

Performance and Economic Evaluation of Membrane Processes for Reuse Applications¹

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Introduction

The following is a brief summary of a study conducted at the Orange County Water District on the use of membrane processes for indirect potable reuse applications. The major results are discussed in the context of the recently proposed Ground Water Replenishment System (GWR) Project. The benefits of the use of membranes for reuse projects are presented as a comparison of O&M costs for a conventional treatment process and the proposed GWR treatment process.

In July 1997, the Orange County Water District (OCWD) and the County Sanitation Districts of Orange County (CSDOC) released a joint report on proposed Ground Water Replenishment System (GWR) projectⁱ. The GWR project, an indirect potable reuse project, is perceived by both agencies to be the best solution to the region's water supplyⁱⁱ and wastewater disposalⁱⁱⁱ problems. To be implemented in three phases by 2020, the GWR project would reclaim 100,000 acre feet (af) of wastewater to augment the local ground water basin, which provides up to 75% of the potable water for nearly two million county residents. Approximately 80% of the total GWR flow would be delivered through a specially constructed thirteen mile pipeline to the OCWD spreading basins located near the City of Anaheim, while the balance would be recharged through groundwater injection.

The use of potable quality reclaimed water on the scale proposed in the GWR project is a logical extension of the existing wastewater reclamation process operated by OCWD at Water Factory 21 (WF21). Since 1976, potable quality reclaimed water produced at WF21 has been injected into coastal aquifers to prevent the ingress of seawater into the groundwater basin. WF21 is based on a conventional treatment process, consisting of flash mixing and flocculation at pH 11.4 using slaked lime, clarification, recarbonation for pH control and granular media filtration. Media filter effluent is treated in parallel through granular activated carbon (GAC), to reduce organics, and reverse osmosis (RO), to reduce salinity, prior to injection.

Although WF21 has operated successfully for over twenty years, the treatment process proposed for the GWR process is based on the use of membranes in place of the conventional RO Pre-treatment process. Clarified secondary effluent from CSDOC would be treated using low pressure membrane processes, such as microfiltration (MF), or ultrafiltration (UF), to removed suspended solids, followed by partial (80%) demineralization, using reverse osmosis (RO), to reduce salinity, organic nitrogen and carbon. The balance of the microfiltered effluent (20%) would be treated with GAC and blended with the RO permeate. The reclaimed water would be disinfected using a combination of ultraviolet radiation and chloramination prior to groundwater recharge.

¹ Proc. American Desalting Association Biennial Conf., Aug.1998, Williamsburg VA

A Brief Summary of Membrane Performance at WF21

MF and UF membranes were first used to treat secondary effluent at WF21 during a research program sponsored by the Office of Water Research and Technology in the late 1970's. However, the MF and UF membranes evaluated in this study were highly susceptible to fouling by the biological moieties in the wastewater and required cleaning at least twice per week^{iv}. Consequently, these experiments were discontinued and the research effort was redirected at understanding the mechanism of biological fouling^v and optimizing the conventional treatment process^{vi}. The first successful study of MF for reuse application occurred at the Reedy Creek Services District, Florida in 1992^{vii}. The MF system used in this study employed a patented gas backwash to control biological fouling and the system operated for three to four weeks before cleaning was required. Subsequently, a two gallon per minute (gpm) MF unit was used at WF21 to treat clarified secondary effluent. The filtrate produced by this system contained exceptionally low numbers of microorganisms, suspended solids and turbidity. In addition, the typical silt density indices (SDI) of the MF effluent were a factor of three lower than the best value for the media filters at WF21. Given that the SDI is an important indicator for RO membrane fouling it was postulated that MF could significantly improve the performance of the RO and reduce the cost of reuse. Experiments to quantify the benefits of using MF as a pretreatment for RO commenced in October 1992 at the pilot scale using a MF/RO system rated at 2.8×10^4 gallons per day (gpd) ($106 \text{ m}^3/\text{d}$). Cellulose acetate (CA) RO membranes operated at a flux of 12 gallons per square foot per day (gfd) downstream of $0.35 \text{ }\mu\text{m}$ MF membranes for up to 13 weeks before cleaning. Similar CA RO membranes, operating at 10.4 gfd downstream of the conventional process are cleaned every four to six weeks.

Deminceralization using RO is an energy intensive process, requiring high pressure to drive water across the semipermeable membrane against an osmotic gradient generated by retained salts. The energy requirements of the RO process were reduced by replacing the CA RO membranes with polyamide (PA) thin film composite membranes which operate at lower pressure. The substitution of the thin film composite membranes for the CA membranes reduced the operating pressure by up to 150 psi at a flux of 10.4 gfd. One set of thin film PA membranes, operating for over 5000 h without cleaning at a flux of 10.4 gfd, attained a feed pressure of 200 psi. In contrast, CA membrane at WF21 routinely reach 330 - 350 psi after 700 hours of operation at 10.4 gfd.

The pressure requirements for the RO process were further reduced by decreasing the pore size of the pretreatment membranes. This effect was observed during the evaluation of a selection MF and UF membranes with pore sizes ranging from $0.35 \text{ }\mu\text{m}$ to $0.01 \text{ }\mu\text{m}$ (Table 1). The UF and MF used were all based on a hollow fine fiber configuration and operate in either a cross flow or dead end mode. Five of the six hollow fiber membranes were contained within a pressure vessel, whereas one set of MF membranes were recessed in a process tank open to the atmosphere. A detailed description of these membrane systems and the operating data can be found elsewhere^{viii}. In general, the RO operating pressures were decreased with decreasing membrane pore size.

Results of the pilot scale studies were confirmed at the demonstration scale on a 0.7 million gallon per day (mgd) ($2653 \text{ m}^3/\text{d}$) MF system followed by a 0.43 mgd ($1640 \text{ m}^3/\text{d}$) RO system. The MF membranes reliably removed suspended solids and bacteria and any membrane failures due to holes and leaks were readily detected and repaired. All indications suggest that the polypropylene MF membranes used in the demonstration project will have a lifetime of five year based on the performance of polypropylene membranes used in the pilot experiments. Between June 1996 and October 1997, the thin

film PA RO membranes, attained a maximum operating pressure of 190 psi at flux of 10.4 gfd after 5000 hours. The RO membranes were cleaned in January 1996 and again in October 1997.

Calculation and comparison of operating and maintenance costs

Operating and maintenance (O&M) cost data for WF21 was collected for the purposes of comparison with projected O&M cost data for the membrane processes proposed for the GWR project. The O&M and capital costs for the GWR project were calculated using a multivariable model developed during the preparation of the GWR project report. This model has proved to be useful for identifying the effect of various membrane process parameters, for example RO pressures and membrane lifetime, on the unit cost of recycled water.

The annual operation and maintenance (O&M) costs for WF21 were based on a survey of the annual power, chemical and maintenance requirements of WF21 for the period 1985 to 1996. The data surveyed included; the electrical demand for pumps, motors and buildings; natural gas for operation of the lime furnace; lime and polymeric flocculant for the flash mixing and flocculation process; carbon dioxide for the recarbonation process. Approximately 1.2 tons (650 mgL^{-1}) of lime is used per one mgd of flow; seventy five percent of the lime sludge is recalcined at 1700°F in a multiple hearth furnace and reused, with the balance disposed to landfills. Chemicals associated with the WF21 RO process include, sulfuric acid, anti-scalant and cleaning chemicals. The survey also included an estimate of the costs for maintenance of equipment and facilities based on the line item expenses for the water production department.

The cost estimate for the GWR project was prepared in accordance with the American Association of Cost Engineers and included provisions for engineering, legal and administrative services and a 20% factor for contingencies. Individual equipment costs were based on letters of quotation from major equipment suppliers and an opinion of probable construction cost for the conveyance facilities was prepared by an independent consultant. Data for the membrane process such as operating pressure and expected membrane lifetime were based on results of the membrane pilot and demonstration studies conducted at Water Factory 21. For the purposes of these calculations the most conservative, or worst case, experimental data were used (Table 1). In addition, a factor of 10% was applied to the total O&M estimate to cover miscellaneous costs. It was assumed that GWR plant would operate 90% of the year excluding those periods of the winter months when the spreading basins receive storm flows. The assumed values can be found in table 4.

Discussion

The GWR project is possible because of the developments made in membrane systems in the last ten years; it would difficult to expand the existing WF21 treatment process to meet the objectives of the GWR project. WF21 is located in a dense residential area where expansion of flocculation and coagulation basins would be limited due to the availability of land. Moreover, the costs associated with the addition of lime at 1.2 tons/mgd and the collection and recycling of the lime sludge would be prohibitive. In contrast, MF and UF processes occupy less space than the conventional process, do not require chemical pretreatment, are easily automated and less maintenance intensive.

The use of MF, or UF, in place of the conventional WF21 RO pretreatment, coupled with the lower energy requirements of thin film composite RO membranes, could reduce the

operation and maintenance costs of indirect potable reuse by at least \$124 per acre foot or 39% (Table 3). A MF or UF system would simplify the reclamation process by eliminating the lime handling, addition and recovery systems and the flocculation, clarification, recarbonation and filtration processes, resulting in lower power and chemical costs. Presently, power costs account for 51% of the total O&M costs of the WF21 reclamation process. By eliminating the sludge collection, de-watering, recalcining and off gas recovery system, plus the conversion from cellulose acetate to thin film composite RO membranes, it would be possible to reduce the power component of the O&M cost by \$98 an acre foot. Similarly, by eliminating the chemicals associated with the flash mixing and flocculation process could reduce the chemical component of the O&M costs by \$29 an acre foot.

In addition to the reduction in O&M costs, the use of MF or UF would significantly increase the capacity of WF21 through the more efficient use of available space. WF21 is located in a neighborhood zoned for medium density housing with some retail and light manufacturing. Given the commercial and residential value of the land it would be prohibitively expensive to use any process other than membranes to produce the flows projected in the GWR project for the year 2020. Membrane processes require only one quarter of the space of conventional treatment processes. The flocculation, sedimentation and recarbonation basins plus the media filters at WF12, occupy 29,000 ft² and treat 15 mgd. The plant footprint productivity for this process is approximately 520 gallons per square foot of plant per day (g/ft²/d). In contrast, the plant footprint productivity of the full scale MF demonstration process is approximately 1900 g/ft²/d.

Elimination of the conventional process, however, removes an important barrier for the inactivation of virus and bacteria required by the Department of Health Services. The addition of lime at the front end of the treatment process raises the pH from 7.4 to 11.4 which, coupled with the two hour detention time in the clarification process, provides up to four, of the necessary six, log removal credits for the inactivation of virus. Consequently water produced with the proposed GWR treatment process that will be used for injection into the existing seawater intrusion barrier must be treated using UV radiation to replace the log removal credits lost through the elimination of the conventional process. This introduces an additional cost of \$9 per acre-foot for the replacement of UV lamps that is not currently incurred at WF21. Reclaimed water produced for groundwater recharge through surface spreading would be disinfected by a more than 2 hours contact with a chloramine residual in the proposed thirteen mile pipeline connecting WF21 and the recharge basins.

It is important to note that the proceeding comparison of O&M costs were based on actual cost data for the WF21 process and predicted data for a membrane based process. A more useful comparison will only be possible after more data has been collected for the costs of operation and maintenance of the 0.7 mgd microfiltration demonstration project. To this end it will probably require at least two years data to be certain of the real financial benefit of membranes over conventional process. Notwithstanding this, the proceeding analysis indicates that membrane process will have some positive effect on the costs associated with indirect potable reuse.

The GWR cost model was also used to develop a relationship between the membrane O&M costs and the total annual, or unit cost, of producing reclaimed water for an indirect potable reuse application. The unit cost of reclaimed water was expressed as the quotient of annual costs and the annual reclaimed water production. In a typical large scale indirect potable reuse application, such as the GWR project, the total cost of the installed membrane and disinfection processes equipment could constitute a little more than one

third (35%) of the total capital cost (Table 4.A). Plant structures, including the membrane buildings, chemical handling facilities and operations buildings, together with the fees associated with design, legal and administrative services and project contingencies could also account for one third of total capital cost. The balance of the total project capital, at least in the case of the proposed GWR project, will be associated with the conveyance system. Although these calculations were specific for the GWR project, it would not be uncommon for an indirect reuse project to have a significant conveyance system connecting the wastewater source to the intake for the potable water supply. Indeed it has been the practice of water and wastewater planning to separate as much as possible the wastewater treatment and discharge facilities from the recharge operations for groundwater basin or the intake system for surface water plant.

The O&M costs of the membrane and disinfection processes constitute only 26% of the unit cost of reclaimed water (Table 4.B). The most significant component unit cost was associated with debt service on the project capital which amounted to 59% of the total annual cost (Table 4.B). Using single variable perturbation approach, it was possible to measure the sensitivity of the unit cost to a variety of process variables (Table 4.C). Not surprisingly, the unit cost of reclaimed water was most sensitive to changes in interest rates (3.43%), the cost of the RO equipment (1.67%), power costs (1.29%) and the cost of the RO pretreatment equipment (1.27%) (Table 4.C). Moreover, it was apparent that the unit cost of water was relatively insensitive to a 10% change in most of the membrane process variables. For example, with power costs fixed at \$0.06/kWh, a 10% increase in RO operating pressures only increased the unit cost of water by 0.56 % (Table 4.C). Consequently, the reduction in RO pressures through the use of thin film composite membranes and “tighter” pretreatment membranes should be viewed as only a small component of the unit cost of reclaimed water. In fact, the unit cost of water for an indirect reuse project, such as the GWR project, would be more sensitive to time on-line (0.87 %) than the effective membrane life, membrane replacement cost and process maintenance cost.

Conclusion

The results of the research conducted by OCWD, and other public agencies, on the use of membranes for indirect reuse applications are encouraging. Membranes processes can significantly increase the capacity, while reducing the O&M costs, of reuse projects when compared to the processes that were “state of the art” in the 1970’s. Furthermore, improvements in both pretreatment UF and MF membranes as well as the RO membranes will reduce the energy requirements of reuse projects. However, because most indirect reuse projects will involve capital costs for both conveyance and treatment, the effect of an single operating parameter on the unit cost of water is moot. The implication of this is that factors which influence process reliability and “time on line” for a membrane process can significantly alter the process economics.

Table 1. RO operating pressures as a function of pretreatment membrane pore size

MF and UF Pretreatment Process			RO Performance	
Material	Pore Size	Pressure (psi)	Pressure (psi)	Cleaning Int. (approx.hours)
polypropylene	0.35	20	200	5000
polypropylene	0.29	20	195	6000
proprietary	0.15	8	150	4000*
polyethylene	0.1	25	150	4000*
polysulfone	0.01	30	140	4800
cellulose acetate	0.01	30	130	1400*

(*) Indicates RO membranes were not cleaned before the experiments were terminated

Table 2. Water Factory 21 operation and maintenance cost data

Annual Value	Summary of 1985 - 1996 operating history		
	Average	Minimum	Maximum
Water Production ¹ (af)	4943	2449	7941
Days on-line	302	212	350
Power Cost (\$/af)	163	119	267
Chemicals (\$/af)	52	37	76
Natural gas (\$/af)	33	20	60
Membranes ² (\$/af)	24	-	-
Maintenance ³ (\$/af)	48	-	-

Costs do not include labor. Values expressed in 1997's

1. Does not include deep well water produced at WF21 and injected into barrier.
2. Membranes replaced every five years at \$395/ element
3. Maintenance cost only expressed as a twelve year average

Table 3 Comparison of O&M costs for conventional and membrane (GWR) process

Cost Category	Reclamation Treatment Costs (\$/af)			
	WF 21 (12 year average)		GWR Process	
	\$/af	%	\$/af	%
Chemicals	52	16	23	12
Power	163	51	65	33
Natural gas	33	10	0	0
Membranes ¹	24	8	51	26
UV Lamps	0	0	9	5
Maintenance	48	15	48	24
Total	320		196	

1. Membrane costs for the GWR process based on \$700/element for thin film composite membranes and \$650 an element for MF membranes.

Table 4. Summary of GWR cost model and sensitivity analysis

4.A. Major capital items as a percentage of total project capital cost (approx. \$ 240 M)				
Advanced Water Treatment Equipment (installed)			35 %	
Plant Buildings & Structures			7 %	
Conveyance System			30.4 %	
Engineering, Administration & Legal			11.1 %	
Contingencies			16.5 %	
4.B Annual cost components as a percentage of unit cost				
Amortized Capital			59 %	
Conveyance (power & maintenance)			5 %	
AWT Process (chemicals, power, maintenance)			26 %	
Staff (Operators)			4.4 %	
Regulatory Monitoring & Reporting			4.6 %	
4.C. Sensitivity Analysis (Sensitivity expressed as percentage change in unit cost)				
Variables	Units	Initial	Perturbed	Sensitivity
Annual Interest rate	%	6	6.6	+ 3.43 %
Equipment Reverse Osmosis	\$/gal/day	0.9	0.99	+ 1.67 %
RO Pre-treatment (MF/UF)	\$/gal/day	0.4	0.44	+ 1.27 %
Power	\$/ kWh	0.06	0.066	+ 1.29 %
Down time	days / year	35.6	39.2	+ 0.87 %
Process maintenance	\$/1000 gal	0.15	0.165	+ 0.58 %
RO operating pressure	psi	180	198	+ 0.56 %
RO membrane life	years	5	5.5	- 0.51 %
UF/MF membrane life	years	5	5.5	- 0.48 %
RO membrane cost	\$/element	700	770	+ 0.46 %
Monitoring & reporting	\$/ year	1.4 x 10 ⁶	1.54 x 10 ⁶	+ 0.46 %
MF/UF membrane cost	\$/element	650	715	+ 0.43 %
Chemicals	\$/1000 gal	0.06	0.066	+ 0.43 %
Labor	\$/h	35	38.5	+ 0.41 %
Building Costs	\$/ft ²	100	110	+ 0.34 %
MF/UF operating pressure	psi	30	33	+ 0.15 %
UV Energy	kW/lamp	4	4.4	+ 0.12 %
Disinfection	\$/gal/day	0.08	0.088	+ 0.04 %

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