# BENCH-SCALE TESTING OF SEAWATER DESALINATION USING NANOFILTRATION

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## Introduction

A majority of Southern California municipalities, including the City of Long Beach, depend on water purchased from the Metropolitan Water District of Southern California. However, due to over-allocation of the Colorado River, this water supply could potentially be restricted in the future. Consequently, the Long Beach Water Department (LBWD) is considering the construction of a 10 million gallon per day (mgd) seawater desalination plant to augment its existing supplies.

Reverse osmosis (RO) is a proven membrane technology for seawater desalination. Although the cost of RO desalinated water has been significantly reduced, it still remains fairly high, as compared to other drinking water sources, mainly due to the high operating pressures required (typically 800-1000 psi). LBWD had recently introduced a patent-pending dual-staged nanofiltration (NF) process as a potentially lower-energy alternative to the traditional RO desalination process. The novel NF process desalts seawater by treating the permeate from the first stage with a second NF stage in order to produce finished water with salinity levels lower than drinking water standards. The primary goal of this novel desalination system is to reduce energy consumption to as low as possible while producing potable water at an acceptable recovery rate.

The Long Beach Water Department, EE&T, Inc., and the University of Nevada (UNR), Reno are engaged on an 18-month long project to better understand and optimize this technology. The UNR focus in this research project is on the theoretical basis for the dual NF concept and includes membrane characterization and bench-scale membrane performance. The objectives of this project are to evaluate three NF membranes for their permeate water flux and ion rejection for both single salt feed water solutions as well as for synthetic seawater solutions. This data will provide the basis for a predictive model and allow the formation of a selection protocol to evaluate possible candidate NF membranes.

## Materials and Methods

The three commercially available NF membranes selected for this study include the NF-90 membrane (FilmTec, Midland, MI), the TS-80 membrane (TriSep, Goleta, CA), and the NE-90 membrane (Saehan, Seoul, Korea). All membranes were supplied as flat sheets and stored in doubly deionized water (DDW) at 5°C. The flux and rejection properties of these membranes were systematically investigated using stirred-cell and bench-scale membrane test units.

The water flux and solute rejection of the three membranes under various solution chemistries are being evaluated using a bench-scale membrane test unit (Figure 1). In this unit, the test solution is pumped from a solution reservoir, through a flat sheet membrane cell (SEPA-CF, Osmonics, Minnetonka, MN), and back to the reservoir. The membrane cell is fitted with both feed and permeate spacers in an attempt to simulate the hydrodynamics of a spiral-wound membrane element. The reservoir houses a stainless steel cooling coil that is connected to a refrigerated recirculating chiller to maintain the experimental temperatures.

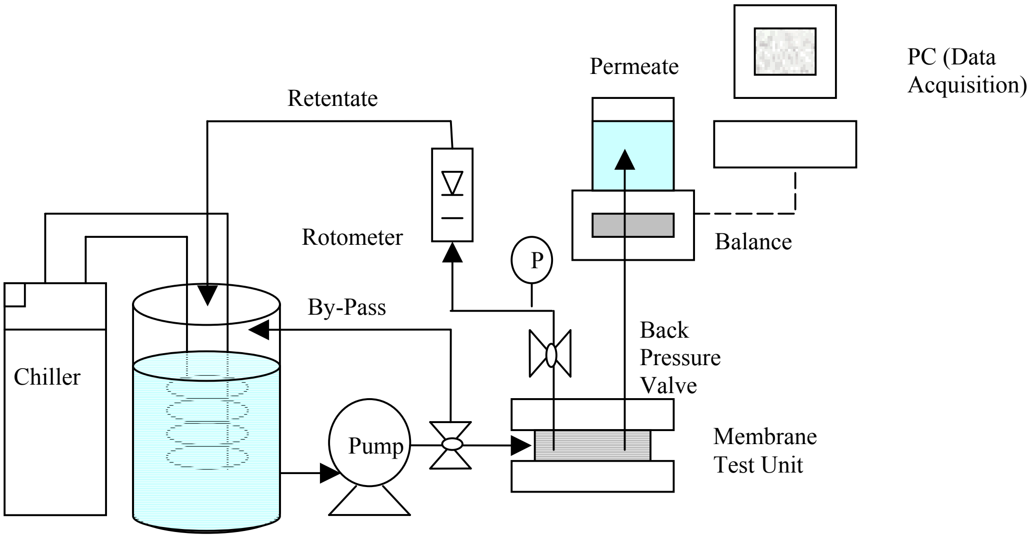

**Figure 1. Bench-scale test unit**

Prior to each set of experiments, the membranes are compacted at 575 psi (the highest experimental operating pressure) for 8 hours using DDW. After compaction, the salt solution is added to the feed reservoir. The solution is recirculated through the system at a low pressure for the equivalent of two tank volumes to ensure adequate mixing. During this time, the temperature is equilibrated to 15°C. The pressure is then increased to the initial operating pressure, and the system is allowed to reach equilibrium over 30 min. This time was found to be sufficient for the flux to reach a stable value. The permeate flux, J, is then measured continuously for 20 min using an electronic balance (Model PB 303-3, Mettler Toledo, Columbus, OH) interfaced with a computer. The permeate water is returned to the feed tank after each experiment. At the end of the 20-min experiment, two 100 mL samples are taken for analysis. This process is repeated for the remainder of the operating pressures. The temperature is then raised to 20°C, and the entire set of experiments is repeated.

The temperature range of 15 to 20 $^{o}$C was based on the seasonal range of temperatures from the Pacific Ocean near Long Beach (i.e., 60 to 70 $^{o}$F). The different molarities for the tests of individual salts bracket the anticipated individual salt concentrations in the feed and permeate of Stage 1. Sodium and potassium are measured using flame emission spectrophotometry; calcium and magnesium using flame atomic absorption spectrometry (AAS); boron with inductively coupled plasma spectrophotometry (ICP); sulfate, bromide, and chloride with ion chromatography (IC); and bicarbonate with an alkalinity titration.

## Results and Discussion

For each experimental condition, water flux and ion rejection are measured. From this data the water and salt mass transfer coefficients are calculated. The water mass transfer coefficient, $k_w$, is calculated using the slope of a best fit line of the flux versus pressure data. Examples of this data are shown for the NF-90 membrane with a variety of NaCl feed solution in Figure 2.

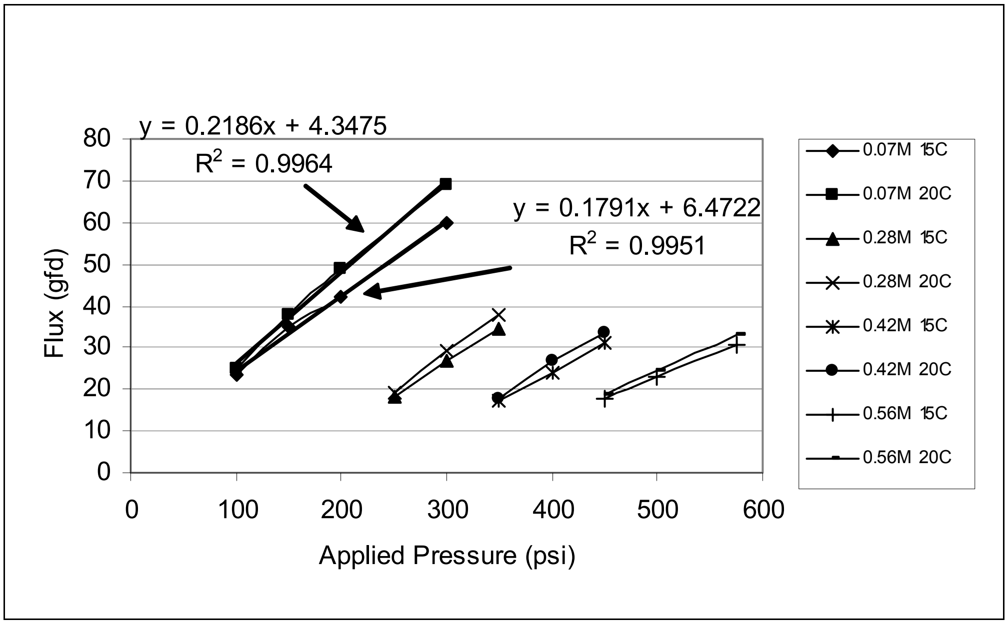

**Figure 2. Permeate water flux for NF-90 experiments with NaCl feed solution (I = 0.07M, 0.28M, 0.42M, 0.56M NaCl and T = 15°C and 20°C)**

The salt mass transfer coefficient, $k_i$, is calculated using:

$$k_i = J_w \left( \frac{1 - R}{R} \right) \qquad (1)$$

where $J_w$ is flux of water and R is the solute rejection. A summary of the operating conditions, water mass transfer coefficients, and solute mass transfer coefficients are shown in Table 1.

**Table 1: Benchscale operating conditions and mass transfer coefficients**

| Salt | Feed Conc. (M) | Feed Conc. (mg/L) | Temperature ($^oC$) | $k_w$ (gfd/psi) | $k_i$ (gfd) cation | $k_i$ (gfd) anion |
|---|---|---|---|---|---|---|
| NaCl | 0.07 | 4,090 | 15 | 0.18 | 2.81 | 2.09 |
| | 0.07 | 4,090 | 20 | 0.22 | 3.41 | 2.16 |
| | 0.28 | 16,360 | 15 | 0.16 | 2.11 | 1.26 |
| | 0.28 | 16,360 | 20 | 0.19 | 2.20 | 1.29 |
| | 0.42 | 24,540 | 15 | 0.14 | 1.49 | 0.96 |
| | 0.42 | 24,540 | 20 | 0.15 | 1.81 | 1.12 |
| | 0.56 | 32,730 | 15 | 0.10 | 2.14 | 1.41 |
| | 0.56 | 32,730 | 20 | 0.11 | 2.56 | 1.60 |
| $CaCl_2$ | 0.001 | 110 | 15 | 0.22 | 0.42 | 1.30 |
| | 0.001 | 110 | 20 | 0.26 | 0.51 | 1.53 |
| | 0.013 | 1,440 | 15 | 0.19 | 0.16 | 1.02 |
| | 0.013 | 1,440 | 20 | 0.22 | 0.18 | 1.21 |
| $MgCl_2$ | 0.003 | 290 | 15 | 0.24 | 0.61 | 2.22 |
| | 0.003 | 290 | 20 | 0.31 | 0.47 | 1.86 |
| | 0.029 | 2,760 | 15 | 0.19 | 0.31 | 0.84 |
| | 0.029 | 2,760 | 20 | 0.23 | 0.36 | 0.94 |
| $MgSO_4$ | 0.003 | 360 | 15 | 0.19 | 0.09 | 0.10 |
| | 0.003 | 360 | 20 | 0.23 | 0.08 | 0.10 |
| | 0.031 | 3,730 | 15 | 0.14 | 0.17 | 0.26 |
| | 0.031 | 3,730 | 20 | 0.17 | 0.18 | 0.29 |
| KCl | 0.01 | 750 | 15 | 0.19 | 4.87 | 10.42 |
| | 0.01 | 750 | 20 | 0.22 | 5.06 | 10.64 |
| NaBr | 0.01 | 1,030 | 15 | 0.19 | 3.90 | 3.63 |
| | 0.01 | 1,030 | 20 | 0.21 | 4.10 | 3.79 |
| $NaHCO_3$ | 0.003 | 250 | 15 | 0.16 | 1.17 | 0.87 |
| | 0.003 | 250 | 20 | 0.19 | 0.87 | 0.58 |
| KI | 6.0E-06 | 1 | 15 | 0.19 | - | 9.03 |
| | 6.0E-06 | 1 | 20 | 0.23 | - | 10.38 |
| $H_3BO_3$ (pH=7.8) | 0.000463 | 30 | 15 | 0.17 | - | 30.28 |
| | 0.000463 | 30 | 20 | 0.19 | - | 43.89 |
| $H_3BO_3$ (pH=9.8) | 0.000463 | 30 | 15 | 0.15 | - | 3.84 |
| | 0.000463 | 30 | 20 | 0.15 | - | 8.32 |

The water mass transfer coefficient ($k_w$) significantly decreases with increasing salt concentration. Increasing the temperature slightly increases $k_w$ and the salt mass transfer coefficients ($k_i$). The boron mass transfer coefficient greatly decreases with increasing pH due to the transition in speciation of boron to the borate ion at higher pH values which the membrane can reject. The $k_i$ values for $Na^+$, $K^+$, and $Cl^-$ are almost an order of magnitude greater than those for $Ca^{2+}$ and $Mg^{2+}$. This is because NF membranes have substantially greater rejections for divalent ions than monovalent ions. The differences in the $k_i$ values for chloride ($Cl^-$) between NaCl, $MgCl_2$, $CaCl_2$ and KCl may be ascribed to the sensitivity of the $k_i$ calculations given the high range of rejection (i.e., a difference of 1 percent in the >90 percent rejection range will have a substantial effect *versus* a 1 percent difference in the 50 percent range of rejection).

Table 2 presents the water and salt permeability data for the synthetic seawater. The $k_w$ for the synthetic seawater experiment matched well with the $k_w$ for the single salt NaCl experiment with approximately the same feed concentration. The values for each $k_i$ are relatively close to those of Table 1 for the corresponding feed concentrations, with all of them showing a better salt rejection than identified in Table 1, except for $Na^+$ and $Cl^-$ where the rejection was equivalent.

**Table 2: Synthetic Seawater Experiments Mass Transfer Coefficients**
**(T = 20 $^oC$, P = 500 and 575 psi, NaCl = 0.486 M, $MgCl_2$ = 0.029 M, $MgSO_4$ = 0.031 M, $CaCl_2$ = 0.013 M, KCl = 0.01 M, $NaHCO_3$ = 0.003 M, and NaBr = 0.001 M)**

| Temperature ($^o$C) | $k_w$ (gfd/psi) | $k_{Na+}$ (gfd) | $k_{K+}$ (gfd) | $k_{Ca++}$ (gfd) | $k_{Mg++}$ (gfd) | $k_{Cl-}$ (gfd) | $k_{Br-}$ (gfd) | $k_{HCO3-}$ (gfd) |
|---|---|---|---|---|---|---|---|---|
| 20 | 0.09 | 1.96 | 2.33 | 0.07 | 0.04 | 1.54 | 2.26 | 0.27 |

Tests for the other NF membranes are still being conducted. The empirical data is being used as part of an optimization model that predicts performance of the NF dual-staged system in terms of permeate flow and water quality based on operating parameters (temperature, pressure) and feed salinity. The model will use the $k_w$ and $k_i$ values obtained from the bench-scale experiments where feed concentrations approach those of seawater along with known parameters (i.e., membrane area, feed ionic composition, and ideal gas constant) to predict recovery and salt concentration in both the brine and permeate.

## Acknowledgments

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