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Large-scale power production by pressure-retarded osmosis, using river water and sea water passing through spiral modules

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Abstract

In principle a very large quantity of electric power could be produced by the worldwide application of pressure-retarded osmosis (PRO) to the osmotic pair, river water/sea water. The utility of the process depends on the economics, i.e., whether the produced energy cost, dollars per kilowatt hour, and the plant capital cost, dollars per kilowatt, can be adequately low. The study was limited to spiral modules, i.e., originally flat sheet membranes. A very important cost item was the "Yuma" specific plant capital cost of 1000 dollars per daily cubic meter of permeate. This value was derived from consideration of the world's largest RO plant, that in Yuma, Arizona, and was used in PRO calculations with modification as required for differences in flux and for economy-of-scale effects. Within these limitations, the key parameters were found to be twofold: First was the K term in PRO. This is the resistance to salt diffusion in the porous substructure and support fabric region of the membrane and must be as low as possible because an increase in K decreases permeate flux virtually exponentially. Second was the size of the PRO plant, characterized by the flow rate of the river utilized. The larger the PRO plant, the more important the economy-of-scale factor becomes in minimizing the energy and power costs mentioned above. A key assumption in the comparative plant cost calculations was that half of such costs would be independent of changes in plant flux and the other half proportional to it. Based on previous PRO tests and *some optimism*, K terms of 10 and zero were considered. A "moderate" river flow rate of 3 million m^3/d flow rate was considered as well as a "large" river size, that of the Mississippi, 1,500 million m^3/d flow rate. The following was found: A "moderate" flow rate PRO plant with an optimistically low K term of 10 d/m (permeate flux 0.29 m^3/m^2d) would give unacceptably high energy and power costs as would a moderate plant with $K = 0$ (flux 0.725 m^3/m^2d). A Mississippi river plant with $K = 10$ would produce marginal energy and power costs, i.e., higher than expected from conventional existing power plants and perhaps acceptable under certain circumstances but with a K value of zero would produce adequately low energy and power costs. If the specific plant capital cost estimate could be reduced from 1000 to 500 dollars per daily cubic meter of permeate, as reported by some RO investigators, all PRO costs would be reduced by about half, thus rendering the moderate flow rate PRO plant with $K = 0$ marginally acceptable and both Mississippi PRO plants acceptable in terms of low energy and power cost. In view of these possibilities and the tremendous amount of benign and renewable energy and power potentially available, it is believed that river water/sea water PRO should be seriously investigated.

Keywords: Power production; Pressure-retarded osmosis; Spiral modules

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1. Introduction and procedure

Fig. 1 shows that 22,300 kW of power could be produced from 3,000,000 m^3/d ("moderate" flow rate) of river water by interaction with seawater in pressure-retarded osmosis (PRO). The Mississippi River delivers $(1.5)(10)^9$ m^3/d to the Gulf of Mexico. Hence as a first approximation PRO power is $(22.3)(1.5)(10)^9/(3)(10)^6 \cong 9{,}800$ megawatts from the Mississippi. The question is whether such potential power could be produced economically by PRO. According to Lee et al. [3], the answer is negative. Because of its importance, the question is reconsidered herein but more extensively. As in the previous study the use of sheet membranes, i.e., spiral modules, is assumed.

The cost data on the PRO plants were largely based on those of the RO plant in Yuma, Arizona [6], the world's largest but still small in comparison to the PRO plants discussed herein. At the Yuma plant the specific cost was 1000 dollars per daily cubic meter of permeate, $\$d/m^3$. Within this limit, the cost of the energy and power were primarily functions of two variables: (1) the flow rate of the river being treated in PRO and (2) the magnitude of K, the resistance to solute diffusivity in the porous substructure of the membrane. Therefore, the calculations were repeated under four different conditions. First: moderate flow rate, K = 10 d/m, illustrated in Fig. 1; second: moderate flow rate, $K = 0$; third: Mississippi flow rate, $K = 10$; fourth: Mississippi flow rate, $K = 0$.

A key assumption in the comparative plant cost calculations was that half of such costs would be independent of changes in the permeate flux and the other half proportional to it. Key results are displayed in Table 4 for all four conditions, but detailed calculations are given herein only for the first, i.e., moderate flow rate, $K = 10$.

2. Flow diagram (moderate flow rate, $K = 10$)

Fig. 1 shows PRO as possibly applied to river water/seawater, the former delivering 3,000,000 m^3/d to the PRO plant, of which 2,000,000 m^3/d of water permeates the membrane and the same volume ultimately passes through the turbine. Permeation and corresponding power acquisition take place against the hydrostatic pressure of the sea water, 12 bars, the osmotic pressure of the seawater being everywhere greater than this hydrostatic pressure.

As can be seen, an amount of diluted seawater equal in volume to the incoming seawater delivers its pressure to the latter by a pressure exchanger.* Such prepressurization eliminates a very large parasitic consumption of power.

Fig. 1 also shows pressurization (and parasitic power consumption) of 0.20 and 0.07 bars in the seawater and river pumps, as explained in Appendix I.

3. Choice of membrane operating parameters, and calculation of permeate flux, m^3/m^2d (moderate flow rate, $K = 10$)

The best sheet membrane appears to be a Filmtec composite BW-30 brackish water membrane. This has a desirably high A (water permeation coefficient) value of 0.078 m^3/m^2d bar, and a desirably low B value of 0.0055 m/d for the salt permeation coefficient, both determined in a RO osmosis test.

As is well known, in PRO with a spiral module, the porous substructure and support fabric are very important in limiting permeation flux. The effect is quantified in the K term (resistance to salt transport in the porous

*A pressure exchanger was suggested by Mr. G.G. Pique of Energy Recovery, Inc., when asked if he could replace the transfer tanks shown to him in PRO papers previously submitted [2,9].

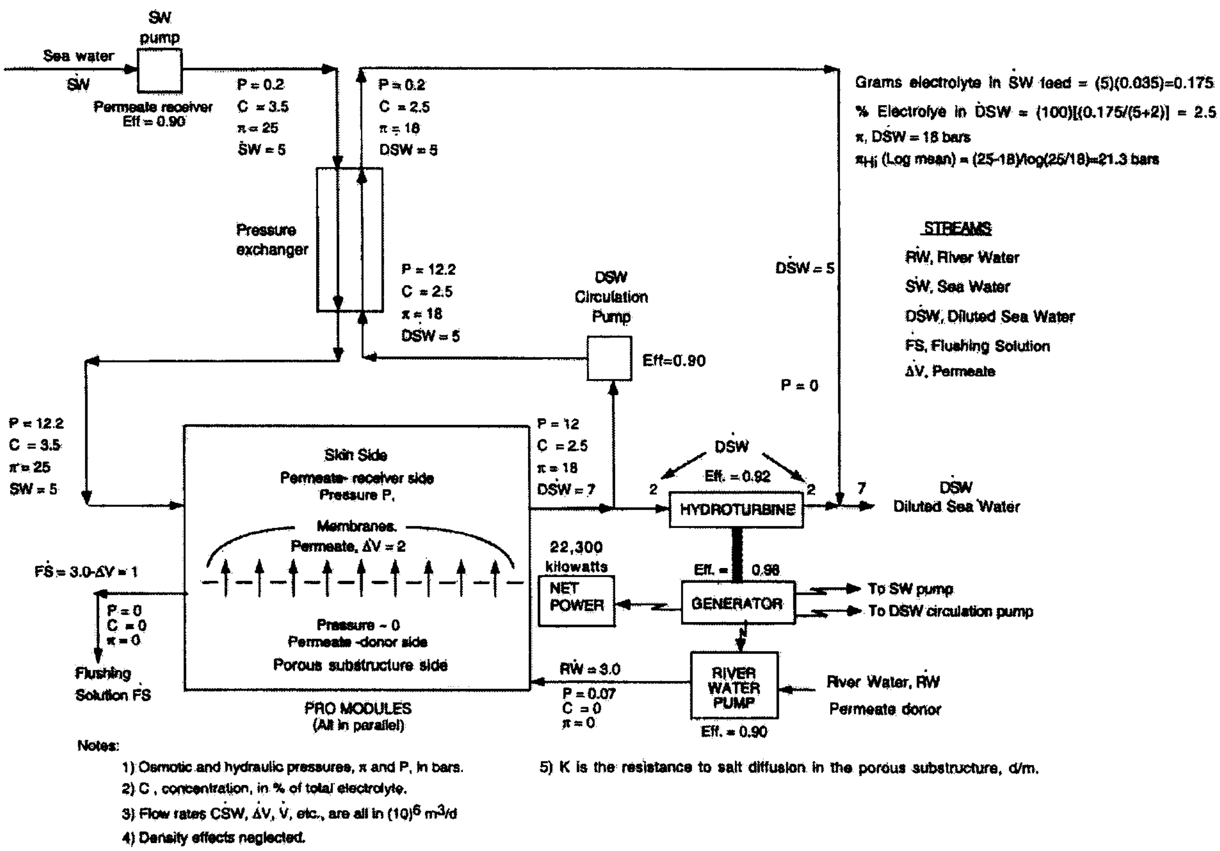

Fig. 1. Pressure-retarded osmosis with river water/seawater (moerate flow rate, $K = 10$ d/m).

substructure and fabric region) of any equation for PRO, including that with fresh water on the porous substructure side [3, Eq. (11)]:

$$J/A = \frac{\Pi_{\mathrm{Hi}}}{1 + (B/J)(\exp JK - 1)} - \Delta P$$

In this equation J is the permeate flux, m^3/m^2d, Π_{Hi} is the osmotic pressure of the saline solution, bars, and ΔP is the hydrostatic pressure difference across the membrane. This equation is useful in PRO (or ordinary osmosis) for estimating J when K is known or vice versa.

Existing, commercially available RO sheet membranes all have such a fabric on the porous substructure side. This fabric is necessary to provide adequate handling strength during spiral module fabrication. Because of this fabric the K term may be well over 100 d/m [1]. This has a very deleterious effect on the permeation flux in PRO. I have *optimistically assumed*, as one possibility, the development of a membrane having a K value of 10 d/m or even zero.

As shown in Fig. 1, the average Π_{Hi} and ΔP terms are 21.3 and 12 bars, respectively, giving the permeate flux J a value of 0.29 m^3/m^2d in the equation above. (Note that if K would be neglected, i.e., considered to be zero, the permeate flux would be 0.725).

4. Operational characteristics (moderate flow rate, $K = 10$)

4.1. Net power generation (Table 1)

The source of gross power generation in PRO is the acquisition of hydrostatic pressure by the permeate as it passes through the osmotic membranes because $\Delta\Pi > \Delta P$. The magnitude of this power is the product of the acquired pressure and the permeate rate. It is converted to electric power by passage through a hydroturbine/generator (Fig. 1) and is reduced in accordance with their respective efficiencies. The power leaving the turbogenerator is shown in item *B* of Table 1 as 25,300 kW. An appreciable fraction of this power is then absorbed by rotating components tabulated in Table 1 in accordance with the resistances encountered as described in Appendix I. As can be seen the net power is 22,300 kW.

4.2. Technical summary (Table 2)

Further details are given on the membrane, module, power and energy requirements.

5. Cost considerations (Table 3) (moderate flow rate, $K = 10$)

Table 3 shows the values obtained in the cost calculations. The most important data of Table 3 are the following:

- Plant cost, dollars per kilowatt, 73,000 \$/kW
- Energy cost, dollars per kilowatt hour, 0.67 \$/kWh. Of the latter, 0.47 \$/kWh is for amortization of plant cost.

It should be kept in mind that, as shown in Appendix II, the high 810 \$d/m^3 specific PRO cost of Item 1 can be largely traced to the high specific cost of the Yuma RO plant, 1000 \$d/m^3. If a PRO plant could be developed with a specific

Table 1
Net power generation, kW (moderate flow rate, $K = 10$)

Assumed fractional efficiencies: Pump, 0.88; turbine, 0.92; motors, 0.88; generator, 0.98 (flow rates on Fig. 1) Convertion factor, 0.00117 is kWd/m^3 bar	
A. Power consumption:	
A1. River water pump and motor (0.00117) (pump flow rate) (pressure) (1/efficiencies) (0.00117 (5) (10)^6 (0.2) (1/0.98) (1/0.88)	285
A2. Seawater pump and motor (0.00117) (pump flow rate) (pressure) (1/efficiencies) (0.00117) (5) (10)^6 (0.2) (1/0.98) (1/0.88)	1360
A3. Diluted seawater circulation pump Assume 0.2 bars pumping pressure (0.00117) (5) (10)^6 (0.2) (1/0.98) (1/0.88)	1360
B. Power generation by hydroturbine and generator (0.00117) (hydroturbine flow rate) (pressure) (efficiencies) (0.00117) (5) (10)^6 (0.2) (1/0.98) (1/0.88)	25,300
C. Net power B − (A1 + A2 + A3)	22,300

Table 2
Technical summary (moderate flow rate, $K = 10$)

1	Permeate flux, m^3/m^2d (Section 3)	0.29
2	Total membrane area, m^2 Permeation rate, Fig. 1/permeate flux, Item 1: 2,000,000/0.29	$(6.9)(10)^6$
3	Number of modules required: 117 m^2/element, 3 elements/module [6], Item 2/(3)(117) = $(6.9)(10)^6/(3)(117)$	19,700
4	Net power, kW (Section 4.1.)	22,300
5	Modular power, Kw/module, Item 4/Item 3 = $22{,}300/(6.9)(10)^6$	1.13
6	Areal power, kW/m^2 membrane, Item 4/Item 2 = $22{,}300/(6.9)(10)^6$	0.00323
7	Area energy, energy delivered during membrane lifetime, kWh/m^2 membrane Assume 7 years membrane life, 330 operating days per year, 24 h/d (Item 6)(7)(330)(24) = (0.00323)(7)(330)(24)	179

Table 3
Cost summary (moderate flow rate, $K = 10$)

1	Plant cost: (Permeate rate) (specific plant capital cost) (Fig. 1, m^3/d) (Appendix II, \$d/m^3) $(2)(10)^6(810)$, \$	$(1620)(10)^6$
2	Plant cost per kilowatt Item 1/(Item C, Table 1), $(1620)(10)^6/22{,}300$, \$ plant cost/kW	73,000
3	Annual amortization of plant cost Assume 3% and 20 years (73,000)(1.03)/20 = \$ amortization/kW year	3730
	Contributions to energy costs, \$/kWh, assuming (330)(24) operating hours per year	
4	Contribution of annual amortization of plant cost (above), (Item 3)/(24)(330) = 3730/(24)(330)	0.47
5	Contribution of membrane replacement (replacement cost, \$/m^2)/areal energy, kWh/m^2 Appendix III/(Table 2), Item 7), 7.3/179	0.041
6	Contribution of labor — by [7], $(4)(10)^6$ \$/y for large plants $(4)(10)^6$/(Item C, Table 1)(24)(330) = $(4)(10)^6/(22{,}300)(24)(330)$	0.023
7	Contribution of operation and maintenance — by [7], annual O&M is 1.5% of capital cost (0.015) (Item 1)/(Item C, Table 1) (24)(330) = $(0.015)(1620)(10)^6/(22{,}300)(24)(330)$	0.14
8	Total energy cost: (4) + (5) + (6) + (7), \$/kWh	0.67

cost in the order of 500 \$d/m^3, the costs of Table 3 would essentially be cut in half.

6. Commentary and conclusions (see Table 4)

This study is based on some rather optimistic estimates. Perhaps chief of these is that the K term, the resistance to solute diffusion in the porous substructure of the membrane, could be reduced to 10 d/m or even to zero, leading to permeation fluxes of 0.29 or 0.725 m^3/m^{2}d, respectively. Accordingly, calculations were made to determine the cost characteristics of the energy produced. In the course of these calculations it became clear that a very large PRO plant could produce energy and power much more cheaply than a small plant, due to economy-of-scale considerations.

These comparisons are shown in Table 4. The calculations leading to data of column 1 on Table 4 have been presented in detail in the previous sections herein. Calculations of data in Columns 2, 3, and 4 of Table 4 are, for brevity, not included herein but followed the procedures for column 1.

The conclusions from Table 4 on PRO energy and power costs are summarized below. They are all based on the high Yuma RO specific plant capital cost of 1000 \$d/m^3. This is justified by the belief that PRO is more complicated than RO. Still, if a value of 500 \$d/m^3 can be achieved for PRO, it will be a big step toward producing low energy and power costs.

1. Even if a K-value of 10 d/m is attained (permeate flux = 0.29 m^3/m^{2}d), PRO with a moderate flow rate river (3,000,000 m^3/d) will not be economical (Column 1).

Table 4
Pressure-retarded osmosis with river water/seawater influence of (1) value of K and (2) scale of operation

		River water Moderate flow rate: (3)(10)^6 m^3/d		Mississippi River (1500)(10)^6 m^3/d flow rate	
		K = 10	K = 0	K = 10	K = 0
		1[a]	2	3	4
A	Permeate flux, m^3/m^2/d	0.29	0.725	0.29	0.725
B	Permeate rate, m^3/d	(2)(10)^6	(2)(10)^6	(1000)(10)^6	(1000)(10)^6
C	Membrane area, m^2 (B/A)	(6.9)(10)^6	(2.76)(10)^6	(3450)(10)^6	(1380)(10)^6
D	Available power, kW	22,300	19,800	(11.2)(10)^6 (11,200 MW)	(9.9)(10)^6 (9900 MW)
E	Plant cost, \$				
F	Unit plant cost, \$/kW (E/D)	(1620)(10)^6	(1050)(10)^6	(234,000)(10)^6	(151,000)(10)^6
G	Energy cost, \$/kWh	73,000	53,300	20,900	15,200
H	Utility (arbitrary decision, based on F and G)	0.67 Unacceptable	0.48 Unacceptable	0.21 Marginal	0.13 Acceptable

[a]The data of Column 1 were obtained as described herein in Sections 2–5, Tables 1–3, and Appendices I–III. Data for columns 2–4 were obtained by similar calculations.
Note: The costs of Items E, F, and G are all based on the specific cost of the Yuma RO plant, 1000 dollars per m^3/d of permeate. If a PRO plant costs could be 500 \$d/m^3, the above costs would be approximately cut in half.

2. If the K-value can be reduced to zero (permeate flux = 0.725), then operation on a very large scale, such as the Mississippi River, will produce large amounts of possibly economic power, approximately 10,000 MW, five times that of Niagara Falls (Column 4).

3. If the Mississippi River would be used with a K value of 10 d/m (permeate flux = 0.29), the utility would be marginal by present energy and power criteria (Column 3). However, it might be worthwhile, considering the tremendous amount of power made available, and the greater possibility of attaining $K = 10$ than $K = 0$.

4. The data of column 2 yields high cost estimates, does not have the attractiveness of a very large power output, and requires that $K = 0$.

From this analysis it is clear that development of an appropriate spiral module membrane for PRO will not be easy, but that this very large benign and renewable source of energy justifies investigation on a proportionately large scale.

7. Symbols

A	—	Water permeation coefficient, m^3/m^2d bar
B	—	Salt permeate coefficient m/d
C	—	Percent of dissolved salt (halides)
$D\dot{S}W$	—	Diluted sea water rate, $(10)^6$ m^3/d
Eff	—	Efficiency, energy out/energy in (dimensionless)
$F{\cdot}S$	—	Flushing solution rate, $(10)^6$ m^3/d
J	—	Permeate flux, $(10)^6$ m^3/m^2d
K	—	Porous substrate resistance to salt diffusion, d/m
P	—	Hydrostatic pressure, bar
ΔP	—	Hydrostatic pressure difference across the membrane, bars
$R{\cdot}W$	—	River water rate, $(10)^6$ m^3/d
$S{\cdot}W$	—	Seawater rate, $(10)^6$ m^3/d
Π	—	Osmotic pressure, bars
$\Delta\Pi$	—	Osmotic pressure difference across the membrane, bars
$\Delta{\cdot}V$	—	Permeate rate, $(10)^6$ m^3/d

Subscripts

H_i	—	High

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Appendix I
Pressure driving forces required for axial flow through the modules

(Moderate flow rate, $K = 10$) (data used in Fig. 1 and Table 1)

1. Seawater circulation pump and motor: The spiral module of [4] consists of six spiral-rolled “elements” in series. Each element is about 1 m long. Kremen [4] stated that for fluxes in the order of 0.5 m^3/m^2d the pressure drop would be about 1.4 bars. However, for a flux of 0.29 and only three elements, it is estimated that the pressure drop would be $(1.4)(0.29)/0.5)(3/6)^2 = 0.20$ bars. (The module length is only half as long and area per module only half as great.)

2. River water pump and motor: The ratio of the average flow rate on the river side to that on the sea water side is $(3+1)/2 = 3$ to $(5+7)(2) = 6$, i.e., the average ratio is $2/6 = 1/3$. Therefore, it is estimated that the pressure drop on the river water side is $(0.20)(1/3) = 0.07$ bars.

3. The pressure drop in the diluted seawater (DSW) circulation pump is arbitrarily estimated at 0.2 bar.

Appendix II
Ratio of plant cost/permeate rate, $d/m³ for RW/ SW PRO plant

(Moderate flow rate, $K = 10$) (used in Table 3)

According to [6], the Yuma RO plant cost 278 million dollars and delivers 278,000 m^3/d of permeate. Thus its ratio, as defined above, is $(278)(10)^6/(278)(10)^3 = 1000$ \$d/m^3. The permeate flux is 0.41 m^3/m^2 d.

It is estimated that for the Yuma RO plant and the PRO plants considered herein, half of the total cost is independent of permeate flux, and the other half is proportional to permeate flux. Now consider a PRO plant with a permeate rate of 278,000 m^3/d but a flux of only 0.29 m^3/m^2 d, as occurs with the *moderate flow rate*, K = *10 plant*. The non-flux related components would cost 278,000,000/2 = 139 million dollars and the flux-related components (139,000,000)(0.41/0.29) = 196 million dollars, a total of 335 million dollars. The ratio of plant cost/permeate rate would be $(335)(10)^6/278{,}000 = 1200$ \$d/m^3.

The *moderate flow rate*, K = *10* plant has a permeate rate of 2 million m^3/d Therefore, we introduce an economy-of-scale factor, as described in [8] to obtain:

$$\text{Final ratio} = (1200)(278{,}000/2{,}000{,}000)^{0.2} = 810 \text{ \$d/m}^3$$

This value is entered into Item 1, Table 3.

Appendix III
Membrane replacement costs per square meter of membrane [5]

(moderate flow rate, $K = 10$) (data used in Table 3)

For a small RO plant, 15,200 m^3/d of permeate, the flux was 0.65 m^3/m^2d so that the required membrane area was 15,200/0.65 = 23,400 m^2. The membrane cost, dollars per year, was \$65,600. Therefore, *assuming* a membrane life of 7 years and x\$/m^2 for the membranes in a small plant:

$$(x)(1/7)(23{,}400) = 65{,}600 \text{ and } x = 19.4 \text{ \$/m}^2$$

Now assume that membrane costs decrease exponentially with increase in permeate rate, just as described in Appendix II. Then the membrane replacement costs would be:

$$(19.4)(15{,}200/2{,}000{,}000)^{0.2} = 7.3 \text{ \$/m}^2$$

as shown in Table 3.