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The Economics of Reverse Osmosis and Ion Exchange

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Introduction

Straight ion exchange (IX), reverse osmosis/ion exchange (RO/IX), and double-pass reverse osmosis (RO/RO) are all viable options when designing a new water treatment plant (1-6). The break-even point in total dissolved solids above which it is more economical to use one of these technologies over the others depends on a number of factors which will be addressed in this paper. The economic factors affecting the break-even point include chemicals, resins, membranes, energy, operating labor, maintenance, and capital-related items. In this paper we will concentrate on the choice of technology for a new water treatment system. A follow-up paper will consider in more detail the factors impacting the decision to retrofit RO ahead of an existing IX system.

In some instances technical considerations will outweigh economics in determining the water treatment technology of choice. For example, in some high purity water applications, double-pass RO has produced water that is substantially lower in organics and particles. Therefore, this process may be preferable to IX or RO/IX even though its production cost is higher than these other alternatives.

It should be noted that The Dow Chemical Company markets both reverse osmosis elements and ion exchange resins. It is our intention to provide an objective study utilizing conservative economic analysis without bias for one technology over another. It is also our intention to show the impact of the latest advances in membrane and resin technology on the total cost to produce water. This article updates the papers written in 1982 and 1987 (4,7) on the economics of reverse osmosis and ion exchange. This updated paper is different in that we also included the impact of system size, the cost of raw water and waste water treatment, uniform particle size (UPS) versus gaussian sized resin (Gaussian), and cellulose acetate (CA) versus thin film composite membrane (TF).

Since 1987 the cost of chemicals and energy has not changed significantly. Higher active surface area elements (400 active square feet) and higher rejection of salt using FILMTEC® FT30 thin film composite membranes have lowered the total cost to produce water from a RO/IX system. The use of UPS resins rather than Gaussian resins has also lowered the total cost of water for straight ion exchange. The cost of both IX resin and RO elements are lower than in 1987 which lowers their periodic replacement costs. And finally the capital estimates for all the water treatment technologies considered were significantly lower than in 1987. The net effect of all these changes on the break-even point above which it is more economical to use RO/IX than straight IX was significant, increasing from 75 ppm in 1987 to 130 ppm in 1994.

Design Basis

The assumptions used in this economic evaluation are listed in Tables A, C, D and E. The water treatment systems were sized to produce three different quantities of mixed-bed quality water. The flow rates were two hundred fifty thousand (250 Mgpd), five hundred thousand (500 Mgpd), and one million gallons per day (1000 Mgpd). Identical storage facilities for product water were assumed for each product water flow rate and for all cases studied. One train was used for the 250 Mgpd system size, two trains for the 500 Mgpd size, and four trains were used for the 1000 Mgpd size.

Table A

Bases and Assumptions for Cost Analysis

Water Analysis, ppm as Calcium Carbonate

Case 1:					
	Ca	31.0	HCO_3	55.5	SiO_2 (as SiO_2) 5.0
	Mg	32.5	SO_4	11.8	
	Na	15.8	Cl	10.5	Temperature 55°F
			NO_3	1.5	pH 7.6
	TDS	79.3	TDS	79.3	
Case 2:		Case 1 x 2	TDS	160	
Case 3:		Case 1 x 4	TDS	320	
Case 4:		Case 1 x 6	TDS	480	
Costs:		Energy		$0.05/KWH	
		Steam		$1.75/1,000 lbs	
		Caustic Soda		$0.16/lb	
		Sulfuric Acid		$0.038/lb (100% basis)	
		Scale Inhibitor		$1.45/lb	
		Lime		$0.02/lb	
		Feed Water		$0.05/1,000 gallons	
		Waste Disposal		$0.05/1,000 gallons	
Depreciation of Capital:				10 years, SL	
System Sizes:				250,000 gpd	
				500,000 gpd	
				1,000,000 gpd	
System Operating Rate:				360 days/year	
Product Water Purity:					
Mixed-bed polished water				< 0.01 ppm sodium	
				< 0.01 ppm silica	
				> 10 megohm-cm	
Double-pass RO				0.5-1.0 megohm-cm	

Four feed water qualities, varying only in the quantity of total dissolved solids (TDS) were utilized in the study. The TDS levels were 80, 160, 320, and 480 ppm (as $CaCO_3$). The quality of the feed water can vary significantly depending on the geographic location, and can affect any system design as well as the need for pretreatment systems, especially where reverse osmosis is contemplated. Surface water sources typically require more pretreatment while ground water sources typically need less. The feed waters used in this study have a high hardness ratio, high alkalinity, and no problems with organics, colloidal particles, or turbidity. Capital was included in the study for pretreatment. Minimal pretreatment was considered for the ion exchange system and moderate pretreatment for the RO systems.

A raw water inlet temperature was assumed to be 55°F, a national average which may vary depending on the geographic location. Unlike previous studies, we did not heat the feed water for this analysis since there are many systems that do not utilize preheating to decrease the feed pressure required for reverse osmosis systems.

Neutralization facilities were included for both the RO/IX and IX systems. The facilities were more extensive in the ion exchange plant because of the cation/anion regenerations and associated concentrated wastes. Primary demineralizer regenerant wastes would be combined and batch treated utilizing lime for neutralization, if acidic, and sulfuric acid, if alkaline. RO concentrate normally requires no neutralization. Neutralization of the ion exchange polisher wastes is incorporated into both systems.

The costs of the most dominant operating factors, energy and caustic, were set at $0.05/KWH and $0.16/lb (100%), respectively. The caustic price reflects a high purity grade specification. The cost of feed water to the RO or IX system and the cost of waste disposal have been considered at $0.05/1000 gallons each. Labor and maintenance costs were also considered in the evaluation. Operating labor was considered minimal at one-eighth to one-quarter man per shift for the relatively continuous RO operations depending on system size. For straight IX, with more batch-type operations, the operating labor was doubled. Maintenance costs were set at 5% of equipment costs.

The initial direct fixed capital (DFC) costs were estimated by obtaining equipment cost estimates from two water treatment system manufacturers, based on defined system criteria provided by the authors. The estimates were then factored to represent a reasonable installed capital cost, which includes piping, instrumentation, auxiliaries, land, and buildings. The base estimates used in this study are listed in Table B for purchased, preassembled (not installed) equipment, including ion exchange resin and membranes. Capital for neutralization, pretreatment, and storage are not included in these totals but were estimated separately. A 10-year straight-line depreciation based on total direct fixed capital, and taxes and insurance at 2% of DFC were assumed.

Table B

Purchased Equipment (Preassembled) Capital Estimates *

	$M			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Feed TDS, ppm as calcium carbonate	80	160	320	480
Straight ion exchange (IX)				
250,000 gpd	$0.24	$0.29	$0.33	$0.40
500,000 gpd	$0.45	$0.53	$0.62	$0.74
1,000,000 gpd	$0.83	$1.00	$1.16	$1.38
Reverse osmosis/ion exchange (RO/IX)				
Thin film composite				
250,000 gpd	$0.31	$0.31	$0.31	$0.31
500,000 gpd	$0.55	$0.55	$0.55	$0.55
1,000,000 gpd	$1.00	$1.00	$1.00	$1.00
Cellulose acetate				
250,000 gpd	$0.36	$0.36	$0.36	$0.36
500,000 gpd	$0.66	$0.66	$0.66	$0.66
1,000,000 gpd	$1.21	$1.21	$1.21	$1.21
Double-pass reverse osmosis (RO/RO)				
Thin film composite/thin film composite				
250,000 gpd	$0.33	$0.33	$0.33	$0.33
500,000 gpd	$0.62	$0.62	$0.62	$0.62
1,000,000 gpd	$1.18	$1.18	$1.18	$1.18
Cellulose acetate/thin film composite				
250,000 gpd	$0.39	$0.39	$0.39	$0.39
500,000 gpd	$0.74	$0.74	$0.74	$0.74
1,000,000 gpd	$1.41	$1.41	$1.41	$1.41

*Estimates are the average of figures provided by Glegg Water Conditioning and U.S. Filter/Illinois Water Treatment

Three-Bed Ion Exchange System

A three-bed ion exchange system utilizing a strong-acid gel cation bed, a vacuum degasifier, a strong-base gel anion bed, and a mixed-resin polishing bed was used in the design comparisons. A flow diagram in Figure 1 depicts the ion exchange system utilized in this study. Table C summarizes the bases and assumptions for the ion exchange computer projections and the subsequent cost analysis.

The degasifier was used to remove the carbon dioxide from the acidic cation effluent in order to reduce the quantity of anion resin and also the amount of caustic regenerant. Inclusion of the degasifier is logical due to the high level of alkalinity in the feed water.

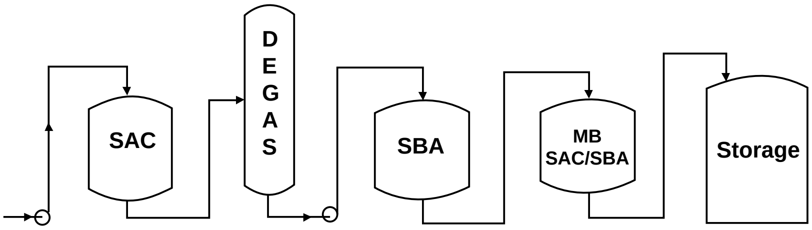
In order to size the ion exchange demineralizer it is necessary to provide water for regeneration and rinse requirements as well as account for outages associated with regeneration cycles. Thus the average feed water flow was 209 gpm for each train which was designed to yield 250,000 gallons per day. The exhaustion times of the cation and anion beds ranged from 20 to 21 hours with 4 hours for regeneration. In all cases the mixed-resin polishers in the three-bed ion exchange system were regenerated every 30 days rather than upon exhaustion.

Comparisons were made utilizing two different types of ion exchange resins. One type of resin was standard gel resins with a gaussian particle size distribution. The other type of resin was gel resins with a uniform particle size distribution.

The computer projections of the primary beds used co-current regeneration as this is the predominant regeneration scheme used in the United States. The proposed system utilized realistic regenerant levels

Figure 1

Three-bed ion exchange flow diagram - 250,000 GPD



	Gaussian Single Beds			Gaussian Mixed Bed		
Case	SAC Resin Volume ft3	SBA Resin Volume ft3	Exhaust Time hours	SAC Resin Volume ft3	SBA Resin Volume ft3	Reg’n Freq. days
1	80	49	20	25	25	30
2	160	85	20	25	25	30
3	321	161	20	25	25	30
4	481	240	20	25	25	30

	UPS Single Beds			UPS Mixed Bed		
Case	SAC Resin Volume ft3	SBA Resin Volume ft3	Exhaust Time hours	SAC Resin Volume ft3	SBA Resin Volume ft3	Reg’n Freq. days
1	74	49	20	25	25	30
2	147	70	20	25	25	30
3	294	133	20	25	25	30
4	441	199	20	25	25	30

Above equipment plus necessary regeneration equipment, minimum pretreatment equipment, and waste neutralization equipment

Table C

Bases and Assumptions for Cost Analysis
Three-Bed Ion Exchange System

Operation Sequence	***Specification***
Pretreatment	
Sand filters	
Carbon beds	
Demineralized Water Train	
Cation resin bed	Strong acid - gel
Degasifier	Removes carbon dioxide
Anion resin bed	Strong base - gel
Mixed resin bed	Strong-acid cation - gel Strong-base anion - gel
Demineralized Water Storage	
Waste Neutralization	
(Waste IX regenerants)	Neutralize to pH 7.0
Equipment efficiency	85%
250,000 gpd - One (1) train	209 gp
500,000 gpd - Two (2) trains	417 gp
1,000,000 gpd - Four (4) trains	834 gpm
Operating efficiency	85%
Regeneration Co-current	
Cation regenerant	H_2SO_4
Anion regenerant	NaOH, 120° F
Regenerations	As needed
Time	4 hours
Resin life	
Cation	5 years
Anion	3 years

and produced water low in sodium and silica with a resistivity of approximately 10 megohm-cm.

Sulfuric acid was used to regenerate the cation resins. The primary cation beds were regenerated with 2%, 4% and 8% acid in a stepwise fashion. The anion beds were regenerated with high purity caustic soda at a temperature of 120°F to maintain a low level of silica leakage. The elevated temperature regeneration sequence included preheat, regeneration, and slow rinse on the anion bed.

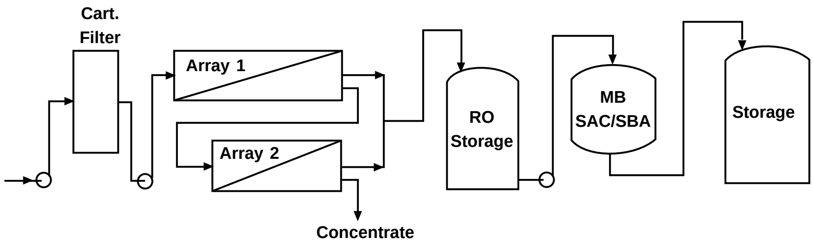
Reverse Osmosis/Mixed-Bed Ion Exchange System

The RO/IX treatment systems are shown schematically in Figures 2 and 3. Since an RO/IX system is nearly a continuous operation, the average inlet RO flow rate is 232 gpm per train with the outlet flow to the IX being 174 gpm or 250,000 gpd of permeate. The feed flow rate increases to 463 gpm for the 500,000 gpd and 926 gpm for the 1,000,000 gpd systems. A 5-micron cartridge filter is required ahead of the RO system as a polishing filter.

The thin film composite (TF) reverse osmosis section consisted of a 5-2 array utilizing 42 high surface area, spiral wound, low pressure RO elements to produce 250 Mgpd (see Figure 2). The 500 Mgpd and 1000 Mgpd system sizes used twice and four times the number of RO elements and pressure vessels, respectively. Feed pressures of 241 to 248 psig were required for operation in the TDS range of 80 to 480 ppm as $CaCO_3$. The addition of a high quality antiscalant ahead of each RO system was used to control the formation of calcium carbonate and calcium sulfate scale in all four cases. Acid addition was used only in Case 4 in order to keep the Langelier Saturation Index (LSI) of the RO concentrate below + 1.5.

Figure 2

Thin film composite reverse osmosis/ion exchange flow diagram-250,000 GPD



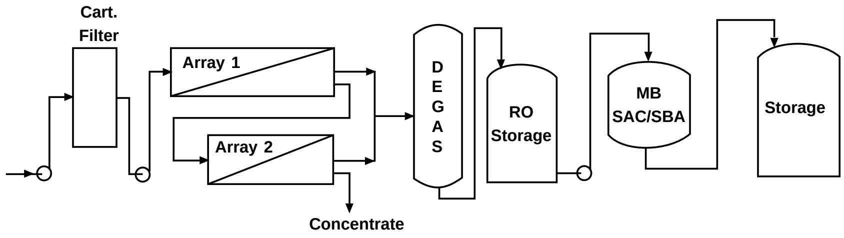
Thin Film Composite RO System

Case	Array 1 PV	Array 1 Total Elements	Array 2 PV	Array 2 Total Elements	Feed Pressure (psig)	Mixed Bed SAC Resin Volume ft3	Mixed Bed SBA Resin Volume ft3	Reg'n Freq. hours
1	5	30	2	12	241	24	39	224
2	5	30	2	12	242	24	39	110
3	5	30	2	12	245	24	39	55
4	5	30	2	12	248	24	39	22

Above equipment plus necessary regeneration equipment for mixed bed, minimum pretreatment equipment, and waste neutralization equipment

Figure 3

Cellulose acetate reverse osmosis/ion exchange flow diagram-250,000 GPD



Cellulose Acetate RO System

Case	Array 1 PV	Array 1 Total Elements	Array 2 PV	Array 2 Total Elements	Feed Pressure (psig)	Mixed Bed SAC Resin Volume ft3	Mixed Bed SBA Resin Volume ft3	Reg'n Freq. hours
1	6	36	3	18	532	29	47	198
2	6	36	3	18	533	29	47	173
3	6	36	3	18	536	29	47	137
4	6	36	3	18	540	29	47	105

The cellulose acetate (CA) reverse osmosis section used 54 spiral wound, high salt rejection RO elements in a 6-3 array to produce 250 Mgpd (see Figure 3). Multiples of this train size were used for the 500 Mgpd and 1000 Mgpd system sizes. The feed pressures for the RO systems were 532 to 540 psig depending on the feed water TDS. Acid addition to a feed pH of 6.0 was utilized in all cases in order to obtain a slightly negative LSI and to minimize the hydrolysis of the CA membranes over their three year life. A high quality scale inhibitor was added for control of calcium sulfate scale.

A degasifier was used with the CA reverse osmosis system to remove the substantial amounts of carbon dioxide generated by acid addition. The degasifier was added to optimize the sizing of the mixed-bed polisher following the reverse osmosis trains.

A system recovery of 75% was used in all cases. Higher recovery levels are theoretically possible at lower TDS levels, however, in order to optimize the total cost to produce water recoveries of 70 to 80% are typically utilized.

The IX portion for the TF and CA membrane systems is a mixed-resin bed polisher containing strong-acid cation and strong-base anion resins. The mixed-bed is required to maintain the high quality water (almost total removal of Na+ and SiO_2) utilized in power plants today. Regeneration with H_2SO_4 and NaOH occurs at weekly intervals for the low TDS case and increases to every 1 to 4 days for the high TDS case. Waste ion exchange regenerants are neutralized to pH 7.0

Table D summarizes design parameters and assumptions that were used for the RO and IX computer projections in the RO/IX system. These projections of product quality and flow rate were run using current reverse osmosis and ion exchange computer design programs.

Table D

Bases and Assumptions for Cost Analysis
Reverse Osmosis/Ion Exchange System

Operation Sequence	***Specification***
Pretreatmen	
Flocculation clarifier	
Sand filters	
Reverse Osmosis Train	
Pretreatment	Acid addition Antiscalant addition 5-Micron cartridge filter
Membranes	
Type	Thin film composite, spiral wound Cellulose acetate, spiral wound
Life	Three years
Recovery	75% in two stages
Feed pressure	248 psig (Thin film) 540 psig (Cellulose acetate)
Temperature	55°F
Degasifier	Cellulose acetate units only
Ion Exchange Polishing	
Mixed-bed	Strong-acid cation - gel Strong-base anion - gel
Demineralized Water Storage	
Waste Neutralization	
Waste IX regenerants	Neutralize to pH 7.0

Double-Pass RO System

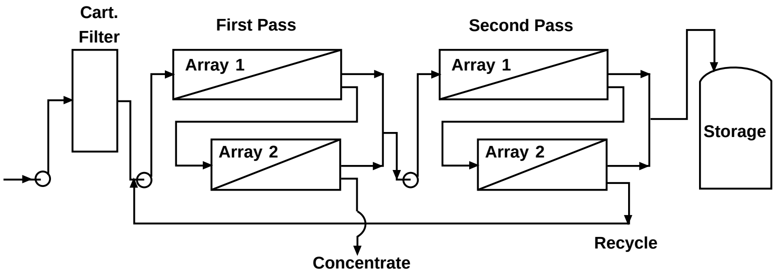
The flow schematics for the double-pass RO systems are shown in Figures 4 and 5. The two RO passes operate in series: the product of the first pass becomes the feed for the second pass. A cartridge filter is used ahead of the high pressure pump for the first pass. Each RO pass consists of two stages or arrays with a high pressure pump ahead of each pass. The concentrate from the first pass goes to drain, whereas the concentrate from the second pass is recycled back to the suction of the first pass pump.

Comparisons are made with two different types of RO elements in the first pass of the double-pass RO system. The performance of RO elements with CA membrane is compared with the performance of RO elements with TF membrane. All evaluations of the double-pass RO system utilized RO elements with TF membrane in the second pass.

An overall recovery of 75% was chosen in order to be consistent with the RO/IX option discussed previously. As mentioned earlier this overall recovery is achieved by recycling the second pass concentrate to the first pass feed inlet. The only waste from the system is the first pass concentrate.

Figure 4

Thin film composite double-pass reverse osmosis flow diagram - 250,000 GPD

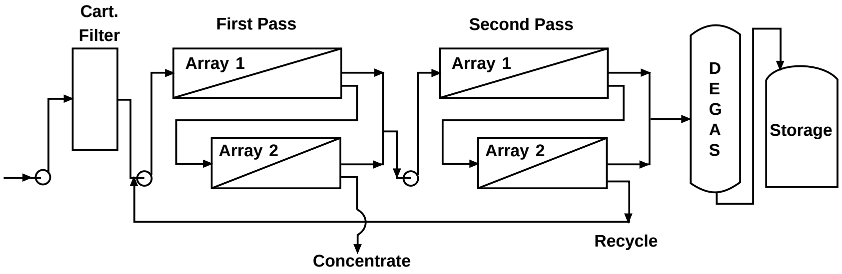


	First Pass -Thin Film Composite			Second Pass -Thin Film Composite		
Case	Pressure Vessels	Number of Elements	Feed Pressure (psig)	Pressure Vessels	Number of Elements	Feed Pressure (psig)
1	8	48	224	6	36	223
2	8	48	226	6	36	223
3	8	48	229	6	36	223
4	8	48	232	6	36	223

Overall Recovery (including recycle) 75%

Figure 5

Cellulose acetate/thin film composite double-pass reverse osmosis flow diagram - 250,000 GPD



	First Pass - Cellulose Acetate			Second Pass - Thin Film Composite		
Case	Pressure Vessels	Number of Elements	Feed Pressure (psig)	Pressure Vessels	Number of Elements	Feed Pressure (psig)
1	10	60	560	6	36	223
2	10	60	562	6	36	223
3	10	60	565	6	36	223
4	10	60	568	6	36	223

Overall Recovery (including recycle) 75%

Table E contains additional bases and design assumptions that were used for computer projections of the RO/RO option. These projections provided estimates of permeate water quality and confirmed proper hydraulic balance of the RO system. Neutralization of final concentrate should not be required for any of the cases considered in this evaluation.

It should be noted that the water quality from the RO/RO option is not equivalent to mixed-bed polisher quality. Due to feed pH requirements, the RO/RO system with cellulose acetate membranes resulted in substantial levels of carbon dioxide in the product water. This is also true to a much lesser degree with the thin film composite membranes. A degasifier was added downstream of the cellulose acetate RO/RO system in order to allow a comparison between the two types of membranes. The final product water from the RO/RO option had a resistivity of about 0.5 to 1.0 megohm-cm.

Table E

Bases and Assumptions for Cost Analysis
Double-Pass Reverse Osmosis System

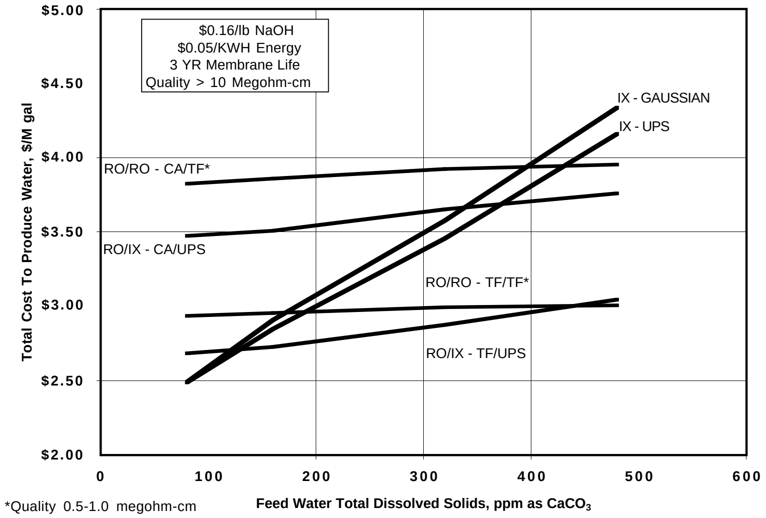
Operation Sequence	**Specification**
Pretreatment	
Flocculation clarifier	
Sand filters	
Reverse Osmosis Train	
Pretreatment	Acid addition Antiscalant addition 5-Micron cartridge filter
Membranes	
Type	Thin film composite, spiral wound Cellulose acetate, spiral wound
Life	Three years in first pass Five years in second pass
Recovery	75% overall
Arrays (for 250 Mgpd system)	
Cellulose acetate/thin film composite	7-3 in first pass 4-2 in second pass
Thin film composite/thin film composite	5-3 in first pass 4-2 in second pass
Feed pressure	
Cellulose acetate/thin film composite	568 psig in first pass 223 psig in second pass
Thin film composite/thin film composite	232 psig in first pass 223 psig in second pass
Temperature	55°F
Degasifier	Cellulose acetate units only
Demineralized Water Storage	
Waste Neutralization	
(Minimal)	Neutralization if necessary

Discussion of Results

The results of this study are summarized in Figures 6 through 10 and Tables F through J showing first the base cases and then the effect of caustic pricing and power pricing. We need to point out that the cost curves presented here only apply when using the set of assumptions as listed. The cost curves and break-even points are likely to change when significant changes in the assumptions occur. For example, in most real world designs the component sizing for an ion exchange system would change rather than adding multiple trains of a fixed size. Also many ion exchange systems would be designed with two 100% trains (or more), with one train in service and the other in standby or regeneration instead of one 100% train as in this study.

Figure 6

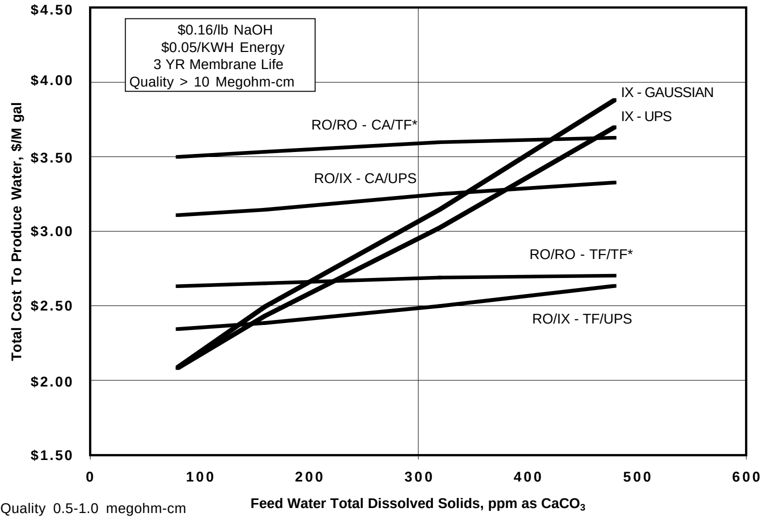
The Economics of Reverse Osmosis and Ion Exchange - 250,000 gpd Base Cases



*Quality 0.5-1.0 megohm-cm

Figure 7

The Economics of Reverse Osmosis and Ion Exchange - 500,000 gpd Base Cases



*Quality 0.5-1.0 megohm-cm

Three-Bed Ion Exchange System

The base case results for the three system sizes are shown in Table F. As would be expected, the total cost to produce water for straight IX increases with increasing feed TDS. For UPS resins the cost increases from $2.05 at 80 ppm as $CaCO_3$ to $3.62 per 1000 gallons of product water at 480 ppm as $CaCO_3$ in the 1000 Mgpd case. The Gaussian resins show a similar trend, increasing from $2.05 to $3.79 per 1000 gallons as the TDS increases.

The effect of increasing system size is to lower the total cost to produce water. When UPS resins are utilized, the total cost to produce water per 1000 gallons is $2.48 to $4.15 for a system size of 250 Mgpd varying with feed TDS. This cost decreases to $2.05 to $3.62 per 1000 gallons as system size increases. Table F shows the effect for UPS resins and Figures 6,7, and 8 compare the total cost of water for Gaussian versus UPS resin.

The IX system designed to treat the 80 ppm feed water was sized to accommodate the hydraulic limitations of the resins rather than the operating capacity of the resins. This resulted in the system design being identical for both the Gaussian and the UPS resins which yielded the same total cost to produce water for both types of resins. The hydraulic limitations did not impact the system designs for the higher TDS waters which were able to take advantage of the higher operating capacity for UPS resins relative to Gaussian resins.

Table F

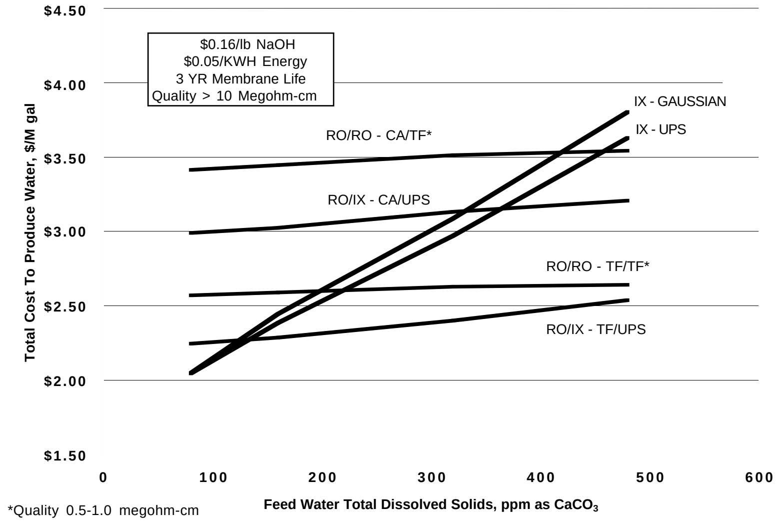
Total Cost to Produce Water
Three Bed Ion Exchange System - Base Case
1,000,000 gallons per day

			$/1,000 Gallons of Product			
			Case 1	**Case 2**	**Case 3**	**Case 4**
Feed TDS*, ppm as $CaCO_3$			80	160	320	480
Chemicals and Energy						
	Energy:	Pumps	$0.06	$0.06	$0.07	$0.07
		Heating	$0.00	$0.01	$0.01	$0.02
	Chemicals:	Sulfuric acid	$0.07	$0.13	$0.27	$0.40
		Caustic	$0.16	$0.23	$0.42	$0.63
		Lime	$0.01	$0.02	$0.05	$0.08
Subtotal			$0.30	$0.45	$0.82	$1.20
Resin replacement			$0.05	$0.07	$0.12	$0.18
Labor			$0.32	$0.32	$0.32	$0.32
Maintenance			$0.19	$0.21	$0.23	$0.26
Raw water/waste disposal			$0.06	$0.06	$0.07	$0.07
Total operating cost			$0.92	$1.11	$1.56	$2.03
Depreciation (10-year)			$0.94	$1.05	$1.16	$1.32
Taxes and insurance			$0.19	$0.22	$0.24	$0.28
Total cost to produce water						
		1,000,000 gpd	$2.05	$2.39	$2.97	$3.62
		500,000 gpd	$2.08	$2.43	$3.02	$3.69
		250,000 gpd	$2.48	$2.84	$3.45	$4.15
Operating costs, % of total						
		1,000,000 gpd	45%	47%	53%	56%
		500,000 gpd	43%	45%	51%	54%
		250,000 gpd	49%	50%	54%	56%

*TDS (Total Dissolved Solids)

Figure 8

The Economics of Reverse Osmosis and Ion Exchange - 1,000,000 gpd Base Cases



The operating cost increase is primarily due to the cost of regenerant chemicals, however, as the TDS load increases the quantity of resin also increases. This increases the resin replacement costs. The cost of raw water and waste water disposal per 1000 gallons of product water is relatively stable as feed TDS increases and as system size increases at $0.06 to $0.07. Capital is a significant factor in the total cost to produce water as the TDS increases, representing 44% to 57% of the total cost to produce water via ion exchange.

The effect of caustic pricing is shown in Figure 9 for the 1000 Mgpd system size. High purity caustic was utilized in the study and is reflected in the relatively high cost. The effect is obviously more significant for the IX system than for the thin film composite RO/IX system. Increasing feed TDS magnifies this effect for the IX cases whereas there is minimal impact for the RO/IX.

Reverse Osmosis/Ion Exchange System

Figures 6 through 8 also show the RO/IX system water production costs to be directly proportional to the feed water TDS. However the effect of increasing feed TDS is much less for RO/IX when compared to IX economics. When reviewing the total operating costs in Tables G and H for the RO/IX systems it is observed that the costs of antiscalant, caustic, sulfuric acid, and labor increase with increasing feed TDS; while the cost of energy, membrane and resin replacement, and maintenance are relatively constant in this TDS range. The capital costs as shown by depreciation expenses are also relatively unaffected by TDS compared to the straight IX system.

Figure 9

The Economics of Reverse Osmosis and Ion Exchange - Effect of Caustic Pricing

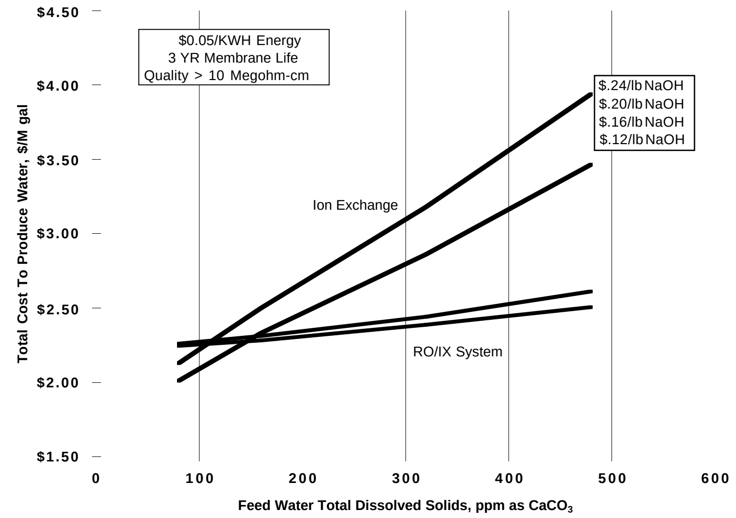


Table G

Total Cost to Produce Water
Reverse Osmosis (Thin Film) / Ion Exchange - Base Case
1,000,000 gallons per day

		$/1,000 Gallons of Product			
		Case 1	**Case 2**	**Case 3**	**Case 4**
Feed TDS*, ppm as $CaCO_3$		80	160	320	480
RO - Chemicals and energy					
Energy:	Pumps	$0.19	$0.19	$0.19	$0.19
Chemicals:	Sulfuric acid	$0.00	$0.00	$0.00	$0.01
	Antiscalant	$0.03	$0.05	$0.08	$0.08
IX - Chemicals and Energy					
Energy:	Pumps	$0.03	$0.03	$0.03	$0.03
	Heating	$0.00	$0.00	$0.00	$0.00
Chemicals:	Sulfuric acid	$0.00	$0.01	$0.02	$0.04
	Caustic Lime	$0.02	$0.04	$0.07	$0.14
Subtotal		$0.27	$0.31	$0.39	$0.49
Resin replacement		$0.02	$0.02	$0.02	$0.02
Membrane replacement		$0.12	$0.12	$0.12	$0.12
Labor		$0.21	$0.21	$0.24	$0.28
Maintenance		$0.22	$0.22	$0.22	$0.22
Raw water/waste disposal		$0.08	$0.08	$0.08	$0.08
Total operating cost		$0.92	$0.97	$1.08	$1.22
Depreciation (10-year)		$1.10	$1.10	$1.10	$1.10
Taxes and insurance		$0.23	$0.23	$0.23	$0.23
Total cost to produce water					
	1,000,000 gpd	$2.25	$2.29	$2.40	$2.54
	500,000 gpd	$2.34	$2.38	$2.50	$2.63
	250,000 gpd	$2.68	$2.72	$2.87	$3.04
Operating costs, % of total					
	1,000,000 gpd	41%	42%	45%	48%
	500,000 gpd	40%	41%	44%	47%
	250,000 gpd	43%	44%	47%	50%

*TDS (Total Dissolved Solids)

When the TF/IX system is compared to the CA/IX system, part of the increased cost to produce water is associated with the degasifier. Since the cost of the degasifier is a function of the amount of carbon dioxide to be removed, increasing feed water TDS and acid consumption by the CA/IX system is reflected in a higher total cost to produce water.

Figure 10 shows the effect of power pricing on the total costs to produce water for thin film composite and cellulose acetate (CA) membrane systems. Power pricing has a significant effect on the total cost as would be expected whereas the effect is minimal on the IX system. The CA/IX system total cost is especially sensitive to power pricing since this design operates at higher feed pressure than the thin film composite system. The effect of power pricing is to increase the crossover point of 130 ppm TDS as $CaCO_3$ to about 180 ppm TDS when the power pricing is $0.12/KWH for the thin film composite membrane system, but the cellulose acetate crossover point increases to about 500 ppm TDS for $0.12/KWH.

Table H

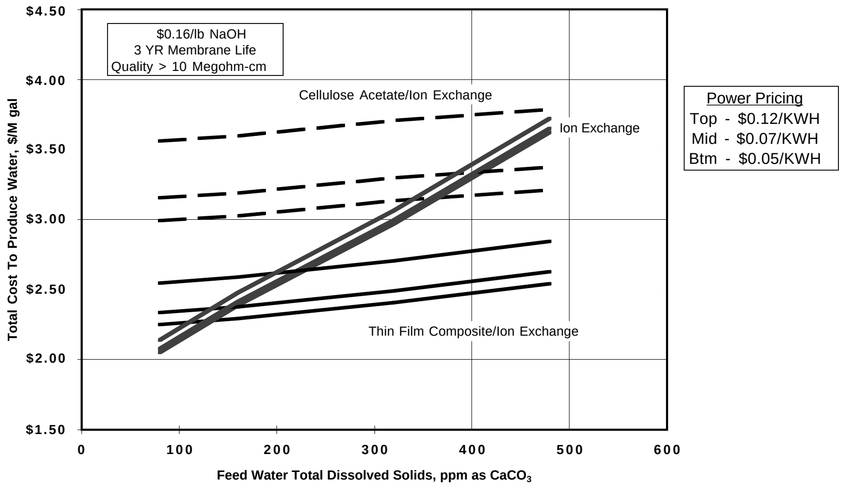
Total Cost to Produce Water
Reverse Osmosis (Cellulose Acetate) / Ion Exchange - Base Case
1,000,000 gallons per day

	$/1,000 Gallons of Product			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Feed TDS*, ppm as $CaCO_3$	80	160	320	480
RO - Chemicals and energy				
Energy: Pumps	$0.38	$0.38	$0.38	$0.39
Chemicals: Sulfuric acid	$0.01	$0.03	$0.05	$0.08
Antiscalant	$0.03	$0.05	$0.08	$0.08
IX - Chemicals and Energy				
Energy: Pumps	$0.03	$0.03	$0.03	$0.03
Heating	$0.00	$0.00	$0.00	$0.00
Chemicals: Sulfuric acid	$0.01	$0.01	$0.01	$0.01
Caustic Lime	$0.03	$0.03	$0.04	$0.05
Subtotal	$0.49	$0.52	$0.59	$0.63
Resin replacement	$0.02	$0.02	$0.02	$0.02
Membrane replacement	$0.13	$0.13	$0.13	$0.13
Labor	$0.21	$0.21	$0.24	$0.28
Maintenance	$0.29	$0.29	$0.29	$0.29
Raw water/waste disposal	$0.08	$0.08	$0.08	$0.08
Total operating cost	$1.22	$1.26	$1.37	$1.44
Depreciation (10-year)	$1.46	$1.46	$1.46	$1.46
Taxes and insurance	$0.30	$0.30	$0.30	$0.30
Total cost to produce water				
1,000,000 gpd	$2.99	$3.03	$3.13	$3.21
500,000 gpd	$3.11	$3.14	$3.25	$3.32
250,000 gpd	$3.47	$3.51	$3.65	$3.76
Operating costs, % of total				
1,000,000 gpd	41%	42%	44%	45%
500,000 gpd	40%	41%	43%	44%
250,000 gpd	42%	43%	45%	47%

*TDS (Total Dissolved Solids)

Figure 10

The Economics of Reverse Osmosis and Ion Exchange - Effect of Power Pricing



Double-Pass Reverse Osmosis System

The change in total cost to produce water for the TF/TF double-pass reverse osmosis system is minimal as the feed TDS increases from 80 to 480 ppm as $CaCO_3$ as shown in Table I. There is a increased sensitivity for the CA/TF double-pass system on total cost because of increased acid consumption as the feed TDS increases as noted in Table J. Energy and membrane replacement costs are the major contributors to the operating costs of these systems (about 31% and 18% for TF/TF, respectively; 41% and 14% for CA/TF, respectively), whereas chemical costs are relatively low in comparison. Capital related costs for the double-pass reverse osmosis systems represent 50% to 56% of the total cost to produce water for the RO/RO systems.

Table I

Total Cost to Produce Water
Double Pass Reverse Osmosis (TF/TF) - Base Case
1,000,000 gallons per day

	$/1,000 Gallons of Product			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Feed TDS*, ppm as $CaCO_3$	80	160	320	480
RO - Chemicals and energy				
Energy: Pumps	$0.37	$0.37	$0.37	$0.37
Chemicals: Sulfuric acid	$0.00	$0.00	$0.00	$0.01
Antiscalant	$0.04	$0.05	$0.09	$0.09
Subtotal	$0.40	$0.42	$0.46	$0.47
Membrane replacement	$0.21	$0.21	$0.21	$0.21
Labor	$0.24	$0.24	$0.24	$0.24
Maintenance	$0.23	$0.23	$0.23	$0.23
Raw water/waste disposal	$0.09	$0.09	$0.09	$0.09
Total operating cost	$1.17	$1.19	$1.23	$1.24
Depreciation (10-year)	$1.16	$1.16	$1.16	$1.16
Taxes and insurance	$0.25	$0.25	$0.25	$0.25
Total cost to produce water				
1,000,000 gpd	$2.57	$2.59	$2.63	$2.65
500,000 gpd	$2.63	$2.65	$2.69	$2.70
250,000 gpd	$2.94	$2.95	$2.99	$3.01
Operating costs, % of total				
1,000,000 gpd	45%	46%	47%	47%
500,000 gpd	45%	45%	46%	46%
250,000 gpd	48%	49%	49%	50%

*TDS (Total Dissolved Solids)

Table J

Total Cost to Produce Water
Double Pass Reverse Osmosis (CA/TF) - Base Case
1,000,000 gallons per day

	$/1,000 Gallons of Product			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Feed TDS*, ppm as $CaCO_3$	80	160	320	480
RO - Chemicals and energy				
Energy: Pumps	$0.62	$0.62	$0.63	$0.63
Chemicals: Sulfuric acid	$0.01	$0.03	$0.05	$0.08
Antiscalant	$0.04	$0.05	$0.09	$0.09
Subtotal	$0.67	$0.70	$0.77	$0.80
Membrane replacement	$0.21	$0.21	$0.21	$0.21
Labor	$0.24	$0.24	$0.24	$0.24
Maintenance	$0.31	$0.31	$0.31	$0.31
Raw water/waste disposal	$0.09	$0.09	$0.09	$0.09
Total operating cost	$1.52	$1.55	$1.62	$1.65
Depreciation (10-year)	$1.57	$1.57	$1.57	$1.57
Taxes and insurance	$0.33	$0.33	$0.33	$0.33
Total cost to produce water				
1,000,000 gpd	$3.42	$3.45	$3.52	$3.55
500,000 gpd	$3.50	$3.53	$3.60	$3.63
250,000 gpd	$3.83	$3.86	$3.92	$3.95
Operating costs, % of total				
1,000,000 gpd	45%	45%	46%	47%
500,000 gpd	44%	44%	45%	46%
250,000 gpd	47%	47%	48%	48%

Conclusions

This economic evaluation considers all of the major factors contributing to the total cost of water including chemicals, resins, membranes, energy, operating labor, maintenance, and capital. Also covered in this study is the effect of system size, new advancements in membrane and resin technology, and CA versus TF membrane technology. Major conclusions to be drawn from this study apply to new water treatment systems and are summarized below:

1. The break even point above which it is more economical to use RO/IX versus straight IX moved from 75 ppm as $CaCO_3$ in 1987 to 130 ppm in 1994 primarily as a result of lower cost of both membranes and resin and lower overall capital estimates. Although the break-even point is higher, most waters demineralized in the U.S. are above this level.

2. Capital continues to have a significant effect on the total cost of water for all options considered ranging from 44% to 60%.

3. The capital cost estimates were significantly lower than they were 5 years ago for all water treatment schemes considered with the reduction being in the range of 25% to 40%.

4. The cost of raw water and waste disposal will vary greatly throughout the U.S. and must be considered on a case by case basis. It was considered in this study but the impact on the total cost of water was minimal representing about 2% to 3% of the total cost of water.

5. The RO/IX option and the RO/RO option involving CA membrane both had a significantly higher total cost of water than their counterparts using TF membrane. This was primarily due to the costs associated with higher pressure operation, higher rates of acid addition and the need for a degasifier with the use of CA membrane.

6. New technology including higher surface area and higher salt rejection RO elements and uniform particle size IX resin lowered the total cost of water for the options considered.

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