Integrated Membrane Desalination Systems- Current Status and Projected Development

Mark Wilf Ph. D and Craig Bartels Ph. D
Hydranautics, California

Abstract

With commercial introduction of modern ultrafiltrattion (UF) and mirofiltration (MF) technologies it was expected that these membrane filtration processes will provide solution for improvement of effectiveness of feed water pretreatment in reverse osmosis (RO) applications. These expectations have been materialized mainly in the applications of reclamation of municipal wastewater. Practically, all new wastewater reclamation systems that use RO for salinity reduction apply UF or MF technology as a pretreatment step of feed water to RO elements. Effectiveness of membrane pretreatment in producing good quality RO feed water is proven and well documented. However, improved quality of MF/UF effluent, as compared to conventional pretreatment comes at a cost that is still significant and in most cases higher then the comparable cost of conventional pretreatment based on media filtration. In wastewater reclamation process with integrated membrane pretreatment, the benefits of significantly lower fouling rates of RO membranes, low cost of chemicals and disposal of pretreatment waste stream, outweighs the higher cost membrane pretreatment equipment. For other difficult RO application, treatment of surface water, the relative economics of MF/UF pretreatment is still being evaluated. Outside wastewater reclamation applications, number of installations using Integrated Membrane Solutions® (IMS) is relatively small. Probably the largest number of IMS systems treating surface water is being built and operated for industrial applications. The higher reliability of production of process water, lower usage of chemicals in the pretreatment step and lower frequency of RO membrane cleaning in IMS systems, has a very high weight factor in selection of the pretreatment technology. The geographical areas experiencing a significant grow in number of IMS systems for industrial applications are southern part of US and Pacific Rim countries with high rate of industrial grow. Most of the IMS systems there treat low salinity surface waters but some process seawater as well. Usually large capacity IMS systems produce process water for electric power stations. A representative example is the seawater RO system at the Yu-Han Power Plant, China, with output capacity of 34,500 m3/day. Outside the Pacific Rim membrane pretreatment is being gradually introduced in seawater plants producing potable water. Examples of large seawater plants with membrane pretreatment are RO plants at Addur, Bahrain (140,000 m3/day UF pretreatment capacity) and Kindasa, Saudi Arabia (90,000 m3/day UF pretreatment capacity). Both plants utilize membrane pretreatment to protect RO membrane elements from fluctuations of feed water quality causes by seasonal changes of seawater. So far the RO units operated on UF/MF effluent are designed in a similar way as the RO system operating with conventional pretreatment. It is possible however, that future RO system will be designed for higher permeate flux rates, taking advantage of better feed quality and improving economics of the integrated desalination process. The paper will describe design configuration and operational experience of large capacity IMS desalination systems. Present and projected economics of IMS configurations will be evaluated and discussed. Projections for expected direction of IMS system design and operating parameters will be provided.

I. FEED WATER QUALITY INDICATORS

The composition and quality of water considered for processing by reverse osmosis is influenced by its origin. Brackish water that originates from deep wells has very low concentration of suspended solids and will require minimum pretreatment. The quality of surface water, which, for RO application is mainly high salinity seawater, will depend on location. At some locations the solids load and bacterial activity will be very low. At some locations it could be influenced by high turbidity run off or seasonal algae bloom. Another potential source of feed water for RO application is treated municipal effluent. Such effluent usually has high concentration of suspended solids and high bacterial activity. However, effective methods of pretreatment have been developed, which result in very stable operation of RO unit in wastewater reclamation plants. Potential water sources for RO applications are characterized in terms of composition of dissolved species, temperature, pH and concentration of particulate matter. Usually the concentration of particulate matter is not measured directly. The quality indicators that are related to suspended particulate matter are turbidity and silt density index (SDI). Water turbidity, usually expressed as nefelometric turbidity units (NTU) is determined through measurements of intensity of light scattered by suspended particles in water sample. The SDI is determined through measuring rate of filtration of water sample through a polymeric filter. The filter has nominal porosity of 0.45 u. As water flows through the filter the colloidal matter will plug filter paper and decrease filtration rate. Measurement of two filtration intervals, usually spaced 15 min apart, enables calculation of SDI according to equation (1):

$$SDI = 100\%(1 - t_1/t_2)/15 \qquad (1)$$

Where t_1 and t_2 is the time required to filtrate 500 ml of water initially and after 15 min of continuous flow of water through the filter.

According to equation 1, the maximum value of SDI is 6.67. In addition to concentration of suspended colloids, the SDI results are affected also by presence of organic matter in the water tested. For water with very high concentration of dissolved organic, like municipal wastewater effluents, the SDI is not measurable. Use of SDI as an indicator of water quality has been frequently criticized for inadequate accuracy and reproducibly and lack of correlation with direct determination of particle concentration (2, 3). Another concern is that the flow pattern during SDI measurement (dead end flow) is significantly different then the flow pattern occurring in RO membrane element (cross flow). In spite of the above deficiencies of SDI it is the major indicator of water quality for RO applications.

The expected average quality of water from the common water sources are summarized in Table 1. In exception of well water, the quality of surface water and secondary effluent can fluctuate in wide range. Seasonal spikes of turbidity are quite common.

Table 1. Expected average water quality from well, surface intake and secondary effluent sources

Quality parameter	Well water	Surface water (seawater)	Secondary effluent
Turbidity, NTU	< 1	< 2	< 2
SDI	< 1	5 - 15	not measurable
Suspended solids, ppm/ml	<5	<5	< 20
TOC, ppm	< 3	< 5	< 20
Scaling potential	low to high	low	low (except in presence of high concentration of phosphates)

Majority of manufacturers of RO membrane elements define upper value of SDI of feed water to RO membranes as 4 to 5 SDI units. However, it is known that operation at the very upper limit of this range could result in membrane fouling and SDI of less than 3 is recommended for stable operation. SDI values are not linear with concentration of colloidal matter. Pictures 1, 2 and 3 shows scanning electron microscopy (SEM) images of SDI filter pad. Picture 1 is of clean filter, Picture 2 is of an image of filter after measurement at SDI = 2.2. Picture 3 corresponds to measurement resulting in SDI = 4.8. A thick layer of deposit is clearly visible on Picture 3.

Figure 1 SEM image of clean SDI filter pad

Another feed water quality indicator is turbidity. In the past the maximum allowed value of turbidity was listed as 1.0 NTU. Although there is no direct relations between SDI and turbidity it has been realized that low values of SDI correspond to much lower turbidity values then 1. The currently recommended limits of feed water turbidity are in the range of 0.1 – 0.2 NTU.

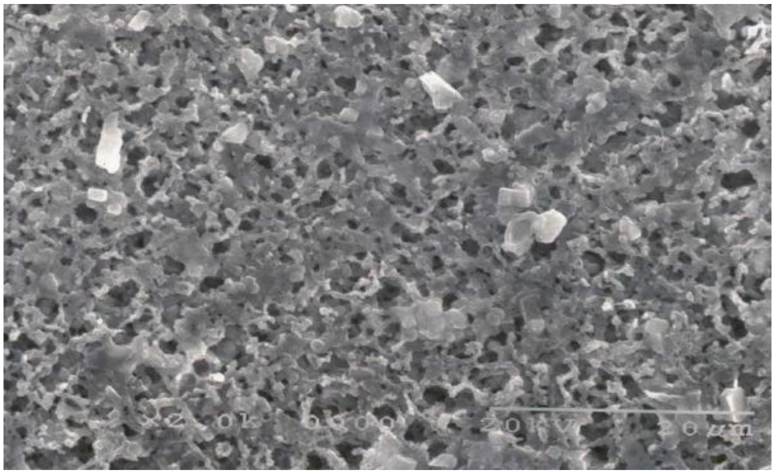

Figure 2 SEM image of SDI filter pad after test. SDI = 2.2

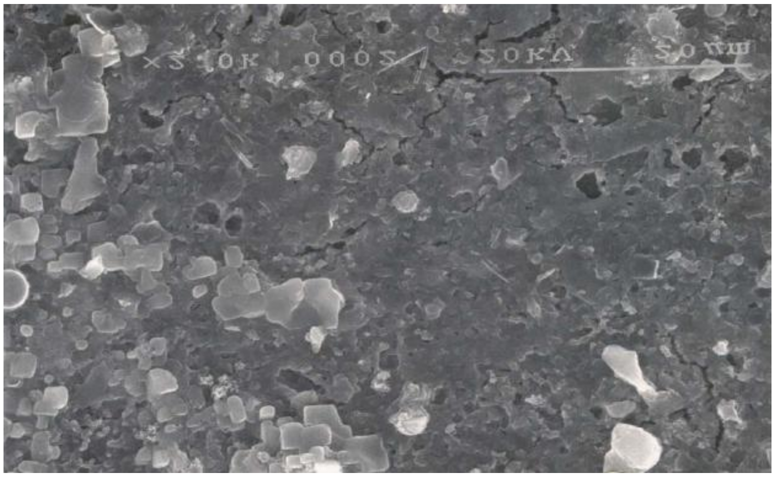

Figure 3 SEM image of SDI filter pad after test. SDI = 4.8

II. PRETREATMENT METDODS OF FEED WATER IN RO PLANTS

Objective of operation of pretreatment system is to produce feed water to RO elements of a quality that would not result in fouling of membrane modules. The membrane elements used in commercial systems are of spiral wound configuration, 200 mm in diameter and about 1 m long. It contains about 37 m^2 of membrane area. The spiral wound element, shown in Figure 4, consists of membrane envelopes connected to and wound around

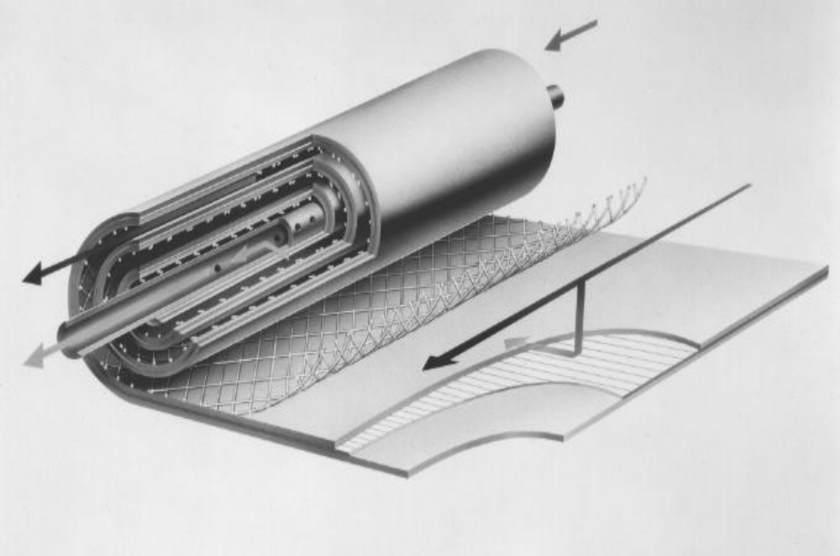

Figure 4. Configuration of spiral wound elements

central product tube. The membrane envelopes are separated by feed spacer which enables passage of feed water parallel to membrane surfaces. The configuration of feed spacer is design to create turbulence in the feed channel which reduces concentration polarization at the membrane surface. The feed spacer is configured as a biplanar net. It is schematically shown in Figure 5. The thickness of feed spacer is in the range of 0.7 – 0.8 mm. However, the hydraulic cross section of the feed channel, due to presence of feed spacer filaments, is even smaller than that (4).

The dimensions of the feed channels and the configuration of feed spacer determine objectives of the pretreatment process in respect of suspended particles. Feed spacer is configured to promote turbulent flow of the feed water. However, at the areas immediately beyond the points of contact of spacer filaments and membrane, eddies are formed. If feed water contains high concentration of suspended colloids, they could deposit in these stagnant areas, initiating membrane fouling. If feed water contains significant concentration of dissolved organics, they could adsorb on the colloidal particles, forming layer of very low water permeability. Such multi-components fouling layer could significantly reduce permeate flow and it is difficult to remove with common cleaning procedures.

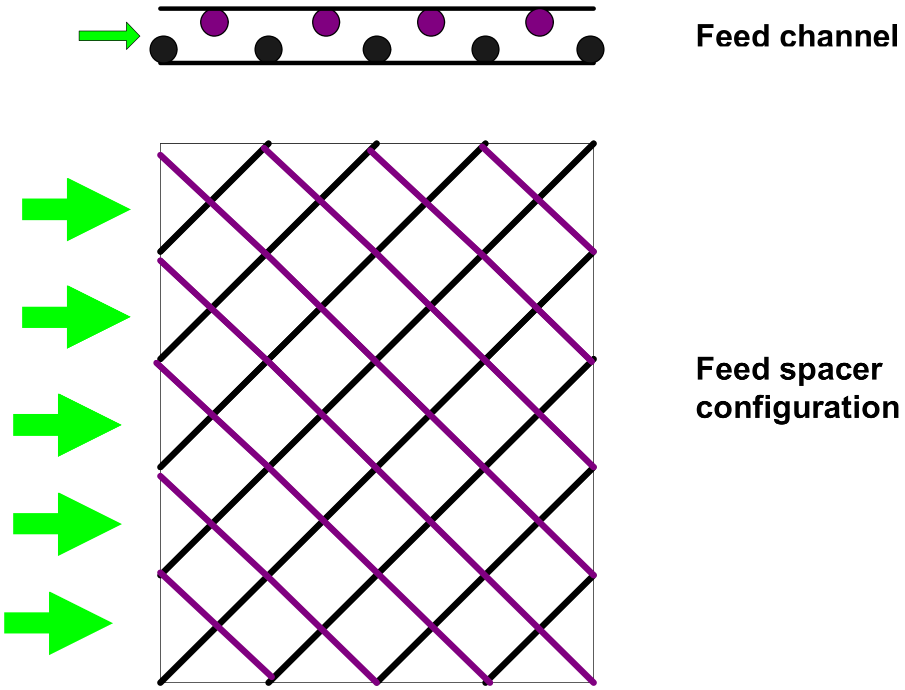

Figure 5. Configuration of feed spacer

2.1 Desalination of well water.

Feed water from brackish wells has consistent quality, usually has very low concentration of colloidal particles and therefore requires minimal treatment. The configuration of pretreatment system in brackish desalination plants is very simple as shown in Figure 6. No media filtration is required. Cartridge filters, placed on suction of high pressure pump act as a safety device, to protect downstream equipment in case of sand particles release from the well.

2.2 **Reclamation of municipal wastewater**

The conditions are entirely different in RO plants operating in municipal wastewater reclamation systems. Secondary effluents have high concentration of colloids, organic matter and bacterial activity. Initial attempts to use conventional pretreatment that included media filtration produced RO feed water that resulted in rapid fouling of membrane surfaces. The decline of permeability was frequently in the range of over 50%. This high rate of permeability decline was experienced even for RO systems designed to operate at low average permeate flux rate not exceeding 17 l/m2-hr. The fouling layer on the membrane surface was determined as being a mixture of colloidal particles, bacteria and organic compounds. Attempts to restore permeability through frequent cleaning were not successful. It was realized that the culprit of formation of fouling layer was high concentration of colloidal particles in the feed water. The solution

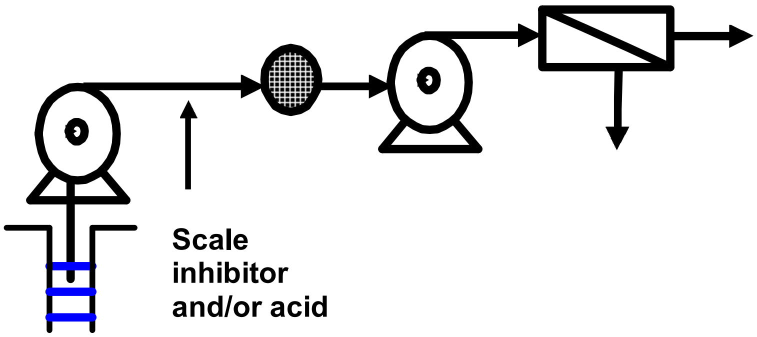

Figure 6. Configuration of brackish plant treating well water

to this problem was replacement of media filtration with membrane filtration in the pretreatment system. The common membrane filtration technology applied is either microfiltration (MF) or ultrafiltration (UF) in capillary configuration, pressure or vacuum driven. Figure 7 shows configuration of wastewater reclamation system with membrane pretreatment. Inclusion of membrane filtration in the pretreatment system practically eliminates colloidal matter from the RO feed water. Examples of municipal wastewater reclamation systems using membrane pretreatment are Bedok and Kranji plants in Singapore. At the Bedok site the first phase of the pretreatment system consists of pressure driven MF unit. The second phase was equipped with submersible UF. At the Kranji plant submersible MF technology is being used. The designed permeate capacity of RO demonstration unit at Bedok site was initially 10,000 m^3/day while the full scale plant was designed for 32,000 m^3/day. The product water capacity at Kranji site is 40,000

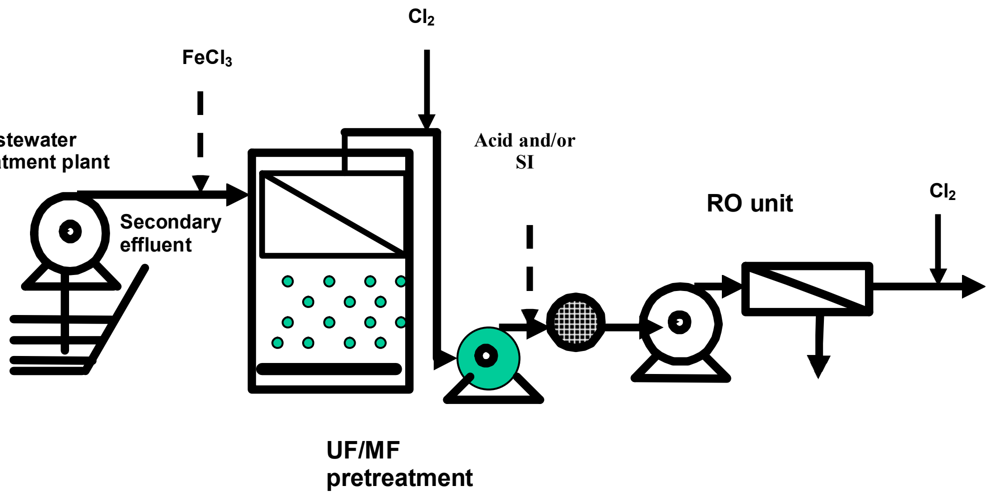

Figure 7. Configuration of wastewater reclamation plant using membrane pretreatment

m^3/day. The demonstration phase of Bedok plant commenced in 2000 and the full scale plants at Bedok and Kranji sites commenced operation at 2003. Configuration and design parameters of Bedok and Kranji plants are summarized in table 2.

Table 2. Configuration and design parameters of wastewater reclamation plants in Singapore.

Parameter	Units	Location: Bedok	Location: Kranji
Feed water type		Secondary effluent	Secondary effluent
Product water capacity	m^3/day	32,000	40,000
Feed salinity	ppm TDS	500 - 1000	300 - 650
Permeate salinity	ppm TDS	< 50	< 50
Recovery rate	%	75	75
Average permeate flux	l/m^2 - hr	17.5	17.5
Array		50:23	49:24
Elements per vessel		7	7
Element type		LFC	LFC

Membrane filtration eliminates colloidal matter but has no effect on concentration of dissolved organics. Adsorption of organics on the membrane surface does not affect internal hydraulics of the RO modules but may reduce permeability. At some locations absorption of organics in wastewater plants could result in up to 30 – 40% reduction of permeability (5). Bedok and Kranji plants utilize Hydranautics low fouling composite (LFC) membrane elements that were specifically developed for processing of feed water with high concentration of dissolved organics. The unique property of LFC membrane is hydrophilic and with stable neutrally charged membrane surface, which has low affinity to dissolved organics. Stable membrane performance in operation in a significant number of large commercial plants validates this approach to prevention of organic fouling. There are also some conventional polyamide composite membranes which have proven effective for wastewater treatment. One example is the ESPA2 membrane which is used at the Orange County and West Basin wastewater treatment plants in California. The combination of membrane pretreatment, that reduces concentration of colloidal matter, with utilization of low fouling RO membranes has been demonstrated as one of the most effective processes configuration for reclamation of municipal wastewater.

2.3 Salinity reduction of surface water.

Particulate and biological load in water from surface sources can fluctuate significantly. It is required that pretreatment require will produce good water quality even at most adverse conditions. In conventional pretreatment systems, the treatment step that provides reduction of colloidal particles is coagulation, flocculation and media filtration. In majority of cases this configuration is very effective. However, it requires good operating skills and adjustment of the operating parameters as the composition and quality of raw water changes. Another approach is to apply membrane filtration unit in place of media filters, similarly as it is practiced in wastewater reclamation systems. Use of membrane filtration is becoming more frequent in industrial system treating low salinity surface water to produce low salinity permeate process water (power and semiconductor industry). Use of membrane pretreatment improves reliability and reduces maintenance (membrane cleaning frequency) of the plant. In industrial application, where process water supply is an essential component of manufacturing plant operation, the higher cost of membrane pretreatment as compared to medial filtration, can be easily justified.

Two representative industrial installations that utilize UF as a pretreatment to RO are plants at Qinbei Power Plant, Henan Province and Baotou Steel, Inner Mongolia. The summary of plant configurations at listed in Table 3. Within the last three years over 40 IMS installations, utilizing Hydranautics Hydracap UF pretreatment, were built in China of combined capacity of about 60,000 m^3/day.

The conditions are quite different for RO seawater desalination systems producing potable water. Here, capital and operating cost are major drivers of process selection. Due to low product recovery in RO seawater units any cost difference incurred in the pretreatment system will strongly affect cost of water produced. Till recently the conventional media filtration has been used almost exclusively as part of the pretreatment in large RO seawater plants. Lately, limited number of medium size plants that utilize

Table 3. Representative configuration of UF+RO plants for industrial applications.

Location	Qinbei Power Plant		Baotou Steel	
System	UF	RO	UF	RO
Raw type	Cooling tower blow-down	UF effluent	Yellow River	UF effluent
Raw water temperature, C	13 – 29		2 – 28	
Raw water suspended solids, ppm			240	
Raw water treatment	Gravity filters		Flocculation, sedimentation, media filters	
Capacity, m3/day	5280	3600	8640	5760 – FFC3 3600 – ESPA2
Element type, unit configuration	Hydracap	LFC1 – single pass	Hydracap	LFC3-LD followed by ESPA2 (2nd pass)
Design flux rate, l/m^2-hr	75	28	81	18 – LFC3 34 – ESPA2

membrane filtration as the pretreatment step are being built and some are operational already (Table 4). The better know plants with membrane pretreatment are Addur, Bahrain (6), Fukuoka, Japan, Kindasa, Saudi Arabia (7) and Yu-Han, China (8).

Table 4. RO seawater plants with membrane pretreatment.

Location	Addur, Bahrain	Fukuoka, Japan	Kindasa, Saudi Arabia	Yu-Han, China
Membrane filtration capacity, m3/day	140,000	96,000	90,000	70,000
Operational status	Operational since May 2000	Operational since May 2005	Initial operation	Initial operation
Membrane technology	Pressure driven UF reverse spiral	Pressure driven UF reverse spiral	Pressure driven UF capillary	Submersible UF capillary
Membrane module manufacturer	Nitto Denko	Nitto Denko	Hydranautics	Zenon

The Addur plant is probably one of the first seawater plants where the concepts of integrated membrane system (IMS) have been implemented. UF filtration system was added as a part of plant rehabilitation process of DuPont hollow fiber desalination plant initiated in 1999. The UF filtration equipment used is unique as it based on spiral wound elements that are backwashed by reversing direction of filtrate flow, so called reverse spiral (RS). At the time of implementation (year 2000) the RS technology was at the early stages of commercial development and number of operational and performance problems were encountered. Subsequently, the problems were solved by product modifications and improvements of operating conditions. Presently the performances of the UF filtration unit are according to specifications.

The Kindasa RO seawater plant commenced operation in year 2000. RO permeate capacity was 14,000 m3/day utilizing Hydranautics spiral wound elements. Feed water is supplied form open intake and treated prior to RO using a conventional filtration system. The pretreatment system operated satisfactory most of the time. However, during seasonal periods of stormy weather or algae bloom poor performances were encountered. Due to increasing potable water demand it was decided to increase system capacity to 40,500 m3/day. For the pretreatment of the expanded system membrane pretreatment was considered. Extensive operation of pilot unit confirmed prior assumption that membrane pretreatment will produce stable feed water quality also during periods when raw water has high turbidity due to algae bloom or stormy weather. Eventually it has been decided to utilize membrane filtration technology based on pressure driven, capillary UF in the pretreatment of the expanded system. The membrane modules that have been selected for the pretreatment system are Hydracap, made by Hydranautics. During the time of writing of this article the RO system, including UF pretreatment, is being prepared for the acceptance test.

III. ECONOMICS OF MEMBRANE PRETREATMENT.

The economic benefits of applying membrane pretreatment in RO units operating in wastewater reclamation plants are well documented (4). Effluent from a conventional pretreatment has very high fouling potential. As a result of formation of fouling layer on membrane surface, feed pressure has to be increased to the range of 20 – 30 bars to maintain designed permeate flow. In systems that utilize membrane pretreatment, fouling resulting from adsorption of organics is moderate and operating pressure at comparable permeate flux is below 15 bars. The difference in energy consumption sufficiently compensates for higher cost of membrane pretreatment.

Benefits of use of membrane pretreatment in RO seawater systems are related to number of operating parameters and detailed analysis is required. Table 5 summarizes configurations and components of the representative conventional and membrane pretreatments. For membrane filtration both pressure driven and submersible technology could be used. However, for this comparison pressure driven capillary technology has been selected,

Table 5. Summary of relevant pretreatment configurations with media filtration and pressure driven membrane filtration treating open intake seawater..

	Conventional pretreatment		Membrane filtration	
Treatment step	Objectives	Equipment component and/or operating parameters	Objectives	Equipment component and/or operating parameters
Initial screening	Remove large debris	Screen 5 – 25 mm	Remove large debris	Screen 5 – 25 mm
Intermittent chlorination (optional)	Mitigate biological activity	1 - 5 ppm active chlorine	Mitigate biological activity	1 - 5 ppm active chlorine
Backwashable fine screening ~ 100 micron			Prevents fiber blockage	Operating pressure 0.3 bar, backwash pressure 3.5 bar
Flocculation - coagulation	Conglomeration of colloidal particles	Ferric dosing 5 – 30 ppm, 0.2 – 1.0 ppm polymer	Conglomeration of colloidal particles	Ferric dosing 0.5 – 1.0 ppm
Filtration	Removal of colloidal particles, some reduction of organics	Gravity media filters. Filtration rates 8 – 15 m^3/m^2-hr, pressure loss 0.1 – 0.2 bar	Removal of colloidal particles, some reduction of organics	Membrane filtration. Filtration rates 70 – 100 l/m^2-hr, pressure 0.1 - 1.0 bar
Backwash	Removal of colloidal matter from filter media	10 – 20 min every 8 – 24 hr	Removal of colloidal matter from membrane surface	1 – 1.5 min every 0.5 hr
Chemical cleaning		Not applicable	Restoration of membrane permeability	Once every 30 – 60 days
Membrane replacement		Not applicable	Maintenance of performance	One load every 7 – 10 years
Recovery rate		90 – 95%		96 – 98%
Filtrate flow per unit area	~ 100 m^3-day/m^2		~ 200 m^3-day/m^2	

Difference in system configurations affects both cost of equipment and operating cost. Table 6 summarizes potential effect of application of membrane filtration in pretreatment system of large RO seawater plant.

Table 6. Effect of application of membrane pretreatment in large RO seawater plant.

Design parameter	Conventional pretreatment	Membrane pretreatment
RO flux	12 – 14.5 l/m2-hr	15 – 18.5 l/m2-hr
Pretreatment footprint	100 m^3-day/m^2	200 m^3-day/m^2
RO membrane replacement rate	10 – 15%/year	8 – 10%/year
UF membrane replacement rate	Not applicable	8 – 10%/year
RO cleaning frequency	2 – 4 per year	0.5 – 1.0 per year
Seawater intake	Dedicated intake structure about 10 m below surface	Shallow locations, shorter intake lines
Equipment cost contribution to the plant cost	$ 100/m3-day	$130/m3 - day
Operating cost: consumable + labor	$0.047/m3	$0.056/m3
Total contribution to water cost	$0.073/m3	$0.091/m3

The results in Table 6 indicate that cost of equipment in large RO seawater system utilizing membrane pretreatment is about 30% higher then in a plant using conventional pretreatment. The operating cost is also higher by about 20%. Assuming the overall water cost produced by large RO seawater plant to be about $0.70/m3, the overall difference represents about 2 – 3%. At sites with good and stable raw water quality the conventional pretreatment will be sufficient. At locations with difficult raw water, use of membrane pretreatment at somewhat higher water cost could be justifiable to assure stable plant operation.

Conclusion

There continues to be a trend toward the use of membrane pretreatment in RO-based systems. When difficult feedwaters are encountered, such as wastewater or difficult surface water, UF/MF pretreatment can effectively reduce membrane fouling rates. The reduced fouling rates lead to lower energy consumption, lower chemical use, longer membrane life, less maintenance labor and greater system on-line time. The cumulative effect of these benefits can make the overall system less expensive despite the UF/MF equipment being more expensive than the conventional pretreatment.

References

1. Standard Test Method for Silt Density Index (SDI) of Water, ASTM procedure D4189 -82.
2. J.C. Schippers and J. Verdouw, The modified fouling index, a method of determining the fouling characteristics of water, Desalination 32(1980)137-148
3. S.G. Yiantsios, D. Sioutopoulos, A.J. Karabelas, Colloidal fouling of RO membranes: an overview of key issues and efforts to develop improved prediction techniques, Desalination 183(2005)257-272
4. G. Schock, A. Miquel, Mass transfer and pressure loss in spiral wound modules, Desalination 64(1987)339-352
5. K. Andes, C.R. Bartels, J. Iong, M. Wilf, "Design considerations for wastewater treatment by reverse osmosis", Intern. Desalination Assoc., World Congress on Desalination and Water Reuse, September 28-October 3, 2003, Bahamas
6. K. Barushid, A. Hashim, T. Kannari, T. Tada and H. Iwahori, UF membrane performance at Addur: expectation, reality and prospects, Intern. Desalination Assoc., World Congress on Desalination and Water Reuse, September, 2005, Singapore
7. Graeme K. Pearce, Santi Talo, Kamran Chida, Amir Basha, Aziz Gulamhusein, Pretreatment options for large scale SWRO plants: case studies of UF trials at Kindasa, Saudi Arabia, and conventional pretreatment in Spain, Desalination 167(2004)175-189
8. Zenon press release