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Desalting Sea Water and Brackish Waters: A Cost Update

S. A. Reed
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OAK RIDGE NATIONAL LABORATORY
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DESALTING SEA WATER AND BRACKISH WATERS:
A COST UPDATE

S. A. Reed   J. V. Wilson

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ABSTRACT

This report, based on first-quarter 1977 dollars, is an update of costs presented in ORNL/TM-5070 (Rev.), which gave cost estimates for desalting seawater and brackish waters based on first-quarter 1975 financial parameters. Cost estimates are given for desalting seawater by distillation and reverse osmosis and for brackish waters using reverse osmosis and electrodialysis. Cost data were computed as a function of plant size and energy cost. In this report, we have included the cost of generating steam and electrical energy on-site using coal-fired boilers as well as oil-fired boilers and dual-purpose electric/seawater distillation plants. While the costs of energy, equipment and labor have continued to rise, they have increased at a relatively modest rate compared with the two years prior to 1975.

On an average, the cost of desalting seawater by distillation has increased approximately 15%. Costs for desalting brackish waters by the membrane processes have increased about 7%.

1. INTRODUCTION

Approximately two years ago, cost data were obtained from U.S. manufacturers of desalting equipment. These data were used to estimate the cost of conversion of seawater by commercial distillation and reverse osmosis systems and brackish waters by reverse osmosis, electrodialysis, and ion exchange systems. This parametric study was published in January 1976 as an Oak Ridge National Laboratory report, ORNL/TM-5070 (Rev.).

This report updates ORNL/TM-5070 (Rev.) by estimating product water costs based on first quarter 1977 installed equipment costs, a levelized fixed charge rate, and energy costs which are current. The format of this report generally follows that of the previous report; however, the parametric treatment of energy costs in this report has been expanded to include the costs of generating steam and electricity using high- and low-sulfur coals, as well as with oil and nuclear fuels.

Since the previous report was prepared, there have been two significant changes in the desalting arena: there are now more vendors of seawater reverse osmosis systems, and the major U.S. manufacturer of vertical tube evaporator plants has temporarily withdrawn from the United States market.

The cost data given in our previous report reflected the very rapid increases in the cost of fuels, as well as the marked escalation in equipment cost and interest rates on borrowed capital during the three years prior to January 1976. Since that time, the cost of fuels has continued to increase, as has the cost of installed equipment, however, at lesser rates of rise.

Overall plant equipment costs have increased about 5%; electrical switchgear has increased on the order of 12%, and civil work up to 25% in some cases. Fixed charge rates have increased from 11.5 to 15.5%.

Overall, operation and maintenance costs have increased about 10%.

On the average, the cost of desalting seawater by distillation has increased about 15%, and desalting brackish waters by the membrane process has increased by about 7%.

While the costs given in this report for desalting seawater by reverse osmosis are substantially higher than those reported in the previous report, we believe that they are representative of today's costs. The costs reported previously were based on data from only one manufacturer, which, in retrospect, appear to have been based on highly optimistic extrapolations of pilot plant results, particularly in the areas of installed equipment and pretreatment costs.

2. BASIS FOR COST ESTIMATES

2.1 Financial Parameters

All cost estimates are based on first-quarter 1977 dollars. Utility financing with a plant-life expectancy of 30 years was used. A levelized fixed charge rate of 15.5% was used in all calculations. The breakdown of the fixed charge rate was as follows:

<u>Component</u>	<u>Percent</u>
Bond interest	3.5
Preferred stock	0.8
Common stock	3.3
Book depreciation	3.3
Property insurance	0.5
Property tax	2.5
State income tax	0.1
Federal income tax	<u>1.5</u>
Levelized total fixed charge rate	15.5

For interest during construction, a rate of 8% was used.

2.2 General Ground Rules

Capital cost estimates excluded certain site specific costs such as those for purchase of land, product water pacification, storage, or conveyance. For the brackish water membrane plants (reverse osmosis and electrodialysis), we did not include the costs of civil work or well

drilling. Costs for civil work and the intake and outfall systems were included in the costs for the seawater distillation and reverse osmosis plants. Generally, these comprised less than 5% of the total capital investment. It must be noted that these costs will vary with site selection.

The assumption was made that all plants would be erected in the continental United States.

2.3 Chemical Costs

Chemical treatment costs were computed using the following unit prices:

<u>Chemical</u>	<u>Unit cost</u>	
	<u>\$/kg</u>	<u>\$/lb</u>
Antifoam	1.870	0.8500
Sulfuric acid (bulk, 100% basis)	0.4202	0.0191
Polyphosphate	2.9700	1.3500
Sodium hexametaphosphate	0.5588	0.2540
Potassium permanganate	1.1000	0.5000
Caustic (NaOH)	0.3520	0.1600
Sodium sulfite	0.0475	0.1045
Chlorine (bulk)	0.2200	0.1000

It is recognized that treatment costs will vary with feedwater characteristics. Our treatment costs are based on typical, rather than specific chemical feed rates.

2.4 Energy Costs

For the distillation systems, it was assumed that electricity would be generated on-site using steam from boilers fired with oil, high sulfur coal (with stack gas scrubbing), low sulfur coal, or nuclear steam from a dual-purpose electric station. Steam and electric costs were based on the following:

<u>Fuel cost</u>	<u>Steam conditions and cost</u>	<u>Electric cost, mills/kWhr</u>
Oil-\$2.17/10 ⁶ Btu (\$13/bbl, 6 x 10 ⁶ Btu/bbl)	Prime, 538°C (1000°F)-\$3.51/10 ⁶ Btu 129°C (265°F)-\$0.95/10 ⁶ Btu 93°C (200°F)-\$0.60/10 ⁶ Btu	32.9
Coal-\$0.84/10 ⁶ Btu (high sulfur, 11,900 Btu/lb @\$20/ton)	Prime, 538°C-\$1.97/10 ⁶ Btu 129°C-\$0.53/10 ⁶ Btu 93°C-\$0.34/10 ⁶ Btu	23.5
Coal-\$0.93/10 ⁶ Btu (low sulfur, 8500 Btu/lb @\$15.85/ton)	Prime, 538°C-\$1.89/10 ⁶ Btu 129°C-\$0.51/10 ⁶ Btu 93°C-\$0.32/10 ⁶ Btu	21.5
Nuclear(1200 MW PWR) dual purpose*	Prime, 274°C (525°F)-\$1.34/10 ⁶ Btu	21.9

For membrane plants it was assumed that they would be operated using electricity purchased from a utility at a commercial rate of 2.4¢/kWhr. As in the previous report,¹ this is an average of current commercial rates charged by three utilities operating in areas where desalting by the membrane processes might be of interest, that is, Texas, Arizona, and Southern California.

As shown in Fig. 1, the average cost of fuel used for electrical generation has continued to rise at a fairly steady rate. Consequently, steam costs have continued to rise (Fig. 2) accordingly.

3. SEAWATER DISTILLATION COSTS**

The cost of product water using vertical tube evaporators (VTEs) and multistage flash evaporators (MSFs) using acid feed treatment as a function of plant size and type of fuel is presented in Fig. 3. For small plants, 3.785 m³/d (1 Mgd) costs range from a high of ~\$1.40/m³ (\$5.30/Kgal) using an MSF plant in combination with an oil-fired boiler, to a low of ~\$1.15/m³ (\$4.40/Kgal) using a VTE plant and low sulfur coal as boiler fuel. Costs of water from both MSF and VTE plants operating on nuclear-generated steam

*Fuel cycle costs based on Ref. 2

**Detailed calculations are given in the Appendix

Fig. 1. Average cost of fuels used for electrical generation in the United States.

Fig. 2. Effect of fuel cost on steam costs.

Fig. 3. Water cost as a function of distillation plant size.

and the MSF plants using high sulfur coal as boiler fuel were intermediate to the costs noted above. At the largest plant size considered, 3.785×10^6 m³/d (100-Mgd), product water costs ranged from ~\$0.55/m³ (2.15/Kgal) for MSF plants using boilers fired with oil as fuel, down to a low of ~\$0.45/m³ (\$1.70/Kgal) for VTE plants with steam generated using low sulfur coal.

Water costs estimated for small (1 and 5 Mgd) MSF plants operating at lower temperature, 88-91°F (190-195°F) using 93°C (200°F) steam to the brine heater and threshold scale control treatment, followed the same trend (see Table A.2 of the Appendix). The maximum cost water was ~\$1.50/m³ (\$5.65/Kgal) from the 3.8×10^6 m³/d (1 Mgd) plant using oil as boiler fuel. The lowest cost water, ~\$1.05/m³ (\$4.00/Kgal) was from the 19×10^6 m³/d (5 Mgd) plant using low sulfur coal as boiler fuel.

4. COSTS OF DESALTING BRACKISH WATER AND SEAWATER BY REVERSE OSMOSIS

Costs of desalting brackish waters with total dissolved solids (TDS) content from about 2000 to 5000 parts per million (ppm) are shown as a function of plant size in Fig. 4. The costs were derived using a purchased power cost of 2.4¢/kWhr. As shown in Fig. 4, water costs ranged from ~\$0.33/m³ (\$1.26/Kgal) at a plant size of $\sim 3.8 \times 10^6$ m³/d (1 Mgd) to ~\$0.24/m³ (\$0.91/Kgal) at 95 m³/d (25 Mgd).

In the 2-year interval since our previous survey was made,¹ considerable progress and interest in reverse osmosis technology for desalting seawater has continued. One 27,000-m³/d commercial unit has been operating in Bermuda on 40,000 TDS feed water, and two units of the same size have been in operation in Malaysian waters using feed water in excess of 38,000 ppm TDS, all producing potable water of good quality. Several larger plants have been designed and a 3-Mgd (11.4×10^6 m³/d) plant to be installed in the Middle East is currently being designed.

Recent estimates for single pass reverse osmosis seawater desalting have shown major changes when compared to the 1975 projections. The data for 1977 shows a decrease in water cost for plants below about 30,000-m³/d of product capacity but a dramatic increase for larger plants. At

Fig. 4. Water cost as a function of reverse-osmosis plant size.

a plant capacity of about one million gallons per day, the 1977 water cost estimates are about two and one-half times those of 1975. These data are illustrated in Figure 5.

An attempt to determine the factors which have caused this increase was made by examining both the capital and operating cost contribution. Tabulated below are the 1975 data taken from ORNL-TM-5070 (Rev.) and that recently developed for the 1977 estimate for a plant having a capacity of one million gallons per day.

	<u>1975</u>	<u>1977</u>
Capital Cost (\$ × 10 ³)	2.17	3.90
Annual Operating Cost (\$/Kgal)		
1. Electricity	.44 (2.2¢/KWh)	.95 (2.4¢/KWh)
2. Chemicals	.05	.06
3. Operation	.05	.50
4. Maintenance	.06	.08
5. Membrane Replacement	.45	.45
6. Fixed Charges	.58 (11.5%)	1.95 (15.5%)
Water Cost (¢/Kgal)	1.63	3.99

The power costs have more than doubled but the 1975 case assumed power recovery while the 1977 estimate did not. Chemicals, maintenance costs, and membrane replacement costs showed small changes (if any). The estimated cost of operation shows a major change indicating that the 1975 data were questionable.

The major impact on water cost is due to the abrupt increase in capital cost (80%) and the increase in fixed charge rate. Of the total increase in fixed charges (58¢/kgal to \$1.95/kgal), about 65% is attributable to increasing the fixed charge rate from 11.5% to 15%. For example, the \$1.95 figure would drop to about \$1.45 if a 11.5% FCR was held.

It appears, in retrospect, that the 1975 data given us were based on highly optimistic extrapolations of pilot plant results. Since firm bids are now being tendered by manufacturers, the data for 1977 is considered to be representative of R.O. seawater desalting costs. Large plants (on the order of 3 mgd) also are now being designed for foreign applications.

Fig. 5. Estimated cost of desalting sea water via reverse osmosis.

5. COST OF DESALTING BRACKISH WATERS VIA ELECTRODIALYSIS

Because the cost of converting brackish waters to potable quality by electrodialysis is highly sensitive to feedwater composition, updated costs presented in Fig. 6 and shown in Table A.6 of the Appendix are based on four different feedwater compositions, as shown in Table 1. These compositions generally represent the range of brackish water compositions found throughout the United States. The costs reflect the modest increase in the cost of purchased power (2.4 from 2.2¢/kWhr) in the arid states, as well as the increase in installed capital costs. Note that these costs are exclusive of the cost of land, feedwater or brine-disposal wells and site preparation, because these can vary considerably, depending on site selection.

Table 1. Chemical compositions of typical brackish waters

Chemical composition (ppm)	Brackish waters			
	No. 1	No. 2	No. 3	No. 4
Sodium (Na)	886	125	630	900
Calcium (Ca)	118	316	116	250
Magnesium (Mg)	72	69	15	70
Chloride (Cl)	131	67	1,054	1,450
Sulfate (SO ₄)	1,943	900	115	590
Bicarbonate (HCO ₃)	473	357	78	210
Hardness as CaCO ₃	590	1,073	354	912
Manganese (Mn)	1	0.10	Nil	0.1
Fluoride (F)			2	
Iron (Fe)	2	1.0	0	0.4
Potassium (K)	16	13	0	5
Nitrate (NO ₃)	6.3	19	9	1
Silicate (SiO ₃)			17	
Total dissolved solids	3,648	1,800	2,076	3,475
pH	7.6	7.9	8.1	7.3
Temperature, °F	70°	70°	70°	70°
Organics (Chemical oxygen demand)	10	7.9		7

Fig. 6. Water cost as a function of feedwater composition and electrolysis plant size.

6. DESALTING BY ION EXCHANGE

Equipment and operating costs were also solicited from vendors of ion-exchange equipment which could be utilized for softening brackish waters. Because of high equipment costs and the increase in prices of chemicals used for regenerating the resins, coupled with the problems of waste disposal, vendors were reluctant to provide us with sufficient data to make detailed cost estimates. It appears that the cost cross-over point for ion exchange relative to reverse osmosis is still about 300 ppm TDS.

REFERENCES

1. S. A. Reed, The Impact of Increased Fuel Costs and Inflation on the Cost of Desalting Sea Water and Brackish Waters, ORNL/TM-5070 Rev. (January 1976).
2. B. E. Prince et al., A Survey of Nuclear Fuel Cycle Economics: 1970-1985, ORNL/TM-5703 (March 1977).

APPENDIX

Table A.1. Costs of desalting seawater in multistage flash seawater distillation plants
 Acid-treated feed; performance ratio = 12; concentration ratio = 2; 85% plant factor
 All costs in thousands of dollars (First-quarter 1977)

Items	Plant capacity (kgd)					
	1	5	10	25	50	100
Construction period, months	18	20	24	36	36	42
Land required, acres	2	3	4	11	13	23
DIRECT CAPITAL COSTS						
Site development and common facilities						
Grading, roads, fencing, gate, service buildings, etc.	222	632	1,012	1,772	2,886	4,408
Intake and outfall systems	197	512	1,283	5,431	9,875	18,762
Electrical utilities and switchgear	111	395	783	1,847	3,807	7,503
Cranes	0	4	4	5	6	31
Subtotal	531	1,544	3,084	9,056	16,575	30,706
MSF distillation plant	4,031	13,912	24,149	47,249	83,999	141,749
Total direct capital costs	4,563	15,457	27,234	56,306	100,575	172,456
INDIRECT COSTS						
Interest during construction	273	1,030	2,178	6,756	12,069	24,143
Project management, overhead, and profit	1,711	5,796	10,212	21,115	37,715	64,671
Subtotal	1,985	6,826	12,391	27,871	49,784	88,815
Working capital	56	194	381	917	1,780	3,540
Contingency	684	2,318	4,085	8,446	15,086	25,868
Total capital cost	7,290	24,796	44,093	93,542	167,226	290,680
Capital cost, \$/gpd	7.29	4.96	4.41	3.74	3.34	2.91
ANNUAL OPERATION AND MAINTENANCE (O&M) COST						
Fixed charges @ 15.5%	1,130	3,843	6,834	14,499	25,920	45,055
O & M labor	125	160	300	500	687	1,281
General & Adm. charges (40% of labor)	49	63	119	199	274	512
Supplies and maintenance materials	26	63	116	291	572	1,112
Chemicals	42	210	420	1,052	2,104	4,208
ANNUAL COSTS EXCLUSIVE OF ENERGY COSTS	1,373	4,341	7,791	16,542	29,559	52,170
I. OIL FIRED BOILER						
Steam @\$0.95/MMBtu	205	1,022	2,048	5,118	10,237	20,474
Electricity @ 32.9 Mills/KWhr	50	254	495	1,276	2,551	5,104
Total annual O&M cost	1,629	5,618	10,335	22,937	42,347	77,749
Cost of water, \$/kgal	5.25	3.62	3.33	2.96	2.73	2.51
II. COAL FIRED BOILER						
A. High Sulfur Coal						
Steam @\$0.53/MMBtu	114	570	1,142	2,855	5,711	11,422
Electricity @ 23.5 Mills/KWhr	36	182	353	911	1,822	3,646
Total annual O&M cost	1,524	5,093	9,288	20,310	37,093	67,239
Cost of water, \$/kgal	4.91	3.28	2.99	2.62	2.39	2.17
B. Low Sulfur Coal						
Steam @\$0.51/MMBtu	110	548	1,099	2,747	5,495	10,991
Electricity @ 21.5 Mills/KWhr	33	166	323	834	1,667	3,335
Total annual O&M cost	1,517	5,056	9,215	20,124	36,722	66,498
Cost of water, \$/kgal	4.89	3.26	2.97	2.59	2.37	2.14
III. NUCLEAR DUAL-PURPOSE STATION						
Steam @\$0.61/MMBtu	131	656	1,315	3,286	6,573	13,146
Electricity @ 21.9 Mills/KWhr	33	169	329	849	1,698	3,397
Total annual O&M cost	1,539	5,167	9,436	20,679	37,831	68,715
Cost of water, \$/kgal	4.96	3.33	3.04	2.67	2.44	2.21

Does not include cost of land.

Includes inspection, manufacturer's overhead and profit on shop-fabricated equipment installed on site.

Electric power generated on site.

Table A.2. Costs of desalting seawater in multistage flash seawater distillation plants
 Polyphosphate feed treatment
 Performance ratio = 10; 194°F maximum brine temperature;
 85% plant factor

Items	All costs in thousands of dollars (First-quarter 1977)	
	Plant capacity (Mgd)	
	1	5
Construction period, months	18	20
Land required, acres	2	3
DIRECT CAPITAL COSTS		
Site development and common facilities		
Grading, roads, fencing, gate, service buildings, etc.	222	632
Intake and outfall systems	197	512
Electrical utilities and switchgear	111	395
Cranes	0	4
Subtotal	531	1,544
MSP distillation plant	4,356	18,252
Total direct capital costs	4,888	19,796
INDIRECT COSTS		
Interest during construction	293	1,319
Project management, overhead, and profit	1,833	7,423
Subtotal	2,126	8,743
Working capital	62	213
Contingency	733	2,969
Total capital cost	7,810	31,723
Capital cost, \$/gpd	7.81	6.34
ANNUAL OPERATION AND MAINTENANCE (O&M) COST		
Fixed charges @ 15.5%	1,210	4,917
O & M labor	125	160
General & admin. charges (40% of labor)	49	63
Supplies and maintenance materials	26	63
Chemicals	49	250
ANNUAL COSTS EXCLUSIVE OF ENERGY COSTS	1,461	5,455
I. OIL FIRED BOILER		
Steam @\$0.60/MMBtu	155	776
Electricity @ 32.9 Mills/KWhr	129	554
Total annual O&M cost	1,747	6,785
Cost of water, \$/kgal	5.63	4.37
II. COAL FIRED BOILER		
A. High Sulfur Coal		
Steam @\$0.34/MMBtu	88	439
Electricity @ 23.5 Mills/KWhr	92	395
Total annual O&M cost	1,642	6,291
Cost of water, \$/kgal	5.29	4.06
B. Low Sulfur Coal		
Steam @\$0.32/MMBtu	83	414
Electricity @ 21.5 Mills/KWhr	84	362
Total annual O&M cost	1,629	6,231
Cost of water, \$/kgal	5.25	4.02
III. NUCLEAR DUAL-PURPOSE STATION		
Steam @\$0.44/MMBtu	114	569
Electricity @ 21.9 Mills/KWhr	86	369
Total annual O&M cost	1,662	6,393
Cost of water, \$/kgal	5.36	4.12
Includes inspection, manufacturer's overhead and profit on shop-fabricated equipment installed on site.		
Does not include cost of land.		

Table A.3. Costs of desalting seawater in vertical tube seawater distillation plants
 Acid-treated feed; performance ratio = 12; concentration ratio = 2; 85% plant factor
 All costs in thousands of dollars (First-quarter 1977)

Items	Plant capacity (Mgd)					
	1	5	10	25	50	100
Construction period, months	10	20	24	36	40	44
Land required, acres	2	3	4	7	10	18
DIRECT CAPITAL COSTS						
Site development and common facilities						
Grading, roads, fencing, gate, service buildings, etc.	222	632	1,012	1,131	2,218	3,460
Intake and outfall systems	170	441	1,103	4,671	8,492	16,136
Electrical utilities and switchgear	109	363	671	1,623	3,247	6,271
Cranes	0	4	4	5	6	31
Subtotal	502	1,441	2,792	7,431	13,965	25,899
VTE distillation plant	3,569	12,704	27,049	43,312	68,774	104,999
Total direct capital costs	4,072	14,146	24,842	50,744	82,740	130,899
INDIRECT COSTS						
Interest during construction	244	943	1,987	6,089	11,032	19,198
Project management, overhead, and profit	1,527	5,305	9,315	19,029	31,027	49,087
Subtotal	1,771	6,248	11,303	25,118	42,059	68,285
Working capital	50	163	322	764	1,476	2,931
Contingency	610	2,122	3,726	7,611	12,411	19,634
Total capital cost	6,505	22,680	40,198	84,239	138,687	221,751
Capital cost, \$/gpd	6.51	4.54	4.02	3.37	2.77	2.22
ANNUAL OPERATION AND MAINTENANCE (O&M) COST						
Fixed charges @ 15.5%	1,008	3,515	6,230	13,057	21,496	34,371
O & M labor	125	160	300	500	687	1,281
General & Admin. charges (40% of labor)	49	63	119	199	274	512
Supplies and maintenance materials	26	63	116	291	572	1,112
Chemicals	31	154	309	774	1,548	3,097
ANNUAL COSTS EXCLUSIVE OF ENERGY COSTS	1,241	3,958	7,076	14,822	24,580	40,375
I. OIL FIRED BOILER						
Steam @ \$0.95/MMBtu	205	1,022	2,048	5,118	10,237	20,474
Electricity @ 32.9 Mills/KWhr	16	77	154	386	773	1,546
Total annual O&M cost	1,463	5,057	9,279	20,328	35,590	62,396
Cost of water, \$/kgal	4.72	3.26	2.99	2.62	2.29	2.01
II. COAL FIRED BOILER						
A. High Sulfur Coal						
Steam @ \$0.53/MMBtu	114	570	1,142	2,855	5,711	11,422
Electricity @ 23.5 Mills/KWhr	11	55	110	276	552	1,104
Total annual O&M cost	1,360	4,583	8,329	17,954	30,843	52,902
Cost of water, \$/kgal	4.41	2.95	2.68	2.31	1.99	1.71
B. LOW Sulfur Coal						
Steam @ \$0.51/MMBtu	110	548	1,099	2,747	5,495	10,991
Electricity @ 21.5 Mills/KWhr	10	50	101	252	505	1,010
Total annual O&M cost	1,362	4,557	8,277	17,823	30,581	52,377
Cost of water, \$/kgal	4.39	2.94	2.67	2.30	1.97	1.69
III. NUCLEAR DUAL-PURPOSE STATION						
Steam @ \$0.61/MMBtu	131	656	1,315	3,286	6,573	13,146
Electricity @ 21.9 Mills/KWhr	10	51	102	257	514	1,029
Total annual O&M cost	1,384	4,665	8,494	18,366	31,668	54,551
Cost of water, \$/kgal	4.46	3.01	2.74	2.37	2.04	1.76

Does not include cost of land.

Includes inspection, manufacturer's overhead and profit on shop-fabricated equipment installed on site.

Electric power generated on site.

Table A.4. Spiral-wound reverse-osmosis plants annual operation and maintenance cost
Feedwater 2000-5000 ppm Tds; 80% recovery; 95% plant factor
All costs in dollars (First-quarter 1977)

Cost items	Plant capacity (Mgd)				
	1	3	5	10	25
Installed capital cost	856,799	1,584,448	2,231,248	4,147,496	10,106,242
ANNUAL O&M COSTS					
Fixed charge @ 15.5%	132,803	245,589	345,843	642,861	1,566,467
Operating labor	37,500	37,500	37,500	37,500	37,500
Maintenance labor	68,750	206,250	343,750	687,500	1,718,750
General & Admn. on labor @ 40% of Labor	42,499	97,499	152,499	289,999	702,499
Chemicals	50,409	151,227	252,046	504,092	1,260,230
Membrane replacement	56,179	168,539	280,899	561,799	1,404,499
Electrical power @ 2.4¢/kwhr	48,825	146,476	244,126	488,254	1,220,636
Total annual O&M cost	436,968	1,053,083	1,656,664	3,212,005	7,910,581
Cost of water, \$/kgal	1.26	1.01	0.96	0.93	0.91
Exclusive of land cost.					

Table A.5. Estimated cost for the conversion of sea water
via reverse osmosis (single pass)

Annual Operation and Maintenance Expense

Cost items	Plant size, kgal/day			
		100	1,000	3,000
Capital cost, \$ x 10 ³	60	430	3,900	11,400
Capital cost, \$/daily gallon	6.00	4.30	3.90	3.80
ANNUAL OPERATING AND MAINTENANCE COST @ 85% plant factor, \$/kgal				
Fixed charges @ 15.5%	3.00	2.08	1.95	1.90
Power	0.97	0.97	0.95	0.95
Chemicals	0.06	0.06	0.06	0.06
Operation	0.65	0.65	0.50	0.50
Maintenance	0.15	0.11	0.08	0.08
Membrane replacement	1.10	0.70	0.45	0.45
Water cost, \$/kgal	5.93	4.57	3.99	3.94

Table A.6. Electrodialysis annual operation and maintenance expense
Feedwater temperature 70 F, 95% plant factor

Items	Feedwater type			
	1	2	3	4
Water recovery, %	87.00	77.50	79.00	87.00
Product purity, (ppm Tds)	500.00	420.00	420.00	420.00
Plant size, 1 mgd ; Stages	3.00	3.00	2.00	3.00
Plant capital cost, \$ x 1000000	0.80	0.64	0.80	0.90
ANNUAL COST, \$ x 1000				
Fixed charges @ 15.5%	123.69	99.28	123.69	139.96
Operating labor	9.10	7.80	9.10	10.40
Maintenance labor #	26.01	17.34	30.34	34.67
General & admn. on labor (@ 40%)	14.04	10.05	15.77	18.03
Filter cartridge replacement	7.01	7.01	7.01	7.01
Other materials and spare parts	6.94	6.94	10.41	10.41
Electricity @ 2.4¢/kwhr	133.16	83.23	95.71	158.12
Total annual cost	319.95	231.64	292.03	378.61
Water cost, \$/kgal	0.92	0.67	0.84	1.09

No chemical costs for scale control were calculated because in large modern plants polarity is reversed on a regular schedule to avoid scale formation in the stacks

Installed cost (in 1977 first quarter dollars) includes overhead, profit, interest during construction (8%), and all startup expenses and operator training. Does not include cost of feedwater or brine-disposal wells, land, or site preparation.

Membrane replacement.

Table A.7. Electrodialysis annual operation and maintenance expense
Feedwater temperature 70 F, 95% plant factor

Items	Feedwater type			
	1	2	3	4
Water recovery, %	87.00	77.50	79.00	87.00
Product purity, (ppm Tds)	500.00	420.00	420.00	420.00
Plant size, 5 mgd ; Stages	3.00	3.00	2.00	3.00
Plant capital cost, \$ x 1000000	4.00	3.27	4.00	4.56
ANNUAL COST, \$ x 1000				
Fixed charges @ 15.5%	620.08	506.15	620.08	706.33
Operating labor	39.00	26.00	39.00	58.50
Maintenance labor #	39.00	26.00	39.00	58.50
General & admin. cn labor (@ 40%)	31.20	20.80	31.20	46.80
Filter cartridge replacement	35.10	35.10	35.10	35.10
Other materials and spare parts	34.75	34.75	52.05	52.05
Electricity @ 2.4¢/kwhr	632.49	395.31	454.59	751.05
Total annual cost	1431.61	1044.11	1271.02	1708.33
Water cost, \$/kgal	0.83	0.60	0.73	0.99

No chemical costs for scale control were calculated because in large modern plants polarity is reversed on a regular schedule to avoid scale formation in the stacks

Installed cost (in 1977 first quarter dollars) includes overhead, profit, interest during construction (8%), and all startup expenses and operator training. Does not include cost of feedwater or brine-disposal wells, land, or site preparation.

Membrane replacement.

Table A.8. Electrodialysis annual operation and maintenance expense
Feedwater temperature 70 F, 95% plant factor

Items	Feedwater type			
	1	2	3	4
Water recovery, %	87.00	77.50	79.00	87.00
Product purity, (ppm Tds)	500.00	420.00	420.00	420.00
Plant size, 10 mgd ; Stages	3.00	3.00	2.00	3.00
Plant capital cost, \$ x 1000000	7.82	6.11	7.82	8.61
ANNUAL COST, \$ x 1000				
Fixed charges @ 15.5%	1212.49	947.20	1212.49	1334.55
Operating labor	80.50	52.00	78.00	117.00
Maintenance labor #	80.50	52.00	78.00	117.00
General & admn. on labor (@ 40%)	64.40	41.60	62.40	93.60
Filter cartridge replacement	70.19	70.19	70.19	70.19
Other materials and spare parts	69.50	69.50	104.10	104.10
Electricity @ 2.4¢/kwhr	1264.97	790.63	909.19	1502.09
Total annual cost	2842.55	2023.12	2514.37	3338.54
Water cost, \$/kgal	0.82	0.58	0.73	0.96

No chemical costs for scale control were calculated because in large modern plants polarity is reversed on a regular schedule to avoid scale formation in the stacks

Installed cost (in 1977 first quarter dollars) includes overhead, profit, interest during construction (8%), and all startup expenses and operator training. Does not include cost of feedwater or brine-disposal wells, land, or site preparation.

Membrane replacement.

**Table A.9. Electrodialysis annual operation and maintenance expense
Feedwater temperature 70 F, 95% plant factor**

Items	Feedwater type			
	1	2	3	4
Water recovery, %	87.00	77.50	79.00	87.00
Product purity, (ppm Tds)	500.00	420.00	420.00	420.00
Plant size, 25 mgd ; Stages	3.00	3.00	2.00	3.00
Plant capital cost, \$ x 1000000	18.14	14.74	18.14	20.41
ANNUAL COST, \$ x 1000				
Fixed charges @ 15.5%	2812.32	2285.01	2812.32	3163.85
Operating labor	201.25	130.00	195.00	292.50
Maintenance labor #	201.25	130.00	195.00	292.50
General & admin. on labor (@ 40%)	161.00	104.00	156.00	234.00
Filter cartridge replacement	175.49	175.49	175.49	175.49
Other materials and spare parts	173.75	173.75	260.25	260.25
Electricity @ 2.4¢/kwhr	3162.43	1976.56	2272.96	3756.33
Total annual cost	6887.48	4974.80	6067.01	8174.91
Water cost, \$/kgal	0.79	0.57	0.70	0.94

No chemical costs for scale control were calculated because in large modern plants polarity is reversed on a regular schedule to avoid scale formation in the stacks

Installed cost (in 1977 first quarter dollars) includes overhead, profit, interest during construction (8%), and all startup expenses and operator training. Does not include cost of feedwater or brine-disposal wells, land, or site preparation.

Membrane replacement.

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