

Review

Forward osmosis: Principles, applications, and recent developments

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Received 30 December 2005; received in revised form 30 May 2006; accepted 31 May 2006

Available online 6 June 2006

Abstract

Osmosis is a physical phenomenon that has been extensively studied by scientists in various disciplines of science and engineering. Early researchers studied the mechanism of osmosis through natural materials, and from the 1960s, special attention has been given to osmosis through synthetic materials. Following the progress in membrane science in the last few decades, especially for reverse osmosis applications, the interests in engineered applications of osmosis has been spurred. Osmosis, or as it is currently referred to as forward osmosis, has new applications in separation processes for wastewater treatment, food processing, and seawater/brackish water desalination. Other unique areas of forward osmosis research include pressure-retarded osmosis for generation of electricity from saline and fresh water and implantable osmotic pumps for controlled drug release. This paper provides the state-of-the-art of the physical principles and applications of forward osmosis as well as their strengths and limitations.

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Keywords: Osmosis; Forward osmosis; Direct osmosis; Desalination; Reverse osmosis; Pressure-retarded osmosis

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Abbreviations: CP, concentration polarization; DOC, direct osmotic concentration; DS, draw solution; FO, forward osmosis; MD, membrane distillation; NPDES, national pollutant discharge elimination system; OD, osmotic distillation; PRO, pressure-retarded osmosis; RO, reverse osmosis; TDS, total dissolved solids; TKN, total Kjeldahl nitrogen (sum of organic nitrogen and ammonia); TMDL, total maximum daily load

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1. Introduction

Osmosis is a physical phenomenon that has been exploited by human beings since the early days of mankind. Early cultures realized that salt could be used to desiccate foods for long-term preservation. In saline environments, most bacteria, fungi, and other potentially pathogenic organisms become dehydrated and die or become temporarily inactivated because of osmosis. Conventionally, osmosis is defined as the net movement of water across a selectively permeable membrane driven by a difference in osmotic pressure across the membrane. A selectively permeable membrane allows passage of water, but rejects solute molecules or ions. Osmotic pressure is the driving force for many of the applications that will be reviewed and discussed herein. Present-day applications of the osmosis phenomenon extend from water treatment and food processing to power generation and novel methods for controlled drug release. This review will focus on osmosis through polymeric membranes, primarily in the field of water treatment and desalination. References to other applications of osmosis will be made when necessary to further understand theoretical and applied aspects of osmosis.

In the field of water treatment, reverse osmosis is generally a more familiar process than osmosis. Because of this, a brief description of the RO process is given prior to further discussion of osmosis. RO uses hydraulic pressure to oppose, and exceed, the osmotic pressure of an aqueous feed solution to produce purified water [1]. In RO, the applied pressure is the driving force for mass transport through the membrane; in osmosis, the osmotic pressure itself is the driving force for mass transport. Numerous publications on the use of RO for water treatment and wastewater reclamation appear in the literature.

Fewer publications on the use of osmosis – or forward osmosis (FO), or direct osmosis (DO) – for water treatment/engineering applications appear in the literature. Nevertheless, FO has been used to treat industrial wastewaters (at bench-scale) [2–4], to concentrate landfill leachate (at pilot- and full-scale) [5–7], and to treat liquid foods in the food industry (at bench-scale) [8–16]. FO is also being evaluated for reclaiming wastewater for potable reuse in life support systems (at demonstration-scale) [17–20], for desalinating seawater [21,22], and for purifying water in emergency relief situations [23]. Recent developments in materials science have also allowed

the use of FO in controlled drug release in the body [24–27]. Pressure-retarded osmosis (PRO), a closely related process, has been tested and evaluated since the 1960s as a potential process for power generation [28–39]. PRO uses the osmotic pressure difference between seawater, or concentrated brine, and fresh water to pressurize the saline stream, thereby converting the osmotic pressure of seawater into a hydrostatic pressure that can be used to produce electricity.

The main advantages of using FO are that it operates at low or no hydraulic pressures, it has high rejection of a wide range of contaminants, and it may have a lower membrane fouling propensity than pressure-driven membrane processes [4]. Because the only pressure involved in the FO process is due to flow resistance in the membrane module (a few bars), the equipment used is very simple and membrane support is less of a problem. Furthermore, for food and pharmaceutical processing, FO has the benefit of concentrating the feed stream without requiring high pressures or temperatures that may be detrimental to the feed solution. For medical applications, FO can assist in the slow and accurate release of drugs that have low oral bioavailability due to their limited solubility or permeability [25].

This paper presents an extensive review of FO and closely-related membrane processes. The review begins with an introduction of the basic principles of the FO process, including comparison to other closely related processes. Special aspects of mass transport in the process as well as the membranes used for the process are described. Strengths and limitations of the FO process in a broad spectrum of applications are reviewed and discussed. And last, the future of FO technology is considered.

2. Osmotic processes

2.1. Classification of osmotic processes

Osmosis is the transport of water across a selectively permeable membrane from a region of higher water chemical potential to a region of lower water chemical potential. It is driven by a difference in solute concentrations across the membrane that allows passage of water, but rejects most solute molecules or ions. Osmotic pressure (π) is the pressure which, if applied to the more concentrated solution, would prevent transport of water

across the membrane. FO uses the osmotic pressure differential ($\Delta\pi$) across the membrane, rather than hydraulic pressure differential (as in RO), as the driving force for transport of water through the membrane. The FO process results in concentration of a feed stream and dilution of a highly concentrated stream (referred to as the draw solution).

PRO can be viewed as an intermediate process between FO and RO, where hydraulic pressure is applied in the opposite direction of the osmotic pressure gradient (similar to RO). However, the net water flux is still in the direction of the concentrated draw solution (similar to FO).

The general equation describing water transport in FO, RO, and PRO is

$$J_w = A(\sigma\Delta\pi - \Delta P) \quad (1)$$

where J_w is the water flux, A the water permeability constant of the membrane, σ the reflection coefficient, and ΔP is the applied pressure. For FO, ΔP is zero; for RO, $\Delta P > \Delta\pi$; and for PRO, $\Delta\pi > \Delta P$. The flux directions of the permeating water in FO, PRO, and RO are illustrated in Fig. 1. Flux directions and driving forces for the three processes were characterized in the early 1980s by Lee et al. [30]. The FO point, PRO zone, and RO zone, along with the flux reversal point, are illustrated in Fig. 2.

2.2. Draw solutions

The concentrated solution on the permeate side of the membrane is the source of the driving force in the FO process. Different terms are used in the literature to name this solution including draw solution, osmotic agent, osmotic media, driving solution, osmotic engine, sample solution, or just brine. For clarity, the term draw solution is being used exclusively in this paper. When selecting a draw solution, the main criterion is that it has a higher osmotic pressure than the feed solution. The osmotic pressures of several solutions being considered for use as draw solutions were calculated using OLI Stream Analyzer 2.0 (OLI Systems Inc., Morris Plains, NJ) [40] and are presented in Fig. 3 as a function of molarity. This software uses thermodynamic modeling based on published experimental data to predict the properties of solutions over a wide range of concentrations and temperatures.

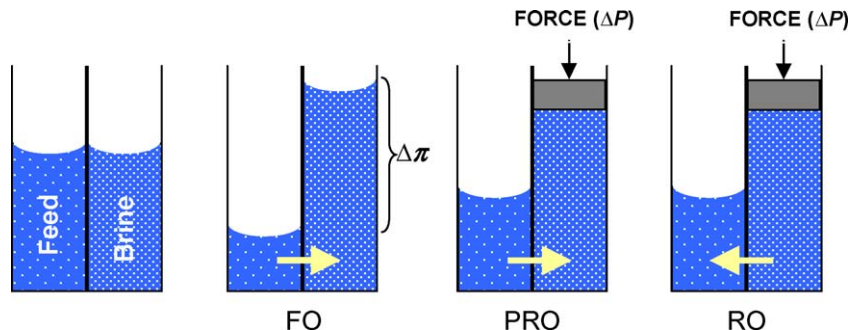


Fig. 1. Solvent flows in FO, PRO, and RO. For FO, ΔP is approximately zero and water diffuses to the more saline side of the membrane. For PRO, water diffuses to the more saline liquid that is under positive pressure ($\Delta\pi > \Delta P$). For RO, water diffuses to the less saline side due to hydraulic pressure ($\Delta P > \Delta\pi$).

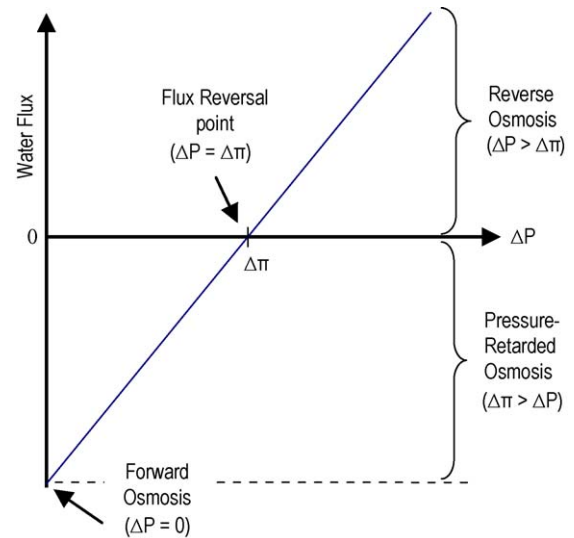


Fig. 2. Direction and magnitude of water flux as a function of applied pressure in FO, PRO, and RO. FO takes place when the hydraulic pressure difference is zero. The PRO zone is where the applied pressure difference is between zero and the flux reversal point, and the RO zone is where the applied pressure difference is greater than the osmotic pressure difference. Figure adapted from [30].

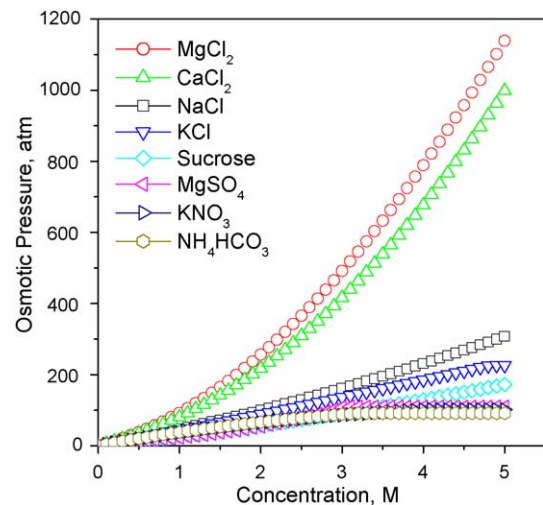


Fig. 3. Osmotic pressure as a function of solution concentration at 25 °C for various potential draw solutions. Data were calculated using OLI Stream Analyzer 2.0 [40].

Another important criterion in some applications of FO is the selection of a suitable process for reconcentrating the draw solution after it has been diluted in the FO process. Very often an NaCl solution is used because it has high solubility and is relatively simple to reconcentrate to high concentration with RO without risk of scaling. Diffusion of the solute from the draw solution through the membrane must also be considered. In specific applications where high rejection is desired, multivalent ion solutions may be preferable. In some applications such as in PRO, seawater may be used as the draw solution. In the past, seawater [28], Dead Sea water [33], and Salt Lake water [34] have been used or considered for draw solutions in various investigations of FO and PRO.

Various other chemicals have also been suggested and tested as solutes for draw solutions, particularly in seawater desalination applications. Batchelder [41] suggested using sulfur dioxide solution as the draw solution in FO desalination of seawater. Glew [42] expanded on this idea and suggested using mixtures of water and another gas (e.g., sulfur dioxide) or liquid (e.g., aliphatic alcohols) as the draw solutions for FO. Glew was also the first to propose the recycling of the draw solution in conjunction with FO. Frank [43] used an aluminum sulfate solution, Kravath and Davis [21] used a glucose solution in FO desalination of seawater, Kessler and Moody [44] used a mixed solution of glucose and fructose for seawater desalination, and Stache [45] used a concentrated fructose solution to create a nutritious drink during FO of seawater. McGinnis [46] suggested a two-stage FO process that takes advantage of the temperature dependent solubilities of the solutes. Specifically, McGinnis suggested solutions of potassium nitrate (KNO_3) and sulfur dioxide (SO_2) as draw solutions for seawater desalination. In a later novel application of FO by McGinnis and coworkers [22,47,48], it was demonstrated that combining ammonia and carbon dioxide gases in specific ratios created highly concentrated draw solutions of thermally removable ammonium salts. This approach produced FO draw solutions with osmotic pressures in excess of 250 atm, allowing unprecedented high recoveries of potable water from concentrated saline feeds and substantial reductions in brine discharges from desalination. In a new nanotechnological approach, naturally non-toxic magnetoferritin is being tested as a potential solute for draw solutions [49]. Magnetoferritin can be rapidly separated from aqueous streams using a magnetic field.

3. Concentration polarization in osmotic processes

The water flux in osmotic-driven membrane processes is described by Eq. (1). In this equation, $\Delta\pi$ represents the osmotic pressure difference across the active layer of the membrane. In such processes, the osmotic pressure difference across the active layer is much lower than the bulk osmotic pressure difference, which results in much lower water flux than expected [30,39,48,50,51]. The lower-than-expected water flux is often attributed to several membrane-associated transport phenomena. Specifically, two types of concentration polarization (CP) phenomena – external CP and internal CP – can take place in osmotic-driven membrane processes as discussed below.

3.1. External concentration polarization

In pressure-driven membrane processes, convective permeate flow causes a buildup of solute at the membrane active layer surface. Referred to as concentration polarization (CP), this phenomenon reduces permeate water flux due to increased osmotic pressure that must be overcome with hydraulic pressure [52–54]. CP due to water permeation is not limited to pressure-driven membrane processes and also occurs during osmotic-driven membrane processes, on both the feed and permeate sides of the membrane. When the feed solution flows on the active layer of the membrane (like in RO), solutes build up at the active layer. This may be called concentrative external CP and is similar to CP in pressure-driven membrane processes. Simultaneously, the draw solution in contact with the permeate side of the membrane is being diluted at the permeate–membrane interface by the permeating water. This is called dilutive external CP. Both concentrative and dilutive external CP phenomena reduce the effective osmotic driving force. The adverse effect of external CP on osmotic-driven membrane processes can be minimized by increasing flow velocity and turbulence at the membrane surface or by manipulating the water flux [55]. However, because water flux in FO is already low, the ability to diminish external CP by reducing flux is limited. For modeling external CP phenomena in FO, equations similar to those developed for CP of pressure-driven membranes can be used [53,54].

Due to the low hydraulic pressure used in FO, membrane fouling induced by external CP has milder effects on water flux compared to the effects in pressure-driven membrane processes. It has been shown that external CP plays a minor role in osmotic-driven membrane processes and is not the main cause for the lower-than-expected water flux in such processes [48].

3.2. Internal concentration polarization

When an osmotic pressure gradient is established across a completely rejecting dense symmetric membrane, as depicted in Fig. 4a, the driving force is the difference in osmotic pressures of the bulk solutions in the absence of external CP. However, FO membranes are asymmetric, adding more complexity to the CP phenomena. When a composite or asymmetric membrane consisting of a dense separating layer and a porous support layer is used in FO, two phenomena can occur depending on the membrane orientation. If the porous support layer of an asymmetric membrane faces the feed solution, as in PRO, a polarized layer is established along the inside of the dense active layer as water and solute propagate the porous layer (Fig. 4b). Referred to as concentrative internal CP [48], this phenomenon is similar to concentrative external CP, except that it takes place within the porous layer, and therefore, cannot be minimized by cross-flow. In FO applications for desalination and water treatment, the active layer of the membrane faces the feed solution and the porous support layer faces the draw solution. As water permeates the active layer, the draw solution within the porous substructure becomes diluted. This is referred to as dilutive internal CP (Fig. 4c) [48].

It can be clearly seen in Fig. 5 that the osmotic pressure difference between the bulk feed and bulk draw solution

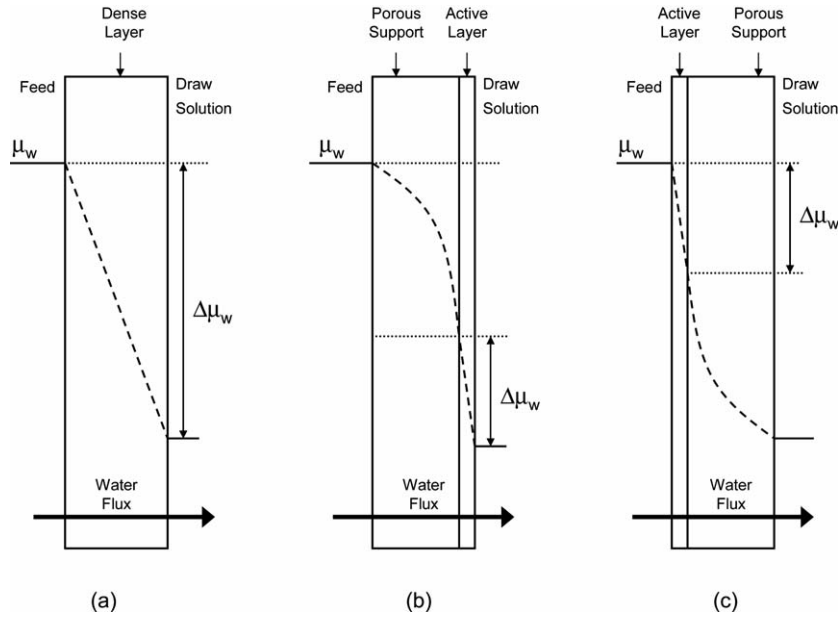


Fig. 4. Illustrations of driving force profiles, expressed as water chemical potential, μ_w , for osmosis through several membrane types and orientations [48]. (a) A symmetric dense membrane. (b) An asymmetric membrane with the porous support layer facing the feed solution; the profile illustrates concentrative internal CP. (c) An asymmetric membrane with the dense active layer facing the feed solution; the profile illustrates dilutive internal CP. The actual (effective) driving force is represented by $\Delta\mu_w$. External CP effects on the driving force are assumed to be negligible in this diagram.

($\Delta\pi_{\text{bulk}}$) is higher than the osmotic pressure difference across the membrane ($\Delta\pi_m$) due to external CP and that the effective osmotic pressure driving force ($\Delta\pi_{\text{eff}}$) is even lower due to internal CP. Furthermore, similar to the operation of heat exchangers, operation of FO in a counter-current flow configuration (feed and draw solution flowing tangential to the membrane but in opposite directions) provides constant $\Delta\pi$ along the membrane module and makes the process more efficient [56].

3.2.1. Modeling concentrative internal concentration polarization

Unlike RO, for which water transport through the membrane is mostly affected by the hydraulic resistance created by the membrane structure, in FO, internal CP in the porous support

layer also substantially affects mass transfer of water across the membrane. The concentration profile across an asymmetric or composite FO membrane for concentrative internal CP is illustrated in Fig. 5a. C_1 and C_5 are the concentrations of the bulk feed and draw solution, respectively; C_2 and C_4 are the concentrations of the feed-membrane and draw solution-membrane interfaces (resulting from external CP), respectively; and C_3 is the concentration at the active layer–support layer interface.

Adopting the models that were developed by Lee et al. [30], Loeb et al. [50] introduced a simplified equation to describe the water flux during FO without consideration for membrane orientation:

$$J_w = \frac{1}{K} \ln \frac{\pi_{\text{Hi}}}{\pi_{\text{Low}}} \quad (2)$$

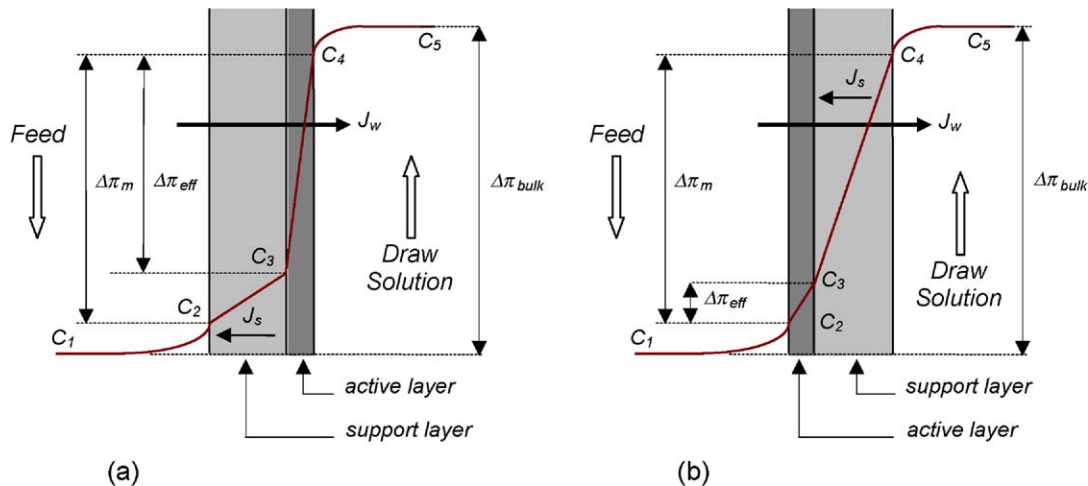


Fig. 5. (a) Concentrative internal CP and (b) dilutive internal CP across a composite or asymmetric membrane in FO.

where K is the resistance to solute diffusion within the membrane porous support layer, and π_{Hi} and π_{Low} are the osmotic pressures of the bulk draw solution (C_5) and feed solution (C_1), respectively, neglecting external polarization effects. K is defined as

$$K = \frac{t\tau}{\varepsilon D_s} \quad (3)$$

where t , τ , and ε are the membrane thickness, tortuosity, and porosity, respectively, and D_s is the diffusion coefficient of the solute. However, it has been recently demonstrated that Eq. (2) is valid only for very low water fluxes [57]. Further development of this equation [50] has led to a more general governing equation for concentrative internal CP:

$$K = \left(\frac{1}{J_w} \right) \ln \left(\frac{B + A\pi_{\text{Hi}} - J_w}{B + A\pi_{\text{Low}}} \right) \quad (4)$$

where B is the solute permeability coefficient of the active layer of the membrane, which can be determined from an RO-type experiment [50] using

$$B = \frac{(1 - R)A(\Delta P - \Delta\pi)}{R} \quad (5)$$

where R is the salt rejection. Eq. (4) can be used to quantify the severity of internal CP; larger values of K are associated with more severe internal CP.

3.2.2. Modeling dilutive internal concentration polarization

The concentration profile across an asymmetric or composite FO membrane for dilutive internal CP is illustrated in Fig. 5b. Loeb et al. [50] presented a simplified governing equation for dilutive internal CP in asymmetric membranes:

$$K = \left(\frac{1}{J_w} \right) \ln \left(\frac{B + A\pi_{\text{Hi}}}{B + J_w + A\pi_{\text{Low}}} \right) \quad (6)$$

Recent studies [48,57] have shown that this simplified governing equation as well as the equation for concentrative internal CP, successfully predict the results obtained during experiments with an FO-designed membrane.

3.3. Influence of internal concentration polarization on water flux

Mehta and Loeb [39,58] studied the effect of the porous support layer on internal CP and the effect of high draw solution concentrations on the overall permeability coefficient of the membrane. Results show that upon swapping the working fluids on the two sides of the membrane, flux (as indicated by the permeability coefficient) sharply declines due to internal CP (Fig. 6).

Experimenting with DuPont B-9 (flat sheet) and B-10 (hollow fiber) Permasep RO membranes, Mehta and Loeb [58] pointed out that A (the membrane permeability constant from Eq. (1)) is not constant in FO and PRO; it declines with increasing osmotic pressure (i.e., increasing concentration) of the draw solution. The decline of A was explained by partial drying or osmotic dehydration of the membrane at high osmotic pressures. Such

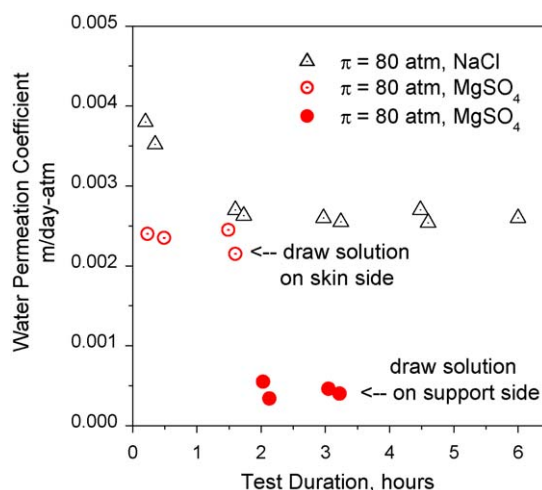


Fig. 6. FO tests with NaCl and MgSO₄ solutions as draw solutions. The effect of internal CP can be seen after 2 h when the support side of the membrane is exposed to the draw solution instead of DI water. The water permeation rate sharply declines after dilutive internal CP starts. Figure adapted from [58].

partial drying can be accompanied by pore contraction, known as “osmotic deswelling”, and hence increased resistance to water transport. Results from recent studies [48,57] confirmed that internal CP is actually the cause of the substantial flux decline.

4. Membranes and modules for forward osmosis

4.1. Membranes for forward osmosis

Generally, any dense, non-porous, selectively permeable material can be used as a membrane for FO. Such membranes [2,3,21,39,50,58–60] have been tested (in flat sheet and capillary configurations) in the past for various applications of FO. Early membrane researchers experimented with every type of membrane material available, including bladders of pigs, cattle, and fish; collodion (nitrocellulose); rubber; porcelain; and goldbeaters’ skin [3].

By 1960, the elements of modern membrane science had been developed and the important discovery that transformed membrane separation from a laboratory to an industrial process was the development of the Loeb–Sourirajan process for making defect-free, high-flux, anisotropic RO membranes [61]. Loeb and co-workers [50,59] investigated the use of asymmetric aromatic polyamide membranes for FO and PRO.

In the 1970s, all studies involving osmosis (mostly PRO studies) used RO membranes, either flat sheet or tubular, and in all cases, researchers observed much lower flux than expected. Votta et al. [2] and Anderson [3] used several commercially available RO membranes and an in-house cellulose acetate membrane to treat dilute wastewater by FO using a simulated seawater draw solution. Kravath and Davis [21] used flat sheet RO membranes from Eastman and cellulose acetate hollow fiber membranes from Dow to desalinate seawater by FO using glucose as the draw solution. Goosens and Van-Haute [60] used cellulose acetate membranes reinforced with mineral fillers to evaluate whether membrane performance under RO conditions can be predicted through FO testing.

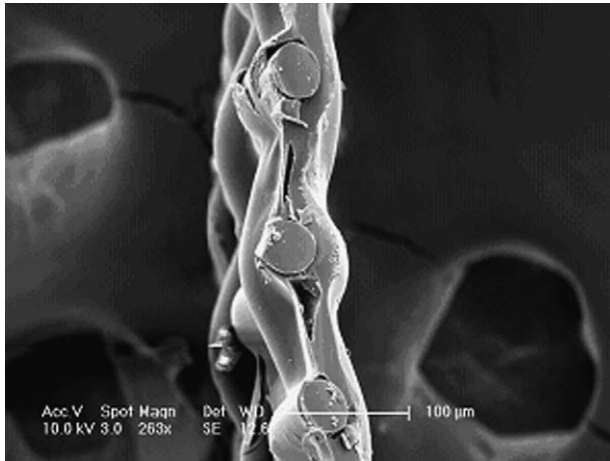


Fig. 7. A cross-sectional SEM image of HTI's FO membrane. A polyester mesh is embedded within the polymer material for mechanical support. The membrane thickness is less than 50 μm . Figure taken from [22].

Also in the 1970s, Mehta and Loeb [39,58] experimented with DuPont B-9 (flat sheet) and B-10 (hollow fiber) Permapsep RO membranes made of an aromatic polyamide polymer. Flux through the B-10 Permapsep membrane was relatively low (approximately $8 \text{ l/m}^2 \text{ h}$ at a driving force of 80 bar).

During the 1990s, a special membrane for FO was developed by Osmotek Inc. (Albany, Oregon) (currently Hydration Technologies Inc. (HTI)). This membrane has been tested in a wide variety of applications by different research groups [5,6,8,16,18,19,48]. It is also used successfully in commercial applications of water purification for military, emergency relief, and recreational purposes [62]. A cross-sectional SEM image of the membrane is shown in Fig. 7 [22]. This proprietary membrane is thought to be made of cellulose triacetate (CTA). It can be seen that the thickness of the membrane is less than 50 μm and it is evident that the structure of the CTA FO membrane is quite different from standard RO membranes. RO membranes typically consist of a very thin active layer (less than 1 μm) and a thick porous support layer. The CTA FO membrane lacks a thick support layer. Instead, the embedded polyester mesh provides mechanical support. Results from various investigations (see Section 5) indicate that the CTA FO membrane made by HTI is superior to RO membranes operated in FO mode. The major contributing factors are likely the relative thinness of the membrane and the lack of a fabric support layer.

In summary, the desired characteristics of membranes for FO would be high density of the active layer for high solute rejection; a thin membrane with minimum porosity of the support layer for low internal CP, and therefore, higher water flux; hydrophilicity for enhanced flux and reduced membrane fouling; and high mechanical strength to sustain hydraulic pressure when used for PRO. The development of improved semi-permeable membranes for FO is critical for advancing the field of FO. Membranes that can achieve high flux and salt rejection, have minimal internal CP, and have high mechanical strength to support high hydraulic pressures will lead to improved performance in current applications as well as development of new applications for FO.

4.2. Membrane modules and devices

Different module configurations can be used to hold or pack membranes for FO. Laboratory-scale modules have been designed for use with either flat sheet or tubular/capillary membranes. Larger-scale applications [5,6,18] have been designed and built with flat sheet membranes in plate-and-frame configurations. Each configuration has advantages and limitations that must be taken into consideration when planning the research or developing the application. Prior to discussing the advantages and limitations of plate-and-frame, spiral-wound, tubular, and bag configurations, differences between continuous flow and batch operation must first be considered.

In continuous flow FO applications, the draw solution is repeatedly reconcentrated/refreshed and reused. In this mode, the feed solution is recirculated on the feed side of the membrane and the reconcentrated/refreshed draw solution is recirculated on the permeate side (Fig. 8). For this reason, modules that use flat sheet membranes are more complicated to build and operate for the FO process compared to pressure-driven processes. For example, the spiral-wound module, one of the most common packing configurations in the membrane industry, cannot be used in its current design for FO because a liquid stream cannot be forced to flow on the support side (inside the envelope). In PRO applications, the pressure of the receiving stream (i.e., the draw solution) is elevated to achieve the high pressure needed for power generation. This requires that the membrane is well supported and able to withstand pressure on the "permeate" side, and that the flow channels are not blocked. In advanced large-scale applications of PRO, additional accessories (e.g., pressure tanks) were suggested by Loeb [33,34] to handle the continuous supply of draw solution at elevated pressures.

In batch FO applications, the draw solution is diluted once and is not reconcentrated for further use. In this mode of operation, the device used for FO is most often disposable and is not reused. Applications using this mode of operation include hydration

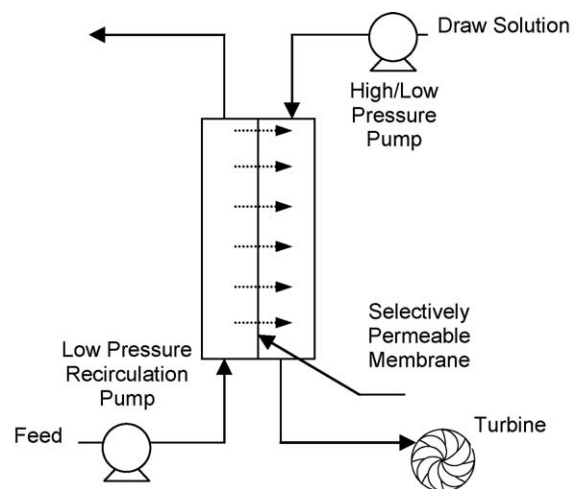


Fig. 8. Flows in FO and PRO processes. Feed water flows on the active side of the membrane and draw solution flows counter-currently on the support side of the membrane. In PRO, the draw solution is pressurized and is released in a turbine to produce electricity.

bags for water purification and osmotic pumps for drug delivery [26,63].

Even considering their limitations, the most readily available semi-permeable polymeric membranes are flat sheet membranes. For continuous flow operation of an FO process, flat sheet membranes can be used in either a plate-and-frame configuration or in a unique spiral-wound configuration.

4.2.1. Plate-and-frame

The simplest device for packing flat sheet membranes is a plate-and-frame module. Plate-and-frame modules can be constructed in different sizes and shapes ranging from lab-scale devices that hold single, small-size membrane coupons to full-scale systems that hold more than 1700 membranes. While the design and construction of large plate-and-frame heat exchangers is well established, the construction of large plate-and-frame membrane modules is more complicated. Two of the main limitations of plate-and-frame elements for membrane applications are lack of adequate membrane support and low packing density. Lack of adequate membrane support limits operation to low hydraulic pressure and/or operation at similar pressures on both sides of the membrane (requiring relatively high process control). Low packing density leads to a larger system footprint, higher capital costs, and higher operating costs (labor for membrane replacement). Other limitations of the plate-and-frame configuration include problems with internal and external sealing, difficulty in monitoring membrane integrity, and a limited range of operating conditions (e.g., flow velocities and pressures) [18].

4.2.2. Spiral-wound

Commercially marketed spiral-wound membrane elements (e.g., spiral-wound RO elements) are operated with only one stream (the feed stream) flowing under direct control of its flow velocity tangential to the membrane. The permeate stream flows very slowly in the channel formed by the two glued membranes and its composition and flow velocity are controlled by the properties of the membrane and the operating conditions. Therefore, in its current design, spiral-wound membrane elements cannot be operated in FO mode because the draw solution cannot be forced to flow inside the envelope formed by the membranes.

Mehta [36] designed and successfully tested a unique spiral-wound element for FO. Both outside-in and inside-out operation can be used. In Fig. 9 (inside-out operation), the draw solution flows through the spacers and between the rolled membranes, in the same way that a feed stream flows in a spiral-wound element for RO. However, unlike RO elements, the central collecting tube is blocked halfway through so that the feed solution cannot flow to the other side. Instead, an additional glue line at the center of the membrane envelope provides a path for the feed to flow inside the envelope. In this configuration, the feed flows into the first half of the perforated central pipe, is then forced to flow into the envelope, and then flows out through the second half of the perforated central pipe. It is worth noting that this configuration can also be efficiently used for PRO. The draw solution outside of the envelope can be pressurized similar to the way it is done in spiral-wound membrane elements for RO.

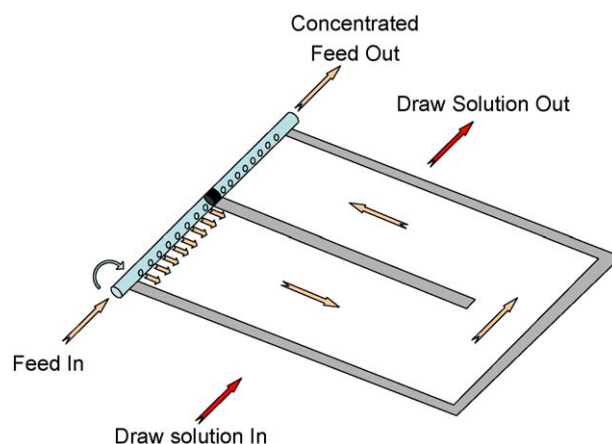


Fig. 9. Flow patterns in a spiral-wound module modified for FO. The feed solution flows through the central tube into the inner side of the membrane envelope and the draw solution flows in the space between the rolled envelopes. Figure adapted from [36].

One of the main limitations in operating a spiral-wound membrane element for RO is the inability to induce flow in the permeate channels (i.e., the inner side of the envelopes) of the membrane element for the purpose of cleaning or backwashing. A unique application of FO for backwashing of spiral-wound RO membranes was investigated by Sagiv and Semiat [64]. Upon stopping the RO process after desalination, water diffused by osmosis from the permeate channels back into the feed side of the membrane, thus cleaning the membrane through osmotic backwashing. In their investigation, a spiral-wound RO membrane was purposely scaled with saturated CaCO_3 solution. At predetermined intervals, the system was stopped for 20 s to allow osmotic backwashing to occur. Preliminary results (Fig. 10) indicate that almost complete recovery of water flux could be achieved.

4.2.3. Tubular

The use of tubular membranes (tubes or hollow fibers) for continuously operated FO processes is more practical for three

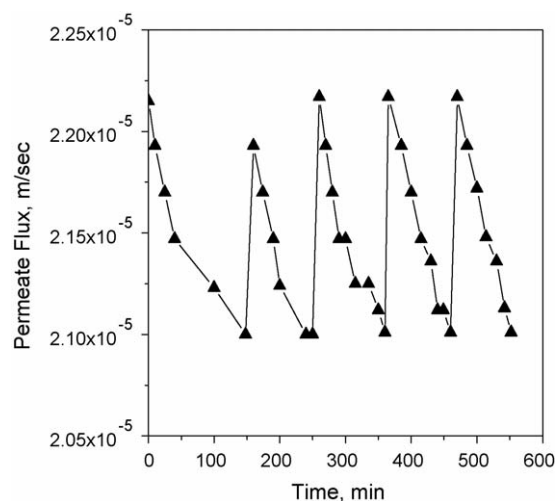


Fig. 10. Effect of osmotic backwashing on the performance of a spiral-wound RO membrane after desalination. The feed solution consisted of 0.5% NaCl and super-saturated CaCO_3 . Figure adapted from [64].

main reasons. First, tubular membranes are self-supported. This means they can support high hydraulic pressure without deformation and they can be easily packed in bundles directly inside a holding vessel. Second, it is much simpler to fabricate tubular modules and packing density is relatively high. Third, these modules allow liquids to flow freely on both sides of the membrane—a flow pattern necessary for FO [65]. Furthermore, it is the authors' opinion that hollow fiber membranes may be most suitable for FO because there is no need for a thick support layer as in flat sheet RO membranes. This will result in reduced internal CP and enhanced performance.

The main difference between hollow fiber and tubular membranes is the flow regime that can be achieved on the bore side. In hollow fibers (internal diameter <1 mm), only laminar flow can be achieved, and therefore, mixing at the membrane surface is limited. Under these conditions, external CP, fouling, and scaling can reduce mass transport across the membrane. In tubular membranes (internal diameter ≥ 2 mm), turbulence can be easily achieved and CP, fouling, and scaling reduced.

That said, to date, the use of tubular semi-permeable membranes (RO membranes) for FO is limited [12,13,58]. Tubular semi-permeable membranes for RO are not as common in the market as flat sheet semi-permeable membranes. This is mainly due to the shift of the membrane industry to develop flat sheet RO membranes rather than tubular RO membranes as a result of excessive fouling and membrane integrity problems with hollow fiber RO membranes. At the time when tubular membranes are specially designed for FO applications, the manufacturer will have to take into consideration membrane characteristics and hydraulic conditions for ultimate optimization of tubular membranes for specific FO applications.

4.2.4. Hydration bags

The hydration bag is another configuration of flat sheet FO membrane. It is a double lined bag; the internal bag is made of an FO membrane and is filled with draw solution (e.g., flavored sucrose) and the external bag is a sealed plastic bag containing the FO bag and the feed water to be treated. The application of hydration bag technology is further described in Section 5.1.5.

5. Modern applications of forward osmosis

Forward osmosis has been studied for a range of applications. Commercial applications, though still limited, are emerging in the water purification field (e.g., extraction bags) and in the pharmaceutical industry (e.g., osmotic pumps). The following section summarizes past and present applications of FO in wastewater treatment and water purification, seawater desalination, food processing, pharmaceutical applications, and power generation.

5.1. Wastewater treatment and water purification

Several modern applications of FO in the field of wastewater treatment have been published in the literature. These include an early study on concentration of dilute industrial wastewater [2,3], an investigation on treatment of landfill leachate [6,7], a

study on direct potable reuse of wastewater in advanced life support systems for space applications [5,18,19], and an investigation on concentration of liquids from anaerobic sludge digestion at a domestic wastewater treatment facility [4]. It is worth noting that in most wastewater treatment applications FO is not the ultimate process, but rather a high-level pretreatment step before an ultimate desalination process.

5.1.1. Concentration of dilute industrial wastewater

One of the first feasibility studies of FO in an industrial application for wastewater treatment was published in 1974 [2] and 1977 [3]. The objective was to use a low energy process to treat industrial wastewater containing very low concentrations of heavy metals for possible reuse. A bench-scale system was used to study the feasibility of using newly commercialized cellulose RO membranes to concentrate dilute real or synthetic wastewater streams containing copper or chromium. Not aware of the effects of internal CP in RO membranes, the authors observed water fluxes ranging from zero to approximately $4.5 \text{ l/m}^2 \text{ h}$ —much lower than the calculated fluxes of $10\text{--}17 \text{ l/m}^2 \text{ h}$ from the mass transfer equation and manufacturer data for the membranes tested in RO mode under equivalent conditions. Attempts to investigate the effects of external CP on flux by varying the feed and draw solution flow rates yielded inconclusive results.

Simulated seawater was used as the draw solution because it is a potentially inexpensive source available in coastal areas. Passage of sodium chloride from the artificial seawater and diffusion of feed contaminants towards the draw solution occurred at a higher rate than expected. Relative salt passage was 1 g NaCl for every 11.5–688 g water passage in the opposite direction. Different approaches to enhance salt rejection were investigated including chemical treatment of the membrane with polyvinyl methyl ether and thermal treatment (tempering) by immersing the membranes in hot water ($60\text{--}93 \text{ }^\circ\text{C}$) for up to 4 min. While chemical treatment showed no effect on flux or rejection, thermal treatment resulted in elevated salt rejection but decreased water flux.

Due to the poor performance of the RO membranes, further pilot-scale testing of the process was called off. The authors concluded that membranes must be improved and specifically 'tailored' for the FO process to be feasible for water treatment.

5.1.2. Concentration of landfill leachate

Landfill leachate is a highly variable feed solution that presents a particularly difficult treatment challenge, especially when high effluent quality is required. It is a complex solution consisting of four general types of pollutants: organic compounds, dissolved heavy metals, organic and inorganic nitrogen, and total dissolved solids (TDS). A typical composition of leachate is given in Table 1. The simplest treatment for landfill leachate is to process it in a wastewater treatment facility. However, wastewater treatment facilities generally focus on treating organics, heavy metals, and nitrogen. They often have no treatment for TDS, and in some cases, treatment facilities even increase TDS concentration [6].

Two commercially available treatment processes that are able to efficiently remove TDS from wastewater are mechanical

Table 1
Raw leachate and final effluent water quality characteristics [6]

Contaminant (metals or salts)	Untreated leachate ($\mu\text{g/l}$)	Recovered water from leachate ($\mu\text{g/l}$)	Rejection (%)	NPDES TMDL ($\mu\text{g/l}$)
Aluminum	1320	ND	100	
Arsenic	39	ND	100	
Barium	305	1	99.67	
Cadmium	4	0.036	99.10	1.8
Calcium	91600	150	99.84	
Chromium	146	ND	100	16
Copper	18	ND	100	18
Iron	8670	24	99.72	
Lead	12	ND	100	5.3
Magnesium	73700	33	99.96	
Manganese	1480	ND	100	
Nickel	81	ND	100	
Phosphorus	5740	ND	100	
Potassium	56000	543	99.03	
Selenium	ND	ND	100	
Silicon	35500	ND	100	
Silver	7	ND	100	
Sodium	1620000	3990	99.75	
Strontium	2370	ND	100	
Titanium	468	ND	100	
Vanadium	132	ND	100	
Zinc	531	ND	100	120

Contaminant	Untreated leachate (mg/l)	Recovered water from leachate (mg/l)	Rejection (%)	NPDES TMDL (mg/l)
Alkalinity	5000	4	99.92	
BOD-5	472	2	99.58	45
Chloride-water	1580	23	98.54	378
COD	3190	ND	100	
Fluoride-free	1	ND	100	
N-Ammonia	1110	1.6	99.86	2.8
TKN	780	ND	100	
pH	8	5.6	30.00	
TDS	2380	48	97.98	
TSS	100	ND	100	
Specific conductance	9940 $\mu\text{S/cm}$	25 $\mu\text{S/cm}$	99.75	

ND = not detected.

evaporation (e.g., vapor compression, vertical tube falling film, horizontal tube spray film, forced circulation) and membrane processes. A comprehensive evaluation of vapor recompression mechanical evaporation, RO, and FO revealed that FO can be very effective in treating landfill leachate [6]. In 1998, Osmotek constructed a pilot-scale FO system to test the concentration of landfill leachate at the Coffin Butte Landfill in Corvallis, Oregon [6,7]. Because this landfill is located in an area that receives more than 1400 mm per year of rainfall, approximately 20,000–40,000 m³ of leachate is generated annually. In order to meet the National Pollutant Discharge Elimination System (NPDES) total maximum daily load (TMDL), the leachate must be treated to a TDS level lower than 100 mg/l prior to land application.

An FO pilot system was tested for 3 months using Osmotek's CTA membrane (Section 4.1) and NaCl as the draw solution. Water recoveries of 94–96% were achieved with high contaminant rejection. Flux decline was not apparent during the processing of raw leachate; however, a flux decline of 30–50% was observed during processing of concentrated leachate. Almost complete flux restoration was achieved after cleaning.

The success of the pilot-scale system led to the design and construction of a full-scale system (Fig. 11). In the full-scale system, the raw leachate is collected and pretreated before water is extracted in six stages of FO cells. A three-pass (permeate-staged) RO system produces a stream of purified water for land application and a reconcentrated stream of draw solution at approximately 75 g/l NaCl. The concentrated leachate is solidified before disposal [6].

Between June 1998 and March 1999, the treatment plant treated over 18,500 m³ of leachate, achieving an average water recovery of 91.9% and an average RO permeate conductivity of 35 $\mu\text{S/cm}$ [6]. The concentrations of major contaminants in the feed and effluent of the full-scale FO system are summarized in Table 1. Most contaminants had greater than 99% rejection and final effluent concentrations were substantially lower than the NPDES TMDL levels.

5.1.3. Direct potable reuse for advanced life support systems

Long-term human missions in space require a continuous and self-sufficient supply of fresh water for consumption, hygiene,

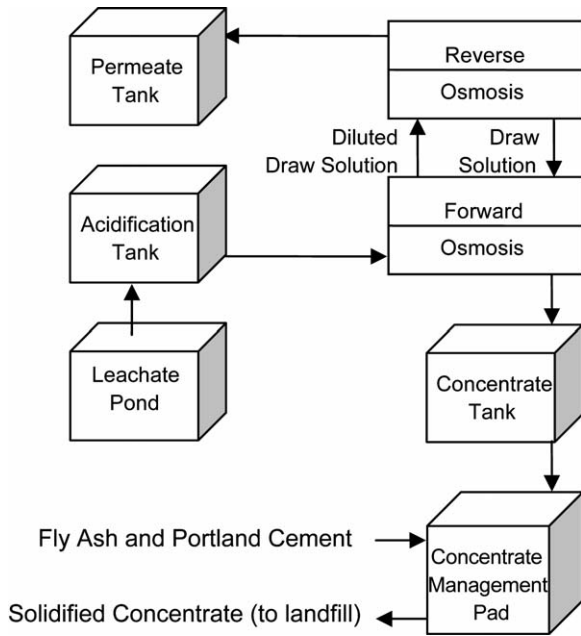


Fig. 11. A flow diagram of the full-scale FO leachate treatment process. Adapted from [6].

and maintenance. Long-range/long-duration missions, like lunar missions or a human Mars exploration mission, depend on a water treatment system that recovers potable water from wastewater generated on board a spacecraft or in the planetary habitat. The three main sources of wastewater that can be reclaimed and reused in long-term space missions are hygiene wastewater, urine, and humidity condensate. The system to treat these wastewaters must be reliable, durable, capable of recovering a high percentage of the wastewater, and lightweight. Additionally, the system should operate autonomously with low maintenance, minimal power consumption, and minimal consumables [66].

A pilot-scale FO system, referred to as the direct osmotic concentration (DOC) system, was developed for direct potable water reuse in space [5,17]. DOC is one of several technologies that are being evaluated by the U.S. National Aeronautics and Space

Table 2

Water flux through one FO membrane and four RO membranes in FO mode [18]

Membrane used	Water flux ($l/m^2 h$)
CTA—Osmotek	17.4
Osmonics—CE	1.90
Osmonics—CD	1.97
Hydranautics—LFC1	0.54
Hydranautics—LFC3	0.66

100 g/l NaCl solution was used as the draw solution and DI water as the feed.

Administration (NASA) for water reuse in space. The NASA DOC test unit originally consisted of a permeate-staged RO cascade and two pretreatment subsystems. The first subsystem (DOC#1) utilized an FO process only and the second (DOC#2) utilized a unique combination of FO and osmotic distillation (OD). The OD process targeted the rejection of small compounds, like urea, that easily diffuse through semi-permeable membranes [17,19]. A schematic drawing of the original DOC test unit is shown in Fig. 12.

In the first phase of the DOC study (1994–1999), design, construction, and testing of the basic functions of the DOC unit were accomplished by NASA and Osmotek [17,20]. In the second phase (2002–2004), the NASA DOC unit was transferred to the University of Nevada, Reno for thorough investigation and optimization of the operating conditions of the system [18,19]. The main goals of this phase were to study the long-term performance, advantages, and limitations of DOC, and to validate data for a mass metrics comparison between the DOC system and other potential advanced wastewater reclamation processes. In a current third phase (2004–2007), a new prototype system is being designed and fabricated for delivery to NASA. Although this system will have similarities to the original DOC system (i.e., FO will be used as pretreatment for RO), it will be a unique system with a separate process for urine treatment [67].

Two of the important findings in Phase 2 of this research relate to membrane performance and energy consumption in FO processes. Results in Table 2 indicate that the FO CTA membrane used in this study outperformed commercially available RO membranes. This is likely due to the lower internal CP in

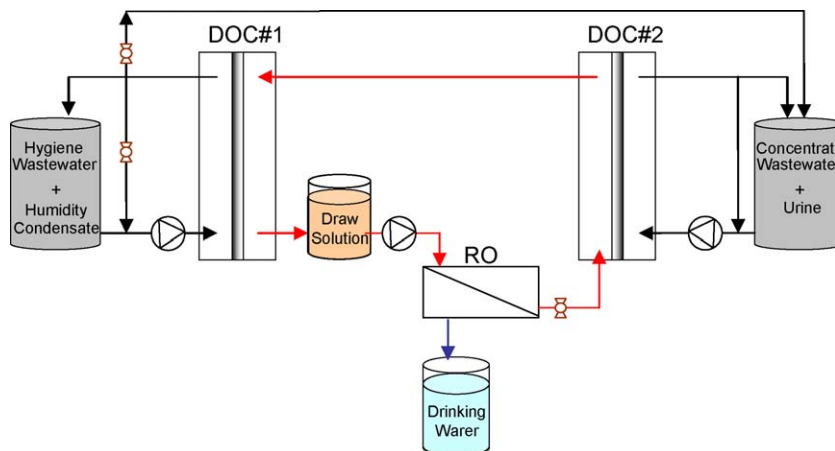


Fig. 12. Flow diagram of the original NASA DOC test unit. Three waste streams are pretreated in DOC#1 and DOC#2. The draw solution is reconcentrated and drinking water is produced by the RO subsystem [18].

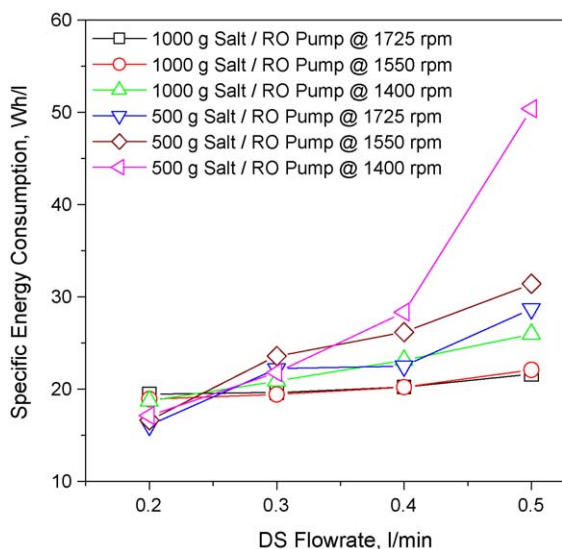


Fig. 13. Specific energy consumption as a function of draw solution flow rate, salt loading, and RO pump capacity for the DOC system [18].

the CTA membrane stemming from the unique structure of this specific membrane (see Section 4.1). Power consumption was measured during operation under variable operating conditions. The parameters that were found to be important in the operation of the process (e.g., draw solution flow rate, RO pump capacity, and the amount of NaCl loaded in the draw solution loop) were varied. The results summarized in Fig. 13 indicate that under variable operating conditions, specific power consumption is almost always less than 30 kWh for every 1 m³ of purified water produced. Further optimization of the process is currently under investigation.

5.1.4. Concentration of digested sludge liquids

Sludges produced in wastewater treatment facilities are most often treated in anaerobic digesters for further degradation of the recalcitrant organic solids and for stabilization of the sludge. After digestion, the sludge is commonly dewatered using a centrifuge which produces concentrated biosolids and a liquid stream (i.e., centrate). The centrate contains high concentrations

of nutrients (e.g., ammonia, *ortho*-phosphate, organic nitrogen), heavy metals, TOC, TDS, color, and TSS. In some agricultural communities the centrate is used as a soil fertilizer [68]; however, the common practice for centrate treatment is to return it back to the headworks of the wastewater treatment facility for re-treatment. When these species are returned to the head of the treatment facility, they increase the facility loading and operating cost, and it is suspected that some of these constituents are recalcitrant and end up in the effluent as nitrogen and phosphorous species.

In a current study [4], FO is being investigated as a potential process for concentration of centrate at the Truckee Meadows Water Reclamation Facility (TMWRF) in Reno, Nevada. The main objectives of this study are to determine the advantages and limitations of using FO to concentrate centrate; to design a hybrid system consisting of FO as pretreatment for RO for concentration of centrate; to develop an economic model and determine the cost effectiveness of the FO process; and to evaluate the potential agricultural use of the concentrated stream as a fertilizer.

Prior to FO, the centrate is pretreated by filtering it through a 150 mesh (<106 μm) sieve. Water is then extracted from the pretreated centrate using a cellulose triacetate FO membrane and an NaCl draw solution. Water flux as a function of draw solution concentration for the pretreated centrate is shown in Fig. 14b. For each trial, the initial draw solution concentration was 70 g/l NaCl; as water diffused through the membrane (over approximately 12 h), the draw solution diluted to approximately 25 g/l NaCl. Thus, after each trial, the system had to be replenished with new, 70 g/l NaCl draw solution. Four tests were performed (trial #1 through trial #4 in Fig. 14a), after which the process was stopped and the membrane was cleaned with sodium hydroxide solution for 20 min. After cleaning, an additional run (trial #5 in Fig. 14a) was performed to test flux restoration. Also in Fig. 14a, a curve indicating FO performance on DI water feed is given to illustrate the maximum flux that can be achieved with the CTA membrane under similar operating conditions and the effect and magnitude of flux decline due to decreased driving force and membrane fouling. It can be seen that over the course of each trial, flux declines due to the decline of driving force. The flux

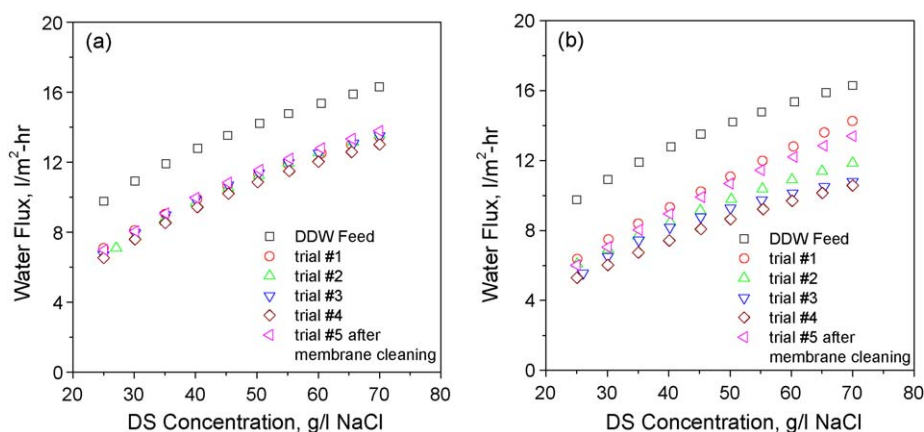


Fig. 14. Water flux as a function of draw solution (DS) concentration during FO concentration of (a) pretreated centrate and (b) non-pretreated centrate (b) [4]. Flux decline between trials is due to organic and suspended solids fouling. Flux was markedly restored after a short cleaning cycle with sodium hydroxide.

decline between each trial (for trials #1 through #4) is the result of membrane fouling over time. After the short cleaning cycle (between trials #4 and #5), the flux was completely restored to its initial level. A similar performance was observed when raw (not pretreated) centrate was used as the feed solution (Fig. 14b). However, the extent of flux decline between trials was much more apparent and was attributed to greater fouling caused by high concentrations of suspended solids (Fig. 14). Some flux restoration after cleaning was achieved; however, complete flux recovery was not obtained. Phosphorous rejection exceeded 99% and ammonia and total Kjeldahl nitrogen (TKN) rejections were approximately 87% and 92%, respectively. Color and odor compounds were almost completely rejected. It is expected that a combination of FO and RO (for draw solution reconcentration) will result in even higher rejections of pollutants from the final effluent.

5.1.5. Forward osmosis for source water purification—hydration bags

The use of FO for water purification was briefly introduced in Section 4. The concept of hydration bags was developed for military, recreational, and emergency relief situations when reliable drinking water is scarce or not available [63,69]. Hydration bags are one of the few commercial applications of FO. Although slower than other water purification devices, FO hydration bags require no power and only foul minimally, even when used with muddy water. The high selectivity of an FO membrane ensures that in most situations and for most sources of water, the permeating water is free of microorganisms, most macromolecules, and most ions.

In the hydration bags, an edible draw solution (e.g., a sugar or beverage powder) is packed in a sealed bag made of a semi-permeable FO membrane [63]. Upon immersion of the bag in an aqueous solution, water diffuses into the bag due to the osmotic pressure difference and slowly dilutes the initially solid draw solution. At the end of the process the diluted draw solution can be consumed as a sweet drink containing nutrients and minerals. In this regard, hydration bags represent an ultimate treatment process; not a pretreatment process. For small, personal devices (Fig. 15), the process can take 3–4 h to completely hydrate a 12 oz beverage. The extraction

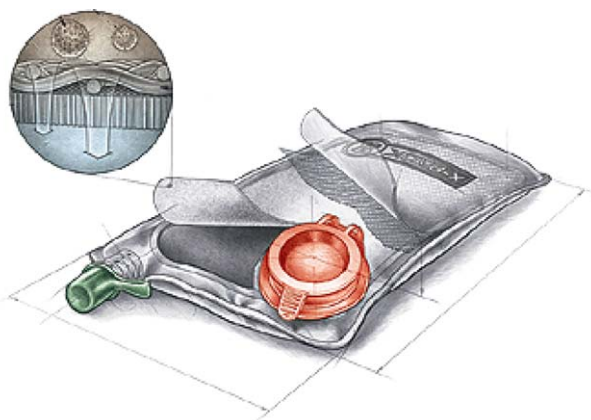


Fig. 15. Illustration of water purification hydration bag [69].

bags can be placed directly in the source water or they can be suspended in another sealed plastic bag that holds the source water—providing better mobility and autonomy to the user. In recent years, the military procured hydration bags for emergency and relief efforts around the world [23]. Yet, there is debate among experts whether hydration bags provide water treatment per se because the product is not pure water but a sweet drink that can only be used for specific applications.

5.2. Seawater desalination

Several patents have been awarded for different methods and systems for water desalination by FO [41–43,45–47,70–73]; however, most of them have not matured or proven feasible. Very few peer-reviewed publications on FO desalination could be found. Kravath and Davis [21] investigated desalination of Atlantic Ocean seawater by FO using cellulose acetate flat sheet and hollow fiber membranes and glucose solution as a draw solution. Kessler and Moody [44] and Moody and Kessler [74] modeled and tested similar applications of FO for desalination. Their objective was to develop a batch desalination process for emergency water supply on lifeboats, not as a continuous process for seawater desalination.

In recent bench-scale studies [22,47,48], it was demonstrated that when using a suitable FO membrane (e.g., the FO CTA membrane) and a strong draw solution (highly soluble ammonia and carbon dioxide gases), seawater can be efficiently desalinated with FO. The draw solution was formed by mixing together ammonium carbonate and ammonium hydroxide in specific proportions [48]. The salt species formed include ammonium bicarbonate, ammonium carbonate, and ammonium carbamate. Analysis of the process has shown that an osmotic pressure driving force ($\Delta\pi$) as high as 238 bar for a feed water with a salt concentration of 0.05 M NaCl, and as high as 127 bar for a feed water with a salt concentration of 2 M NaCl, can be achieved with the ammonia/carbon dioxide draw solution [48]. This is a rather high driving force considering that 2 M NaCl is equivalent to brine from seawater desalination at approximately 70% water recovery.

A schematic drawing of the novel ammonia–carbon dioxide FO process is illustrated in Fig. 16. Water is extracted from seawater and dilutes the ammonia–carbon dioxide draw solution. Upon moderate heating (near 60 °C), the draw solution decomposes to ammonia and carbon dioxide. Separation of the fresh product water from the diluted draw solution can be achieved by several separation methods (e.g., column distillation or membrane distillation (MD)). The degasified solution left behind is pure product water and the distillate is a reconcentrated draw solution available for reuse in the FO desalination process.

Bench-scale FO data demonstrates that the ammonia–carbon dioxide FO process is a viable desalination process. Salt rejections greater than 95% and fluxes as high as 25 l/m² h were achieved with the FO CTA membrane with a calculated driving force of more than 200 bar [22]. Although this is a relatively high flux, much greater flux is actually expected for such a high driving force. Further analysis of the results [48] has indicated that the performance ratio (defined as experimental water flux

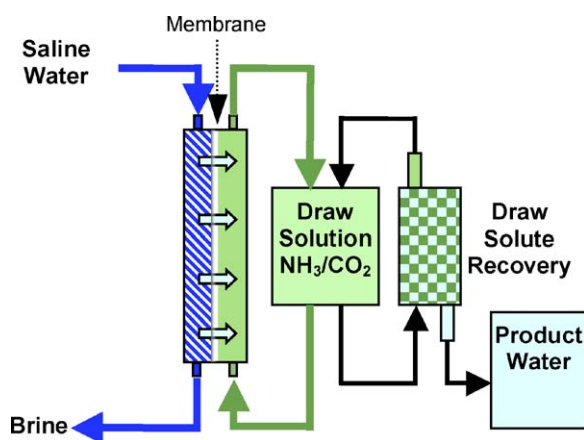


Fig. 16. Schematic drawing of the novel ammonia-carbon dioxide FO process [22].

divided by theoretical water flux) of the FO CTA membrane used was at most 20%, and on average between 5% and 10%. This lower-than-expected flux is attributed to internal CP.

All of the previous, yet limited, work on FO as an alternative desalination process has exposed the two major limitations of FO—lack of high-performance membranes and the necessity for an easily separable draw solution. Moreover, when considering seawater desalination, and especially when high water recovery is desired, FO can be utilized only if the draw solution can induce a high osmotic pressure.

5.3. Food processing

Although osmotic treatment of food products (e.g., preserved fruits and meats) is very common in the food industry [75], FO treatment for concentration of beverages and liquid foods has been studied at laboratory-scale only [8,11–14,16]. FO has several advantages as a process for concentrating beverages and liquid foods, including operation at low temperatures and low pressures that promote high retention of sensory (e.g., taste, aroma, color) and nutritional (e.g., vitamin) value, high rejection, and potentially low membrane fouling compared to pressure-driven membrane processes.

Several patents have been awarded for inventions of FO devices and methods for the concentration of liquid foods [76,77]. Short summaries of the main studies are provided below in chronological order.

Two detailed summaries were published on the potential use of FO in the processing of liquid foods. Petrotos and Lazarides [14] reviewed low pressure membrane processes – FO, OD, and MD – for concentration of liquid foods. Jiao et al. [11] provided a more comprehensive summary on membrane processes (including FO (DOC)) for concentration of fruit juices.

Popper et al. [15] were the first to use modern techniques and first generation polymeric RO membranes to concentrate fruit juices. They used both tubular and flat sheet cellulose acetate membranes and achieved an average water flux of $2.5 \text{ kg/m}^2 \text{ h}$ using saturated NaCl as the draw solution. Highly concentrated fruit juices were produced but salt was found to diffuse through the membrane into the grape concentrate.

Based on the development of a new plate-and-frame membrane module for FO [77] by Osmotek Inc., Beaudry and Lampi [8] published a short summary on the use of the DOC process for concentration of fruit juices. They recommended that 72°Brix sugar solution be used as the draw solution. Herron et al. [77] were awarded a patent on a membrane module and a method to concentrate fruit juices and wines. Laboratory test results showed water fluxes as high as 4 and $6 \text{ l/m}^2 \text{ h}$ for orange juice and coffee, respectively. These relatively high fluxes are partially due to the high turbulence achieved in their FO module [77]. In the summary of the invention, the inventors recommended the use of 50–85 wt.% sugar solution as the draw solution.

Wrolstad et al. [16] compared the sensory characteristics of red raspberry juice concentrated by FO with that concentrated by vacuum evaporation. High fructose corn syrup was used as draw solution. Descriptive sensory analysis revealed no significant difference between the products of the two processes. Compositional differences between the two types of processed juice concentrate were minor. No comparison of other aspects (e.g., capital cost or energy requirements) was provided to further address the benefits or limitations of the FO process.

Adopting the methods of Herron et al. [77], Petrotos et al. [12,13] further explored the optimal conditions by which FO can be used in the concentration of tomato juice—one of the most concentrated vegetable juices. Petrotos and co-workers used custom-made tubular thin-film composite aromatic polyamide membranes and different draw solutions including sodium chloride, calcium chloride, calcium nitrate, glucose, sucrose, and polyethylene glycol 400 (PEG400). Results showed that membrane thickness and draw solution viscosity are the main factors controlling water flux in the FO concentration of tomato juice. Thinner membranes and lower viscosity draw solutions yielded higher water fluxes, and therefore, faster juice concentration. In addition, it was shown that pretreatment in the form of filtration, especially ultrafiltration, enhances the efficiency of the FO process. In further studies, Dova et al. [9,10] investigated and modeled the impact of process parameters (e.g., membrane characteristics, feed and draw solution concentrations, and flow rates) on process performance using thin-film composite aromatic polyamide RO membranes.

From these studies, the FO process appears to have a number of advantages over evaporation and pressure-driven membrane processes for concentration of liquid foods. Low energy use, low operating temperatures and pressures, and high product concentrations are the main advantages. However, similar to other industries, the lack of optimized membranes and an effective recovery process for the draw solution are the main limitations to transforming FO into a full-scale process in the food industry.

5.4. The pharmaceutical industry—osmotic pumps

The oral route, which is still the most acceptable mode of administration of prescription drugs, may have limitations in achieving desired outcomes. In special circumstances, extended release, targeted delivery, or especially accurate dosage of a remedy in the body is required—particularly in cases of chronic illnesses. Additional benefits of the controlled release of drugs

include decreased dosing frequency, more regular drug concentration in the bloodstream, enhanced bioavailability, improved patient compliance, and reduced side effects [25]. For example, delivering therapies to specific cells can be an obstacle in treating neurodegenerative diseases, such as Parkinson's disease and Huntington's disease. Targeting treatment to the brain is difficult because the blood–brain barrier blocks many drugs [78]. In other cases, a drug can have low oral bioavailability (e.g., it can have low solubility or limited permeability) in the gastrointestinal tract [25].

Controlled- or modified-release of drugs is possible through the use of osmotic pumps. Osmosis offers several advantages as a driving force for constant pumping of drugs, including accurate mass transfer. For example, when considering targeted treatment, osmotic pumps can deliver medicine directly to the cerebrospinal fluid, where it is ultimately taken up into neurons.

The development of osmotic pumps was pioneered with the commercialization of the ALZET[®] osmotic pump for animal studies in the mid-1970s [26]. More recently, osmotic principles have been applied to human therapy, resulting in the development of drug delivery systems such as the DUROS[®] system [27], OROS[®] Push-Pull[™], L-OROS[™], and EnSoTrol[®] [25] that can release drugs continuously for up to 1 year. Recently, osmotic pumps have been studied as regulated systems for the acquisition, metering, buffering, delivery, and assay of fluid biological samples [79].

The principal components of a typical osmotic drug-delivery system are illustrated in Fig. 17. The osmotic pump is contained in a titanium alloy cylindrical reservoir that is 4 mm in diameter and 40 mm in length. This reservoir protects the drug molecules from enzymes, body moisture, and cellular components that might deactivate the drug prior to release. A polyurethane membrane covers one end of the reservoir. Like other semi-permeable membranes, it is permeable to water but almost completely impermeable to ions. The osmotic engine (i.e., the draw solution) occupies a portion of the cylinder behind the membrane. The draw solution is most often NaCl and a small amount of pharmaceutical excipients in a tablet form. An elastomeric piston separates the draw solution from the drug formulation in the drug reservoir. The drug may either be a solution or a suspension and either aqueous or non-aqueous in nature. The drug must be stable at body temperature (37 °C) for extended periods of time, usually from 3 months to 1 year. The drug exit port is a small orifice located at the opposite end of the titanium cylin-

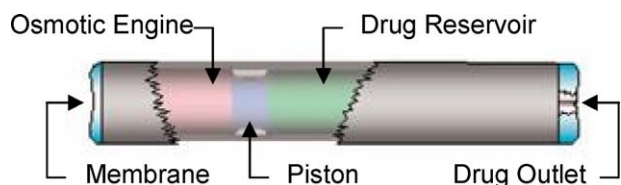


Fig. 17. Cross-section of the implanted DUROS[®] System [27]. A polyurethane membrane covers one end of the reservoir. The osmotic engine (i.e., the draw solution) occupies a portion of the cylinder behind the membrane. An elastomeric piston separates the draw solution from the drug formulation in the drug reservoir. Upon diffusion of water into the osmotic engine, the piston is pushed and the drug is released through the drug outlet orifice.

der. Exit ports can range from simple, straight channels to more complicated design configurations [27].

When the osmotic pump is brought into contact with an aqueous solution or wet environment, water diffuses through the membrane into the draw solution compartment. As pressure builds up, it expands the draw solution compartment, pushes the piston, increases the pressure in the drug compartment, and consequently induces the release of the drug through the orifice. The rate of water diffusion is the most important design aspect of an osmotic pump because it dictates the rate at which the drug will be released. Theeuwes and Yum [26] summarized the principles of design and operation of osmotic pumps and methodically described the design criteria for constant delivery rate.

The volumetric flux of water into the draw solution compartment of osmotic pumps can be described by the simplified Kedem–Katchalsky equation (Eq. (1) in Section 2). When the pump is placed in an environment with an osmotic pressure of π_e , $\Delta\pi$ can be expressed as

$$\Delta\pi = \pi_{DS} - \pi_e \quad (7)$$

where π_{DS} is the osmotic pressure of the draw solution. ΔP can be expressed as

$$\Delta P = \Delta P_d - \Delta P_e \quad (8)$$

where ΔP_d is the internal pressure difference associated with the drug delivery through the orifice and ΔP_e is the pressure necessary for the piston to compress the drug reservoir. To achieve constant water flux, and hence constant delivery rate, the right-hand side of Eq. (1) must be constant. This condition can be met only if both terms, $\sigma\Delta\pi$ and ΔP , are constant (assuming that the membrane permeability coefficient is constant)

$$\sigma(\pi_{DS} - \pi_e) = \text{constant} \quad (9)$$

and

$$\Delta P_d - \Delta P_e = \text{constant} \quad (10)$$

Eq. (9) can be satisfied if (1) the amount of draw solution in the osmotic pump can ensure saturation in the water solution, (2) the osmotic pressure of the environment is negligible, and (3) the reflection coefficient is constant. Implantable osmotic pumps in the human body can easily meet these three requirements [26]. Starting from solid or very concentrated draw solution, and assuming a small drug reservoir, the draw solution can be kept saturated throughout the delivery time period and at much higher osmotic pressure than the osmotic pressure in the human body. The values of ΔP in Eq. (10) can be reduced to almost zero by controlling the orifice size and by selecting a highly deformable partition between the draw solution and drug compartments [26]. Even so, when a low molecular weight salt is used as a draw solution, $\Delta\pi$ will generally always be much greater than ΔP .

5.5. Osmotic power—pressure-retarded osmosis

Renewable energy can be extracted wherever two streams of different salinity or different chemical potential meet. Consid-

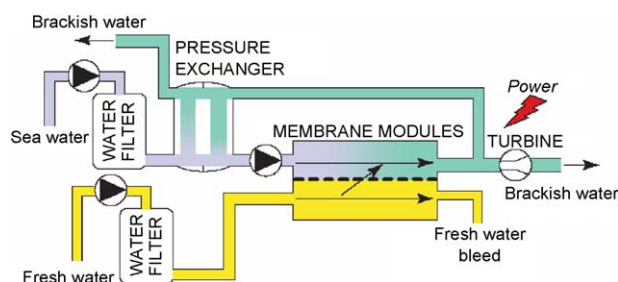


Fig. 18. Simplified process layout for a PRO power plant [28].

ering that the salinity of seawater yields osmotic pressures of approximately 2.7 MPa and that the osmotic pressure of river water is relatively insignificant, a large portion of the 2.7 MPa can be used for power generation. PRO (as briefly described in Section 2 and illustrated in Figs. 1 and 2) is one method that can be used to realize this energy.

A schematic drawing of power generation by PRO is illustrated in Fig. 18. Fresh water is pumped into a PRO module containing membranes, in principle, similar to the semi-permeable FO membranes described earlier. The fresh water flows on one side of the membrane and diffuses through the membrane into the pressurized side of the membrane filled with seawater. The diluted and pressurized seawater is then split into two streams; one is depressurized in a turbine to generate power and the second passes through a pressure exchanger to assist in pressurizing the incoming seawater. The two key components of a PRO facility are the pressure exchanger and the membrane. Loeb et al. [33,80] suggested two possible steady-state flow systems that differ in their means of pressurizing the draw solution entering the permeate-receiver side of the membrane: pump pressurization of the draw solution (as depicted in Fig. 18) and permeate pressurization of the draw solution using at least two tanks capable of withstanding the pressure of the permeate-receiver side [33,80].

Power generated by PRO from seawater has certain features that make it very attractive. It is a large and unexploited resource; it is renewable; its use has minimal environmental impact; and compared to other potential sources of energy from the ocean, its density (i.e., power capacity per physical size) is high [38,81]. Estimates suggest that global power production potential from salinity gradients is on the order of 2000 TWh per year [28].

For the last several decades, the PRO process for power generation has been continuously studied by Loeb and co-workers [31–35,39,50,58,59,82]. Additionally, Jellinek and Masuda [29] generated power from PRO pilot testing. Wick [38] compared PRO and reverse-electrodialysis for power generation from salinity gradient sources. Currently, an intensive study of PRO for power generation is being funded by the European Union and being conducted by a joint effort of Statkraft SF of Norway, ICTPOL of Portugal, SINTEF of Norway, GKSS-Forschungszentrum of Germany, and Helsinki University of Technology of Finland with the main objective being to develop membranes for PRO power that have a production capacity equivalent to at least 4 W/m^2 [28].

The development and future success of PRO for power generation will, in turn, have great influence on the success of FO

for water treatment and desalination. Both processes depend on the same semi-permeable membranes that at this time do not commercially exist.

6. Concluding remarks

The increased attention to FO from various disciplines arises from the fact that FO can be employed in many fields of science and engineering including water and wastewater treatment, seawater/brackish water desalination, food processing, drug delivery, and electric power production. Despite the lack of robust membranes and membrane modules for FO, basic research on FO and the development of new applications of FO are steadily growing. Currently, the most important measure to be taken in order to advance the field of FO is the development of new membranes in both flat-sheet and hollow fiber configurations. The membranes need to provide high water permeability, high rejection of solutes, substantially reduced internal CP, high chemical stability, and high mechanical strength. For the future, high-density packing methods for well-performing flat-sheet FO membranes (such as the modified spiral-wound module shown in Fig. 9) must be further developed. Development of draw solutions that can induce high osmotic pressure is another important step towards further progress of the FO process. Most desirable are draw solutions that require low energy for regeneration or reconcentration, that are easily separable from the product fresh water, that have low or no toxicity, and that are chemically non-reactive with polymeric membranes.

Acknowledgments

The authors acknowledge the support of the Office of Naval Research, Award Nos. N00014-03-1-1004 and N00014-05-1-0801, and the support of the U.S. National Aeronautics and Space Administration (NASA), Award No. NNA04-CL12A.

Nomenclature

<i>A</i>	water permeability coefficient ($\text{m}^3/\text{m}^2 \text{ s Pa}$)
<i>B</i>	solute permeability coefficient (m/s)
<i>C</i>	concentration (mol/l)
<i>D</i>	diffusivity (m^2/s)
J_w	water flux ($\text{m}^3/\text{m}^2 \text{ s}$)
<i>K</i>	resistance to salt transport in the porous support (s/m)
<i>P</i>	hydraulic pressure (Pa)
<i>t</i>	membrane thickness (m)

Greek letters

Δ	difference operator
ε	membrane porosity
μ	chemical potential
π	osmotic pressure (Pa)
σ	reflection coefficient
τ	pore tortuosity

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