The competitive pricing for seawater desalination has now made many coastal communities reexamine the possibility of augmenting their water supply from the sea. One of the most significant factors in successfully and cost-effectively operating a reverse-osmosis (RO) seawater desalting plant is the ability of the pretreatment system to consistently produce high-quality feedwater and relatively microbe-free water for RO processing.

With the advent of microfiltration (MF) and ultrafiltration (UF) membranes, the concept of utilizing these low-pressure filtration membranes for pretreatment has caught the attention of desalination plant developers and engineers. MF and UF economically penetrated the water treatment market during the 1990s. The potential benefits offered by membrane pretreatment compared to conventional pretreatments include:

- improved pretreated water quality, in terms of lower suspended solids and less biological content, resulting in improved RO operation;
- fewer RO membrane cleanings, with resulting cost savings in cleaning chemicals;
- lower RO pressure drops from fouling, resulting in lower energy costs;
- longer RO membrane life associated with long-term improved pretreated water quality;
- increased flux rates in the RO system due to higher-quality pretreatment;
- smaller plant footprint size, resulting in reduced capital investment;
- lower overall costs for chemicals and sludge handling if conventional technologies included lime softening or other chemically intensive conventional pretreatments.

To date there has been limited information published regarding piloting of membrane filtration pretreatment for seawater reverse-osmosis membrane application (Galloway 2003; Henthorne et. al. 2003; Glueckstern 2002; Genkin 2002; Henthorne 2002; Mansdorf 2002; Harris 2001; Truby 2000; Goto 1999; Alawadhi 1999). Although the published literature does review the applications potential for the use of this pretreatment process, there is little to no verification of the membrane filtration benefits that could be realized and what specific cost savings could result as compared to conventional pretreatment for seawater RO.

Overview of Membrane Processes

Understanding membrane application requires understanding the characteristics of drinking-water membrane processes. Reverse osmosis (RO), nanofiltration (NF), electrodialysis reversal (EDR), ultrafiltration (UF) and microfiltration (MF) are the membrane processes which have application to drinking water (Taylor et al, 1989). Combinations of membrane processes with other processes have become known as integrated membrane systems (IMSs).

Although a conventional NF process consists of a pretreatment and post-treatment process before and after the NF, which could be described as integrated, this is described as conventional. Accepted examples of IMSs include coupling MF with NF or combining coagulat

Table 2:
Summary of Membrane-Process Applications for Drinking-Water Regulations

Continued from page 33

1. Diffusion-controlled membranes (RO & NF) are required for control of total dissolved solids (TDS), total hardness (TH), chlorides, and DBP precursors.
2. Charge-controlled membranes (EDR) can remove TDS, TH, chlorides, etc.
3. Size exclusion-controlled membranes can control particles, turbidity, and cysts.

Productivity

Productivity is essential at any water treatment facility. Productivity is affected by the design of the membrane process and fouling. Designers can select membranes for specific treatment characteristics. Once selected, a designer can select operating conditions for that membrane process.

A primary consideration affecting productivity is fouling. The four primary mechanisms of fouling are scaling, plugging, adsorption, and biological growth. The primary means of controlling fouling by mechanism and unit operation are shown in **Table 4** and described below:

1. Scaling control is typically required for all RO/NF membrane systems in either surface or groundwaters and is achieved by acid and/or antiscalent addition.
2. Plugging control is typically required for all RO/NF membrane systems in either surface or groundwaters and is achieved by feedwater turbidities and SDIs less than 0.2 NTU and 2, respectively.
3. Bio-fouling control is typically required for aerobic surface or groundwaters and is achieved by NH_2Cl or addition of other bactericidal agents.
4. Organic fouling can occur in surface water systems with TOC > 3-6 mg/L and is typically reduced by coagulation, sedimentation, and filtration; however, the significance of organic fouling is not known.

Pilot-Scale Case Study: San Patricio Municipal Water District

The pilot project was accomplished at the San Patricio Municipal Water District (SPMWD) facility near Corpus Christi, Texas. This facility is located in Corpus Christi Bay along the northwestern coast of the Gulf of Mexico.

The project was funded by the U.S. Bureau of Reclamation to address the needs of the desalting community regarding membrane pretreatment for seawater desalination applications. The project team consisted of Aqua Resources International (ARI) in partnership with the SPMWD, Advanced Membrane Systems (AMS), and Boyle Engineering Corporation. The project was cost-shared through contributions from the MF/UF and RO membrane manufacturers, the SPMWD, and the principal project partners.

The project involved two phases of piloting. The initial phase involved optimizing the membrane (MF/UF) and conventional pretreatment systems, while the second phase of experimentation compared the membrane and conventional pretreatment in parallel with downstream seawater RO trains for six to nine months.

The principal purpose of this project was twofold:

- Evaluate the performance of membrane filtration pretreatment versus conventional filtration pretreatment for seawater reverse-osmosis desalination, in terms of improved pretreated water quality and impact on RO performance.
- Determine the subsequent cost benefits of membrane filtration compared to conventional pretreatment options by establishing life-cycle cost comparisons.

Siting and Test Conditions

The seawater source for the pilot testing was Gulf of Mexico water using the bay adjacent to the SPMWD facility. The water quality of the bay normally fluctuates between 29,000 mg/L and 40,000 mg/L of salinity. During the pilot testing, salinity fluctuations of 7,000 mg/L to 36,000 mg/L of salinity were experienced because of extreme weather patterns. Turbidities of the raw seawater varied from 2 NTU to over 100 NTU. These huge water-quality swings were not anticipated and caused operational difficulties.

Table 3:
Summary of Membrane-Process Applications for Drinking-Water Regulations

Parameter	***Membrane Process***				
	EDR	RO	NF	UF	MF
TDS	Yes	Yes	Yes	No	No
TH	Yes	Yes	Yes	No	No
T & O	No	Yes	Yes	No	No
TOC	No	Yes	Yes	No	No
Color	No	Yes	Yes	No	No
Fe & Mn	No	Yes	Yes	No	No

Table 4: Fouling Control by Pretreatment System

	A/AS	MF/UF	CS F	NH_4Cl	AOC Removal
Scaling	+	-	-	-	-
Plugging	-	+	+	-	-
Adsorption	-	+	+	-	-
Bio-fouling*	-	+ (feed)	-	+	+

*MF/UF will remove biofoulants from feedwater;
yet MF/UF will not stop growth from occurring within the RO equipment.

Phase I of the study consisted of operating the pretreatment systems to screen the optimum operating parameters for each system, including flux, recovery, backwash frequency, operating pressures/vacuum, and CEB (chemically enhanced backwash) and cleaning frequency, as appropriate. The pretreatment systems tested include:

- PT–1: Zenon Zeeweed 1000 UF unit
- PT–2: Norit UF unit
- PT-3: Hydranautics Hydracap UF unit
- PT-4: Memcor CMF MF unit
- PT-5: Pall MF or UF unit
- PT-6: Conventional pretreatment consisting of:
  - Coagulant addition
  - Multi-media filtration (sand, anthracite, and garnet)

Phase II testing consisted of adding two seawater reverse-osmosis (SWRO) systems to follow the pretreatment systems. One SWRO system was fed from combined MF/UF pretreated feedwater, the second from conventionally pretreated feedwater. Optimum RO conditions for flux and cleaning frequency were delineated. During the study, overall cost data was collected for the combined pretreatment-SWRO systems. A general flow diagram for the pilot testing is shown in **Figure 1.**

Table 5:
Phase I Dependent Variables

Water Quality:
1. Filtrate bacterial counts using epifluorscence, counts/Ml
2. Filtrate turbidity, NTU, measured by online turbidimeters
3. Filtrate TOC, limited
4. Filtrate SDI

Process:
6. Filtrate run time, between backwashes and cleaning at specific flux rate, hours
7. Water recovery, %
8. Fouling rate of downstream RO elements
9. Cleaning frequency, hrs^{-1}
10. Ability to operate w/wo chemical pretreatment

Cost:
11. Chemical assumption, $/day
12. Power cost, $/day (estimated)
13. Feed and backwash pressures and volumes
14. O&M time required, (estimated)
15. Capital cost at optimum flux and recovery

Dependent and Independent Variables

The dependent variables for Phase I testing are shown in **Table 5**. **Table 6** lists the additional Phase II dependent variables. Phase I dependent variables are also measured in Phase II. The independent variables for Phases I and II are listed in Table 7.

Operation Progress And Pilot Experiences

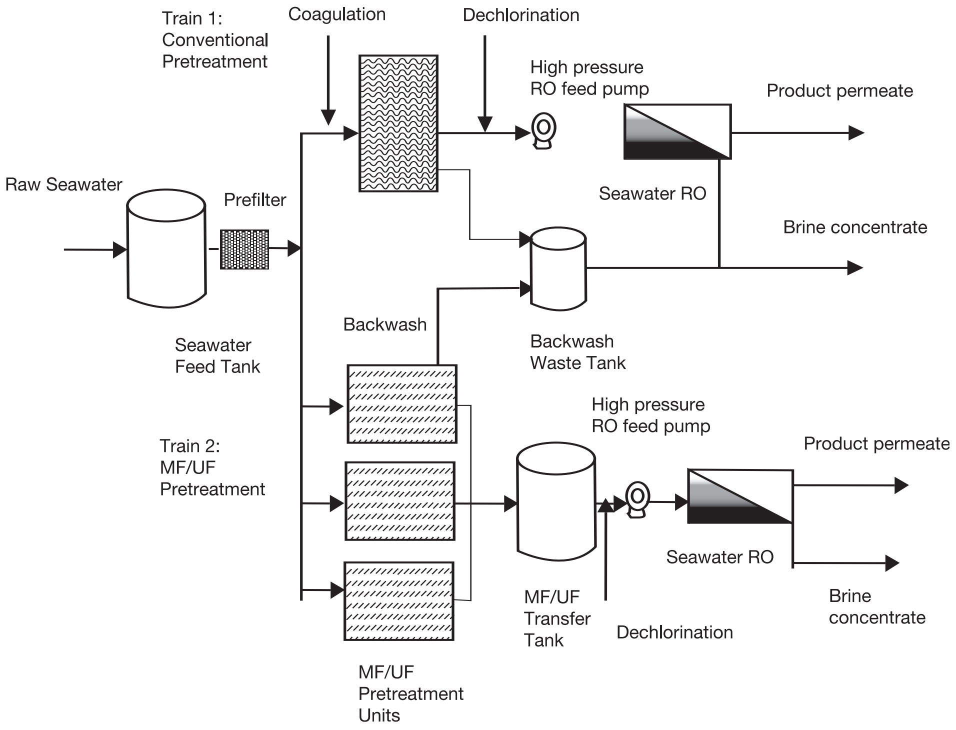
Pilot testing for Phase I began in April 2002. Phase II testing was performed throughout 2003 and was completed in 2004. The MF/UF units arrived onsite on a staggered schedule; the goal for the pilot was to have the MF/UF systems operate as long as possible, whenever they arrived on site.

The initial thinking was that during the evaluation, MF/UF operating and finished water comparisons could be investigated; however, due to the staggered equipment schedules and quality problems encountered in the water supply, maintaining a sufficient quantity and quality of source water limited operation. Thus, the most challenging aspects of the pilot study were 1) maintaining sufficient and consistent raw water through the intake, and 2) the fluctuating and extreme water quality.

A temporary pilot intake structure was located approximately 300 feet from the shoreline, two to three feet from the surface. The intake pump was located on the shoreline

Continued on page 36

Figure 1: Process Flow Diagram of San Patricio Pilot



Continued from page 35

because of concerns about placing a submerged pump offshore at this unprotected location. The feedwater was then pumped approximately 1.8 miles to the pilot equipment.

Maintaining continuous pump operation was the "Achilles Heel" of the project, as the initial intake pump suffered from difficulty maintaining prime and corrosion problems. A subsequent second pump was installed that was thought to be more suitable for the application; however, corrosion remained an issue and intake debris still required considerable labor to maintain operation.

The difficult water-quality issues were primarily a function of heavy sediment and grass carrying over into the MF/UF systems. A number of different strainers were evaluated, none of which were sufficient to handle the loadings. Finally, an Arkal SpinKlin disk pre-filtration unit was installed to treat all raw water, which worked exceptionally well for removing sea grasses prior to the membrane filtration and conventional pretreatment units. The 130-micron prefilter operated at 9 to 11 m^3/hr (40-50 gpm) and had the ability to backwash at specific time intervals or by pressure drop across the filter. Normal operation of the unit was one backwash per day for 70 seconds at 13.6 m^3/hr (60 gpm), providing for 90 percent water recovery in the operation.

After prefiltration was in place, the membrane and conventional pretreatment units no longer exhibited clogging from grasses and grit. The raw feedwater quality inlet turbidity ranged from 2 to over 100 NTU, and the inlet salinity varied from 7,000 to 36,000 mg/L. This tremendous variation is a function of the heavy rains sustained in the area (August through December 2002) and the significant run-off influence on the Corpus Christi Bay location. SDI_{15} values were unobtainable for the feedwater because of its poor quality.

The Hydranautics unit produced filtrate with turbidities consistently of about 0.02 NTU, while the Norit unit produced water of 0.03 to 0.04 NTU. SDI_{15} values were consistently well below 3 and varied between 0.5 and 2.0. The Norit unit optimized performance at approximately 50 gfd, 93 to 94 percent water recovery and no coagulant addition. The Hydranautics unit operated successfully at 60 gfd, 92 to 93 percent water recovery and less than 1.5 ppm ferric chloride as a coagulant.

Due to the extremely poor feedwater quality and downtime on the intake pump, the Zenon unit was not able to operate for any significant time period and was removed from the site by Zenon before the SpinKlin prefilter installation and operation. A Memcor unit was installed in June 2003 and produced filtrate with turbidities consistently of 0.03 NTU or less and recoveries of about 95 percent.

The conventional media filtration consists of anthracite, sand, and garnet in a pressurized, single-stage design, operating at a loading rate of only 1 gpm/ft^2. The coagulant addition was optimized initially using jar testing, but the fluctuating feedwater quality made it necessary to continually re-evaluate the ferric chloride dosage. Generally, the optimum ferric chloride dosage was in the range of 5 to 6 ppm.

Filtrate turbidity for the conventional system varied from 0.1 to 0.3 NTU, and the SDI varied from 3.4 to 5.5 but was generally in the range of 3.7 to 4.0. The conventional pretreatment operated at 95.9 percent water recovery.

The SWRO skids operated successfully with the exception of a problem with chlorine carryover from the membrane filtration CEB cycles. The Norit's CEB rinse time was initially inadequate and very gradually chlorine damage reduced the RO membrane performance. The problem was remedied by increasing the rinse time after the CEB in the Norit system, by periodically checking the Norit filtrate after the CEB for chlorine residual, and by placing a 1-ppm sodium bisulfite dechlorination drip upstream of both RO skids. The initial set of RO membranes (Koch) were replaced and operation was resumed using Toray RO membranes.

The Norit system plumbing had a six-foot dead spot in its piping that never rinsed properly and subsequently fed into the UF system once the CEB was completed. To compensate, the sodium bisulfite dosage was increased to 2 ppm and the frequency of the chlorine CEB was reduced to remedy this problem.

RO seawater desalting performance differed significantly between conventional and membrane treatment trains. The RO train utilizing conventionally pretreated feedwater required cleaning after approximately 980 hours of operation. The RO train receiving feedwater from the membrane pretreatment units has performed significantly better, having required no cleaning in over 1,300 hours of operation.

The salt rejection has declined from 99.6 percent to 99.3 percent in the membrane filtration pretreatment RO train due to chlorine damage. The RO operating flux on both trains is very high, due to the RO pilot design, at 13 to 14 gfd. This is significantly higher than one would design a full-scale plant due to increased energy consumption, and provided a rather extreme operating scenario that was used to evaluate the pretreatment performance.

Table 6:
Phase II Dependent Variables

Water Quality:

1. Salt transport coefficient, B
2. Salt rejection, %
3. Permeate TDS estimated from conductivity, mg/L
4. TOC, mg/L
5. UV absorbence at 254 nm, limited

Process:

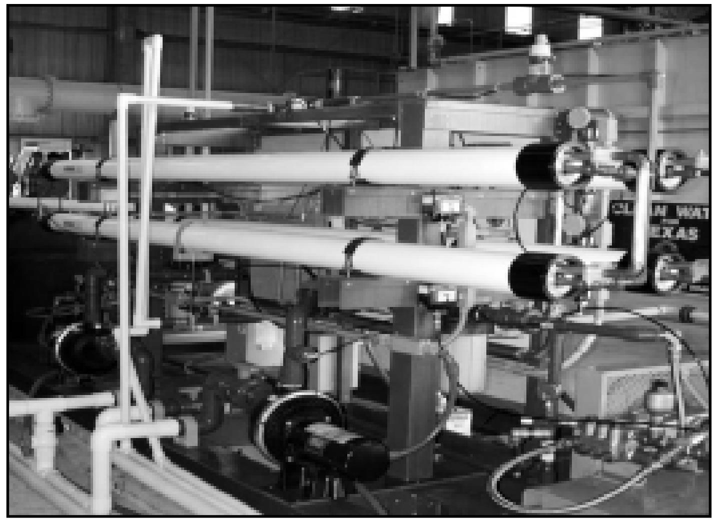
6. Water transport coefficient, A, gfd/psig
7. Normalized flux, gfd
8. Membrane degradation, increase in A and B
9. Pressure drop across membranes, psi

Cost:

10. Power cost, $/day, estimated
11. Cleaning frequency and requirements
12. O&M time required, estimates
13. Capital cost at optimum flux and estimated recovery

Table 7: Phase I and II Independent Variables

Independent Variable	***Note/Comment***
Pretreatment Systems	PT-1: Zenon Zeeweed 1000 UF
	PT-2: Norit UF
	PT-3: Hydranautics Hydracap UF
	PT-4: Memcor CMF MF
	PT-5: Pall MF or UF
	PT-6: Conventional
Pretreatment Water flux (gfd)	Low, medium and high
Pretreatment Backwashing	As results dictated
Pretreatment Coagulant Addition	As results dictated and at manufacturers' direction
RO Water Flux (gfd)	Low and high
Operating Time	As results dictated



Photograph of skid-mounted parallel seawater reverse-osmosis pilot plant unit.

Summary of Case-Study Findings

The results of the pilot study are summarized as follows:

- Membrane filtration pretreatment systems require lower or no chemical addition to achieve better water quality compared to conventional pretreatment, in this case 0 to 1.5 ppm compared to 5 to 6 ppm ferric chloride, respectively.
- Membrane filtration provides consistent pretreated feedwater quality with SDI values of 0.6 to 2.0, regardless of the raw feedwater quality. Conventional pretreatment requires constant coagulant optimization and has difficulty meeting SDI values less than 5 when the raw feedwater quality exceeds turbidity values greater than 10 to 15 NTU.
- Cleaning frequency was approximately every 1,000 hours (42 days) using conventional, compared to no significant RO cleaning requirements for membrane pretreatment.
- Higher RO flux operation of 12 to 14 gfd is technically feasible using membrane pretreatment, but would not be the most cost-effective scenario in terms of energy usage.
- Chlorine carryover from membrane pretreatment CEB and cleanings must be very carefully controlled.
- The total water cost for membrane pretreatment is less than media filtration if cleaning frequency is reduced even by one cleaning cycle per year.

Acknowledgements

The authors wish to acknowledge the contributions of the following organizations and individuals:

- San Patricio Municipal Water District management team, including Jim Neismith, Don Roach, and the dedication and resolve of Ryan Quigley;
- U.S. Bureau of Reclamation technical representatives, including Frank Lietz;
- Zenon Corporation, including David Barker;
- Norit, including Judith Green Herschell (now with Inge) and Chris White;
- Memcor, including Dawn Guendert;
- Hydranautics, including Uri Papouktchiev (now with Norit).

References

- *Alawadhi, A., A. Hedha and B. Hallmans. "Rehabilitation of Ad Dur RO Desalination Plant, Bahrain." IDA Congress Proceedings. San Diego, CA; (1999).*
- *Galloway, M., A. Gottberg and J. Mahoney. "UF for Seawater RO Pretreatment." AWWA Membrane Conference Proceedings. Alanta, GA (2003).*
- *Genkin, G. "MF and UF as Pretreatment for RO Plants: Summary of Test Results and Comparative Analysis." Israel Desalination Society Conference. Haifa, Israel (2002).*
- *Glueckstern, P. "Comparative Cost of UF versus Conventional Pretreatment for SWRO Systems." Israel Desalination Society Conference. Haifa, Israel (2002).*
- *Goto, T., H. et. al. "MF Membrane Pretreatment for SWRO." IDA Congress Proceedings. San Diego, CA (1999).*
- *Harris, C. "Membrane Integration for Seawater Desalting." AWWA Membrane Conference Proceedings. San Antonio, TX (2001).*
- *Henthorne, L. and E. Jankel. "Analysis of MF and UF Applications for RO Pretreatment and Applicability to the Arabian Gulf." IDA Congress Proceedings. Bahrain (2002).*
- *Henthorne, L. "Evaluation of Membrane Pretreatment for SWRO Desalination." Israel Desalination Society Conference. Haifa, Israel (2002).*
- *Mansdorf, Y. "Pretreatment Options for Effluent Desalination in Israel." Israel Desalination Society Conference. Haifa, Israel (2002).*
- *Taylor, J.S., S.J. Duranceau, W.M. Barrett and J.F. Goigel. Assessment of Potable Water Membrane Applications and Research Needs. Denver, CO: American Water Works Association Research Foundation (1989).*
- *Taylor, J.S. and S.J. Duranceau. "Membrane Case Studies: Past Present and Future" in Membrane Technology in Water and Wastewater Treatment, Ed. P. Hillis. Cambridge, UK: The Royal Society of Chemistry (2000).*
- *Truby, R. "Desalination Growth Around the World Driven by Multiple Membrane Systems." North American Membrane Society Proceedings. Boulder, CO. (2000).*