units. In this case, the permeate from NF1 is combined with the permeate from NF2 before it is purified in SRO1 defined as a *dual double-pass system*. The reject from SRO1 is combined with the reject from NF2 and purified in SRO3. The BRO system recovery is 84% resulting an overall recovery of 96% (384 gpm/400 gpm) for the RO plant. The product water recoveries for NF1, NF2, SRO1 and SRO3 were 70%, 50%, 89% and 35%, respectively. The NF1, NF2, SRO1 and SRO3 units were either single or multi-stage arrays, i.e. 3:2, 5:0, 8:4:3 and 2:0, respectively. The membrane elements, respectively, were 40 cm diameter ESNA1-LF, 20 cm diameter ESNA1-LF-4S, 20 cm diameter CPA2-4040 and 20 cm diameter ESPA1-4040.

In all the above discussed cases, the brine system product water is blended with the PRO product water. The TDS of the blended product water for Case IC is 26 ppm as compared to 39 ppm for Case ID. Both are higher than 18 ppm for Cases IA and IB, which operated at lower recoveries. The rejection of NF membranes was considerably lower than the RO membranes as expected (Table 3).

The modelling data show that the brine recovery systems designs in Figs. 6 and 7 though very effective may be complicated to operate because of several control valves that require adjusting simultaneously to

Table 4
Brine recovery SRO design summary – high TDS water

Case*	PRO feed water TDS (mg/L)	PRO feed flow (gpm) (1)	PRO product flow (gpm) (2)	SRO feed water TDS (mg/L)	SRO feed flow (gpm) (3)	SRO product flow (gpm) (4)	SRO rec. (%)	SRO pump power (kW)
II	563	120	90	2200	30	18	60	4
IIIA	945	285	213	3640	72	43	58	9
IIIB	945	800	600	3640	200	120	60	22
IIIC	945	1200	900	3640	300	186	62	38
IV	1705	533	400	6650	133	80	60	19

Notes: The membrane system designs were modelled using Dow/Film-Tec ROSA software 6.1.
*For feed water analysis, refer to Table 2.
1 $m^3/h = 4.4$ gpm.
PRO recovery (2/1) = 75%.
SRO recovery = (4/3).
SRO feed water pH 6.5–6.8; temperature 65 °F (18 °C).
Average flux = 10–12 gfd (17–20 L/m^2 h).

achieve the desired productivity as shown in Fig. 1 [4]. Automatic control of these modulating valves to the desired set points can be especially difficult. A simplified process scheme that evolved from the above designs is discussed next.

Case IE, *Table 3*. In this case shown in Fig. 8, the PRO brine flows to RO unit, SRO4 at 100 gpm (22.7 m^3/h), and the SRO4 reject flows to NF unit, NF3 at 50 gpm (11.4 m^3/h). Unlike the two cases discussed above, this design is not based on double-pass membrane units. The SRO4 and NF3 membrane arrays were 3:0 and 6:4, respectively. The membrane elements, respectively, were 40 cm diameter ESPA2+ and 20 cm diameter ESNA1-LF-4S.

The system is simple and yet capable of achieving a recovery of 84% for the BRO system. The product water recoveries for SRO4 and NF3 were 50% and 68%, respectively. The product water TDS, however, was considerably higher equal to 191 ppm but well below the US EPA maximum of 500 ppm.

In the earlier designs (Figs. 4 and 5) the brine system permeate was blended with the PRO permeate. In this design, the brine product water is mixed with the PRO feed water as shown in Fig. 9 resulting in a PRO feed water with lower TDS and higher flow rate. This proved to be a very attractive option; the PRO unit was able to operate at a higher recovery of 79% producing the best quality product water with TDS equal to 12 ppm. The overall system recovery was 96%. In addition, the specific energy consumption was nearly one-half of that in Cases IC and ID (Table 3).

Because of the simplicity of the design shown in Fig. 9 and much higher performance, this flow scheme was selected for designing and evaluating the performance of RO/NF integrated high recovery brine systems with more aggressive feed waters and a broad range of flow rates.

4.2. Brine recovery membrane system design – high TDS water

The design for Cases II, III and IV given in Table 2 was based on the conditions given below. In all the cases the water has higher TDS, hardness, alkalinity and silica than Case I.

- PRO feed water TDS = 500–1700 ppm (nominal).
- PRO feed water flow rates = 120–1200 gpm (27–270 m^3/h).
- PRO recovery = 75%.
- PRO reject flow rates = 30–300 gpm (7–70 m^3/h).
- PRO reject/brine TDS = 2200, 3600 and 6600 ppm (nominal).

The membranes used to model the systems were Dow/Film Tec. The RO membranes were BW30-400/34i (40 cm diameter) and BW30-4040 (20 cm diameter). The NF membranes were NF90-400 (40 cm diameter) and NF90-4040 (20 cm diameter). The design data is summarised in Tables 4 and 5. All process flow schemes are similar to the ones shown in Figs. 8 and 9. (col.8). Three highlighted cases, II, IIIC and IV, are illustrated in Figs. 10–12.

The data in Table 5 show that the brine system recovery [SRO + NF] varies between 79% and 83%. This translates to an overall system [PRO + BRO] recovery in all cases between 95% and 96% when the PRO unit recovery is 75% where BRO stands for SRO + NF.

Table 5
Brine recovery system design summary – high TDS water

Case*	PRO feed flow (gpm) (1)	PRO product flow (gpm) (2)	SRO product flow (gpm) (3)	NF feed flow (gpm) (4)	NF product flow (gpm) (5)	NF rec. (%)	Brine system rec. # (%)	Overall rec. + (%)	NF pump power (kW)	Brine system energy consum.** (kWh/m^3)
II	120	90	18	12	7	58	83	96	1.5	0.97
IIIA	285	213	43	29	14	48	79	95	2.5	0.89
IIIB	800	600	120	80	40	50	80	95	7.5	0.81
IIIC	1200	900	186	114	55	48	80	95	9	0.86
IV	533	400	80	53	27	51	81	95	7.5	1.1

Notes: The membrane system designs were modelled using Dow/Film-Tec ROSA software 6.1.
*For feed water analysis, refer to Table 2.
Refer to Table 4.
1 m^3/h = 4.4 gpm.
PRO recovery (2/1) = 75%; NF recovery = (5/4).
#Brine system recovery = (3 + 5)/(1 − 2).
+Overall recovery = (2 + 3 + 5)/1.
NF feed water pH 6.5–6.8; temperature 65 °F (18 °C).
**SRO power + NF power/SRO permeate + NF permeate, (kW÷gpm) × (4.4 gpm÷m^3/h).
Average flux = 10–12 gfd (17–20 L/m^2 h).

The specific energy consumption varied between 0.81 and 1.1 kWh/m^3. These numbers were higher than those for Case IE in Table 3 due to much higher feed water TDS and osmotic pressure resulting in higher pump power. For example, the brine TDS in Fig. 9 is 1269 ppm compared to 2200, 3640 and 6650 ppm in Figs. 10–12, respectively (see also Table 2).

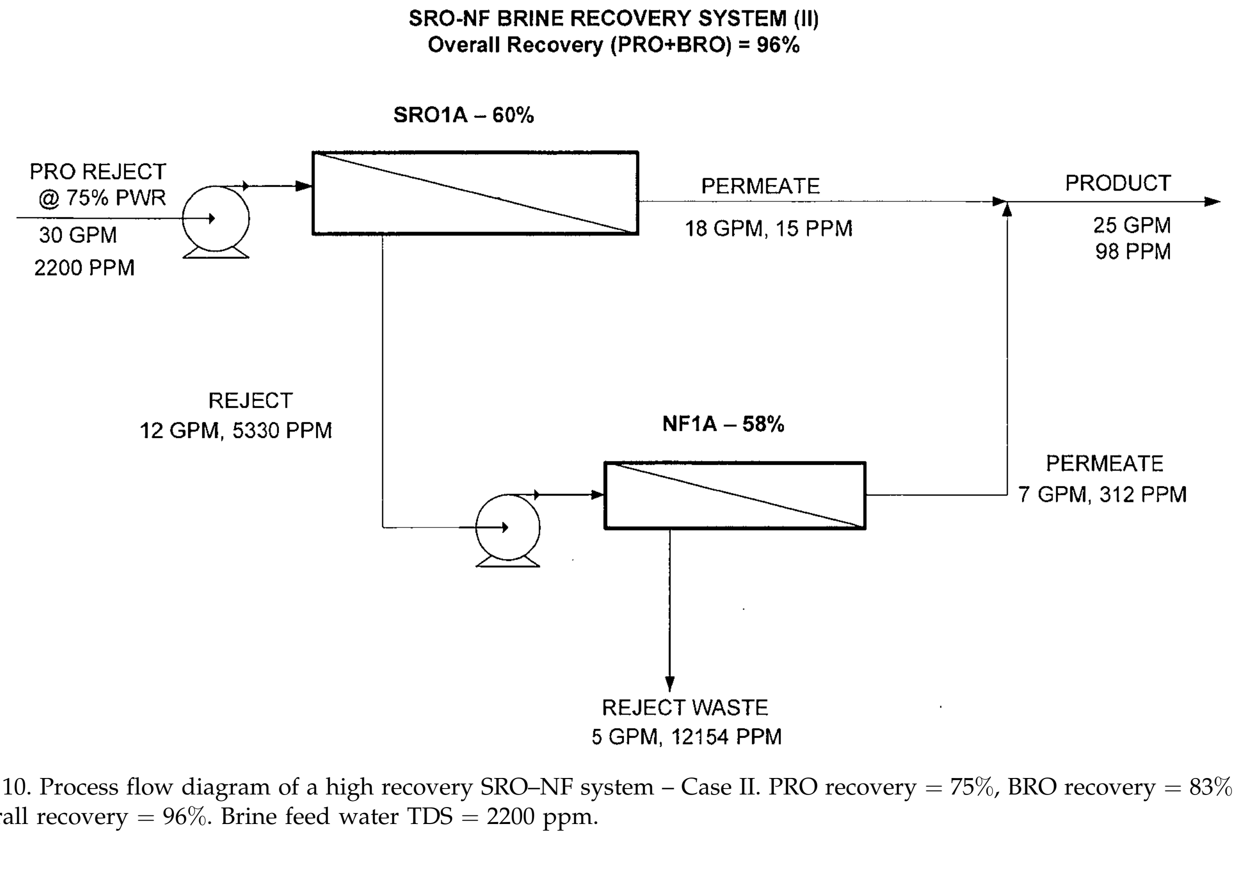

Fig. 10. Process flow diagram of a high recovery SRO–NF system – Case II. PRO recovery = 75%, BRO recovery = 83% and overall recovery = 96%. Brine feed water TDS = 2200 ppm.

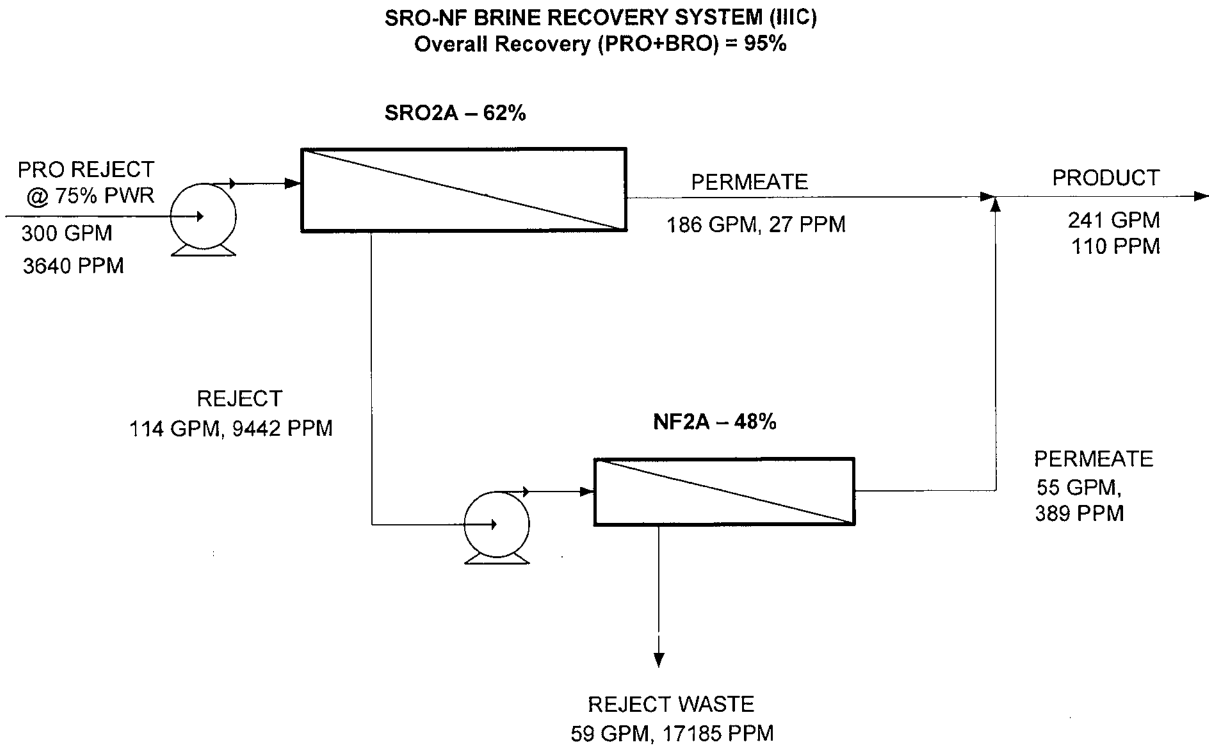

Fig. 11. Process flow diagram of a high recovery SRO–NF system – Case IIIC. PRO recovery = 75%, BRO recovery = 80% and overall recovery = 95%. Brine feed water TDS = 3640 ppm.

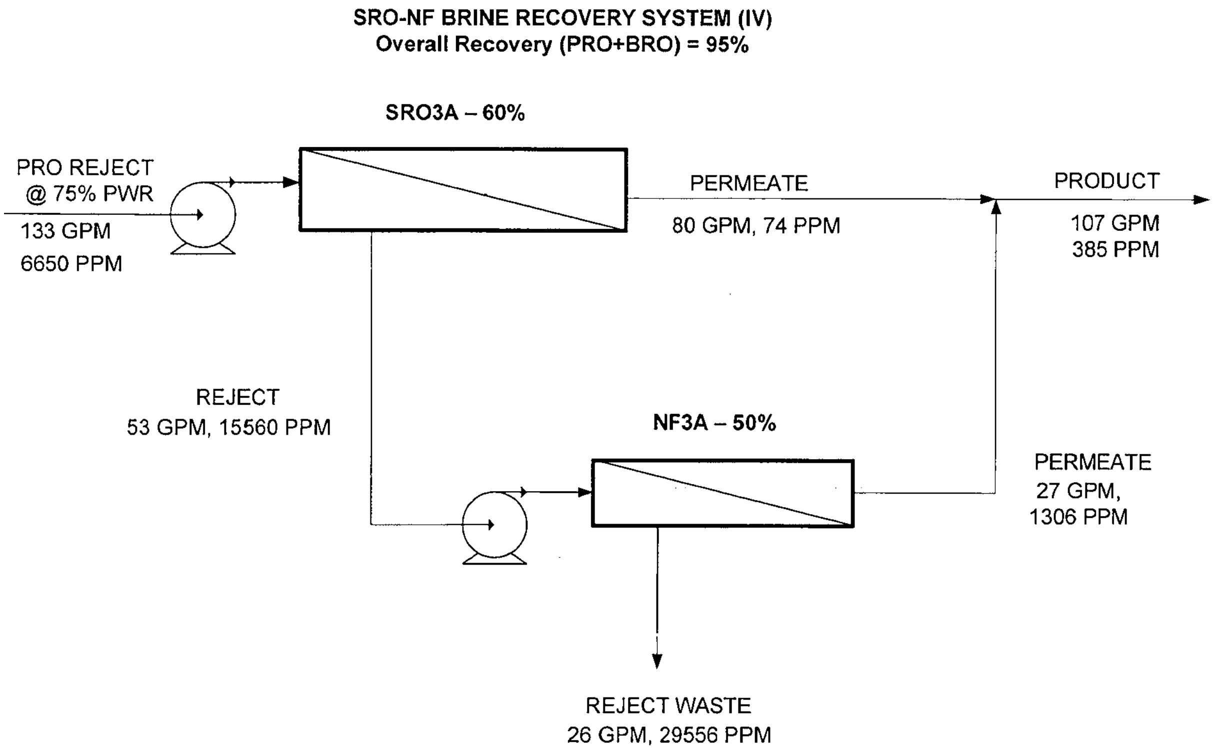

Fig. 12. Process flow diagram of a high recovery SRO–NF system – Case IV. PRO recovery = 75%, BRO recovery = 81% and overall recovery = 95%. Brine feed water TDS = 6650 ppm.

Case II, Tables 4 and 5. In this case shown in Fig. 10, the PRO brine flows to RO unit, SRO1A at 30 gpm (6.8 m^3/h), and the SRO1A reject flows to NF unit, NF1A at 12 gpm (2.7 m^3/h). The SRO1A and NF1A units were three-stage arrays (3:0) containing 20 cm diameter membrane elements.

The product water recoveries for SRO1A and NF1A units were 60% and 50%, respectively. The brine system recovery, therefore, was 84% (25 gpm product/30 gpm feed). Since, the PRO unit recovery was 75% (90 gpm product/120 gpm feed), the overall system [PRO + BRO] recovery was 96% (115 gpm product/120 gpm feed).

The brine system feed (PRO reject) TDS is 2200 ppm (Table 2). The SRO unit permeate TDS is 18 ppm while the NF unit permeate TDS is quite high equal to 312 ppm. The SRO and NF blended product water TDS, however, is only 98 ppm. When the BRO product water is blended with the higher flow rate and higher quality PRO product water (see Table 2), the overall potable water TDS would be much lower.

Case IIIC, Tables 4 and 5. As shown in Fig. 11, the PRO brine flows to RO unit, SRO2A at 300 gpm (68 m^3/h) and the SRO2A reject flows to NF unit, NF2A at 114 gpm (26 m^3/h). The SRO2A and NF2A units were three-stage (6:4:2) and two-stage (4:2) arrays, respectively, containing 40 cm diameter membrane elements.

The product water recoveries for SRO2A and NF2A units were 62% and 48%, respectively. The brine system recovery, therefore, was 80% (241 gpm product/300 gpm feed). Since, the PRO unit recovery was 75% (900 gpm product/1200 gpm feed), the overall system [PRO + BRO] recovery was 95% (1141 gpm product/1200 gpm feed).

The brine system feed water TDS (PRO reject water) is 3640 ppm as given in Table 2. The SRO unit permeate TDS is 27 ppm while the NF unit permeate TDS is quite high equal to 389 ppm. The SRO and NF blended product water TDS, however, is only 110 ppm. When the BRO product water is blended with the higher flow rate and higher quality PRO product water (see Table 2), the overall potable water TDS would be much lower.

Case IV, Tables 4 and 5. As shown in Fig. 12, the brine flows to RO unit, SRO3A at 133 gpm (30 m^3/h) and the SRO3A reject flows to NF unit, NF3A at 53 gpm (12 m^3/h). The SRO3A and NF3A units were three-stage (3:2:1) and two-stage (2:1) arrays, respectively, containing 40 cm diameter membrane elements.

The product water recoveries for SRO3A and NF3A units were 60% and 51%, respectively. The brine system recovery, therefore, was 81% (107 gpm product/133 gpm feed). Since, the PRO unit recovery was 75% (400 gpm product/533 gpm feed), the overall system [PRO + BRO] recovery was 95% (507 gpm product/533 gpm feed).

The brine system feed water TDS (PRO reject water) is 6650 ppm as given in Table 2. The SRO unit permeate TDS is 74 ppm while the NF unit permeate TDS is very high equal to 1306 ppm. The SRO and NF blended product water TDS, however, was 385 ppm. Although quite high, it is well below the US EPA standard of 500 ppm and the WHO standard of 1000 ppm. When the BRO product water is blended with the higher flow rate and higher quality PRO product water (see Table 2), the overall potable water TDS would be much lower.

5. Discussion and Conclusions

Volume reduction of brine streams at industrial RO membrane plants is a major issue because of disposal costs. Further, to conserve water and reduce plant operating costs, the reject wastewater needs to be reclaimed. It is also important in the case of inland communities especially in arid regions because the RO brine stream raises the salt concentration of soil to unacceptable levels for downstream agricultural and other uses [3].

Lime softening is the most common process as discussed earlier in the paper. Recently, other techniques have been suggested such as a hybrid membrane process that utilizes a fluidized bed crystallizer [11], forward osmosis [12] and direct contact membrane distillation [13]. None of these is a viable technology yet. Other technologies include membrane vibratory shear enhanced process (VSEP) and high efficiency RO (HERO™) process [6]. The latter is very effective for treating water with high silica but, is quite equipment intensive. It consists of pre-treating the PRO water with ion exchange and acid followed by degasification, and

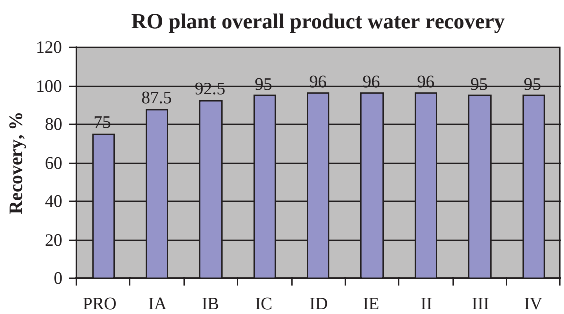

Fig. 13. Bar chart showing overall product water of the RO plant for all cases.

then adding caustic soda to raise the pH to 10–11, which results in increasing the silica solubility to 1500 ppm.

Much simpler state-of-the-art SRO–NF brine recovery processes were demonstrated in this study. The design performance data depicting overall product water recovery (OPWR) for all the cases investigated with the PRO reject water TDS between 1000 and 7000 ppm are illustrated in Fig. 13. The cost of the system varies between $40,000 for the 30 gpm system (Case II) and $140,000 for the 300 gpm system (Case IIIC).

The data show that the PRO–SRO–NF hybrid membrane process is capable of achieving OPWR of 95–96% with minimal in-line chemical treatment for brine streams with the following component concentrations: silica < 60 ppm, sulfate < 1000 ppm, hardness < 2500 ppm and LSI < 1.8. Increasing the recovery of the RO plant from 75% to 90% is not difficult but increasing it from 90% to 96% is quite complex.

In order to achieve OPWR > 96% and for higher hardness and silica feed waters, several treatment options come into play including:

- IX softening of PRO feed water and reduce the pH to <6.0 or increase the pH to >9.0 to increase silica solubility.
- Soften PRO reject water with lime softening followed by clarification with a conventional clarifier for large flows and a cross-flow MF process for low flows as shown in Fig. 2. Polishing filtrate RO is required.
- A PRO–electrodialysis (ED) hybrid process to achieve up to 98% recovery [14]. The process involves treating the PRO reject by ED, precipitating excess calcium sulfate in the concentrate stream and obtaining an ED concentrate with TDS > 10%.
- Process the final reject water stream from the SRO–NF system with lime softening followed by clarification with a cross-flow MF. Recycle the MF filtrate to the SR–NF system.

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