



Mark Wilf Ph. D., and Kenneth Klinko

IMPROVED PERFORMANCE AND COST REDUCTION OF RO SEAWATER SYSTEMS USING UF PRETREATMENT.

ABSTRACT

RO seawater systems that operate on a surface feed water originating from an open intake source require an extensive pretreatment process in order to control membrane fouling. Considerations of long term performance stability lead to a design concept of operation at a low permeate flux rate and low permeate recovery. In recent years the nominal performance of composite seawater membrane elements has improved significantly, and new effective water microfiltration technologies have been introduced commercially. These developments can be utilized to improve the quality of surface seawater feed to the level comparable to, or better than the water quality from the well water sources. These new developments enable a more advanced RO system design which should result in increased reliability and lower water cost.

Introduction.

The economics of water desalting using reverse osmosis technology has been continuously improving. Due to the improvement of reverse osmosis membrane technology, the present cost of desalting of low and medium salinity brackish water in a growing number of cases is competitive with conventional water supply. This is especially true if pumping over a long distance is required, or if extensive water treatment has to be applied. Even though the prices of seawater membrane elements are only slightly higher than the prices of brackish membrane elements, the cost of RO desalting of seawater is significantly higher than the cost of the RO process applied to treat the brackish feed. This is primarily because seawater systems require significantly higher cost pumping equipment and use more corrosion resistant piping made of expensive alloy steel. Also due to the nature of seawater feed from an open intake and relatively low recovery rate the pretreatment system is significantly more expensive than the one required in the brackish RO systems. At the prevailing design and economic conditions the cost of membrane elements contributes to only 6% - 8% of the total water cost produced in RO seawater system. The major water cost contribution results from the cost

of process equipment and power consumption. The RO process parameter which has the largest effect on investment and operating cost is the permeate recovery rate. The feed flow is inversely proportional to the design recovery rate. Therefore, the recovery rate affects directly the size and cost of all process equipment and power consumption. However, in seawater RO systems, the recovery rate can not be increased at will, as higher recovery results in higher average feed salinity, which results in higher osmotic pressure and increased permeate salinity.

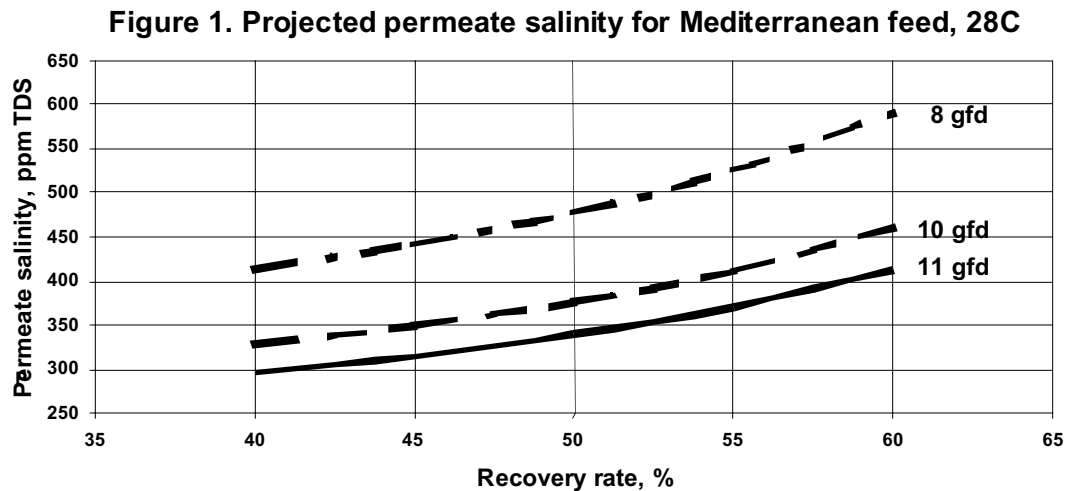
Parameters of the RO process

The operating parameters of seawater RO system are mainly function of feed water salinity and temperature. For example, for seawater feed of about 38,000 ppm TDS salinity and water temperature in the range of 18 - 28 C, the RO systems are designed to operate at a recovery rate in the range of 40% - 45% and with an average permeate flux in the range of 7 - 8 gfd (11.9 - 13.5 l/m²-hr). At the above operating conditions the feed pressure is in the range of 800 - 1000 psi (55 - 70 bar) and permeate salinity is in the range of 300 - 500 ppm TDS. For a given feed water salinity and salt rejection of the membrane elements used, the permeate salinity is a function of feed water temperature, recovery rate and permeate flux. An increase in feed water temperature results in an increased rate of salt and water diffusion across the membrane barrier at the rate of about 3% per degree Centigrade. Because RO plants usually operate at a constant flux rate, the changes of permeate salinity follow closely the changes in feed water temperature (1). Permeate salinity is inversely proportional to the average permeate flux. Higher permeate flux increases the dilution of salt ions which passed the membrane, and therefore results in lower permeate salinity. The average permeate flux rate in seawater systems is maintained at relatively low values: 7 - 8 gfd for surface seawater feed and 10 gfd (16.8 l/m²-hr) for seawater from beach wells. The difference in flux rates between the two water source types results from better quality of the well water and therefore, a lower fouling rate of the membranes. These flux values are relatively low and only about 50% of the permeate flux values used in brackish RO systems. Attempts to operate seawater systems at higher flux rates have usually resulted in irreversible flux decline. Until recently, the design recovery rate of new commercial seawater RO systems has been increased subsequently to the availability of membrane elements with increasingly higher salt rejection. So far, the maximum recovery in seawater RO systems has been mainly limited by the membrane salt rejection or the ability to produce permeate water of potable quality. Figure 1 displays permeate salinity as a function of recovery rate and permeate flux. The calculation were conducted for Mediterranean seawater feed of salinity of 37,500 ppm TDS and feed temperature of 28 C for a recovery range of 40 - 60% and flux rate of 8 - 11 gfd. Nominal 99.6% salt rejection membrane elements were used. For calculations of permeate quality, the membrane salt passage was increased by 15%. This is to account for projected 5% per year salt passage increase during 3 years of an average membrane life (20% membrane

element replacement per year). As expected, a higher recovery rate requires operation at an average flux rate above the standard value of 8 gfd. This is to maintain an acceptable permeate salinity, especially during the periods of high feed water temperature. The obvious questions are what is the optimum recovery rate of seawater systems in respect to product water cost, is such recovery achievable with the current performance of commercial seawater membranes, and is it possible to operate RO membranes on surface seawater at a higher flux rate.

Process economics

Recovery rate has a major impact on the economics of the seawater RO process. The size of all process equipment which is determined according to feed or concentrate flow will decrease with increased recovery rate. This applies to the size of the feed water supply system and power consumption of intake pumps. The size of all pretreatment equipment; storage tank, booster pumps, filtration equipment and chemical dosing systems is determined according to the feed flow. The same considerations apply to sizing of concentrate piping and of the outfall facility. The design permeate flux rate affects the number of membrane elements installed, number of pressure vessels, manifold connections and size of membrane skid. The effect of the above parameters on investment cost will be



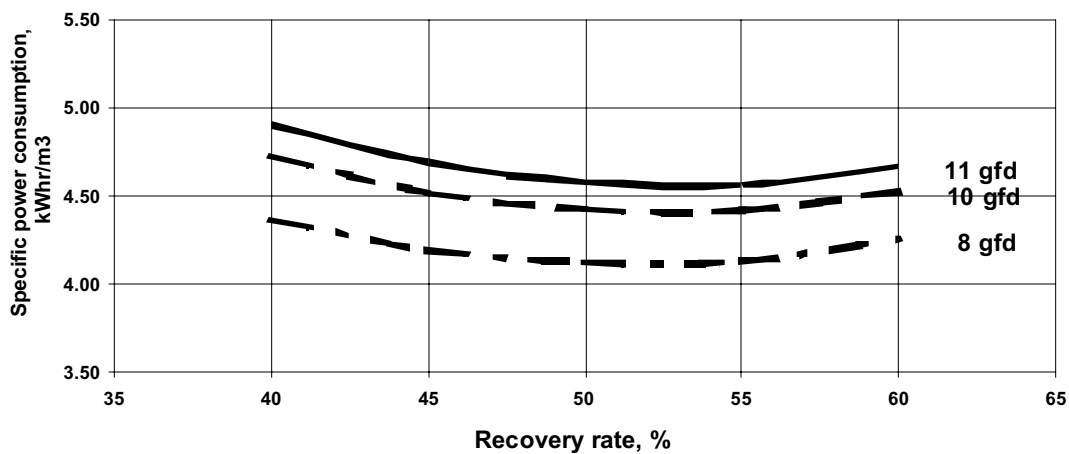
examined on an example for a 6 mgd (22,700 m³/day) system operating on Mediterranean seawater from an open intake. The cost estimation of the conventional reference design is based mainly on the data developed by G. Leitner (2), P. Shields and I. Moch (3). Table 1 contains a comparison of equipment cost (including 35% indirect cost) of the basic design

Table 1. Effect of recovery rate and permeate flux on cost of 6 mgd (22,700 m³/day) RO seawater system (in 1000 s US\$).

| Investment cost component | Reference design: 45% recovery, 8 gfd flux | HRF design: 55% recovery, 11 gfd flux | Equipment cost change, % |
|---|--|---|--------------------------------|
| Intake and outfall | 940 | 830 | -11.7 |
| Pretreatment | 5,000 | 4,390 | -12.2 |
| Membranes | 2,000 | 1,450 | -27.5 |
| Process equipment | 16,050 | 13,650 | -15.0 |
| Product water treatment | 400 | 400 | 0 |
| Site development | 670 | 640 | -4.5 |
| Total investment | 25,060 | 21,360 | -14.8 |
| Specific investment, \$/m ³ - day | 1,104 | 940 | -14.8 |

and a system operating at high recovery and high permeate flux, (HRF design). The basic design consists operation at 45% permeate recovery and 8 gfd flux rate. The HRF design consists operation at 55% recovery and flux rate of 11 gfd. The combined effect of higher recovery and higher flux rate results in significant reduction of the investment cost components. These savings are transferred to the total water cost. However, the higher recovery rate and higher permeate flux require higher a feed pressure. Therefore, specific power consumption will be higher. The increase in feed pressure with recovery rate at a given permeate flux is due to the increase in the average feed salinity and osmotic pressure. For pressure calculations, a 20% flux decline has been assumed due to fouling and compaction. Figure 2 contains values of specific power consumption for increasing recovery rate. As shown in Figure 2, for a given flux rate, the minimum specific power consumption corresponds to a recovery rate of about 50%. Changing the design parameters from a 45% recovery rate and 8 gfd flux to a 55% recovery rate and 11 gfd results in increase of specific power consumption of the high pressure pump from 4.2 kWh/m³ to 4.6 kWh/m³. This difference of 0.4 kWh/m³ at 18

Fig 2. Projected power consumption for Mediterranean feed, 18 C



C will decrease slightly at a higher feed water temperature. At a feed water temperature of 28 C (the high temperature limit for this evaluation) this difference will be about 0.3 kWhr/m³. Table 2 contains results of comparison of water cost components for operation at standard conditions with projected costs for operation at high flux, high recovery rate. For calculations of water cost the following economic parameters were used: interest rate: 8%, plant life: 20 years, replacement cost of 8 seawater membrane element: \$800; maintenance: 3% of capital; power cost: \$0.06/kWhr; plant load factor 95%. The cost of chemicals is based on the use of chlorine, inorganic flocculant, polymer, sodium bisulfite, and scale inhibitor in the pretreatment system. Operation at the high recovery rate and increased permeate flux improves process economics. However, maintaining stable membrane performance at the higher flux rate requires a significant improvement in feed water quality compared to the quality obtained from conventional pretreatment applied to surface seawater. The combined effect of lower investment and improved operating conditions is about 8% decrease of total water cost.

Table 2. Effect of recovery rate and permeate flux on total water cost in RO seawater system (in US\$).

| Water cost components | Reference design: 45% recovery, 8 gfd flux | HRF design: 55% recovery, 11 gfd flux | Water cost change, % |
|-------------------------------------|--|---|-------------------------|
| Capital cost | 0.320 | 0.275 | -4.0 |
| Membrane replacement | 0.050 | 0.037 | -26.0 |
| Maintenance | 0.095 | 0.084 | -12.0 |
| Power consumption | 0.252 | 0.276 | +9.5 |
| Chemicals & cartridge filters | 0.060 | 0.050 | -17.0 |
| Labor | 0.050 | 0.040 | -20.0 |
| Total water cost, \$/m ³ | 0.827 | 0.762 | -7.9 |

The conventional pretreatment process.

The objective of the pretreatment process is to reduce the concentration of fouling constituents in the feed water to the level that would provide stable, long term performance of membrane elements. In RO seawater systems membrane fouling can develop due to the presence in feed water of colloidal and particulate matter, dissolved organics, and as a result of biological growth in the RO system. The formation of inorganic scale, sometimes encountered in the tail position elements in brackish systems does not present a problem with the majority of seawater feeds. Precipitation of sparingly soluble salts from RO seawater concentrate is less likely to occur due to the relatively low recovery rate, high ionic strength, and low concentration of bicarbonate ion. Membrane fouling due to the first three fouling factors: e.i. particulate matter, organics

and biogrowth, usually is most pronounced in the lead elements. It has been postulated based on results of recent research work on membrane fouling processes (4, 5) that colloidal fouling is accelerated by high ionic strength and permeate drag forces (permeate flux). The high ionic strength of a treated solution reduces mutual double layer repulsion between colloidal particles and between the particles and membrane surface. Permeate flux, which results in drag forces perpendicular to the membrane surface, forces colloidal particles and organic macromolecules into the membrane pores and the foulant layer on the membrane surface. In seawater applications, the combination of high ionic strength and the presence of colloidal particles and dissolved organics results in higher fouling rates at a lower permeate flux than encountered in the brackish applications. The fouling process affects membrane performance by affecting both water flux and salt passage. Under high fouling conditions permeate flux is reduced and a higher feed pressure is required to produce the design flow. Usually, there is a parallel increase in salt passage, resulting in a higher salinity of permeate. Advanced stages of particulate or biological fouling will result in blockage of feed channels and increased pressure drop.

The conventional pretreatment system for surface seawater feed usually consists of breakpoint chlorination, up to a residual of 0.5 - 1.0 ppm, followed by in-line coagulation and flocculation. Aggregated colloidal particles are removed in two stage pressure multimedia filters. The two stage filtration, roughing filtration followed by polishing filters, is an effective configuration for producing a more consistent feed quality during backwash steps and also during periods of seasonal deterioration of raw water quality. After media filters, and ahead of the cartridge filtration unit, scale inhibitor and sodium bisulfite is added to the feed water. The above configuration of the pretreatment system is effective in reducing the silt density index (SDI) of the raw water from an unmeasurable values (complete plugging of the test filter) to a range of 2 - 3 SDI unit for the feed water. Regardless of the actual configuration of the pretreatment system, the above range of feed water SDI is very common for most of seawater plants receiving seawater from an open intake (6, 7, 8). However, the conventional pretreatment, consisting of media and cartridge filtration, does not represent a definite barrier to colloids and suspended particles. The quality of feed water produced, fluctuates significantly in respect of particulate matter. During filter backwashing, the filtration rates of filters remaining in operation increases, thus increasing the possibility of break through. Also, after the backwash, during the period of formation of filtration cake, large concentrations of colloidal particles are carried over with the filtration effluent. Apparently for these reasons the design average flux rate in seawater systems operating on surface water, has to be limited to about 8 gfd range.

The membrane pretreatment process.

The use of membranes as a definite barrier in the pretreatment process has been proposed in the past (9, 10). Ultrafiltration (UF) and microfiltration (MF) membranes have the ability to produce feed water of significantly better quality than the conventional

pretreatment process based on media and cartridge filtration. However, the conventional, spiral wound configuration of ultrafiltration membrane elements was not suitable for the treatment of highly fouling surface water. UF elements could not operate at high flux rates without severe fouling of membrane surfaces and plugging of feed channels. High cross flow feed velocities, required to reduce concentration polarization, resulted in high power consumption. Membrane cleaning, frequently required, was cumbersome and not very effective in restoring permeate flux. New microfiltration and ultrafiltration technology offered recently is based on a large ID capillary membrane configuration. The capillary bore is 0.7 - 0.9 mm diameter. Membrane material consists of polypropylene, sulfonated polyether sulfone or cellulose acetate. In some elements design the feed - permeate flow is outside in, others has inside out direction.

There are two common novel properties of the new commercial capillary equipment;

1. A frequent, short duration, automatically sequenced flushing (or backflushing in some models) of the capillary fibers, which enables to maintain stable permeate flux rates with little off-line time.
2. The ability to operate at a very low cross flow velocity, or even in a direct flow (dead end) mode.

The off-line time due to pulse cleaning is very short, comparable the to off line time of conventional filters due to filter backwashing. The frequent pulse cleaning results in a stable permeate flux rates. The feed pressure is in the range of 1 to 2 bar. Operation at low feed pressure and low cross flow or in a direct filtration mode results in high recovery rates and very low power consumption, of about 0.1 kWhr/m³ of filtrate. The membrane type is either microfiltration (nominal pore size 0.2 micron) or ultrafiltration (molecular weight cut off 100,000 - 200,000 Dalton). The dimensions of capillary ultrafiltration modules are in the range of 100 - 130 cm long and 20 - 32 cm in diameter. In actual field operation, a single module can produce 30 - 150 m³/day of filtrate. This new capillary technology has been developed to treat potable water, which originates from surface sources. Compared to conventional technology, it offers modular design, high capacity from a small foot print, no need for continuous handling and dosing of chemicals, and limited labor requirements. The major advantage, however, is inherent to membrane technology: the existence of a membrane barrier between feed and permeate which enables a several log reduction of colloidal particles and pathogens.

This technology has been extensively tested and a large number of systems, mainly based on microfiltration membranes, are already in operations. Following the success in potable water applications, the capillary technology has been proposed and tested as a potential pretreatment for RO systems operating on highly fouling water. One of the first targets was the RO processing of municipal effluents. The objective was to replace the expensive and cumbersome conventional tertiary effluent treatment and increase the current level of design flux rate of the RO system. Following successful field test results commercial system have been built and are being operated for wastewater reclamation. Application of the capillary technology as a pretreatment to seawater systems seems to be very advantageous as well. A limited number of tests on the operation of capillary units with seawater indicate that very good quality RO feed can be produced consistently (11). The

cost of the capillary membrane pretreatment is estimated to be similar to cost of the extensive conventional pretreatment, which is usually required for the surface seawater. The use of capillary technology will simplify the pretreatment system and reduce the use of chemicals. It will eliminate the need of a continuous presence of free chlorine, and produce feed water with very a low concentration of colloidal particles. The potential for blockage of the feed channels of the seawater spiral elements will definitely be smaller in operation with high quality feed water containing very low concentrations of particulate matter. Moreover, reduction of the fouling rate will reduce the frequency of chemical cleaning, and should result in a significant increase in the useful membrane life. This in turn will reduce cost of chemicals, cleaning associated labor and membrane replacement cost.

Summary.

An increase in recovery rate and permeate flux in seawater systems can improve the economics of the desalting process. Implementation of high recovery, high flux operation requires better quality of the feed water. New capillary membrane technology used as a pretreatment step has the potential to produce feed water quality which will enable to operate seawater membranes at a higher flux rate. The new technology has demonstrated reliable operation at variety of operating conditions. It is cost competitive with conventional pretreatment technology, and will result in higher reliability and better overall economics of reverse osmosis seawater desalting. The combined savings due to lower investment and operating cost and ability to optimize system operating conditions due to better feed water quality should result in about a 10% reduction in total water cost.

References

1. M. Wilf and K. Klinko, Performance of commercial seawater membranes, desalination, 96 (1994) pp 456 — 478.
2. G. Leitner, Cost of seawater desalination in real terms, 1979 through 1989, and projections for 1999, Desalination 76 (189) 201 — 213.
3. P. Shields and I. Moch, Evaluation of global sea water reverse osmosis capital and operating cost, Proceedings of the ADA Conference, Monterey, California, August 1996, vol. , 44 - 60.
4. X. Zhu and M. Elimelech, Fouling of reverse osmosis membranes by aluminum oxide colloids. Journal of Environmental Engineering, December 1995, 884 - 892.
5. S. Hong and M. Elimelech, Fouling of nanofiltration membranes by natural organic matter. Proceedings of 1996 ADA Conference, Monterey, August 1996, 717 - 727.
6. E. Ebrahim, M. Abdel-Jawad and M. Safar. Conventional pretreatment for the Doha reverse osmosis plant: technical and economical assessment. Proceedings of ADA 1994 Biennial Conference, Pal Beach, Florida, September 1994, vol. I 149 — 163

7. Y. Ayash, H. Imai, T. Yamada, T. Fakuda, Y. Yanaga and T. Taniyama. Performance of reverse osmosis membranes in Jeddah Phase I plant. *Desalination*, 96 (1994) 215 - 224.
8. S. Kremen, M. Wilf and P. Lange. Operation results and economics of single stage and two stage large size sea water reverse osmosis systems, *Proceedings of the Twelfth International Symposium on Desalination and water Reuse*, Malta, April 1991, vol. 2
9. G. Tanny, R. D Agostino and M. Wilf, Membrane microfiltration as a pretreatment for seawater reverse osmosis. *Proceedings of the 7th International Symposium on Fresh Water from the Sea. (Amsterdam 1980)* vol. 2, 307 - 317.
10. B. Ericson and B. Hallmans, Membrane filtration as a pre-treatment method - a cost comparison, *Proceedings of IDA World Conference on Desalination and Water Reuse*, Washington, August 1991, vol. 2
11. M. Miller, M. Silbernagel, T. Kuepper and W. Varnava, Testing prefiltration for the military ROWPU, *Proceedings of the 1966 ADA Conference*, Monterey, August 1966, pp. 467 - 485.