Existing & Emerging Concentrate Minimization & Disposal Practices for Membrane Systems

Sandeep Sethi, Steve Walker, Jörg Drewes, and Pei Xu

Sandeep Sethi is a senior project engineer with Carollo Engineers and Steve Walker is a project manager with the firm. Both work in Carollo's Sarasota office. Jörg Drewes is an assistant professor at the Colorado School of Mines in Golden, Colorado. Pei Xu is a research assistant professor at the school.

As water demand increases and freshwater sources are becoming increasingly stressed in the U.S., there is an impetus for water utilities to treat impaired water sources such as brackish groundwater, irrigation return water, and seawater to meet increasing demands. The efficiency of desalination technology used to treat such waters has improved over the last decade, but there are currently certain key limitations that need to be addressed to make this technology more cost effective.

A key issue that stands out is the low productivity or recovery that results in a large volume of concentrate, high-energy use, and relatively high treatment costs. A related major challenge is the disposal of the concentrate, in a cost-effective, environmentally sustainable manner—especially for inland sites.

Currently the recovery from the conventional application of desalting processes, including reverse osmosis (RO), electrodialysis reversal (EDR), and thermal evaporation processes, is limited. Some 20 to 50 percent of the feed stream is wasted as byproduct or concentrate.

The disposal of such quantities of concentrate is not only a loss of valuable resource and energy, but also a challenge in itself—especially for inland facilities, and with regard to environmentally sustainable disposal options.

Though several concentrate disposal methods are available (such as surface water or sewer discharge, deep well injection, evaporation ponds, and thermal evaporation), there are inherently high costs, accessibility constraints, permit challenges, and other limitations associated with all methods. These limitations are becoming more apparent and challenging with stricter regulations.

The emerging and promising approaches to desalting and its concentrate management that aim to enhance overall recovery and reduce concentrate volume are a key to the future success of this technology.

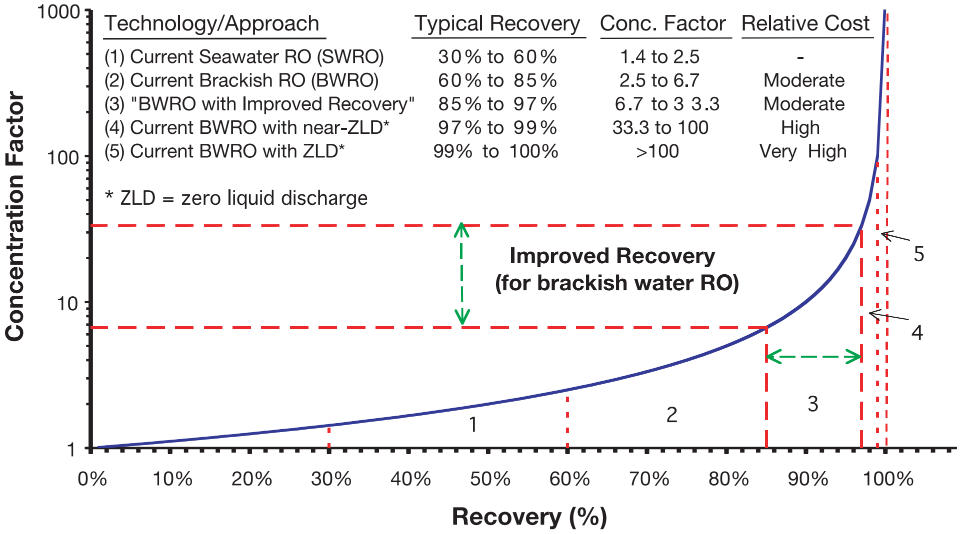
This work forms part of an ongoing AWWA Research Foundation project (Project #3030) that focuses on the various methods of concentrate minimization and disposal, including identification and assessment of the promising and emerging methods, approaches, and technologies.

This article offers an overview of the available existing (commercialized) methods and the promising and emerging (currently non-commercialized) methods in the industry.

Recovery Limitations

Desalting processes separate water molecules from the feedwater, resulting in a concentrate (or brine) stream that is more concentrated than the feedwater. A higher recovery (volume ratio of product to feedwater) is preferable because it results in more product water (greater production), reduced feedwater (less resource usage), reduced wastewater (less treatment and less disposal volume), and consequently multiple cost savings.

Figure 1. Illustration of Recovery Enhancement Possibility for Brackish Water Reverse Osmosis



Technology/Approach	Typical Recovery	Conc. Factor	Relative Cost
(1) Current Seawater RO (SWRO)	30% to 60%	1.4 to 2.5	-
(2) Current Brackish RO (BWRO)	60% to 85%	2.5 to 6.7	Moderate
(3) "BWRO with Improved Recovery"	85% to 97%	6.7 to 3 3.3	Moderate
(4) Current BWRO with near-ZLD*	97% to 99%	33.3 to 100	High
(5) Current BWRO with ZLD*	99% to 100%	>100	Very High

* ZLD = zero liquid discharge

As the recovery ratio increases, however, the concentration of the dissolved ions in this stream becomes high enough to form precipitable compounds such as calcium carbonate, calcium sulfate, silicate, and barium sulfate.

These precipitates form a scale on process surfaces such as membranes, flow channels, and heat transfer surfaces, reducing the process efficiency and limiting the process recovery. Typically, acid or scale inhibitors are added to reduce alkalinity and prevent the formation of precipitable salts, allowing a somewhat higher recovery.

In RO processes, the other parameter limiting recovery is driving pressure, since the osmotic pressure of the concentrate stream increases with increasing concentration, which in turn increases the driving pressure requirement, which itself is limited by the design tolerances of the membrane and associated process components.

The concentration factor, which is an indication of the concentration levels on the feed-concentrate side of the membrane in an RO system, increases with recovery and is illustrated in Figure 1. Also illustrated are the relative ranges of recovery for current seawater RO (SWRO), brackish water RO (BWRO), and brackish water RO coupled with zero-liquid-discharge (ZLD) or near-ZLD processes.

Thus, taking the example of BWRO, the current recovery ranges from about 60 to 85 percent. A BWRO system with a ZLD or near-ZLD process incorporates further processing of concentrate via thermal evaporation, concentration, or crystallization into solid salts (e.g., by using thermal evaporators, crystallizers, or spray dryers). While very high recoveries—greater than 97 percent—can be achieved using near-ZLD or ZLD processes, they are currently also characterized with relatively high to very high costs.

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Thus, as illustrated in Figure 1, there is a practical "window", between 85 to 97 percent, to where recovery could potentially be improved for BWRO while avoiding significant corresponding increases in costs. This is essentially the goal of emerging and promising technologies for recovery enhancement and concentrate minimization.

Existing Concentrate Minimization & Management Methods

Several methods for concentrate management and disposal exist and have been commercialized, while several are emerging. An overview of the existing methods is presented first, followed by a description of several emerging and promising methods.

Conventional concentrate management technologies for BWRO and SWRO include surface water discharge, sewer discharge, deep well injection, evaporation ponds, land application, and thermal evaporation toward zero liquid discharge, or near-zero liquid discharge applications.

Surface Water Discharge

Surface water discharge to a receiving body is the most common concentrate disposal practice in the U.S. This method is employed by approximately 48 percent of all desalting facilities in the country (Mickley, 2001).

Access to possible receiving bodies, such as a river, lagoon, or ocean is required. An NPDES permit is required and permit limits may include total suspended solids, total dissolved solids (TDS), and specific nutrients and metals, such as arsenic. Disposal costs are low if the length of the pipeline to the receiving body is reasonable and the concentrate meets the permit requirements.

Sewer Discharge

Discharge of concentrate to an exising sewage collection system is the second most common concentrate disposal practice in the U.S. and is employed by approximately 40 percent of all desalting facilities in the country (Mickley, 2001). It requires a permit from the local sewage agency. The permit may impose limitations to protect the sewers and treatment plants' infrastructure, the treatment process, and final effluent and biosolids quality.

Smaller volume discharges are typically economical and may have limited permitting requirements.

Deep Well Injection

Deep well injection (DWI) or subsurface injection involves the disposal of concentrate into a deep geological formation that will serve to isolate the concentrate permanently from shallower aquifers that may be used as a drinking water source. Regulatory considerations include the receiving aquifer's transmitivity and TDS, and the presence of a structurally isolating and confining layer between the receiving aquifer and any overlying source of drinking water.

DWI injection is typically economical and employed only for larger concentrate flows (> 1 mgd) and thus is used for larger RO plants.

Evaporation Ponds

In this method, the concentrate is pumped into a shallow lined pond and allowed to evaporate naturally using solar energy. Once the water has evaporated, the salt sludge is either left in place or removed and hauled offsite for disposal.

Evaporation ponds can be a viable option in relatively warm, dry climates with high evaporation rates, level terrain, and low land costs. They are typically economical and are employed only for smaller concentrate flows.

Land Application

Land application, such as spray irrigation, is a beneficial reuse of concentrate. It can be used for lawns, parks, golf courses, or crop land.

Land application depends on the availability and cost of land, percolation rates, irrigation needs, water quality tolerance of target vegetation to salinity, and the ability to meet groundwater quality standards.

Zero Liquid Discharge and Near-Zero Liquid Discharge

These are essentially thermal methods, such as thermal evaporators (vapor compression), crystallizers, and spray dryers that can reduce the concentrate to a slurry (near ZLD) or a solid product for landfill disposal (ZLD).

While these methods are well established and developed, their capital and operating costs are currently relatively high and can exceed the cost of the desalting facility, so this option is typically not employed except for special situations (such as an inland desalination facility with no sewer or surface water access) coupled with very small flows.

Emerging Concentrate Minimization & Management Methods

A review of emerging and promising (not yet commercially significant) desalination and concentrate management methods is presented in this section. Brief descriptions of each key emerging technology are outlined, including key attributes and technology status.

Emerging methods that aim to enhance recovery and thus minimize concentrate include the physical-chemical or biological treatment of primary RO concentrates, seeded slurry processes to remove scaling compounds in a controlled fashion, dewvaporation, membrane distillation, forward osmosis, and new methods based on softening pretreatment and pH control, among others.

Emerging concentrate management technologies may consider newer methods based on evaporation that aim to reduce the footprint requirement of traditional evaporation ponds, reuse applications, or recovery of some sort of useful solids as byproducts for beneficial uses.

Two-Phase Reverse Osmosis with Intermediate Chemical Precipitation

This is a physical-chemical approach to enhancing the recovery of an RO process through treating and minimizing concentrate, using established technologies such as lime soda softening and a second-phase RO (Williams et al., 2002). The approach is based on treatment of the concentrate from a primary RO system using a physical-chemical process, followed by its subsequent treatment in a secondary RO system.

The concentrate treatment step focuses on removing cations of concern via precipitation to reduce the scaling potential of the concentrate. The steps involved are chemical treatment and precipitation for removing calcium, magnesium, and other sparingly soluble salt components, followed by filtration (media filtration or membrane filtration) for removing solids carryover from the precipitation process.

Since the secondary RO system will be operated at a higher TDS, it will require higher pressures than the primary RO system. The combined recovery of the process is estimated and reported to be 95 percent or greater for brackish water.

This technology includes an application of established unit processes and relatively low additional energy requirements. Considerations include additional chemicals, production of sludge from the chemical precipitation process, and the footprint and costs of chemical feed and storage facilities and the secondary RO system. The approach was recently pilot tested at the Metropolitan Water District of Southern California (Williams et al., 2002).

Two-Phase Reverse Osmosis with Intermediate Biological Reduction

This is a biological approach to enhancing the recovery of an RO process through treatment and minimization of concentrate, using established technologies such as biological reduction and a second-phase RO (Williams and Pirbazari, 2003).

Like the physical-chemical approach described above, this approach is based on the treatment of the concentrate from a primary RO system, followed by its treatment in

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a secondary RO system; however, the concentrate treatment step focuses on removing anions (sulfate and carbonate, via biological treatment followed by air stripping) to reduce the scaling potential of the concentrate from the primary RO process.

The core of the process is the biological reactor where sulfate is biochemically reduced to sulfide. The reaction is favorable under anaerobic conditions when a carbon source (electron donor) is present.

Sulfides and carbonates are subsequently air-stripped under acidic conditions. The hydrogen sulfide and other reduced sulfur species in the off-gas must be neutralized (i.e., oxidized) prior to off gas discharge.

Following this, a gravity thickener followed by media filtration (or microfiltration) is needed to remove biological and other solids. The filtered water is concentrated in a separate, downstream secondary RO process, or it can be recycled back to the influent of the primary RO process. The combined recovery of the process is estimated and reported to be 95 percent or greater for brackish water.

The technology includes an application of established unit processes and relatively low additional energy requirements. Considerations include additional chemicals and biological treatment, production of sludge from the solids removal process, and footprint and costs of additional unit processes and the secondary RO system. This approach has recently been tested at bench scale at the Metropolitan Water District of Southern California (Williams and Pirbazari, 2003).

RO with Softening Pretreatment and High pH Operation (High Efficiency RO™)

This patented technology consists of the key components of a hardness and alkalinity removal step, a degasification step to remove carbon dioxide, and caustic addition to increase the pH of the RO feedwater. It was originally developed to provide ultrapure water to the microelectronics industry.

For municipal brackish water, the process combines a two-phase RO process with chemical pretreatment of primary RO, intermediate ion exchange treatment of primary RO concentrate, and high pH operation of secondary RO (Jun et al, 2004). The (secondary) RO step operates as a "high-efficiency" system due to ion exchange pretreatment and high pH operation, so the system is called High Efficiency Reverse Osmosis (HERO™).

The concentrate of the primary RO is treated in weakly acidic cationic (WAC) exchange resins. The carbon dioxide from the concentrate is removed and the pH is raised above 10 to allow operation of the secondary RO at high recoveries.

Operating the negatively charged membranes at a high pH is reported to allow better removal of both weakly ionized anions as well as the strongly ionized species. The solubility of silica is increased at high Ph, which allows greater recovery rates on high silica waters. The combined recovery of the process is estimated and reported to be greater than 90 percent for brackish water, with typical target recovery rates of about 95 percent.

The technology includes the application of established unit processes, negligible potential of silica or calcium carbonate scaling or biological fouling, higher rejection of both weakly ionized anions and strongly ionized species, and minimized cleaning. Considerations include proprietary technology, additional chemical and ion exchange treatment, production of sludge from the chemical treatment process, and footprint and costs of additional unit processes and secondary RO system. This approach has been installed at full-scale at several industrial facilities (electronics and ultrapure water applications, and in power industry for cooling water recycling).

Two-Pass Nanofiltration

Although NF is commonly used for softening, in this approach two passes of NF are used in series to remove adequate amounts of salt and produce freshwater from seawater. The first pass removes greater than 90 percent of the salinity, and the second pass removes greater than 93 percent, resulting in a total salt reduction of about 99.5 percent (Tseng et al., 2003).

The first NF pass operates at a pressure around 525 psi, and the second NF pass operates at a lower pressure around 250 psi. This implies lower overall energy requirements compared to the operating pressures of about 800 psi or higher that are typically employed in conventional RO desalination.

The presence of two passes of NF implies two barriers to contaminants, and therefore increased reliability of water quality. It also implies increased flexibility; for example, the second pass can be operated at a higher pH by addition of a base, which allows better rejection of boron. The overall recovery from the process is about 30 to 45 percent for seawater desalination, which is comparable to conventional RO desalination.

The approach is characterized by lower operating pressures and energy costs for seawater desalination, multiple barrier technology, and use of established unit processes. Limitations include overall recovery comparable to conventional RO desalination.

This approach has been pilot tested by the Long Beach Water Department, California, since October 2001. The Long Beach Water Department has applied for a patent on the process, which is being optimized in terms of membrane selection and operation.

Seeded Slurry Precipitation and Recycle

This technology uses crystals to precipitate scaling compounds in a membrane application and is known as slurry precipitation and recycle RO (SPARRO). Seed crystals are introduced in a tubular RO membrane such that the scaling compounds are precipitated (on seed crystals rather than on the membrane) and removed in a controlled fashion (Juby and Schutte, 2000).

The concept involves circulating a slurry of seed crystals within the RO system. The seed crystals serve as preferential growth sites for calcium sulfate and other calcium salts and silicates, which begin to precipitate as their solubility products are exceeded during the concentration process within the membrane tubes. The preferred growth of scale on the seed crystals prevents scale formation on the membrane surface.

Since the seed slurry is recirculated within the membranes, the process is confined to the use of a membrane configuration that will not plug, such as tubular membrane systems. Gypsum crystals are used to precipitate calcium sulfate.

The water to be desalted is mixed with a stream of recycled concentrate containing the seed crystals and fed to the RO process. The concentrate with seed crystals is processed in a cyclone separator to separate the crystals, and the desired seed concentration is maintained in a reactor tank by controlling the rate of wasting the upflow and/or underflow streams from the separator. The combined recovery of the process is reported to be greater than 90 percent.

The technology is characterized by relatively low energy costs. Considerations include requirement of tubular RO membranes, footprint of tubular membranes, and additional chemicals. This approach has been tested at pilot scale in South Africa, at the East Rand Proprietary Mines (Juby and Schutte, 2000).

Membrane Distillation

The membrane distillation (MD) process consists of passing heated brackish or seawater over a porous, hydrophobic membrane surface (Sirkar and Li, 2003). The membrane allows water vapor to penetrate the hydrophobic membrane while repelling the liquid water. The clean vapor is subsequently carried away from the membrane and condensed as pure water, either within the membrane package or in a separate condenser system.

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MD differs from other membrane technologies in that the driving force for desalination is the difference in vapor pressure of water across the membrane, rather than the feed pressure that forces the liquid water through the membrane. The driving gradient for vapor production can be enhanced by heating the feedwater, which increases the vapor pressure and with that the penetration rate. The energy source for feed heating and/or for a vacuum system to sweep away the vapor may be low-grade thermal energy, such as supplied by low-pressure steam, waste heat, solar energy, or geothermal energy.

A variety of arrangements and configurations can be used to induce the vapor through the membrane and to condense penetrant gas. Common to all concepts is that the feedwater directly contacts the membrane. Condensation is typically achieved via four process configurations:

Air-Gap Membrane Distillation. This configuration, which is the most common and most versatile arrangement, provides an air gap after the membrane, followed by a cool surface for condensation to occur.

Direct-Contact Membrane Distillation. The cool condensing solution (pure water) directly contacts the membrane and condenses the vapor as it passes through the membrane. The coolant liquid flows countercurrent to the feedwater. This is the simplest configuration. It is best suited for applications such as desalination and concentration of aqueous solutions.

Sweep-Gas Membrane Distillation. A sweep gas pulls the water vapor out of the membrane gap for subsequent condensation outside of the membrane package. This approach is especially advantageous when volatiles must be removed from an aqueous solution.

Vacuum Membrane Distillation. Vacuum is applied to the penetrant membrane space to pull the water vapor out of the system. This concept is useful when volatiles are to be flushed from aqueous solutions.

The technology is characterized with low temperature requirements (typically 60°C to 70°C); possible use of low-grade heat (solar, industrial waste heat, or desalination waste heat may be used); minimal pretreatment needs; and negligible scaling or precipitation concerns. Considerations include need of waste heat to obtain better economics. MD technology is currently in the development and demonstration phase.

Capacitive Deionization

During capacitive deionization (CDI), ions are adsorbed onto the surface of porous electrodes by applying a low voltage electric field, producing deionized water. Liquid flows between high surface electrode pairs having a potential difference of 1.3 DC voltage. The negative electrodes attract positively charged ions such as calcium, magnesium, and sodium. Conversely, the positive electrodes attract negatively charged ions such as chloride, nitrate and silica.

The major mechanisms related to the removal of charged constituents during electronic water treatment are physisorption, chemisorption, electrodeposition, and/or electrophoresis. Unlike ion exchange, no additional chemicals are required for regeneration of the electrosorbent in this system. Adsorbed ions are desorbed from the surface of the electrodes by eliminating the electric field, resulting in the regeneration of the electrodes (Farmer et al., 1996; Tran et al., 2002). The efficiency of CDI strongly depends upon the surface property of electrodes such as their surface area and adsorption properties (Pekala et al., 1998).

The Lawrence Livermore National Laboratory (LLNL) began its research into capacitive deionization technology (CDT) in the late 1980s. LLNL developed and optimized carbon aerogel materials, which multiplied the effective surface area of the deionization electrodes by a factor of 60,000, dra-

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matically improving their capacity to attract and hold charged water constituents. Carbon aerogel is an ideal electrode material because of its high electrical conductivity, high specific surface area, and controllable pore size distribution (Yang et al., 2001; Ying et al., 2002).

The carbon aerogels exhibit a higher selectivity in removal of certain ions, such as iodide, than NaCl. This selectivity can allow recovering certain valuable elements from brines (Xu and Drewes, 2005).

CDT systems are characterized with a simple, modular, plate-and frame construction, and low energy requirement. For the development of cost-effective CDT systems, the manufacturing of carbon aerogel needs to be improved while production cost should be reduced. Long regeneration time and carryover of ions following regeneration limit the efficiency of treatment of highly saline water and decrease the production recovery (Xu and Drewes, 2005).

The technology of capacitive deionization is still in the developing stage. Bench-scale experiments have been conducted at Colorado School of Mines using brackish groundwater as part of a research study sponsored by Bureau of Reclamation. An industrial CDT unit with a capacity of 1000 gpd is planned for testing by Colorado School of Mines at a gas production well during late 2005.

Dewvaporation

Dewvaporation technology involves the desalination of seawater and brackish water, suitable for small plant applications. Another potential application of dewvaporation technology could be in the volume reduction of RO concentrates by an order of magnitude (Hamieh et al., 2001).

Dewvaporation is a specific process of humidification-dehumidification desalination. Brackish water is evaporated by heated air, which deposits fresh water as dew on the opposite side of a heat transfer wall. The energy needed for evaporation is supplied by the energy released from dew formation.

Heat sources can be combustible fuel, solar or waste heat. The tower unit is built of thin plastic films to avoid corrosion and to minimize equipment costs. Towers are relatively inexpensive since they operate at atmospheric pressure.

A carrier gas such as air is brought into the bottom of the tower on the evaporation side of a heat transfer wall at a typical wet bulb temperature of 69.8°F. The wall is wetted by saline feedwater, which is fed into the evaporation side at the top of the tower. As the air moves from the bottom to the top of the tower, heat is transferred into the evaporation side through the heat transfer wall, allowing the air to rise in temperature and evaporate water from the wetting saline liquid, which coats the heat transfer wall.

Concentrated liquid leaves from the bottom of the tower, and hot saturated air leaves the tower from the top at 189.3°F. Heat is added to this hot air by an external heat source, increasing the air humidity and temperature to 190.2°F. This hotter saturated air is sent back into the top of the tower on the dew formation side. The dew formation side of the tower, being slightly hotter than the evaporation side, allows the air to cool and transfer condensation heat from the dew formation side to the evaporation side.

Finally, pure water condensate and saturated air leave the dew formation side of the tower at the bottom at 119.7°F. Total external heat needed is made up of the heat needed at the top to establish a heat transfer temperature difference and the heat needed to establish a temperature offset between the saline feed stock and the pure water condensate. The tested recovery is reported as 82 to 85 percent for brackish water and 67 percent for seawater.

The technology is characterized by elimination of scaling problems, since the evaporation occurs at the liquid-air interface and not at the heat transfer wall. Considerations include cost, affordability, small scale, and concentrate disposal.

The technology of dewvaporation is still being developed. Final demonstration project towers have been built and operated at Arizona State University (ASU) laboratories. The Salt River Project and the ASU Office of Technology Collaborations and Licensing are sponsoring the dewvaporation pilot plant program as an extension of grassroots support by the U.S. Bureau of Reclamation (Beckman, 2002). The basic laboratory test unit produces to 150 gallons per day. Eight of these units form a 1,000-gallons-per-day demonstration pilot plant of the dewvaporation process.

Forward Osmosis

In forward osmosis (FO), like RO, water transports across a semi-permeable membrane that is impermeable to salt; however, instead of using hydraulic pressure to create the driving force for water transport through the membrane, the FO process utilizes an osmotic pressure gradient.

A "draw" solution having a significantly higher osmotic pressure than the saline feedwater flows along the permeate side of the membrane, and water naturally transports across the membrane by osmosis. Osmotic driving forces in FO can be significantly greater than hydraulic driving forces in RO, potentially leading to higher water flux rates and recoveries. With the use of a suitable draw solution, very high osmotic pressure driving forces can be generated to achieve high recoveries that, in principle, can lead to salt precipitation.

The saline feedwater is fed to the FO unit, which, in principle, can incorporate spiral wound or hollow fiber membrane modules. The feedwater and draw solution flow tangent to the membrane in a crossflow mode. Through osmosis, water transports from the seawater across the salt rejecting membrane and into the draw solution.

High osmotic pressure gradients can lead to a high recovery given appropriate staging of the process. To yield potable water, the diluted draw solution is sent to a separation unit, comprising a distillation column or a membrane gas separation unit. The separated draw solution is recycled back to the FO unit.

The FO process is characterized by relatively low fouling potential, low energy consumption, simplicity, and reliability (Cath et al., 2005a). With the suitable draw solution and appropriate semi-permeable membrane, the FO process can lead to salt precipitation, i.e., zero liquid discharge.

Considerations include need of appropriate draw solution and membranes, which are the primary obstacle to a feasible FO process. An effective draw solution solute must have very specific characteristics. It must have a high osmotic efficiency and must also be non-toxic, since trace amounts may be present in the product water. Chemical compatibility of the membrane is also a key concern because the draw solution can react or degrade the membrane. Most importantly, for processes involving the production of potable water, the draw solute must be separated and recycled easily and economically.

Previous studies have reported that commercial RO membranes are not suitable for the FO process because of relatively low product water fluxes attributed to severe internal concentration polarization in the porous support and fabric layers of the RO membrane. One of the important tasks for future research is the development of a semi-permeable FO membrane having high salt rejection and minimal internal concentration polarization to realize higher product water fluxes.

The technology of FO is still being developed. A bench-scale FO unit has been built and operated at Yale University laboratory (McCutcheon et al., 2005) supported by the Office of Naval Research.

FO also was used as pretreatment for RO in a direct osmotic concentration (DOC) system for wastewater reclamation in space (Cath et al, 2005a and 2005b). The study was sponsored by NASA's Ames Research Center. The NASA DOC test unit built by Osmotek Inc. was tested at the University of Nevada, Reno. The DOC system provided high wastewater recovery (>95 percent).

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Wind Aided Intensified Evaporation (WAIV)

This technology uses wind energy to enhance the evaporation on wetted surfaces, and thus can be classified as an enhanced evaporation process. The concept is based on exploiting wind energy to evaporate wetted surfaces that are packed in high-density footprint (Gilron et al., 2003). It therefore helps mitigate the large land area requirement of a typical evaporation pond.

The concentrate is sprayed over vertical transport surfaces to reduce the pond footprint. The hydrophilized evaporation surfaces can consist of woven nettings, or nonwoven geotextiles, or tuff (vocanic rock) arranged in trays. Materials with no internal surfaces (netting) are less susceptible to plugging than those with internal surfaces (nonwoven geotextiles).

By deploying such surfaces in arrays with large lateral dimensions, significant height and with minimal depths, the wind can be exploited while it is still less than saturated with vapor. Packing the surfaces should be optimized so they are high enough to get a good enhancement of evaporation while not causing any unnecessary wind blockage.

While process recovery is not directly impacted, this concentrate disposal method offers a new way to implement land evaporation in a reduced area. The pilot study reported that the method allowed increasing the evaporative capacity per area footprint by a factor of 10 or more.

This technology is characterized with relatively low energy costs and reduced footprint and land area requirement, compared to traditional evaporation ponds. Considerations include requirement of a climate with high evaporation rates. This approach has been tested at pilot scale in Israel, at the Blaustein Institute for Desert Research Center in Sde Boker.

Salt Solidification and Sequestration

Desalination concentrate is often viewed as an undesirable residual that requires disposal. If the chemical components in concentrate can be solidated and used as a future source, the recovery of the system can be enhanced and the concentrate minimized.

Jibril and Ibrahim (2001) proposed a process involving absorption of ammonia in brine. The ammoniated brine was then contacted with CO_2. In a series of reactions, concentrated NaCl was converted into valuable products such as $NaHCO_3$, Na_2CO_3, NH_4Cl, and $MgCl_2$. Sandia National Laboratories developed salt adsorption and sequestration techniques to recover salts from brine. Certain layered materials are able to sequester inert inorganic materials around anionic and cationic brine water components at room temperature. The crystallized precipitates can be used as a sellable building material (incorporated into cement, etc.).

The patented SAL-PROC™ process also uses sequential or selective extraction to recover beneficial salts from inorganic saline waters, such as irrigation drainage, produced water, and RO concentrate. Depending on the chemical composition of the saline feedwater, the process route may involve one or more steps of reaction and evapo-cooling supplemented by conventional mineral and chemical processing steps.

SAL-PROC technology has been tested by Geo-Processors Inc. in field trials and piloting. The technology was used to recover salts from the concentrate of a multistage-RO system during treatment of coal bed methane produced water, in Queensland, Australia.

The characteristics of salt solidification include salt recovery and resale and near zero liquid discharge. The sale of products from the facilities could provide significant payback to the projects and could cover the costs involved in installing and running the full-scale facilities. The economics and market of products, however, are under investigation.

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