APPLICATION OF DIRECT OSMOSIS:
POSSIBILITIES FOR RECLAIMING WELLTON-MOHAWK DRAINAGE WATER

by

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Because the limited amount of fresh water in arid climates restricts agriculture expansion, much research has been devoted to searching for methods for obtaining fresh water from brackish water. Direct osmosis has been considered as one of these methods by several individuals (Murray, 1968; Moody and Kessler, 1971; Muller, 1974). The previous paper (Kessler and Moody, 1975) considers the design characteristics for direct osmosis hydration and dehydration applications. The following discussion considers the applicability of direct osmosis for reclaiming brackish agriculture effluent by using a concentrated fertilizer solution to provide the osmotic driving pressure. The direct osmosis product is a low concentration fertilizer water. A detailed discussion of reclamation possibilities for brackish drainage water from the Wellton-Mohawk Irrigation and Drainage District is presented as an example for the method.

GENERAL BACKGROUND

Colorado River water reaching Imperial Dam (18 miles upriver from Yuma, Arizona) has an average annual flow of about six million acre feet and contains about 850 ppm (1.2 tons/acre foot) dissolved solids. This water provides irrigation for over one million acres of land of which 169,000 acres are in the Yuma area, 486,000 acres are in the Imperial and Coachella Valleys, and 350,000 acres are in Mexico (Bureau of Reclamation, 1975).

By current irrigation practices, the undesirable salts, which are carried into the soil with the irrigation water and are then concentrated in the root zone by evapotranspiration, are removed from the root zone by the application of extra water which percolates the salts down away from the root zone. When this extra water causes the groundwater table to rise high enough to threaten the root zone with waterlogging, it must be removed by a drainage system.

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In the Yuma area, brackish drainage water returned to the Colorado River from the 62,000 acre Wellton-Mohawk Irrigation and Drainage District has increased the salinity of the Colorado River water delivered to Mexico at Morelos Dam. The salty Colorado River water has caused the Mexican farmers to complain that the salt is accumulating in the soil and is making the land unfit for farming. To alleviate the politically embarrassing situation, a reverse osmosis desalting plant is being planned to desalt part of the 175,000 acre feet of the 3000 ppm drainage water from the Wellton-Mohawk Irrigation and Drainage District. The treatment of Wellton-Mohawk drainage water will result in the following annual outputs:

(a) 101,000 acre feet/year -- desalted water
(b) 43,000 acre feet/year -- brine waste
(c) 31,000 acre feet/year -- untreated 3000 ppm water

Fractions (a) and (c) are returned to the Colorado River for use in Mexico. Fraction (b) is channeled sixty miles south where it is dumped into Santa Clara Slough in Mexico (U. S. Dept. of Interior, 1973a).

Estimated cost for the 101,000 acre feet of desalted water is $136 per acre foot (U. S. Dept. of Interior, 1973a). For the 62,000 acres in the Wellton-Mohawk (U. S. Dept. of Interior, 1973b), $222 per acre each year will be required to desalt the drainage water from land which currently produces crops with an average annual value of $500 per acre (U. S. Dept. of Interior, 1973b). (The average value of the annual crop production can be expected to increase up to $600 per acre as young citrus trees come into full production). Because the cost to desalt the drainage water preempts a large fraction of the total value of the crop produced, it is obvious that it is desirable to find a cheaper method of reclaiming the brackish drainage water. A less expensive method may be a direct osmosis system which uses a concentrated fertilizer solution to provide the osmotic driving pressure.

DIRECT OSMOSIS RECLAMATION OF BRACKISH DRAINAGE WATER

QUANTITY OF FERTILIZER AVAILABLE TO DRIVE THE DIRECT OSMOSIS PROCESS

In order to determine the volume of brackish water which can be reclaimed by fertilizer-driven direct osmosis, one needs to know the quality of fertilizer normally used in the area. Data from the Yuma area, Imperial Valley and Coachella Valley indicate that approximately one half of the total irrigated acreage is planted year round to crops which require nitrogen fertilizer (eg. cotton, citrus, wheat, sorghum, barley and lettuce), (U. S. Dept. of Interior, 1973b). The assumptions that the same proportion of non-leguminous crops is cultivated in the Mexican border area, and that 200 pounds per acre of nitrogen are applied each year to these crops, produce the numbers in table 1 for fertilizer usage in the area. If all nitrogen is applied in the ammonium sulfate form, an estimated 251,500 tons of ammonium sulfate would be required in the Yuma area, Imperial and Coachella Valleys and the Mexican border area.

TABLE 1

ESTIMATED QUANTITIES OF NITROGEN FERTILIZER APPLIED TO LANDS IRRIGATED FROM IMPERIAL DAM

Location	Total Irrigated Acres	Tons of N Applied	Equivalent tons of $(NH_4)_2SO_4$
Yuma	169,000	8,500	42,500
Imperial and Coachella Valleys	486,000	24,300	121,500
Mexico	350,000	17,500	87,500
Entire Area	1,005,000	56,300	251,500

VOLUME OF WATER OBTAINED PER UNIT OF FERTILIZER WITH A DIRECT OSMOSIS COUNTERCURRENT SYSTEM

For the direct osmosis method of brackish water reclamation, the continuous counterflow model shown schematically in fig. 1 is the design used in pilot experiments. Batch designs are also possible. The membrane used in pilot experiments was supplied through the courtesy of ROGA division of Universal Oil Company. It is a flat reverse osmosis asymmetric cellulose acetate membrane. The membrane constant as listed by ROGA is

$$K = 10^{-5} \frac{\text{grams } H_2O}{\text{cm}^2\text{-atm-sec}},$$

and the membrane rejects about 98% NaCl under reverse osmosis conditions. Although this type of flat membrane is shown in fig. 1, the membrane may be either flat or tubular and may be packed into space-saving cartridges as is done with reverse osmosis units.

With the counterflow model, the osmotic pressure (which is proportional to the concentration) of the fertilizer product water (which includes the water obtained from the brackish water) is only slightly higher than the osmotic pressure of the brackish feed water. This low concentration of the fertilizer product water is essential for maximizing the quantity of fresh water which can be obtained with a given amount of fertilizer. The rate at which water flows through the membrane is proportional to the average osmotic pressure difference across the membrane. Therefore, although a very low fertilizer concentration in the product water indicates that a large volume of fresh water

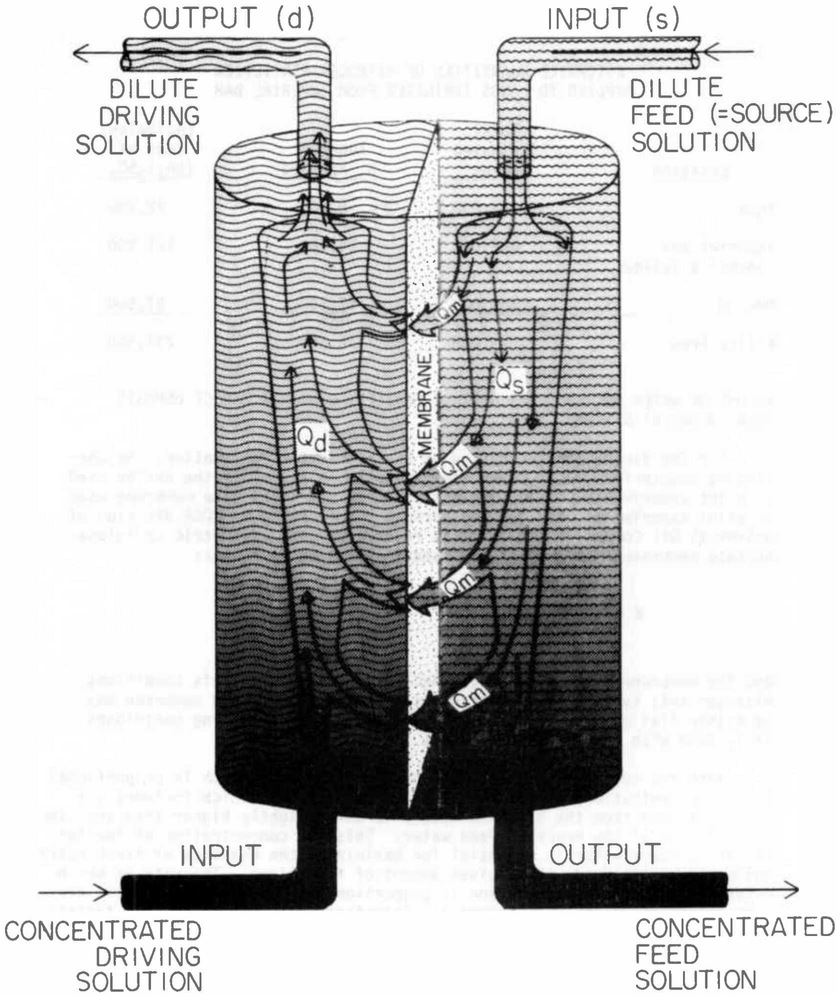

Fig. 1 Schematic view of continuous flow countercurrent extractor. Q_s, Q_d and Q_m are the feed (=source) and driving solution currents, and the membrane current. The density of shading symbolizes solute concentration, the width of the streams, current magnitudes.

is reclaimed per unit of fertilizer, the low osmotic pressure of this product water lowers the average osmotic pressure difference across the membrane and reduces the total membrane flow rate.

The counterflow model can also be designed to maximize the concentration of the brine waste, thereby reducing its disposal problem. While reverse osmosis at applied pressures of 350 psi can reclaim a maximum of 90% of the fresh water in 3000 ppm brackish water and leaves at least 10% of the fresh water to be thrown out in the brine waste, concentrated ammonium sulfate solution with an osmotic pressure greater than 4000 psi can reclaim more than 99% of the fresh water in 3000 ppm brackish water (barring precipitation) and can reduce the volume of brine waste by a factor of ten.

Table 2 lists the quantities of ammonium sulfate fertilizer required for obtaining an acre foot of water from 3000 ppm NaCl brackish water and the resulting membrane flow rates. The membrane flow rates are preliminary results of experimental work with a flat reverse osmosis cellulose acetate membrane. These membrane flow rates can be considered to be minimum values for the process and are subject to improvement as the process is optimized. The experimentally observed relationship between membrane flow rate and direct osmosis fertilizer efficiency is shown graphically in fig. 2, where the direct osmosis fertilizer efficiency may be defined as:

$$e = \frac{\eta}{\eta_{max}} = \frac{\frac{1}{c_{prod}} - \frac{1}{c_{feed}}}{\frac{1}{c_{min}} - \frac{1}{c_{feed}}} = \frac{c_{min}(c_{feed} - c_{prod})}{c_{prod}(c_{feed} - c_{min})} \doteq \frac{c_{min}}{c_{prod}} \doteq \frac{\pi_{min}}{\pi_{prod}}$$

where: η = volume of fresh water obtained per unit of fertilizer; (liters/mole)

η_{max} = maximum possible volume of fresh water obtainable per unit of fertilizer;

c_{prod} = concentration of the fertilizer in the product water; (moles/liter H_2O)

c_{min} = concentration of the fertilizer water having the same osmotic pressure as the brackish feed water;

c_{feed} = concentration of the fertilizer feed solution;

π_{prod} = osmotic pressure of the fertilizer product water; (atm.)

π_{min} = osmotic pressure of the brackish feed water.

TABLE 2

QUANTITIES OF AMMONIUM SULFATE REQUIRED FOR OBTAINING AN ACRE FOOT OF WATER BY DIRECT OSMOSIS FROM 3000 PPM NaCl BRACKISH WATER AND THE EXPERIMENTALLY OBSERVED MEMBRANE FLOW RATES.

The counterflow geometry is as shown in fig. 1 with membrane and counterflows vertical.

Membrane constant = $10^{-5} \frac{\text{grams } H_2O}{\text{cm}^2\text{-atm-sec}}$

Reverse osmosis NaCl rejection = 98%

Ammonium sulfate feed concentration = 5.75 molal

Brackish feed water concentration = 3000 ppm NaCl (π = 2.4 atm.)

Brine waste concentration = approx. seawater concentration (35,000 ± 20,000 ppm)

Efficiency of fertilizer use in the direct osmosis process.	Concentration and osmotic pressure of the ammonium sulfate product water.	Tons of ammonium sulfate required to produce an acre foot of reclaimed water.	Membrane Flow rates in $\frac{\text{Gallons}}{\text{Day-Ft}^2}$
100% (limiting case)	4900 ppm 6.66 t.a.f. .037 molal π = 2.4 atm.	6.73	0 (Estimated)
64%	7700 ppm 10.4 t.a.f. .058 molal π = 3.4 atm.	10.5	.57
35%	13,700 ppm 18.7 t.a.f. .104 molal π = 5.8 atm.	19.2	1.26
16.4%	29,000 ppm 39.6 t.a.f. .22 molal π = 11.5	40.9	3.28
ROGA Reverse Osmosis Pilot Unit - Yuma, Arizona			8.88

(Average Hydrostatic Pressure is 325 psi (22 atm.))

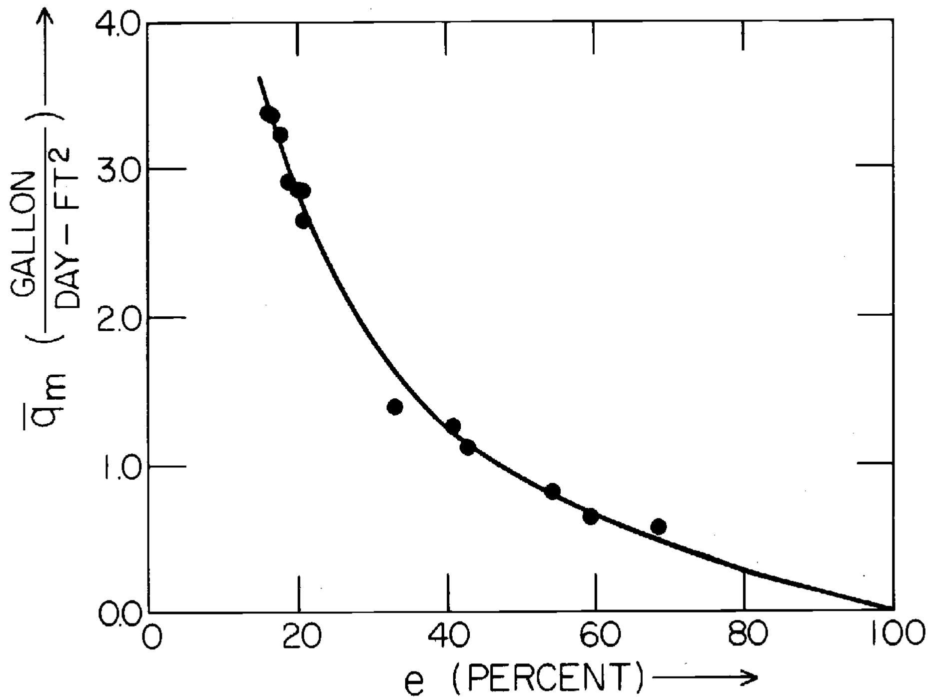

Fig. 2. The observed membrane flow rate, per unit area of membrane, or "flux", $\bar{q}_m$, is graphed versus the direct osmosis fertilizer efficiency, e. Data is from pilot experiments with a direct osmosis countercurrent extractor. Fertilizer efficiency is defined in the text. Operating conditions are those listed in the top half of Table 2. This graph is to be compared with Fig. 3, Kessler and Moody 1975. The results are similar, but detailed correspondence cannot be made because of inadequate experimental controls on $q_d(0)$ and $c_s(0)$, defined op. cit.

Table 2 and fig. 2 indicate that a high direct osmosis fertilizer efficiency is necessarily associated with a lower total membrane flow rate. Thus, savings in fertilizer tend to be offset by higher plant costs.

A fixed size direct osmosis plant is flexible in that it can reclaim a non-constant supply of brackish water by simply varying the feed rate of the concentrated fertilizer solution. For an above-average incoming brackish water flow, the fertilizer efficiency can be temporarily sacrificed (by increasing the fertilizer feed rate), in order to increase the total membrane flow rate of the fixed size plant. For a below-average incoming brackish water flow, lower membrane flow rates are required and the fertilizer efficiency can be increased (by reducing the fertilizer feed rate).

VOLUME OF WATER WHICH CAN BE OBTAINED WITH THE LOCALLY AVAILABLE FERTILIZER

How much fresh water can be obtained from 3000 ppm brackish water by direct osmosis using fertilizer normally applied in the nearby areas? Table 3 incorporates the fertilizer usage data of table 1 and the direct osmosis efficiency data of table 2 in estimating the quantities of fresh water which can be reclaimed from 3000 ppm brackish water. For the drainage water from the Wellton-Mohawk, the desalting requirement is 101,000 acre feet per year. At 64% efficiency with 251,500 tons of ammonium sulfate, fertilizer-driven direct osmosis can produce 24,000 acre feet a year of fertilizer water from 3000 ppm brackish water. If reclamation by direct osmosis is less expensive than reclamation by reverse osmosis, then direct osmosis may be utilized for a portion of the total desalting requirement, thereby reducing the required size of the reverse osmosis plant. In addition, because of the high osmotic pressure of concentrated ammonium sulfate, ammonium sulfate-driven direct osmosis can reduce the volume of brine waste to be disposed to a fraction of the volume of brine waste left by reverse osmosis.

TABLE 3

QUANTITIES OF FRESH WATER WHICH CAN BE OBTAINED FROM 3000 PPM BRACKISH WATER BY FERTILIZER-DRIVEN DIRECT OSMOSIS USING AMMONIUM SULFATE TO PROVIDE THE NITROGEN NORMALLY USED IN THE YUMA, IMPERIAL AND COACHELLA VALLEYS AND MEXICAN BORDER AREA.

Location	Tons of $(NH_4)_2SO_4$ Used	Acre Feet of Water Obtained from 3000 ppm Brackish Water at Direct Osmosis Fertilizer Efficiencies of: 100%	64%	35%	16%
Yuma	42,500	6,300	4,100	2,210	1,040
Imperial and Coachella Valleys	121,500	18,100	11,600	6,330	2,920
Mexico	87,500	13,000	8,300	4,560	2,140
Entire Area	251,500	37,400	24,000	13,100	6,150

ADVANTAGES OF BRACKISH WATER RECLAMATION BY DIRECT OSMOSIS

Because direct osmosis takes place with zero hydrostatic pressure gradient across the salt-separating membrane, it is a low maintenance, low technology process, unlike reverse osmosis. The energy required for desalination by direct osmosis is supplied by the fertilizer manufacturing process, thus the energy used is a form of by-product recovery. This energy (of solution) is normally wasted when the fertilizer is spread on the ground or added directly to the irrigation water. Specifically, the energy required to obtain an acre foot of desalted water from 3000 ppm brackish water by reverse osmosis is 1790 kwh1/. (Wang, 1975). The thermal energy from natural gas or other fossil fuel required to produce 1790 kwh at 38% efficiency is

$\frac{1790 \text{ kwh} \times 3413 \text{ btu/kwh}}{.38} = 16.1 \times 10^6$ btu. The thermal energy from natural gas which is required to manufacture the ammonia portion of one ton of ammonium sulfate is

$(32 \times 10^6 \text{ btu/ton } NH_3) \times (.257 \text{ tons } NH_3\text{/ton } (NH_4)_2SO_4) = 8.22 \times 10^6$ btu

(Vancini, 1971). For 10.5 tons of ammonium sulfate, which is the fertilizer required at 64% efficiency to obtain an acre foot of fertilizer water from 3000 ppm brackish water, the energy requirement to synthesize the ammonia portion is

$(10.5 \text{ tons}) \times (8.22 \times 10^6 \text{ btu/ton}) = 86.3 \times 10^6$ btu. Therefore, at the 64% direct osmosis efficiency level about 18.6% of the energy cost of manufacturing the ammonia portion of the fertilizer is saved by using the fertilizer to drive the direct osmosis process. (This number does not include the additional fertilizer cost of producing and transporting the sulfuric acid fraction of the ammonium sulfate, where the sulfuric acid is a by-product of the copper mining industry).

The most pressing reason for reclaiming brackish water in the lower Colorado is to improve the quality of the water delivered to Mexico at Morelos Dam to be about the quality of Colorado River water at Imperial Dam. Reverse osmosis desalts part of the Wellton-Mohawk brackish drainage water and returns this water to the Colorado River for use by Mexico. The drainage water reclaimed by direct osmosis is reused by the farmers in the area, thereby in effect increasing the irrigation efficiency. Specifically, assuming one half ton of ammonium sulfate is applied per acre and five acre feet of irrigation water is used each year, about one percent of the total irrigation requirement can be supplied by reclaiming the brackish drainage water with direct osmosis at 64% efficiency,
(0.5 tons/acre)/(5 acre ft/acre x 10.5 tons/acre ft) x 100% = (approx.) 1%.

1/ At reverse osmosis conditions of:
80% recovery of the brackish water;
65% pressure pump efficiency;
400 psi hydrostatic pressure;
Without high pressure energy recovery from the brine waste.
(1 acre foot = 3.26×10^5 gallons)

In other words with the fertilizer which is applied to 100 acres of wheat and sorghum, the farmer can reclaim enough water from the brackish drainage to irrigate an additional acre of land which will produce an additional $500-$600 income per year. With the irrigation efficiency increased by one percent, about one half of one percent (about one half the acreage in each area uses nitrogen fertilizer) less water is diverted at Imperial Dam, and this approximately 24,000 acre feet of Colorado River water is allowed to continue down-river to Mexico at Morelos Dam. Although the reclamation of the brackish Wellton-Mohawk drainage water has been discussed throughout this paper, the direct osmosis reclamation of a fraction of the drainage water in each irrigated area for reuse in that area serves the same purpose, namely that of delivering Imperial Dam quality water to Mexico at Morelos Dam. The latter approach reduces the problem of storage and distribution of the fertilizer water. The low technology inherent in direct osmosis plants makes it suitable for the operation of many small units.

SUMMARY

In summary, a direct osmosis plant can reclaim twenty to thirty thousand acre feet of Wellton-Mohawk brackish drainage water using no more nitrogen fertilizer than is normally used in the Yuma, Coachella Valley, Imperial Valley and the bordering Mexican areas. On a per-acre basis, ammonium sulfate-driven direct osmosis can reclaim about one percent of the total irrigation requirement from 3000 ppm brackish water. The efficiency of fertilizer use in fertilizer-driven direct osmosis must be weighed against the total water output rate in order to determine the optimum direct osmosis plant size. Although preliminary experiments have membrane flow rates of .57 to 3.28 gpd/ft^2 at 64% and 16.4% direct osmosis fertilizer efficiencies respectively, these flow rates can be expected to increase as the process is optimized. Neglecting the energy cost of the sulfuric acid fraction of the fertilizer, 18.6% of the energy cost of manufacturing the ammonia portion of the ammonium sulfate fertilizer can be recovered by using direct osmosis to desalt the 3000 ppm water. This by-product energy recovery of the manufacture of the fertilizer and the low technology inherent in direct osmosis processes make direct osmosis an appealing water reclaiming process.

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