

“HEURISTIC ANALYSIS OF BRACKISHWATER TREATMENT BY REVERSE OSMOSIS PROCESS”

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ABSTRACT

Treatment of brackish water and sea water with the help of reverse osmosis process is feasible and a viable solution to meet the fresh water deficiency in an arid region. Total dissolved solids can be reduced to a level acceptable for drinking water. High purity water for industrial uses can also be obtained with the application of the RO process. Useful materials may also be recovered from the reject water. RO plants of various sizes (both large and small) have been in operation successfully in a number of countries which shows the reliability and predictability of the reverse osmosis process. For the efficient operation of reverse osmosis plants care is needed in determining the raw water quality, in understanding of the chemistry of the process, in designing the pre-treatment of the raw water, in selecting membrane and in setting the level of recovery of product water. The reject brine, at high pressure, may provide a secondary source of energy in large systems.

1. INTRODUCTION

Many communities living along sea coast, on islands and in the arid regions do not have sufficient natural freshwater resources. In such cases, sea water and brackish water, containing large amount of total dissolved solids (TDS) and chlorides, can be made suitable for use after reducing the TDS (Parker 1985; Schippers 1985; Temperley 1987; Torres et al. 1985; Wade 1985; Gross 1986; Muylle 1986; Samuel 1986).

The following processes may be used to reduce various ranges of total dissolved solids in water (Twort et al 1985).

Process	Removable Range of Total Dissolved Solids (mg/L)
Ion exchange	500 - 1500
Electrodialysis	500 - 3000
Reverse Osmosis (RO) with Standard Membrane	1000 - 5000
Reverse Osmosis (RO) with High Resistance Membrane	5000 and Over
Distillation	Above 30000

Selection of processes for water desalination requires careful evaluation of process efficiency and of capital and operating costs. However, the RO process has a broad range of capability, and is being increasingly used to produce pure water from salt water.

The main objective of this paper is to discuss the application of the RO process in reducing the large amount of dissolved solids in brackishwater. The properties of the membranes used in the RO process, the pre-treatment required of the raw water, and the operation of the treatment system are examined. The chemistry of the process is explained for better understanding of what transpires during the treatment process. The effect of feed water quality and the level of recovery of product water on the membrane, including brine disposal problems, are discussed.

In an osmosis process water passes through a semi-impermeable membrane from pure water or a weak solution into a more concentrated solution (Fig. 1). A semi-permeable membrane has the property of allowing the solvent to pass in both directions, but it prevents or retards the passage of ions. This effect can be reversed by applying sufficiently high pressure to the more concentrated solution and as a result, ion-free water can be separated from salt water by moving through the membrane. This process is known as reverse osmosis and may be viewed as a filtration process on a molecular, or ionic scale as the dissolved materials that can pass through the membrane are very small in size (Levine et al 1985; Sunderstrom and Klei 1987) (Fig. 2) (Appendix 1).

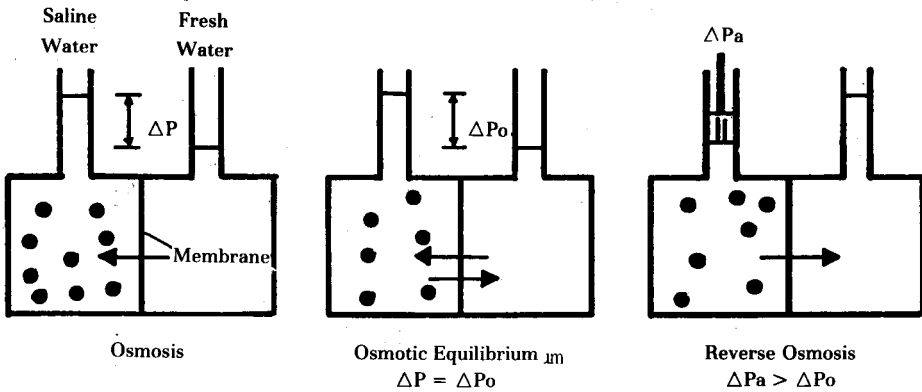
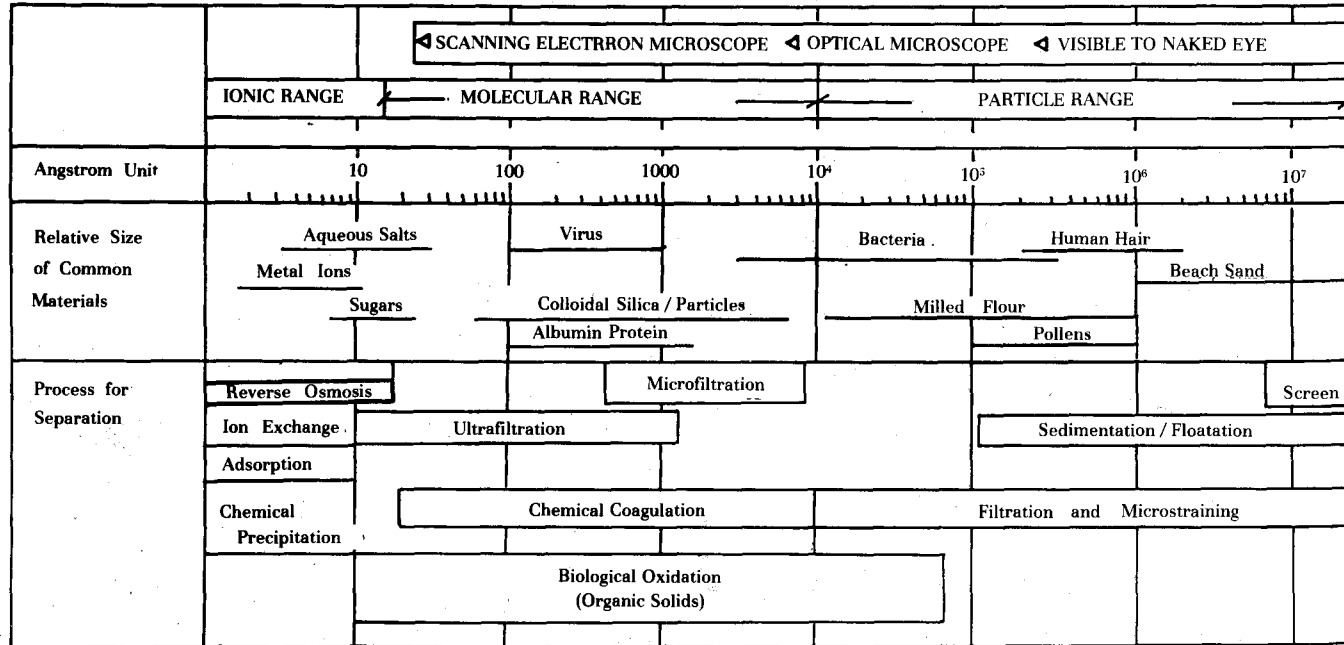


Fig. 1 : Conceptual Model of Osmotic and Reverse Osmosis Processes .

The number of RO plants producing potable, or industrial process water has increased considerably in recent years, especially in arid regions where the groundwater is generally brackish (TDS 2000 - 2500 mg/L), or seawater is available (TDS 30,000 mg/L and above) (Walton 1987; Samuel 1986). Presently RO is being used for water treatment in just over one hundred countries including USA, Gibraltar, Malta, Carribean Islands, Saudi Arabia, Libya, Qatar, Bahrain and Oman (Walton 1987; Gros 1986). With the number of plants increasing membranes are becoming less costly, have better performance and have longer lives (Crosslay 1983; Torres 1985; World Water 1986).

RO is also being used to produce chemical process water for the electronics industry, to treat industrial wastes and to control toxic metals in leachates from the landfill, to demineralize irrigation returnflows, to recover economically valuable raw materials such as proteins and precious metals from waste streams, to remove materials which are difficult to separate from water, and to permit water reuse and recirculation in high rise buildings (Irwin 1987; Marquardt 1987 and 1988; Squires 1984; Wolrd Water 1987).



1 Angstrom Unit = 10⁻¹⁰ m

Fig. 2 : Application of Unit Processes for Various Particle Ranges.

To combat fresh water deficiency a number of proposals have recently been put forward in different countries. Libya proposed the transfer of fresh water from Turkey to water deficient countries like Saudi Arabia and Arabian Gulf countries (George 1987; World Water 1987). India developed a plan to connect all its rivers to control floods and to balance deficits in dry areas. Pakistan proposed to transport water from the glaciers in the Himalayas to the water deficit areas in the south.

Such proposals to transport freshwater from either neighbouring countries, or from one region to the other region in the same country, have far reaching political as well as economic and environmental implications. Despite the billions of cubic meters of stored water behind Aswan Dam in Egypt, the cost of piping water from the Nile River to remote areas made it uneconomical (George 1987). Therefore, exploitation of water resources close to the areas of its use still remains an attractive proposition, if reliable treatment technology is available.

2. MATERIALS, CHARACTERISTICS AND TYPE OF MEMBRANES

The membrane material used in the reverse osmosis process typically consists of a cellulose acetate composition, or of mixed esters of cellulose. These are mixed with polymer casting solution, swelling agents and solvating agents. The fabrication process influences the rate of flow of water through the membrane and the selectivity of the product membrane (Scott 1981).

Synthetic materials like polyamides, diamines plus amino-isophthalic acid, or polyethers, polybenzindiazoles, polyoxidiazoles, and piperazine based complexes are also used to manufacture the membrane. Since the membrane surface is extremely thin (0.05×10^{-6} to 0.25×10^{-6} mm thick), it must be supported on a dense material backed by spongy layers about 100 microns thick to withstand high pressure.

Membranes having the following four configurations are available on the market: tubular; hollow fiber; flat plate; spiral wound and rolled flatsheets (Fig. 3). Typical water fluxes vary between 5×10^{-3} and 10^{-2} $\text{m}^3 / \text{m}^2 / \text{day}$ for hollow fibers and 0.5 and 1 $\text{m}^3 / \text{m}^2 / \text{day}$ for cellulose sheets. It should be noted that the stacking densities for hollow fibers are about ten-times greater than for rolled sheets and as a result are more space efficient in space required per unit of flux rate (Sunderstrom and Klei 1987).

Heuristic Analysis of Brackishwater Treatment by Reverse Osmosis Process

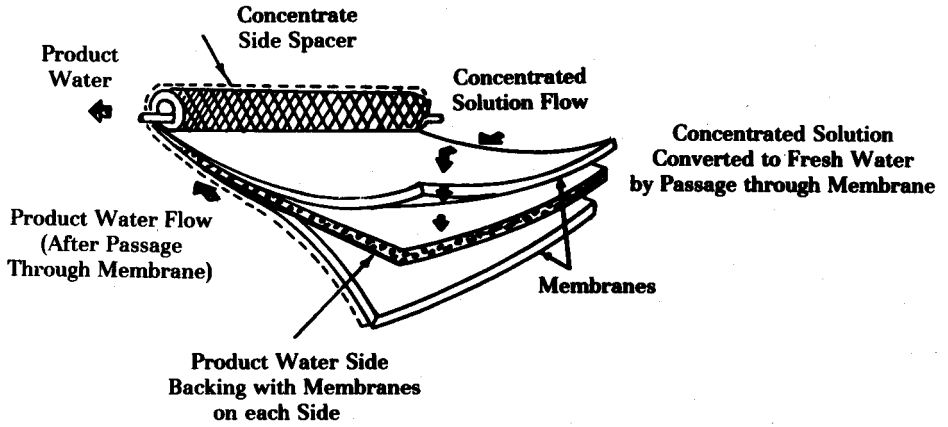


Fig. 3a : Spiral Wound Membrane Module .

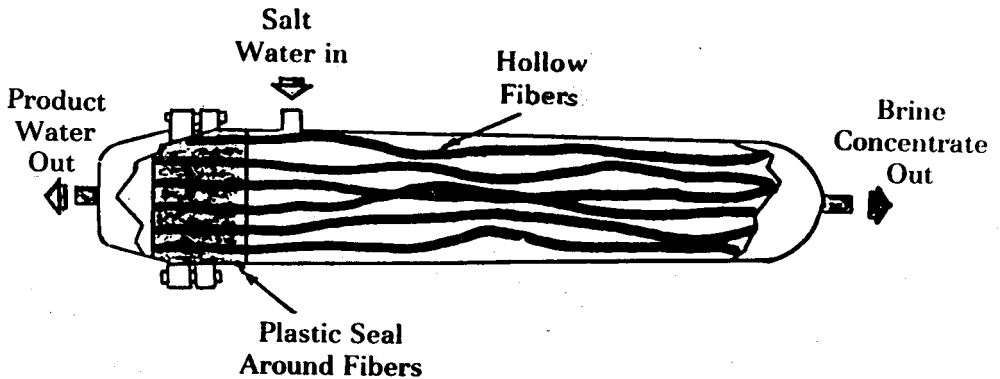


Fig. 3b : Hollow Fiber Process

The membrane should allow sufficient waterflux and should withstand the required pressures. It should also display resistance to compaction, stability with temperatures, resistance to organic matter, and it should produce bacteriologically pure water. Membranes with these specifications will have increased life and will result in minimum maintenance problems.

Shamim Ahmad

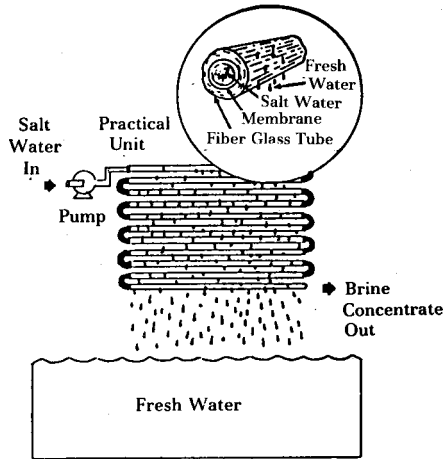


Fig. 3c : Tubular Process.

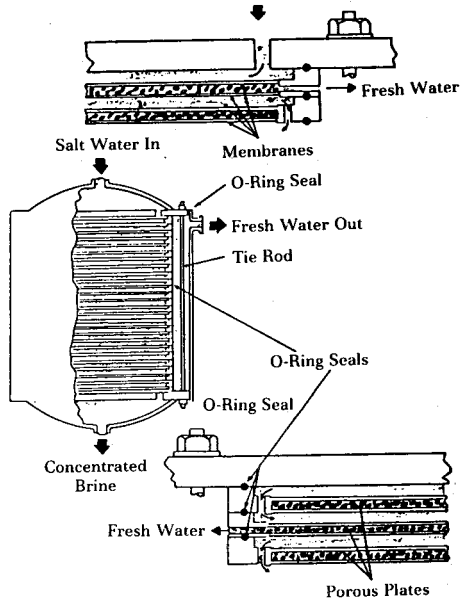


Fig. 3d : Plate and Frame Process Design.

3. OSMOTIC PRESSURE

The osmotic pressure P may be calculated as follows:

$$P = CRT \quad (\text{N/m}^2) \quad (1)$$

where: C = difference in concentration between the feed and the permeate (moles / m^3)

R = molar constant of a perfect gas (8.324 J/mole $^\circ\text{K}$)

T = absolute temperature ($^\circ\text{K}$)

The smaller the molecule, i.e. the lower the molar mass, the greater the osmotic pressure set up by the same difference in concentration (Appendix 2). Smaller molar mass materials require greater pressure as compared to higher molar mass materials.

4. FLUX EQUATIONS

The pressure applied to the membrane is a function of the osmotic pressure, the resistance of the membrane to flow, the required flow and the temperature (Tchobanoglous and Schroeder 1985).

Flux of water may be determined as follows:

$$F_w = w(P_a - P) \quad (2)$$

Solute flux is described as follows:

$$N_s = K_s (C') \quad (3)$$

where; F_w = Flux of water through the membrane ($\text{kg} / \text{m}^2, \text{s}$)

- w = Flux rate coefficient involving temperature, membrane characteristics, solute characteristics (s/m)
- P_a = Applied pressure (KPa)
- P = Osmotic pressure (KPa)
- N_s = Flux of salt through the membrane (kg/m²,s)
- K_s = Overall mass transfer coefficient for salt (m/s)
- C' = Difference in concentration between the feed and the permeate (kg/m³)

The solute rejection, "e", is defined as the efficiency of rejection from the permeate of a specific solute:

$$e = (C'_f - C'_p) / C'_f \quad (4)$$

where C'_f and C'_p are solute concentrations in the feed and permeate respectively.

The required membrane area and the permeate total dissolved solids concentration can be determined with the equations given here. An example of the relevant calculations are shown in Appendix 3.

5. PROCESS CHEMISTRY

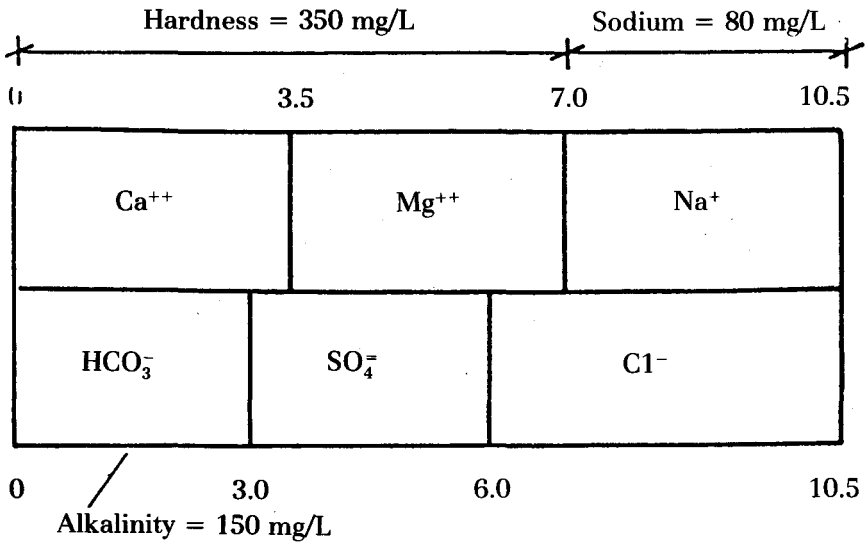
A study of the brackish water quality shows that generally calcium, magnesium and sodium cations are present in large concentrations (see Table 1). The dominant anion is chloride with relatively lower concentration of sulphate and bicarbonate anions. Non-carbonate hardness is present in large quantities which consequently prevents reduction in total dissolved solids by precipitation softening method. If softening is done by excess lime, sodium carbonate must be added to precipitate non carbonate hardness. The effect of sodium carbonate is to replace calcium and magnesium cations with sodium cation (see Fig. 4) (Clark et al 1977; Steel and McGhee 1984). Consequently, sodium concentration in the water increases which is undesirable. The addition of excess lime and soda does not considerably reduce the total dissolved solids, as it just replaces calcium and magnesium ions with sodium ions (Hammer 1987).

Table 1 : Examples of Raw and Treated Water Quality in Arab Countries using RO Process for Water Treatment. (All Values in mg/L except where stated).

Ionic Concentration	Qatar		Saudi Arabia		Saudi Arabia		Tunisia	
	Raw	Treated	Raw	Treated	Raw	Treated	Raw	Treated
Na ⁺	430	58	559	-	159	-	950	80
K ⁺	17	2.3	31	-	22	-	-	-
Ca ⁺⁺	248	6.0	216	-	171	-	170	5
Mg ⁺⁺	87.5	1.22	74.4	-	55	-	90	3
Fe ⁺⁺	-	-	-	-	4.0	-	0.51-1.0	-
HCO ₃ ⁻	161.1	3.9	256	-	214	-	200	6
SO ₄ ⁻	571	0.82	422	-	450	-	750	6
Cl ⁻	830	74	1030	-	363	-	1350	140
NO ₃ ⁻	12	2.7	-	-	4.3	-	-	-
SiO ₂	-	-	-	-	22-37.5	-	-	-
TDS	2400	170	2600-2700	350	1600	<100	3600	250
Temperature (°C)	28	-	-	-	54.5	-	14	-
CO ₂	-	-	-	-	34	-	-	-
pH value	7.4	-	7.8	-	-	7.8	-	-

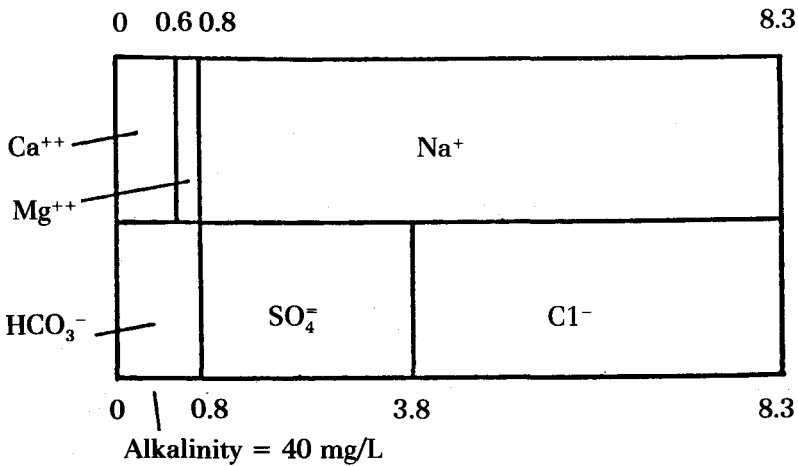
Heuristic Analysis of Brackishwater Treatment by Reverse Osmosis Process

Shamim Ahmad



Initial TDS = 900 mg/L

(a) Raw Water



Final TDS = 600 mg/L

(b) After Softening

Fig. 4 : Bar Graph for Precipitation by Softening .

Heuristic Analysis of Brackishwater Treatment by Reverse Osmosis Process

Typical brackish water and treated water quality are presented in the form of a bar-graph which shows the effectiveness of RO process in removing large amount of total dissolved solids in water (see Fig. 5). For comparison few examples of brackish water treatment in Arab countries using RO process are given in Table 1. TDS values of the raw water and treated water are presented in the scatter diagram (see Fig. 6) which indicates that a suitable quality of water is produced by RO process. The RO process has been found reliable and has shown to perform predictably well over a long period of time (MEW & S 1985; Gross 1986).

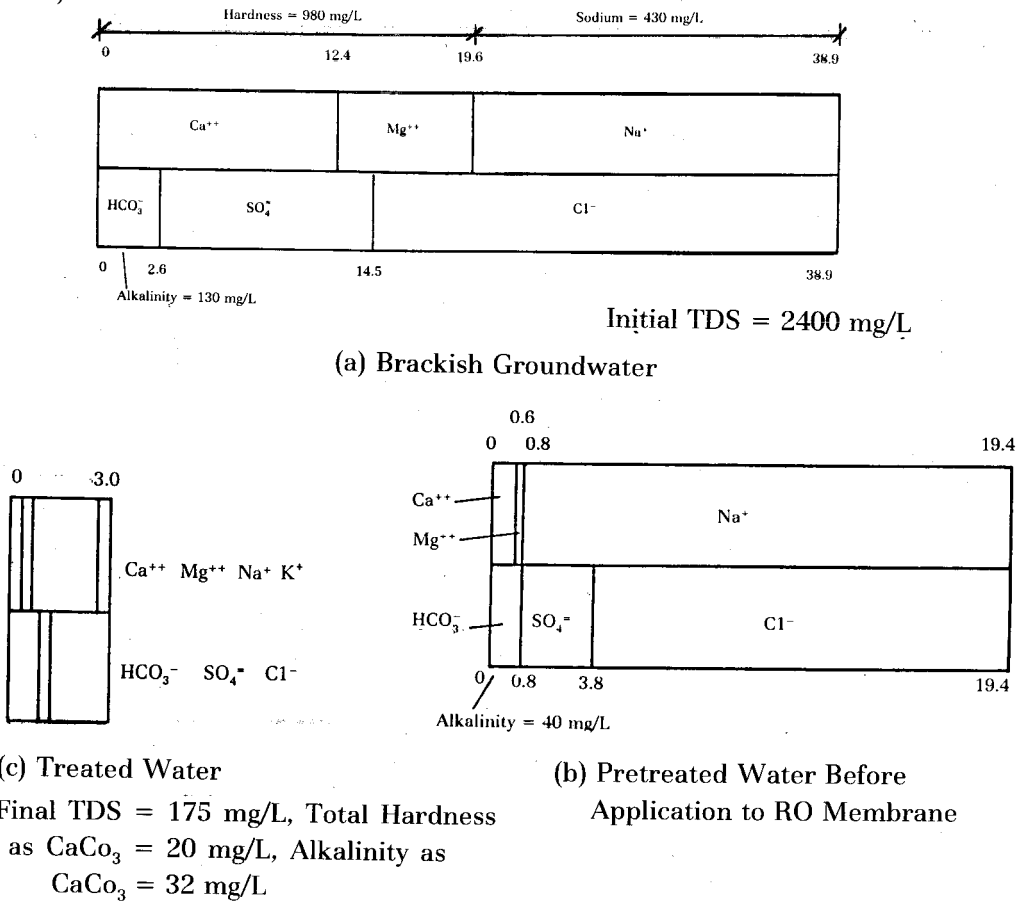


Fig. 5 : Bar Graph Representing Raw Water and Treated Water Quality

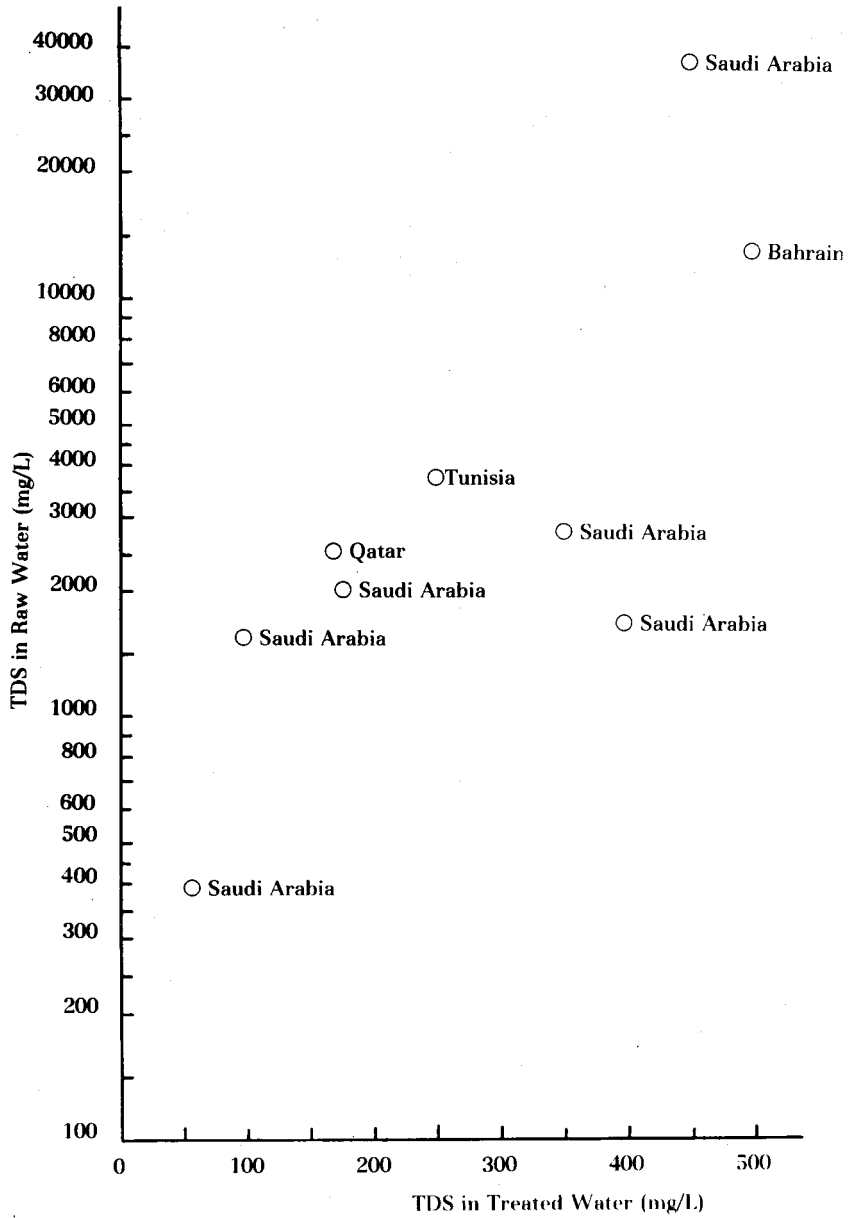


Fig. 6 : Relationship Between TDS in Raw Water and Treated Water .

6. PRETREATMENT TECHNIQUES

The pretreatment of raw water is necessary to avoid fouling and clogging of membranes due to suspended solids and colloids. The more common foulants are silica, iron, calcium carbonate, calcium sulphate, strontium sulphate, barium sulphate and heavy metals. It is also important to know the presence of dissolved gases like oxygen, carbon dioxide, hydrogen sulphide and volatile organic compounds in the raw water. Membranes are sensitive to the raw water composition and are affected by variations in the composition and contaminations. Therefore the raw water quality and the pretreatment process are to be monitored carefully.

Standard turbidity measurements are not adequate to detect fouling potential and therefore the concentration of colloids is determined by measuring SILT DENSITY INDEX (SDI) of water. SDI is calculated from the rate of plugging of a 0.45 micron millipore filter when water is passed through the filter at 2 bar (Pohland 1981) (Appendix 4). The SDI value criteria for treatment and applications are given in Table 2. Pretreatment by pressure filters may reduce SDI by factor of 2 i.e. from 6 to 3 and ultrafilters, which are generally used for small plants may reduce SDI to 1.0.

Table 2 : Silt Density Index

	SDI	Remarks
Well Water	0.5-1.0	No difficulty with respect to suspended solids
Treated Surface water;		
(a) For municipal use	6	Additional pretreatment required
(b) For membrane application	3	Desirable

The maximum allowable temperature range for membrane varies between 35° and 80°C depending upon the membrane material and the stage of treatment. The pH value should be between 4 and 11. Sometimes water has to be cooled and its pH value adjusted if the temperature and the pH-value are outside the normal operating range. Some membranes are sensitive to chlorine and therefore it has to be removed from the water before application to RO process.

Pretreatment may consist of aeration, softening, pressure filters, 5 µm cartridge filter, addition of sulfuric acid and sodium hexametaphosphate to convert enough of bicarbonates to carbonate ions and carbonic acid so as to obtain a negative saturation index (SI) and to prevent scale formation. Other means of controlling scale formation may include addition of polymeric scale control additives.

Hydrogen sulfide and carbon dioxide gases are removed from the product water by degasification. Caustic soda and zinc phosphate are added at the end of the process to adjust the pH and control corrosion.

A general layout of RO plant with various pretreatment components is shown in Fig. 7. Some of the components are optional depending upon the raw water quality and the end use of produced water. A reverse osmosis module with the membrane tube in the foreground is shown in Fig. 8. It is skid mounted and therefore easy to install. Modules can be easily added to the existing system if the plant capacity needs expansion.

7. OPERATION

RO process has low energy requirements since the separation is entirely in the liquid phase and no vaporization is needed. Removal of the total dissolved solids mostly depends on the raw water quality, the pretreatment technique and the membrane quality.

Recovery from a properly pretreated water remains more or less constant. With marginally pretreated water periodic cleaning is necessary as a result of which productivity can vary. With poorly pretreated water frequent cleaning is required and production of water is more often interrupted.

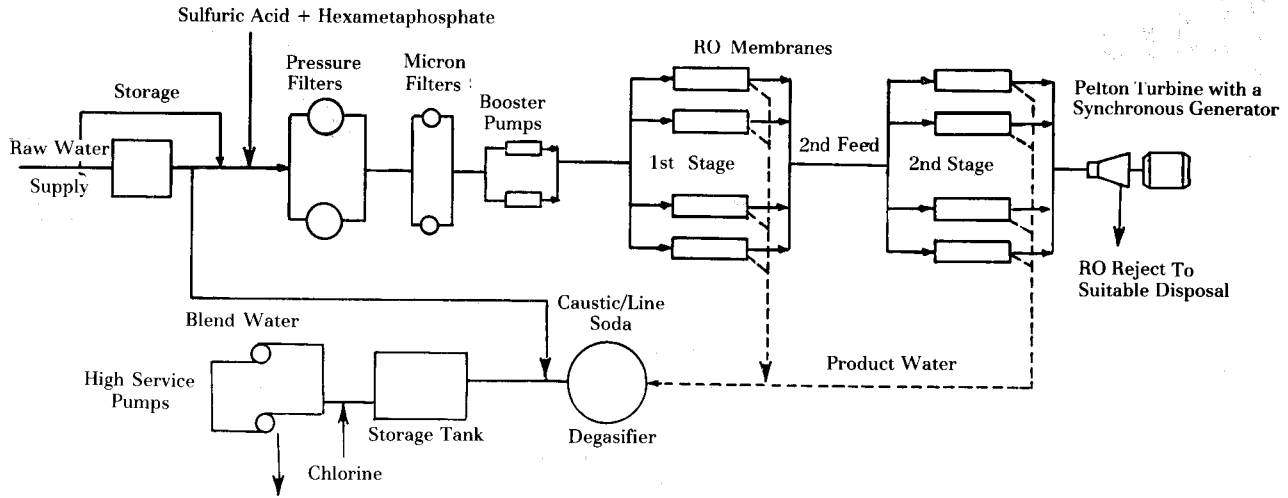


Fig. 7 : Water Treatment Plant Layout with Pretreatment and Energy Recovery.

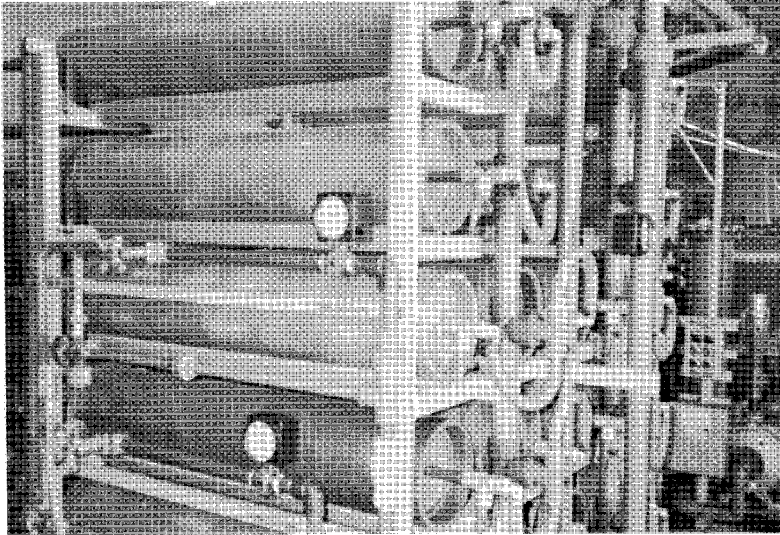


Fig. 8 : RO Module Showing the Membrane Tubes.

Theoretically, the pressure to be exerted on the sea water to produce freshwater through the membrane must be greater than 24.8 bar which is the osmotic pressure of sea water (Spiegler 1977). As a general guide the applied pressure may be in the following ranges (Muyllé 1986).

Mean Pressure at 25°C	Low	Mean	High
In bar	12 - 14	26 - 28	50 - 70
TDS mg/L	2000	6000	40,000-50,000

The higher the TDS concentration, the higher is the pressure required for the RO process. For seawater the applied pressure usually lies between 65 and 80 bar whereas for brackish water between 30 and 40 bar (Klein 1987). At the end of the process the brine leaves the permeator with a pressure 3 to 4 bar below the operating pressure. Large quantities of rejected brine at such high pressure may provide a secondary source of energy in large systems. By using an energy recovery turbine the power consumption may be reduced by 30% or more (Reisesterer 1985; Klein 1987).

8. RECOVERY AND REJECT WATER

Greater product recovery will produce brine with higher concentration. For 50% recovery the concentration of reject water will be twice that of feedwater concentration; similarly for 75% recovery the reject water concentration will be four times the concentration of feedwater (Appendix 5). Highly concentrated brine may be scale forming which will reduce the life of the membrane. However higher recovery may be obtained in stages.

Recovery has a bearing on the operation of RO process because the reject water is in contact with the membrane. The following analysis indicates that for a high recovery (say 90%) a membrane may not cope with the brine concentration. To ascertain this the saturation index (SI) of the brine and the solubility of calcium sulphate ions in the brine must be determined; this will help to find whether the water is non-scale forming or scale forming.

The relevant chemistry is presented in Appendix 6 which shows that for 75% recovery the SI is negative. The negative value shows that the water is non-scale forming. Solubility product of calcium sulphate indicates that it is also non-scale forming.

For 90% recovery the brine is scale forming as its SI value is positive and the solubility product is more than the solubility product of calcium sulphate showing saturation and hence scale forming.

Excess lime precipitation softening and filtration by acidification for pH adjustment can produce a feed water with low calcium ion concentration. In this case SI will be negative and such feedwater if used in the RO system will yield higher recovery and the operation will be satisfactory.

9. COSTS

It is difficult to compare the costs of RO process systems reported in the literature because of the lack of homogeneity in concepts and various energy policies. The sensitivity to variations in factors such as fuel costs and RO

membrane life is probably of grteater significance than the actual cost levels (Wade 1985). However, to give a general idea the design and operation data including the costs of RO plants in the middle east countries are presented in Table 3 (Marquart 1987; Muyelle 1986; Scott 1981; Torres et al 1985; Twort 1985; Wade 1985).

**Table 3 : Typical Design and Operating Data for
RO Plant in Middle East Countries**

Plant Capacity	100 - 40,000 m ³ /d of fresh water
Membrane Life	3 to 5 years
Capital Cost	\$ 1700 - 3000/m ³ , day
Annual Cost	\$ 1.29 - 1.86/m ³
Power Consumption	2 - 10 Kwh/m ³

10. BRINE DISPOSAL

If desalinated water is only used for drinking and culinary purposes, the quantity of brine produced is small. It may be discharged to sanitary sewers as the wastewater in such cases is made up of brackish groundwater and the contribution of salinity from the reject brine is negligible. There is little problem, if it is discharged to the sea, and no reuse is anticipated. If the treated wastewater is to be reused, then brine cannot be discharged into sewers instead it has to be discharged to the sea.

For inland cities, the quantity of brine could be much larger because desalted water may be the only source of supply. Evaporation ponds may be used for the disposal of brine. Inland plants may be designed for high recovery (say 90%) of water.

11. CONCLUSION

The RO process produces water of suitable quality for many uses. It is being increasingly used to reduce the total dissolved solids from brackish water as well as sea water. The use of RO process is now feasible as well as viable. Among the important factors to be considered in the design of RO plants are: full understanding of the chemistry of the process, raw water quality, level of recovery of water, operation strategy, choice of a suitable membrane, and brine disposal.

REFERENCES

1. Clark, J. W., Viessman (Jr.), W. and Hammer, M.J. 1977. Water Supply and Pollution Control. IEP-Don Donnelley, Harper and Row Publishers, N.J. 3rd Edition.
2. Crosslay, I.A. 1983. Desalination by Reverse Osmosis; in Desalination Technology, Development and Practice. Edited by Andrew Porteous, Applied Science Publishers, London.
3. Degremont 1979. Water Treatment Handbook. John Wiley and Sons, New York.
4. George, Alan 1987. Turkey plans \$2 billion Gulf water pipe line. MEW & S, Aug. p 140.
5. Gros, H. 1986. Reverse Osmosis for Water Treatment on the Kerkenna Islands, Tunisia. MEW & S, Oct. p. 200-202.
6. Hammer, Mark J. 1987. Water Supply in Saudi Arabia. Part 1: Desalinated Seawater. MEW & S, May, p. 50-51; Part 2: Reverse Osmosis of groundwater. MEW & S, August p. 130-135.
7. Irwin, Ed. C.J. 1987. Going Sewerless. ASCE Civil Engineering, Nov. p. 74-75.
8. Klein, H.H. 1987. The New Pump-turbine Concept: Energy Recovery for Economically Efficient Seawater Desalination. MEW & S, Aug., p. 134-135.
9. Levine, A.D. Tchobanoglous, G. and Takashi, A. 1985. Characterization of the size distribution of contaminants in wastewater: Treatment and Reuse Implications. Journal WPCF Vol. 57, No. 7, p. 805-816.
10. Lorch, W. (Ed) 1981. Handbook of Water Purification. McGraw Hill Book Company, New York.
11. Marquardt, O.K. 1987. Reverse Osmosis Process for Removing Nitrate from Water. JIWSA, Aqua No. 1, p. 39-44.

12. Middle East Water and Sewage (MEW & S) 1985. RO Desalination Plant provides Potable and Industrial Water. May/June 1985, p. 121-126.
13. Muylle, R. 1986. Desalination Plant Technology Optimization. JIWSA, Aqua No. 1, p. 5-9.
14. Parker, B. 1986. An Examination of the Various Technologies. JIWSA, Aqua No. 3, p. 149-150.
15. Pohland, Hermann, W. 1981. Raw Water Pretreatment Requirements of Reverse Osmosis Plants. MEW & S, Oct/Nov., p. 285-291.
16. Reiserer, J.C. 1985. Pelton Turbines for Power Recovery Applications in Reverse Osmosis Plants. MEW & S, Sept/Oct., p. S12-S13.
17. Samuel, A. 1986. Desalination of Seawater and Brackish Water: The Current State of Art and A Review of Problems and Future Development. JIWSA, Aqua No. 5, p. 242-248.
18. Schippers, J.C. 1987. Desalination and Water Reuse on Lanzarote and Gran Canaria. JIWSA, Aqua No. 6, p. 311-314.
19. Scott, J. (Ed), 1981. Desalination of Seawater by Reverse Osmosis, Pollution Technical Review No. 75. Noyes Data Corporation, New Jersey, USA.
20. Squires, R.C. 1985. Membrane Techniques for Renovating Industrial Effluents. JIWSA, Aqua No. 3, p. 160-171.
21. Spiegler, K.S. 1977. Salt-water Purification. 2nd Edition, Plenum Press, New York.
22. Steel, E.W. and McGhee, T.J. 1984. Water Supply and Sewerage. McGraw Hill Book Co. 5th Edition.
23. Sunderstrom, D.W. and Klei H.E. 1979. Waste-water Treatment. Prentice Hall Inc. N.J.
24. Tchobanoglous, G. and Schroeder, E.D. 1985. Water Quality. Addison Wesley Pub. Co. U.S.A.
25. Temperley, T.G. 1987. Desalination as an Alternative to Natural Water Resources, MEW & S, August, p. 143.
26. Torres M., Vera J.A. and Fernandez F. 1985. 20 years of Desalination in the Cannery Islands-Was it worth it? JIWSA, Aqua, No. 3, p. 151-155.

27. Twort, A.C., Law, F.M. and Crowley, F.W. 1985. Water Supply. Edward Arnold, London, 3rd Edition.
28. Wade, N. 1985. Choice of Desalination and Power Plants. MEW & S, Sept/Oct. p. S3-S6.
29. Walton, N.R.G. 1987. The Water Supplies of Bahrain Island – 21 years on. Journal of Institute of Water and Environmental Management, Vol. 1, No. 2, p. 231-238.

APPENDIX I

In case of simple filtration and microfiltration (filtration through millipore, sartorius or similar types of filter papers) the chemical properties of the solution do not change, whereas in ultrafiltration and reverse osmosis process (which retain molecules depending upon the membrane used) separation of the dissolved species modifies the chemical potential and creates a gradient (Degremont 1979).

APPENDIX II

Calculation of Osmotic Pressure:

Concentration of solute = 100 kg/m³; T = 300 °K; For a compound of molar mass of 0.05 kg/mole:

$$\text{Osmotic pressure} = CRT = [100 \text{ (kg/m}^3\text{)} - 0.05 \text{ (kg/mole)}] \times 8.314 \text{ (J/mole }^\circ\text{K)} \times 300 \text{ }^\circ\text{K} = 50 \times 10^5 \text{ N/m}^2$$

Similarly osmotic pressure for compounds of different molar mass can be calculated:

Molar mass (kg/mole)	Osmotic pressure (N/m ²)
0.5	5 x 10 ⁵
5.0	0.5 x 10 ⁵
50	0.05 x 10 ⁵

Hence, it may concluded that smaller the molecule i.e. lower the molar mass, greater is the osmotic pressure set up by the same difference in concentration.

APPENDIX III

Calculation of Membrane Area and Permeate Total Dissolved Solid Concentration

A brackish water having a TDS concentration of 2500 g/m^3 is to be desalinated using cellulose acetate membranes having a flux rate coefficient w of $1.8 \times 10^{-6} \text{ s/m}$ and a mass transfer rate coefficient K_s of $1.2 \times 10^{-6} \text{ m/s}$. The product water is to have a TDS of no more than 500 g/m^3 . The flow rate Q is to be $0.01 \text{ m}^3/\text{s}$. The net pressure will be 4000 KPa . Calculate the membrane area required and the permeate TDS concentration (Tchobanoglous and Schroeder 1985).

Solution

$$1. \quad F_w = w (P_a - P) = (1.8 \times 10^{-6} \text{ s/m}) (4000 \text{ kg/m.s}^2) \\ = 7.2 \times 10^{-3} \text{ kg/m}^2.\text{s}$$

$$Q = F_w \left(\frac{1 \text{ m}^3}{1000 \text{ kg}} \right) A$$

$$A = \left(\frac{(0.01) \times (1000)}{7.2 \times 10^{-3}} \right) = 1389 \text{ m}^2$$

$$2. \quad N_s = K_s C'$$

$$QC_p' = N_s A = K_s (C_f' - C_p) A.$$

$$C_p' = \frac{K_s (A) C_f'}{Q + K_s A} = \frac{(1.2 \times 10^{-6} (1389) (2.5))}{0.01 + 1.2 \times 10^{-6} (1389)}$$

$$= 0.375 \text{ kg/m}^3 = 375 \text{ g/m}^3 < 500 \text{ g/m}^3$$

APPENDIX IV

$$SDI = P_{30}/T = [1 - (t_i / t_r)] 100 / T$$

where

SDI = Silt Density Index

P_{30} = Pluggage at 2 bar feed pressure, %

T = Total test time (usually 15 min, but may be less if 75% pluggage occurs in less than 15 min)

t_i = Initial time required to obtain sample after 15 min or less, (seconds)

t_r = Time required to obtain sample after 15 min or less (seconds)

The procedure for concluding SDI test can be found elsewhere (Lorch 1981).

APPENDIX V

Reject water concentration depends upon recovery desired and feed water concentration as shown below:

Feed Water Conc	Recovery (%)	Reject Water Conc.
X	50	2X
X	75	4X
X	90	10X

Example :

For 75% recovery : $Q(100) = 0.75 Q(5) + 0.25 Q(Z)$
 $Z = 385 \text{ mg/L} = 4X$

Shamim Ahmad

$$\begin{aligned} \text{For 50\% recovery} & : Q(100) = 0.5 Q(5) + 0.5 Q(Z) \\ & Z = 200 \text{ mg/L} = 2X \end{aligned}$$

$$\begin{aligned} \text{For 90\% recovery} & : Q(100) = 0.9 Q(5) + 0.1 Q(Z) \\ & Z = 955 \text{ mg/L} = 10X \end{aligned}$$

APPENDIX VI

Chemistry of Reverse Osmosis Process:

The scale forming potential of the feedwater is evaluated based on the chemical composition of brine.

For 75% recovery the ionic concentration in the brine is approximately four times the concentration in the acidified water (Appendix 5).

$$\begin{aligned} \text{Ca}^{++} = 12.37 \text{ meq/L}; & = 248 \text{ mg/L}; \text{Ca}^{++} \text{ in brine} = (4) (248) = 992 \text{ mg/L} = \\ & 0.902/40 = 0.0248 \text{ moles/L} \end{aligned}$$

$$\text{Alkalinity} = 0.8 \text{ meq/L} = (0.8) (50) = 40 \text{ mg/L}$$

$$\text{Alkalinity in brine} = (4) (40) = 160 \text{ mg/L} = 160/(5) = 3.2 \text{ meq/L}$$

$$\text{Sulphate ion (SO}_4\text{=)} = (11.94) (4) = 47.6 \text{ meq/L} = 2.285/96 = 0.0238 \text{ moles/L}$$

$$\begin{aligned} \text{Saturation Index (SI)} & = \text{pH} - [\text{pCa}^{++} + \text{p(Alk)} + (\text{pK} - \text{pK}')] \\ & = 6 - [\text{p}(1/0.0248) + \text{p}(1000/3.2) + 2.11] \\ & = 6 - 6.2 = -0.2 \end{aligned}$$

The negative value of SI shows that the water is non-scale forming but corrosive.

Product of $[\text{Ca}^{++}] [\text{SO}_4\text{=}] = (0.0248) (0.0238) = 0.5 \times 10^{-3}$ which is less than the solubility product constant $K_{sp} = 10^{-3}$ sequestered with sodium hexametaphosphate. Therefore water is unsaturated and hence non-scale forming.

Heuristic Analysis of Brackishwater Treatment by Reverse Osmosis Process

For 90% recovery the ionic concentration in the brine is approximately ten times the concentration in the acidified water (Appendix 5).

$$\text{Ca}^{++} = 12.37 \text{ meq/L} = 248 \text{ mg/L}$$

$$\text{Ca}^{++} \text{ in brine} = (10) (248 \text{ mg/L}) = 2.48/40 = 0.062 \text{ moles/L}$$

$$\text{Alkalinity in brine} = (10) (40) = 400 \text{ mg/L} = 400/50 = 8 \text{ meq/L}$$

$$\text{Sulphate ion (SO}_4^{-}) = (10) (11.9) = 119 \text{ meq/L} = (119) (48) \text{ mg/L} = 5.712/96 = 0.0595 \text{ moles/L}$$

$$\text{Saturation Index [SI]} = 6 - [p(1/0.062) + p(1000/8) + 2.1] = + 0.6.$$

As the SI value is positive, the water is scale forming.

The product of $[\text{Ca}^{++}] [\text{SO}_4^{-}] = (0.062) (0.0595) = (3.7) 10^{-3}$ which is greater than $K_{sp} = 10^{-3}$, which indicates that the brine is saturated and hence scale forming.