

ADVANCED MEMBRANE PROCESS FOR WATER AND WASTEWATER RECOVERY

Riad Al-Samadi, Ph.D., P. Eng.

Advanced Water Solutions (AWS)

Burlington, Ontario,

Canada

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ABSTRACT

Improving the recovery of permeate from existing and new reverse osmosis membrane systems offers several benefits to people and industry since it increases water availability and minimizes waste. The **ARROW**[®] and **ZERO**[®] and **ZDW-RO**[™] processes alleviate membrane scaling limitations and enable increased product water recovery of 95% - 98% from RO and NF membrane systems. These patented processes provide a rapid economic payback of less than 2 years based on savings in raw water and effluent disposal costs.

INTRODUCTION

Water is a precious, invaluable commodity that the world needs more and more each day. As the world population grows, the demand for good quality water by people, industry and agriculture has also increased rapidly. Unfortunately, the availability of good quality water has also been adversely affected by global warming. According to the World Bank and UNFPA¹:

“Human-induced climate change is expected to negatively impact agricultural productivity throughout the tropics and sub-tropics, decrease water quantity and quality in most arid and semi-arid regions, and harm ecological systems and their biodiversity”. More than 1 billion people (i.e. 15% of the world’s population) lack clean water and more than 2.5 billion live without adequate sanitation. The Millennium Declaration target is to “halve the proportion of people without access to safe drinking water and basic sanitation by 2015”.

On the positive side, during the past 5-6 decades, reverse osmosis (RO) membrane technologies have evolved as a reliable, low-energy and economical desalination, water purification and wastewater reclamation tool that can be used to address the growing need for potable and industrial water worldwide. There have been several important developments in the design and manufacture of RO membranes in recent decades, including:

- The production of chemically stable polyamide membranes resulting in longer service life.
- Membranes that require low operating pressure, thus reducing energy consumption.
- Higher rejection RO membranes that deliver better product water quality at low to moderate operating pressures.
- Large RO elements, e.g. 16-inch and 18-inch elements that can be used in high capacity desalination plants in order to reduce capital cost and footprint.

In spite of these developments, one of the main limitations of RO membranes is the production of a significant volume of RO concentrate which typically ends up as a waste stream that must be disposed of safely since it contains most of the contaminating salinity, hardness, silica and other potentially harmful organic and inorganic contaminants. These streams can be as large as 30-50% of the treated water and often

represent a disposal challenge or a substantial additional treatment cost via thermal evaporation, crystallization or release to sewage treatment plants, if available.

In view of the ever-increasing fresh water and sewage disposal costs, the large RO membrane concentrates should not be disposed of, since they represent a pretreated stream that is free from oil, suspended solids, colloids and biological matter. Instead, the concentrates should be treated and purified further to recover more pure (i.e. desalinated) water in an economical manner, while reducing the net influent water consumption and eliminating or minimizing the reject stream.

This paper aims at addressing the RO membrane concentrate limitation by introducing a series of advanced and patented membrane-based water purification processes that economically achieve RO permeate recoveries in the range 95% - 98%, thereby minimizing water and waste and contributing to a sustainable environment.

PROBLEM STATEMENT – LIMITATIONS OF CURRENT MEMBRANE PROCESSES

While RO and other membrane desalination processes including electro-deionization achieve effective water purification, the extent of purified water recovery is in most cases limited by the concentration of scale-precursors and the concentration of fouling and colloidal material in the raw water. These compounds deposit on the membrane surface, undermine the rate of permeation (i.e. the flux) and result in premature cleaning and subsequent failure and membrane replacement. Calcium and magnesium are common scale precursors that form temporary (or permanent) insoluble hardness compounds as they concentrate over the RO membrane surface, including calcium and magnesium carbonate, fluoride and sulphate.

While temporary calcium and magnesium hardness (i.e. due to carbonate) can be addressed by acidifying the water, permanent (sulphate) hardness is relatively independent of the pH. Silica also has a limited solubility, which increases by increasing the pH, e.g. by addition of caustic soda. Unfortunately, increasing the pH converts the relatively soluble calcium bi-carbonate to the rather insoluble calcium carbonate, resulting in scale deposition on the membrane surface.

To complicate the matter further, most water sources from aquifers contain a mixture of calcium, carbonate alkalinity, sulphate and silica, thus undermining the pre-treatment system's ability to achieve high RO membrane system recoveries (i.e. > 80%) by simple pre-conditioning with acid and/or anti-scalant. Typical low-pressure first stage RO membrane systems can achieve recoveries in the range 60% - 80%, depending on the influent composition and pre-treatment method. In "Whole House RO" systems, the RO permeate recovery is kept in the low range of 25% - 50%, and certainly no higher than 70% since these systems are expected to be maintenance-free, with minimum cleaning or RO membrane replacement.

The treatment of 20% - 40% reject volume using thermal (evaporative) processes, even with energy recycling as in multi-stage flash distillation systems or vapor recompression evaporators and crystallizers, is very costly both in terms of capital and energy costs.

Alternatively, there are processes where the reject stream from an existing RO system is processed further using a second, high pressure RO stage, after additional conditioning (e.g. by pH adjustment and/or anti-scalant addition) or chemical softening with cold-lime or hot-lime. This approach will achieve additional water recovery, totaling perhaps up to

85%-90%, depending on the water quality and inter-stage softening method used. However, this method is not cost-effective since it treats a relatively large first stage RO concentrate stream. The chemical precipitation equilibrium will leave a significant concentration of sparingly soluble calcium compounds and silica that will limit the overall recovery due to precipitation upon further concentration over the second stage RO membranes.

HIGH RECOVERY PROCESS DESCRIPTION

The high-recovery processes discussed in this paper comprise a number of configurations whose design depend on the influent water flowrate, its hardness, the concentration of silica relative to other hardness precursors and its total dissolved solids (TDS). These process configurations minimize the scale potential of the water by *continuously* removing hardness ions (i.e. calcium, magnesium, silica, barium, etc.) from the RO concentrate stream as they build up. Hardness and silica are removed efficiently by a process of ion exchange softening, chemical precipitation softening or a combination of these processes, depending on the raw water composition.

The process includes the following key steps:

Pretreatment - Effective pre-treatment could include fine media filtration, ultrafiltration (UF) or microfiltration (MF) membrane treatment, aeration and anti-scalant addition to reduce the scale potential. If the influent contains a significant concentration of biodegradable organic compounds, aerobic biological reactor pretreatment combined with or followed by UF/MF membrane filtration will be required. Pre-treatment should target a Silt Density Index (SDI_{15}) < 4 and preferably < 3.

First Stage RO (RO-1) - The pretreatment step is followed by the first stage RO purification step (RO-1). RO-1 treats a large portion, typically 50% - 75%, of the influent at low pressure. In many cases, this step could be an existing RO system that produces a large reject stream of up to 30% of the influent volume, due to fouling and high scale formation potential. If this is an existing RO, it is necessary to review the pre-treatment system design since it might require enhancements to ensure compatibility with the high recovery process.

Second Stage RO (RO-2) - The second stage RO step (RO-2) treats concentrate from RO-1, combined with an appropriate flowrate of recycled RO-2 concentrate after softening. The flowrate of the treated, high-TDS, low-hardness, recycled RO-2 concentrate is computed based on mass balance and scale prediction calculations to ensure very low scale formation potential over the second stage RO membranes at the targeted overall process permeate recovery. The overall process permeate recovery is the total permeate from RO-1 and RO-2 membranes, expressed as a percentage of the influent water flowrate, typically > 95%. It should be noted that for low-flow and/or relatively high TDS influent scenarios, there may be no need for the second stage RO, i.e. sufficing with a single stage high-recovery RO system.

RO Concentrate Softening and Recycle - The next key step is the RO-2 concentrate softening step. Hardness removal from the volume-reduced high TDS RO-2 concentrate can be achieved cost-effectively by chemical precipitation of calcium, magnesium and silica hardness, as well as other multivalent sparingly soluble ionic compounds. If the silica concentration is not limiting, however, concentrate softening can be achieved

simply by ion exchange, using strong acid cation exchange resins, weak acid cation exchange resins or chelating resins. The chemical precipitation step utilizes caustic soda and/or soda ash, depending on the ratio of alkalinity to calcium hardness. Magnesium may also be added, depending on the relative concentration of silica in the RO-2 concentrate. Effective solids contacting is necessary to ensure efficient hardness and silica and reduced chemical consumption. After softening, the hardness-free RO-2 concentrate is recycled to the front-end of RO-2 at a sufficiently high flowrate to ensure low scale potential of RO-2 feed, based on mass balance computations.

A small RO-2 concentrate reject stream is removed from the process in order to control the TDS (and osmotic pressure) of the second stage RO concentrate, since the second stage is typically operated at a maximum pressure of 900 - 1000 psig.

In the case of chemical precipitation softening, a small slurry reject stream is also removed from the bottom of the small clarifier and pumped out directly to a solar evaporation pond where it is disposed of, along with the small RO-2 concentrate bleed stream. Alternatively, the concentrate reject stream can be sent to a small mechanical vapor compression evaporator, spray dryer or flash evaporator to enable close to 100% water recovery in an economical manner. The slurry reject stream typically has a suspended solids concentration < 1% which enables its direct transfer as slurry, thus alleviating the need for costly and labor intensive thickening and solids filtration equipment. The combined volume of the two small reject streams is < 5%, giving an overall process recovery > 95%.

The high recovery process is designed with flexibility to control the relative recoveries obtained from the first and second RO stages in order to prevent scale formation due to feedwater variability, while achieving the maximum system recovery.

High Recovery Process Configurations - Depending on the influent water flowrate and the relative concentration of silica and hardness ions, the process will have one of several patented configurations, including the following:

- RO-RO-CP
- RO-RO-IX
- RO-CP-IX-RO
- CP-RO-IX-RO
- CP-IX-RO

Where the term “CP” identifies the chemical precipitation softening method and “IX” for ion-exchange softening.

MAIN FEATURES OF HIGH RECOVERY PROCESSES

Permeate Recovery - The achievable overall process permeate recovery is determined almost entirely by the feedwater TDS and the RO System design pressure. For influents with TDS < 1000 mg/L, it would be possible to achieve overall permeate recoveries in the range 97% - 98% by operating at close to 1000 psig. For influents with TDS < 500 mg/L, a recovery of 99% has been demonstrated on a commercial scale.

Fouling and Scale Mitigation - Contrary to prevailing RO processes, by incorporating effective pretreatment, inter-stage or post RO softening with CP and/or IX, the high

recovery process designs also ensure very low RO membrane fouling and scale formation, resulting in a long membrane service life and minimum operation and maintenance costs. This has been demonstrated over several years in desalination, wastewater reclamation and drinking water production, involving very infrequent membrane cleaning or replacement.

Efficient Process Configuration - Positioning the softening step downstream from the RO membranes or between the 1st and 2nd stage RO systems results in significant improvements in the softening process efficiency, reduced capital cost and better hydrodynamic, since the RO concentrate pressure is used to drive flow through the softening steps.

Design and Application Versatility - The robust design is equally effective in treating surface water including purification/demineralization of municipal water supply, brackish water and industrial and municipal effluents.

Product Water Quality - Product water from the high recovery process will typically have a TDS < 10 mg/L, hardness < 1 mg/L as calcium carbonate and conductivity < 10 μ S/cm. High purity product water quality can be achieved by adding a 2nd pass RO system and/or mixed bed IX polishers or continuous deionization systems.

CASE HISTORY 1 – PHARMACEUTICAL EFFLUENT RECOVERY PILOT TRIALS

The high recovery industrial wastewater treatment process was demonstrated during 3-month pilot trials at the site of a major pharmaceutical company in New Jersey (U.S.). The pilot plant treated wastewater containing treated biological process effluents and cooling tower blowdown which contained elevated concentrations of ionic compounds, with TDS of approximately 1500 mg/L and sodium of approximately 200 mg/L. The main objectives of the high recovery process were to reduce the sodium concentration to < 10 mg/L and achieve clean water recovery > 94%.

As shown in the photograph below, the high recovery process pilot system consisted of feed pretreatment system, a single 4-inch element RO system designed to operate at up to 1000 psig and a downstream reject softening train that included chemical precipitation, filtration and ion exchange. The influent wastewater was pretreated with a small ultrafiltration pilot unit (not shown in the photograph) in order to remove suspended solids and colloidal matter and produce pretreated influent with a SDI₁₅ of < 3.0.

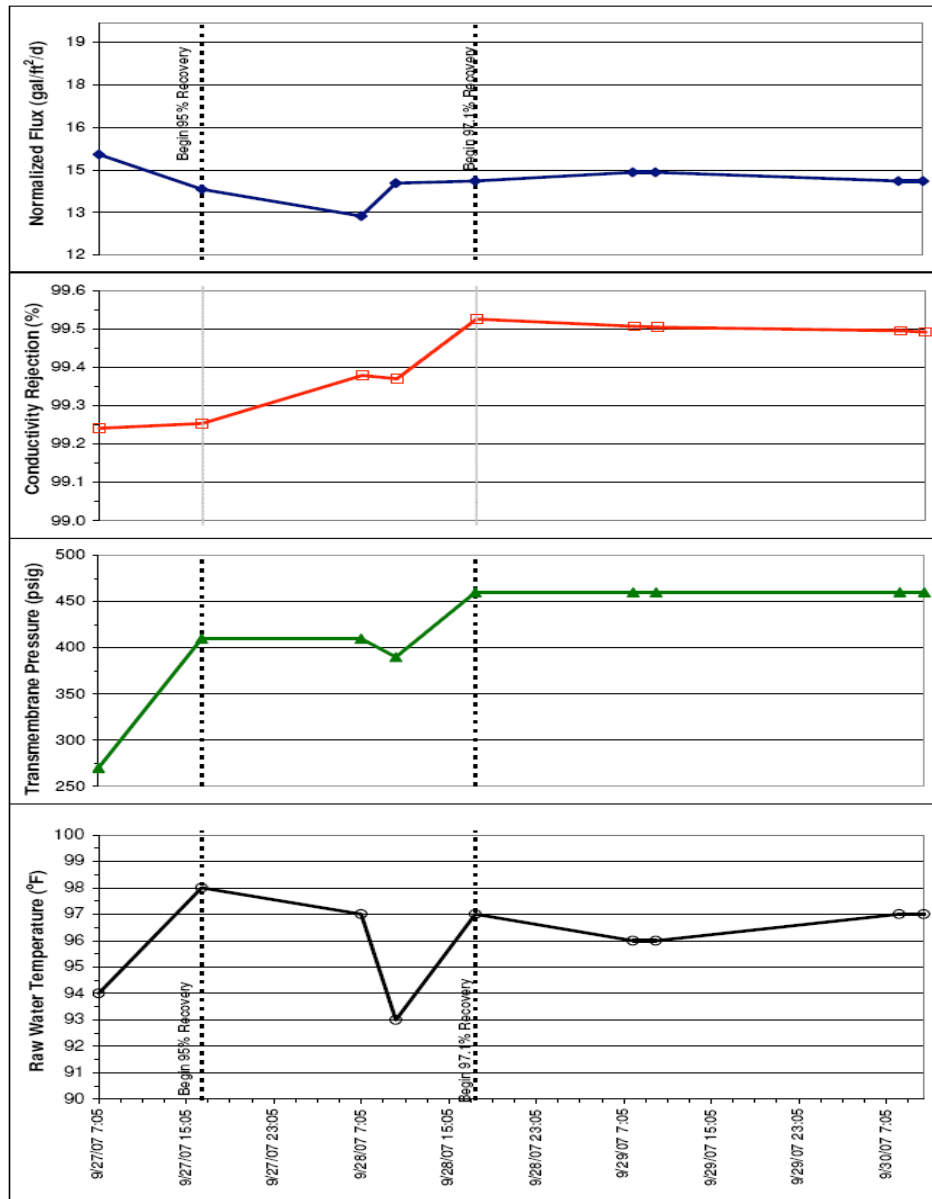
The pilot plant was operated in several test modes, including Stability Mode where both RO permeate and reject streams are recycled to the feed tank, thus maintaining constant composition and recovery, and Modified Batch Mode where only the RO concentrate is recycled, allowing the permeate recovery to increase to the desired test range of 80% to 98%. The pilot plant was also operated in the Feed and Bleed Mode where both the RO permeate and concentrate are removed and flowrates adjusted to give the desired permeate recovery, as in full-scale systems. The process tests included ion-exchange softening, chemical precipitation softening or both in series. The following results were achieved:



1. **The process achieved > 94% recovery.** After demonstrating stability of the normalized RO membrane permeate flux and conductivity rejections at 75% recovery, 80% recovery, 88% recovery and 92.5% recovery, the recovery in the IX softening configuration was increased to 95.0% recovery and then to 97.1% recovery and maintained at these recoveries for 1-2 days to verify the flux stability, as shown in Figure 2. Similarly, the RO membrane was operated in the chemical precipitation (CP) softening configuration at 94.0%, 95.5%, 96.0% and 97.0% respectively during Month 3 of the 3-month pilot program, as shown in Figure 3, which displays the temperature, trans-membrane pressure, normalized flux and conductivity rejections during these tests.

The pilot system exceeded the 94% recovery target for both the ion exchange and chemical precipitation modes. Both modes of operation achieved $\geq 97\%$ recovery. After allowing approximately 1% - 1.5% of the volume for regeneration of the IX resin and for RO membrane cleaning, it is expected that the process will achieve an overall product water recovery in the range 94% - 95%, based on raw water design specifications (i.e. TDS of 1420 mg/L). The selected mode of operation, i.e. CP and/or IX softening will depend on the wastewater quality (i.e. conductivity, silica, total hardness). The full-scale system should have the flexibility to operate in either mode. By performing the chemical precipitation and IX softening after (i.e. downstream from) the first stage or the second stage RO membranes, the capital

Figure 2. (80% - 97% Recovery, IX Feed & Bleed Mode)



and operating cost of the overall process are reduced substantially.

2. **The permeate water quality achieved < 10 mg/l sodium.** As shown in Table 1, the RO permeate quality for the higher recovery ranges of 90% to 97% consistently met the permeate sodium concentration target of < 10 mg/l.

Figure 3. (75% - 97.6% Recovery, CP Mode)

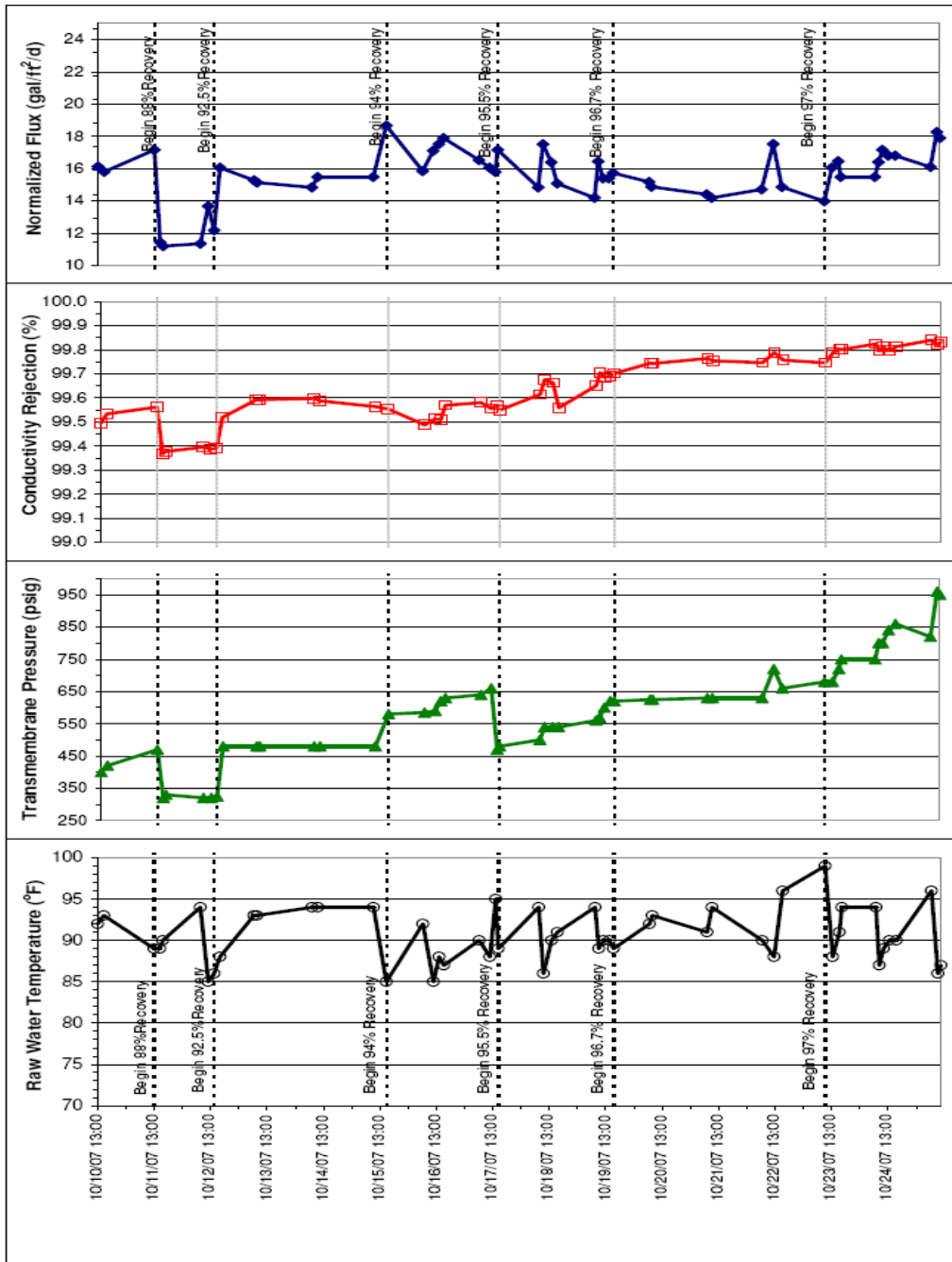


Table 1. Summary of Water Composition Data in IX Mode at Different Permeate Recoveries (90% - 97%)

Parameter	RO Raw Feed				RO Permeate				RO Feed/Concentrate				Pre-IX	Post IX
	90%	95%	96%	97%	90%	95%	96%	97%	90%	95%	96%	97%	96%	96%
pH, units	7.11	7.82	7.28	7.74	5.94	5.88	6.93	6.11	5.64	5.6	5.54	5.77	5.50	4.13
Turbidity, NTU	0.67	0.27		0.11				< 0.09	0.21	0.4	0.53	0.66	0.43	2
Total Suspended Solids, mg/L	< 3.0	< 3.0		< 3					< 3.0	< 3.0	< 3.0	< 3	< 3.0	< 3.0
Conductivity, umhos/cm	976	1,880	1,940	1,720	60.7	104	143	219	6,690	16,600	21,200	19,600	17,400	18,700
Total Dissolved Solids, mg/L	599		1,140	900	29.5	51.5	76.5	99.5	4,910	10,900	12,300	14,100	12,700	12,000
Chemical Oxygen Demand mg/L				30.3	< 12.8	< 12.8		44.2						
Total Organic Carbon, mg/L	5.1	13.6	12.0	10	< 1.0	1.0	1.3	1.6	38.2	62.1	69.1	83.7	73.7	70.6
Alkalinity pH 8.3			< 0.46				< 0.46	ND						
Alkalinity pH 4.5			207	146			< 0.46	ND			31.8	46.3		
Total Iron (Fe), mg/L		< 0.05	< 0.05	< 0.05				< 0.05		0.523	0.692	0.699	0.466	1.11
Na, mg/L	60.2	135	117	109	9.7	3.78	4.71	6.98	1380	807	775	1,040	1,130	914
Silica (SiO ₂), mg/L				32.9					210	334	164	222	320	424
Al, mg/L		< 0.08	< 0.08	< 0.08						0.822	1.13	1.12		
Ba, mg/L										0.299		0.217		
Ca, mg/L		143	137	112	0.07	0.14			100	251	308	192	256	8.24
Mg, mg/L		65.8	64.4	51.7	0.02	0.07			41.2	116	143	272	116	3.54
K, mg/L		65.5	71.9	59.3	0.657	21.9	31.3	37.9			3,140	3,530		
F, mg/L			0.29								1.3			
Br*, mg/L			5.2	6.6			< 2.0	< 2.0			38.8	45.3		
Cl, mg/L			326	329	7.2	17.5	21.7	25.8			4,430	5,260		
SO ₄ , mg/L			212	197	< 1.5	24.4	3.6	3.3			1,980	2,430	2,100	2,000
PO ₄ , mg/L			3.8	6.4							80.4	112		
CO ₃ , mg/L			< 0.46	nd			< 0.46	< 0.46				< 0.46		
HCO ₃ , mg/L			207	146			< 0.46	< 0.46			38.8	46.3		

3. **FILMTEC Membranes were superior in performance over other Low Fouling membrane.** Both the TW30-4040 and SW30-4040 membranes showed consistent conductivity rejections > 99% over the relatively high temperature range of 90 – 100 °F and no significant decline in normalized flux. These membranes were therefore recommended for the full scale system. The performance of RO membrane from another supplier did not consistently meet the manufacturer's specifications for conductivity rejection of > 99%, especially at the high temperatures. Additionally, normalized flux rates were below expected targets, even after the application of a rigorous cleaning regime for the membrane.
4. **Alum addition resulted in significantly higher SDI values.** Initial tests showed significant aluminum concentrations of > 0.1 mg/L in the influent wastewater, exceeding the RO membrane operating criterion of < 0.05 mg/L and causing RO membrane fouling and permeate flux loss. After relocation of the alum injection point downstream of the pilot system raw water take off point, the SDI₁₅ values were reduced and the membrane fouling rate was within acceptable range (i.e. < 5% - 10% normalized flux loss per month of operation).
5. **The use of appropriate antiscalant is required to avoid membrane fouling and scaling.** Vitec™ 4000 antiscalant was used during the pilot tests and is the recommended antiscalant for the full scale system. This proprietary liquid antiscalant is formulated to inhibit silica, sulfate, and carbonate scale formation and disperse colloidal particles in thin film RO membrane separation systems. This antiscalant is unique in that it inhibited silica scaling at higher concentrations than typical antiscalants, a feature that allowed significantly increased permeate recoveries of the treated wastewater, having a silica concentration of 25-30 mg/L, even when using IX softening.
6. **Weak Acid Cation (WAC) resin in sodium form required for efficient hardness removal under IX mode.** WAC resin is required for efficient hardness removal at conductivity levels > 10,000 µS/cm. This level of conductivity is expected when the permeate recovery exceeds approximately 80% recovery. In order to operate at this high level of conductivity and achieve a high removal efficiency of total hardness, WAC cation resin must be regenerated in the sodium form. The WAC resin must first be regenerated by hydrochloric acid, to be followed by sodium hydroxide treatment. Hydrochloric acid is the preferred regenerant rather than sulfuric acid in order to eliminate the potential of calcium sulfate scaling that can occur with the use of sulfuric acid regenerant, especially in view of the high expected concentrations of calcium hardness on the IX resin.
7. **More efficient (total) hardness removal can be achieved with the addition of Soda Ash under chemical precipitation mode.** Due to the low raw water alkalinity, the addition of soda ash may be required to improve the efficiency of calcium carbonate precipitation. The full-scale plant should be designed with soda ash addition capability to further enhance the hardness removal rate. The plant should also be designed with more efficient solid contacting in the chemical precipitation chamber to ensure effective precipitation and hardness removal. As an additional safeguard, WAC IX "hardness polisher" should be installed downstream from the chemical precipitation step to ensure optimum hardness removal with minimum chemical usage and TDS addition.

8. Silica reduction to sufficient levels was achieved with chemical precipitation.

The results of the chemical precipitation portion of the testing demonstrated successful removal of silica down to the levels required for the high recovery process operation at recoveries > 95%, with no evidence of silica scale formation. Maintaining silica levels < 350 ppm and preferably < 300 mg/L via dosing with polymeric antiscalant is required to prevent silica scale from occurring on the RO membrane.

CASE HISTORY 2 – HIGH RECOVERY COSMETICS PLANT WATER PRODUCTION

A consumer products manufacturer (Company) installed an RO system to demineralize city water at their New Jersey manufacturing facilities, producing 100 gpm of low TDS water for process use and utilities (boiler & cooling towers). An electrodeionization unit (EDI) is also used to polish the RO permeate and achieve a resistivity of 17 MOhm-cm.

Operating at a permeate recovery in the range 65% - 71%, the existing RO system was producing a large reject stream of 40-50 gpm which was sent to drain. The Company was interested in using the high recovery process since the cost of water and sewer use charges in New Jersey are quite high (viz. \$5 and \$13.7 per 1000 gallons, respectively). The Company's criteria was to recover the capital investment in the high recovery process in less than 3 years, and preferably in 1-2 years through water cost savings.

A high recovery membrane-based system was designed, built and supplied to the Company within a period of six months. The process included a "bolt-on" second-stage RO membrane system and an ion exchange water softener installed downstream of the RO membranes and driven by the RO concentrate pressure. The engineering design and computer simulations were based on a detailed water analysis that included the pH, TDS, main cations, anions and silica. In view of the uniform municipal water quality used by the plant, the design did not require any bench-scale or pilot testing.

The high recovery process has been running at the Company's facilities in New Jersey since April 2008. Table 2 displays a summary of the specifications and purification performance of the existing RO system and the new high recovery membrane system. The high recovery system operates at overall recoveries in the range 93% - 95% and produces 100 gpm of high quality product water for the plant, with the TDS typically in the range 8 - 10 mg/L. The permeate TDS depends on the City water TDS, temperature and the overall process recovery, as well as the age of the RO membranes. The high recovery membrane system generates only 5 - 7 gpm of RO rejects which is sent to drain, compared to > 40 gpm with the original RO system exclusively, thus saving > \$300,000 in annual operating costs. The high recovery system requires a minimum of maintenance, typically a single RO membrane clean per annum.

**TABLE 2. 2-STAGE HIGH RECOVERY MEMBRANE SYSTEM SPECIFICATIONS
(IMPACT OF RECOVERY ON WASTE VOLUME, COST AND PRODUCT QUALITY)**

PARAMETER	UNITS	CASE 1	CASE 2
		PRETREAT + RO 71% RECOVERY	PT + EXISTING RO + HR PROCESS, 95% R
PROCESS CONFIGURATION		Pretreatment + RO	RO1-RO2-IX Softening & Recycle
GENERAL:			
Water Temperature	°C	15.0	15.0
Raw Water pH		8.3	8.3
Raw Water TDS	mg/L	381.3	381.3
Raw Water Hardness	mg/L as CaCO ₃	180.6	180.6
Raw Water Silica	mg/L	13.0	13.0
EXISTING RO (RO-1):			
RO-1 Feedwater Flowrate	gpm	140.9	105.26
RO-1 Permeate Flowrate	gpm	100.0	74.7
RO-1 Permeate Recovery	%	71%	71%
RO-1 Permeate TDS	mg/L	2.1	2.1
RO-1 Permeate Hardness (as CaCO ₃)	mg/L	0.58	0.58
RO-1 System Operating Pressure	psig	200.0	200.0
NEW ARROW™ RO-2:			
RO-2 Feedwater Flowrate	gpm		30.5
RO-2 Permeate Flowrate	gpm		25.26
RO-2 Permeate Recovery	%		45.2%
RO2 Permeate Hardness	mg/L as CaCO ₃		0.93
RO-2 Permeate TDS	mg/L		32.5
RO-2 System Operating Pressure	psig		230.0
RO-2 Recommended Design Flux	gfd		12.0
Overall Process Summaries:			
Overall Process Product Water Flowrate	gpm	100.0	100.0
Overall Membrane Process Recovery	%	71.0%	95.0%
Net Savings in Raw Water Use & Rejects to Sewers	gpm	0.00	35.6
Overall Process Product Water TDS	mg/L	2.1	10.9
Overall Product Water Hardness (as CaCO ₃)	mg/L	0.58	0.74
Reject Stream Flowrate	gpm	40.9	5.26
Reject Stream TDS	mg/L	1307.2	7807.0
Reject Stream Hardness as CaCO ₃	mg/L	622.5	629.6
Reject Stream Silica Concentration	mg/L	44.6	255.4
MEMBRANE SYSTEM CAPITAL COST	\$	\$300,000	\$750,000
ANNUAL OPERATING AND MAINTENANCE COST	\$	\$39,328	\$57,499
WATER PRODUCTION COST	\$/ 1000 gal	\$13.96	\$8.51
CAPEX (PAY-BACK PERIOD)	Years	NA	1.57

Table 3 displays details of several cost scenarios involving variable existing RO system permeate recoveries of 65%, 71%, 75% and 80%. For each of these RO1 permeate recoveries, Table 3 shows the positive impact of increasing the overall membrane process product recovery from 65%, 71%, 75% or 80%, to higher recoveries up to 98%. The 71% RO1 permeate recovery scenario was selected in Table 3 instead of 70% since it represents the upper end of the permeate recovery of the Company's existing RO system.

Fortunately, most of the cost benefit is realized by operating in the overall recovery range 90% to 95%, which is readily achievable at low to moderate pressures in the range 200 psig – 400 psig for surface water and low-salinity brackish water. If the objective is to achieve “zero liquid discharge” or if the raw influent water salinity is high, however, process economics will favor operation at higher permeate recoveries of 97% - 99%, with 2nd stage RO system design pressures of up to 950-1000 psig. In this case, the small reject stream can be evaporated safely in a secure surface pond, mechanical

TABLE 3. ARROW® HIGH RECOVERY PROCESS COST BENEFIT ANALYSIS SPREADSHEET

Product Water Flowrate: 100 gpm

RO1 RECOVERY (%)	OVERALL SYSTEM RECOVERY (%)	ANNUAL O & M COST (\$)	RAW WATER FLOWRATE (GPM)	RO1 PERMEATE FLOWRATE (GPM)	RO2 PERMEATE FLOWRATE (GPM)	RO2 REJECT FLOWRATE (GPM)	WATER/DISCHARGE SAVINGS (GPM)	ANNUAL COST (\$)	CAPEX/PAYBACK PERIOD (YEARS)
65%	65%	\$40,377	153.85	100.00	0.00	53.85	0.00	\$862,416	NA
65%	80%	\$61,103	125.00	81.25	18.75	25.00	28.85	\$644,621	2.07
65%	90%	\$58,567	111.11	72.22	27.78	11.11	42.74	\$505,575	1.26
65%	95%	\$57,499	105.26	68.42	31.58	5.26	48.58	\$447,029	1.08
65%	98%	\$56,910	102.04	66.33	33.67	2.04	51.81	\$414,769	1.01
71%	71%	\$39,328	140.85	100.00	0.00	40.85	0.00	\$733,583	NA
71%	80%	\$61,103	125.00	88.75	11.25	25.00	15.85	\$644,621	5.06
71%	90%	\$58,567	111.11	78.89	21.11	11.11	29.73	\$505,575	1.97
71%	95%	\$57,499	105.26	74.74	25.26	5.26	35.58	\$447,029	1.57
71%	98%	\$56,910	102.04	72.45	27.55	2.04	38.80	\$414,769	1.41
75%	75%	\$38,721	133.33	100.00	0.00	33.33	0.00	\$659,145	NA
75%	80%	\$61,103	125.00	93.75	6.25	25.00	8.33	\$644,621	30.98
75%	90%	\$58,567	111.11	83.33	16.67	11.11	22.22	\$505,575	2.93
75%	95%	\$57,499	105.26	78.95	21.05	5.26	28.07	\$447,029	2.12
75%	98%	\$56,910	102.04	76.53	23.47	2.04	31.29	\$414,769	1.84
80%	80%	\$38,049	125.00	100.00	0.00	25.00	0.00	\$576,567	NA
80%	90%	\$58,567	111.11	88.89	11.11	11.11	13.89	\$505,575	6.34
80%	95%	\$57,499	105.26	84.21	15.79	5.26	19.74	\$447,029	3.47
80%	98%	\$56,910	102.04	81.63	18.37	2.04	22.96	\$414,769	2.78

vapor compression evaporator/crystallizer combination, a spray dryer or a flash evaporator, depending on the flowrates and the specific site criteria.

The high recovery process design may involve a single RO membrane stage or two RO stages, depending on the influent water flowrate, total dissolved solids and the concentration of hardness, silica and other contaminants. The primary objective is to treat a large fraction of the water using a low-pressure RO system operating in the pressure range 200-400 psig, and up to 600 psig, thus reducing the capital cost and energy cost. The selection of a single stage or 2-stage RO system design is determined by computer design simulations which estimates the capital and operating costs for several design scenarios, determines the overall process unit treatment costs in \$'s per 1000 gallons treated and arrives at the optimum process design.

In the case of the Company in New Jersey where their existing RO system was operating in the recovery range 65% - 71%, Table 3 shows that by installing the high recovery system and operating in the 93% - 95% recovery range, the CAPEX can be recovered over a relatively short period of 1.2 to 1.7 years. An electrical energy cost of \$0.06 per kW.hr has been assumed in these computations.

SUMMARY

This paper describes a high recovery membrane process developed and piloted successfully in desalination, wastewater reclamation and drinking water production. The process has been installed and operated at industrial facilities in North America over the past 5 years, achieving **permeate recoveries in the range 95% - 98%** in an economical manner reflected by **CAPEX recovery period of 1-3 years**. The process design configurations ensure **virtually complete elimination of fouling and scale formation**, thus requiring very low membrane cleaning frequency or replacement and substantially **reduced maintenance** when compared to conventional RO systems.

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