Forward osmosis (FO) is an osmotically driven membrane process that uses osmotic pressure of concentrated solutions, including seawater, to extract clean water from low salinity solutions. In a new approach, FO uses the difference in salinity of seawater and impaired water as the driving force to dilute seawater with reclaimed water through a tight FO membrane. By diluting the seawater feed stream to a reverse osmosis (RO) desalination plant, the energy demand of desalination is reduced, and two tight barriers are in place to enhance rejection of contaminants that might be present in the impaired water feed stream. Bench- and pilot-scale osmotic dilution tests were conducted with synthetic seawater as a draw solution and with secondary and tertiary effluent from a domestic wastewater treatment plant as feed streams. Impaired surface water from the South Platte River in Colorado was also tested as a feed stream to the osmotic dilution process. Although water flux was generally low, flux decline caused by fouling was minimal during weeks of continuous operation. Multiple membrane barriers provided more than 90 percent rejection of organic and inorganic solutes. In addition, the hybrid FO–RO process was found to be economically and technically feasible across a broad range of operating conditions.

Forward Osmosis–Reverse Osmosis Process Offers a Novel Hybrid Solution for Water Purification and Reuse

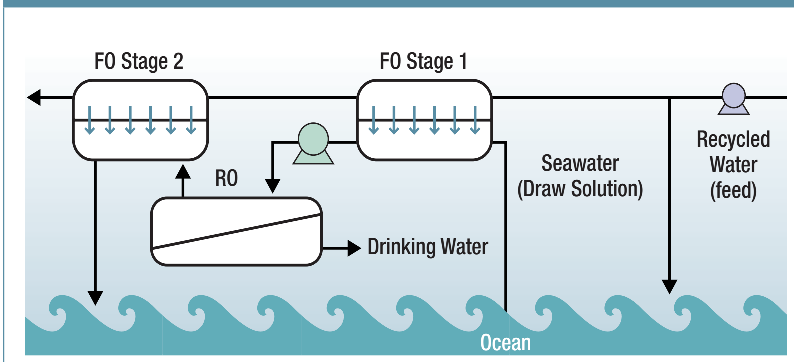
Tzahi Y. Cath, Jörg E. Drewes, Carl D. Lundin, and Nathan T. Hancock

As water resources become more contaminated and overallocated, new water sources must be developed. Although many costal areas are turning to reverse osmosis (RO) desalination, the energy requirements can be a large drawback. The high energy required for seawater RO (SWRO) desalination can be mainly attributed to overcoming the osmotic pressure of seawater, which also limits maximum system recovery. There are only a few ways to reduce energy requirements, one of which is to reduce feedwater osmotic pressure by diluting the SWRO feed stream, thereby reducing the required applied pressure and potentially increasing recovery.

Treated wastewater effluents are often discharged to the ocean without providing any beneficial use. Likewise, many rivers flow into the ocean and their water (mostly with impaired quality) is lost without beneficial use. In some areas, wastewater treatment plant effluent is put into nonpotable reuse systems. Some progressive utilities have started using impaired water for indirect potable reuse (Miller, 2006). It might be more economical to pursue direct potable reuse in some circumstances. The two problems of high energy demand and wasted impaired water could be synergistically solved if an impaired water stream could be safely used to dilute seawater before SWRO desalination.

In a new approach, forward osmosis (FO) uses a saline stream (seawater or brackish water concentrate, also referred to as draw solution) to extract water from a source of impaired water, thereby purifying the impaired water and diluting the saline stream. FO uses an osmotic pressure differential as the driving force, drawing water through a semipermeable membrane and rejecting almost all dissolved contaminants in the process (Cath et al, 2006). Figure 1 shows a schematic of the new hybrid osmotic dilution process. Seawater is diluted by an impaired

Figure 1. Hybrid FO–RO system for water reuse and energy recovery



Rejection of nutrients (ammonia and nitrate) by each subsystem (FO and RO) and combined was investigated.

water stream through an FO membrane in the first osmotic dilution stage. The diluted seawater is processed through an RO desalination system, which rejects salts and dissolved contaminants that may have crossed the membrane from the impaired water source. A second-stage osmotic dilution process can be implemented to dilute seawater before discharge and to further concentrate and reduce the volume of the impaired water stream. Most important, because the saline water is diluted during the first-stage osmotic dilution process, the energy required for subsequent RO desalination of the diluted saline water is reduced. Thus, the energy demand of the desalination plant is decreased, and two significant barriers are in place to reject contaminants in the impaired stream.

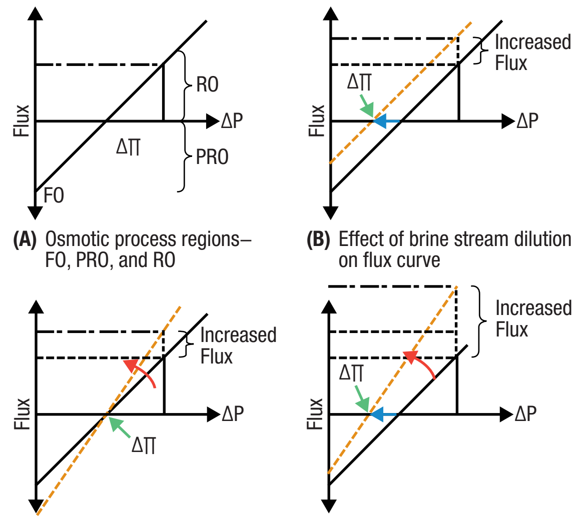
Because of the uncertainty regarding transport of solutes through semipermeable membranes, having multiple barriers in place to reject potential contaminants is important. Although it has been previously shown that RO and nanofiltration membranes can reject most solutes present in impaired water, it is unknown to what extent the rejection mechanisms will remain valid for FO. However, because FO membranes are dense and semipermeable membranes are made of polymers similar to those used in RO membrane manufacturing, it is expected that adding an osmotic dilution process in series will provide additional solute rejection.

Process Characteristics

A simple example of an osmotic process, with a theoretically perfect membrane, can help illustrate process dynamics. For a given set of solutions, a curve can be generated relating applied pressure on the brine side of the membrane to the water flux across the membrane. Figure 2 illustrates such curves of water flux as a function of ΔP. When $\Delta P = 0$ (Figure 2A), water flux is negative. Water diffuses from the diluted feed into the brine in an FO mode. As pressure increases, water flux becomes less negative, and the system operates in pressure retarded osmosis mode (Loeb, 1976; Loeb et al, 1976).

At the flux reversal point, osmotic pressure difference equals applied pressure ($\Delta P = \Delta\pi$). When pressure on the feed side is increased further, the system operates in RO mode, the water flux becomes positive, and pure water diffuses from the concentrated brine to the diluted stream. Each curve in Figure 2 is valid only for a single set of solution chemistries. For example, if the brine is diluted, the curve shifts up, as illustrated in Figure 2B. Consequently, the flux reversal point occurs at lower applied pressure, which indicates that $\Delta\pi$ for the new condition is lower. Also, at a given pressure, flux is higher in RO mode. Or, alternatively, at a constant flux, needed

Figure 2. Changes in the water flux/pressure curves for feed dilution and/or increased membrane permeability



(A) Osmotic process regions– FO, PRO, and RO

(B) Effect of brine stream dilution on flux curve

(C) Effect of increased membrane permeability on the flux curve

(D) Combined effects of B and C

pressure is reduced, proportionally reducing energy demand.

Since the 1990s and until recently, FO membranes have been made by one manufacturer[1]. Although the materials used for those membranes are similar to the materials used for some RO membranes (i.e., cellulose-acetate based), FO membrane structure is different, consisting of a dense cellulose-triacetate polymer cast onto a polyester mesh for mechanical support. Also, FO membranes are thin (~ 50 µm). It has been shown that FO membranes outperform commercially available RO membranes operated in FO mode (Cath et al, 2005). If improved membranes were available, FO and osmotic dilution process efficiency could be enhanced. If FO membrane permeability increases, the flux pressure curve rotates around the flux reversal point (in this case, counterclockwise), and water flux increases at a specific applied pressure (Figure 2C). This effect is expected when changing from a conventional RO membrane to an ultra low-pressure RO membrane. The combined effects of diluting the brine and increasing membrane permeability are illustrated in Figure 2D.

The main objectives of a recent study funded by the Water Research Foundation (Cath et al, 2009) was to investigate the performance, advantages, and limitations of a hybrid FO–RO process for simultaneous treatment of impaired and saline water.

Methodology

Bench-scale studies were carried out at the Colorado School

Figure 3. Water flux as a function of time for individual bench-scale experiments conducted with secondary effluent feed and various seawater draw solution concentrations

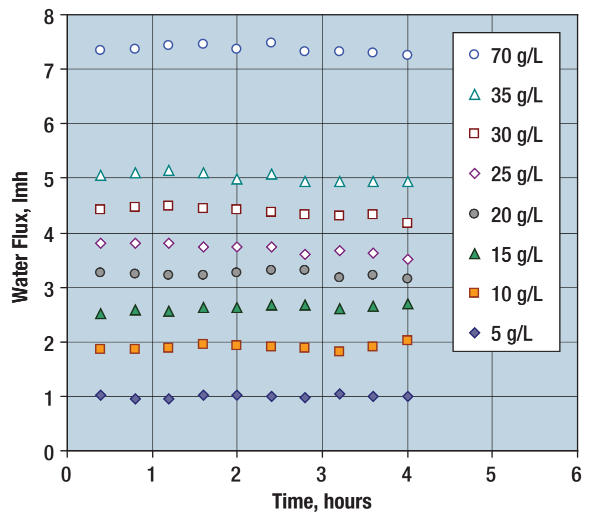
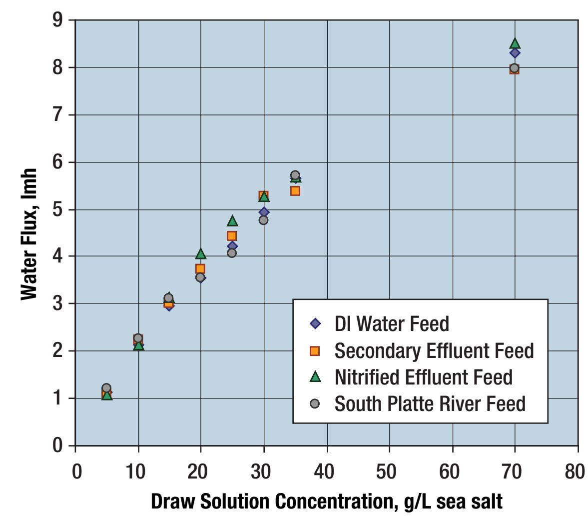


Figure 4. Water flux as a function of draw solution concentration for bench-scale FO experiments



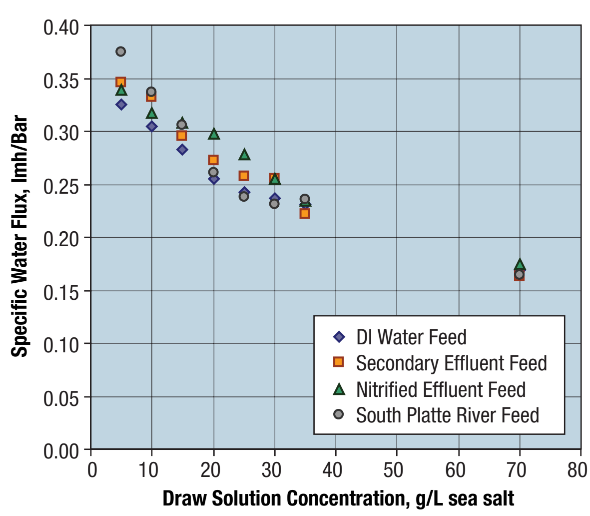
of Mines (Golden, Colo.), and a long-term pilot-scale study was conducted at the Denver Water Recycling Plant (Denver, Colo.) Baseline performance parameters were investigated with bench-scale tests, including water flux, solute flux and rejection, reverse salt diffusion, and membrane fouling rate. Feed streams included batches of deionized (DI) water, secondary treated effluent, tertiary treated effluent, and South Platte River water. For pilot-scale testing, a continuous stream of screened secondary treated or tertiary treated effluent was used as feed, and synthetic seawater was continuously produced by a pilot-scale RO system. Both systems were equipped with a supervisory control and data acquisition system that allowed constant control of operating conditions (e.g., pressures, temperatures, salinity of draw solution, etc.) and continuous recording of data.

Rejection of nutrients (ammonia and nitrate) by each subsystem (FO and RO) and combined was investigated. Phosphate removal was not measured because previous studies have demonstrated that phosphate is highly rejected by FO membranes (> 99.5 percent) (Holloway et al, 2007). Rejection of organic carbon was measured using ultraviolet (UV) absorption, because high concentration of salts in the draw solution interferes with other analytical methods. Rejection of micropollutants—pharmaceuticals, personal care products, plasticizers, etc.—was investigated through solid-phase extraction and high-performance liquid chromatography. Concentration of contaminants was monitored in the feed, draw solution, and RO permeate. In addition, the economic benefits of the hybrid process were investigated.

Results

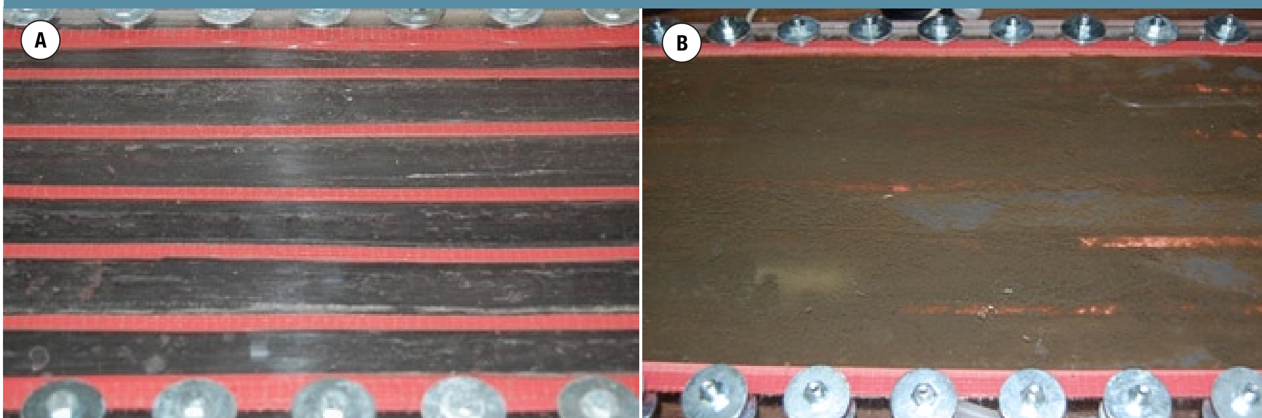
Results at the bench-scale level demonstrated that membrane fouling during four-hour experiments was minimal (Figure 3) and that water flux was relatively low because of the low driving force provided by the seawater draw solution (Figure 4). It is important to note that water flux at similar draw solution concentrations is similar for different feed streams. These results confirmed previous

Figure 5. Specific water flux as a function of draw solution concentration for short-term bench-scale FO experiments



Note: Experiments were conducted at feed and draw solution temperatures of 19°C ±0.1°C and feed and draw solution flow rates of 1.4 L/min.

Figure 6. Pilot-scale osmotic dilution membrane cell (A) before experiment and (B) after seven days of operation (before chemical cleaning)



Note: Experiment was conducted with 35 g/L sea salt draw solution and secondary effluent feed solution. Feed and draw solution temperatures were 22°C ±0.5°C. Feed and draw solution flow rates were 2.4 L/min.

observations on the bench scale that fouling of FO membranes is minimal and that feed streams of variable qualities can be treated by FO with minimal decline in performance.

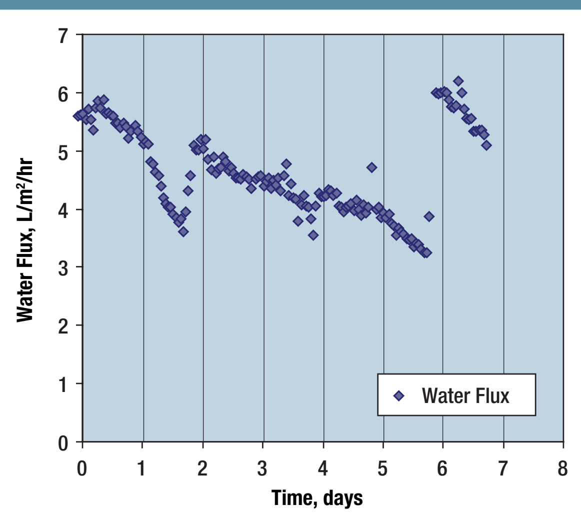
Figure 5 illustrates specific water flux as a function of draw solution concentration for the data presented in Figure 4. As anticipated, specific flux declines at higher draw solution concentrations because of internal concentration polarization, a unique phenomenon in osmotically driven membrane processes (McCutcheon and Elimelech, 2006). Specific flux is consistently lower for the DI water feed than other feed solutions because low total dissolved solids (TDS) in the DI water results in higher driving force. Small differences in values for specific draw solution concentration demonstrated that fouling effects are minimal at bench scale.

Results from pilot-scale experiments revealed that, although the membrane was heavily fouled with suspended solids (Figure 6), flux decline was minimal, and chemical cleaning (30 minutes sodium hydroxide to pH of 8) efficiently restored flux to its initial level (end of sixth day in Figure 7). Rejection results demonstrated that ammonia and nitrate were effectively removed and, with the two barriers (FO and RO membranes), more than 97 percent was removed. Similarly, total organic carbon and UV absorption were more than 97 percent rejected. Additionally, the investigation demonstrated that organic micropollutants of emerging concern—such as clofibric acid, dichlorprop, diclofenac, fenofibrate, gemfibrozil, ketoprofen, mecoprop, naproxen, and salicylic acid—were more than 99.9 percent rejected by the hybrid FO–RO pilot system (Table 1).

Economic Evaluation

To assess the economic feasibility of the hybrid FO–RO process, a model was developed to simulate increasing water recoveries as a function of TDS concentrations, feed and draw solution stream flow rates, FO membrane characteristics, capital cost of FO per unit membrane area, and energy cost. The model was designed to increase water flux through the RO system (constant energy) or decrease the RO system's energy demand (constant RO flux). Results revealed that at the current cost of energy (~ 10¢/kW·h) and realistic cost of FO membranes (~ \$12/m^2), the osmotic dilution process is economically viable for a

Figure 7. Water flux as a function of time during the pilot-scale osmotic dilution experiment with 35 g/L sea salt draw solution and secondary effluent feed solution



Note: Physical cleaning (water jet) was conducted after 1.5 days and 4 days, and chemical cleaning (sodium hydroxide) was conducted after 5.5 days of continuous experiment. The experiment was conducted with feed and draw solution temperatures of 22°C ±0.5°C.

Table 1. Concentration of organic micropollutants after eight days of operation for pilot-scale hybrid FO-RO experiment with 35 g/L draw solution concentration and secondary effluent feed					
	Diclofenac ng/L	Gemfibrozil ng/L	Ibuprofen ng/L	Naproxen ng/L	Salicylic Acid ng/L
Feed	155	960	385	435	360
Draw Solution	65	1650	255	360	85
Permeate	nd	nd	33	nd	nd

Note: The temperature of the feed and draw solutions was 22°C ±0.5°C and the feed and draw solution flow rates were 2.4 L/min (nd = not detected).

small treatment plant (~ 200 m^3/day) to recover up to 60 percent from the impaired stream (Cath et al, 2009). On-going life-cycle assessment of the osmotic dilution hybrid process revealed that each m^2 of currently available commercial FO membrane in the osmotic dilution process can save more than 8 Watts in the operation of an SWRO desalination plant.

Future Implementation

This investigation demonstrated that the hybrid osmotic dilution process for SWRO desalination is technologically and economically viable. Water reclamation and energy savings can be accomplished by adding a membrane contactor between two existing streams (i.e., seawater and impaired water).

Because the investigation was not conducted in a coastal area or with a continuous seawater supply, the field study was accomplished with a pilot-scale RO system that continuously reconcentrated the diluted draw solution and produced two streams: a clean water stream and a brine stream to be used again as draw solution. Under these conditions, accumulation of contaminants in the draw solution is inevitable and must be considered. In implementations where the seawater draw solution flows in a one-through pattern, dual barrier characteristics of the hybrid process will be more apparent.

Results also revealed that pretreating impaired water to remove suspended solids and improving feed channel hydraulics in the FO membrane modules are important steps to further enhance the hybrid process.

Acknowledgments

The authors thank the Water Research Foundation for its financial, technical, and administrative assistance in funding and managing the project from which this information was derived. Comments and views detailed herein may not reflect the views of the Water Research Foundation, its officers, directors, affiliates, or agents. The authors also recognize the California Department of Water Resources for its financial contribution to this project. In addition, the authors acknowledge assistance from Dr. Eric Dickenson, Dr. Dean Heil, and Brandy Laudig, Colorado School of Mines; Russell Plakke, Denver Water Recycling Plant; and Hydration Technologies Innovations and Dr. Edward Beaudry for providing FO membranes and technical support.

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[1]Hydration Technologies Innovations, Albany, Ore.

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Editor's Note

This article is an updated, peer-reviewed version of a paper that was presented at the 2009 AWWA Membrane Technology Conference, March 15–18, Memphis, Tenn.