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Demonstration of Membrane Zero Liquid Discharge for Drinking Water Systems

A LITERATURE REVIEW

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DEMONSTRATION OF MEMBRANE ZERO LIQUID DISCHARGE FOR DRINKING WATER SYSTEMS

A LITERATURE REVIEW

by:
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This purpose of this literature review is to collect background information to assist in the selection of membrane brine minimization/zero liquid discharge (ZLD) technologies for pilot testing in Colorado. The lead author of the literature review was Arturo Burbano with assistance from Philip Brandhuber.

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ABSTRACT AND BENEFITS

Abstract:

At present, water utilities have been reluctant to undertake high pressure (reverse osmosis or nanofiltration) membrane projects due to the uncertainty surrounding the availability of feasible disposal options for the concentrate produced by high pressure membrane systems. Zero liquid discharge (ZLD) is a sustainable disposal option that may represent a long-term solution to concentrate disposal for utilities that need to implement membrane treatment to produce safe water.

In order to assist in the selection of appropriate ZLD technologies for pilot testing at two sites in Colorado, a comprehensive literature review of existing ZLD technologies was performed. This literature review begins with a brief overview of existing concentrate disposal options followed by an in-depth literature review that examines various ZLD technologies that could be evaluated by pilot test. The categories of ZLD options considered by this literature review include:

- Intermediate Treatment
- Thermal-Based Technologies
- Pressure Driven Membrane Technologies
- Electric Potential Driven Membrane Technologies
- Alternative Technologies

Benefits:
- Provide a summary of existing concentrate disposal techniques.
- Review and compare the design, performance and costs of ZLD technologies.

Keywords: Concentrate management, zero liquid discharge (ZLD), brine minimization, membrane treatment.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ARROW	Advanced Reject Recovery of Water
BC	Brine Concentrator
BCRS	Brine Concentrator and Recovery System
BBARWA	Big Bear Area Regional Wastewater Agency
CDPH	California Department of Public Health
CP	Concentration Polarization
DT	Disc Tube
DV	Dewvaporation
EC	Electrocoagulation
ED	Electrodialysis
EDM	Electrodialysis Metathesis
EDR	Electrodialysis Reversal
FBC	Fluidized Bed Crystallizer
FO	Forward Osmosis
GPD	Gallons Per Day
GPM	Gallons Per Minute
GFD	Gallons Per Square Feet Per Day
EVRAS	Evaporative Reduction and Solidification
HEEPM	High Efficiency Electro-Pressure Membrane
HERO	High Efficiency Reverse Osmosis
IBR	Intermediate Biological Reduction
kW	kilo Watt
kWh	kilo Watt hour
LCZ	Lower Convecting Zone
MF	Microfiltration
NCZ	Non-Convecting Zone
POTW	Publicly Owned Treatment Works
PPM	Parts Per Million
PP	Polypropylene
PS	Pellet Softener
PTFE	Polytetrafluroethylene
PVDF	Polyvinylidenefluoride
MD	Membrane Distillation

MEMS	Multi-Effect Multi-Stage
MGD	Million Gallons per Day
MWH	Montgomery Watson Harza
NF	Nanofiltration
O & M	Operation and Maintenance
OPUS	Optimized Pretreatment and Separation
PPM	Parts Per Million
RO	Reverse Osmosis
SGSP	Salinity Gradient Solar Pond
SPARRO	Seeded Slurry Precipitation and Recycle
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UCZ	Upper Convecting Zone
UF	Ultrafiltration
VSEP	Vibratory Shear Enhanced Process
WAC	Weak Acid Cation
WAIV	Wind Aided Intensified Evaporation
ZLD	Zero Liquid Discharge

EXECUTIVE SUMMARY

Increasing demands for potable water in Colorado and other arid locations in the United States have forced drinking water utilities to consider using water from lower quality sources. These lower quality sources may include brackish groundwater or surface water sources impacted by industrial or municipal discharges. Lower quality sources require the use of advanced treatment technologies such as reverse osmosis (RO) or nanofiltration (NF) membranes to treat the water to a level suitable for human consumption. At present, drinking water utilities have been reluctant to undertake RO or NF membrane projects due to the uncertainty surrounding the availability of feasible disposal options for the concentrate. Wastewater utilities in turn have been reluctant to accept membrane concentrate for treatment in their plants.

Zero liquid discharge (ZLD) is a sustainable disposal option that may represent a long-term solution to concentrate disposal for water utilities that need membrane treatment to produce safe drinking water. It may also help alleviate the pressure wastewater treatment plants are under to accept membrane concentrate streams. The primary barrier to implementing ZLD in Colorado is the lack of cost and performance data developed for drinking water systems under conditions unique to Colorado. A pilot test demonstrating ZLD will help address the technical and financial uncertainties which currently hinder its implementation.

In order to assist in the selection of appropriate ZLD technologies for pilot testing at two sites in Colorado, a comprehensive literature review of existing ZLD technologies was performed. This literature review begins with a brief overview of existing concentrate disposal options followed by an in-depth literature review that examines various ZLD technologies that could be evaluated by pilot test. The categories of ZLD options considered by this literature review include:

- Intermediate Treatment
- Thermal-Based Technologies
- Pressure Driven Membrane Technologies
- Electric Potential Driven Membrane Technologies
- Alternative Technologies

Existing concentrate disposal options that potentially can be implemented in Colorado include surface and sewer discharge, deep-well injection, evaporation ponds and land application. Like many other location in the United States however, environmental concerns, high cost or hydrogeologic conditions limit the applicability of these options for the disposal of concentrate from large capacity membrane plants.

Intermediate treatment is used to remove sparingly soluble salts from treated water to increase recovery. As the name implies, these technologies are used in between the primary RO step and the final brine minimization technology. The intermediate step can be accomplished with multiple technologies including lime softeners, pellet softeners (also known as fluidized bed crystallizers), nanofiltration, and activated alumina.

Thermal-based technologies use heat to separate water from the concentrate stream, in order to reduce overall volume of the concentrate stream. Some technologies, such as brine concentrators and crystallizers also provide additional recovery. With other technologies (Wind Aided Intensified Evaporation, solar ponds, spray dryers, Evaporative Reduction and Solidification), the water is not captured and therefore does not increase the system recovery. The maturity of these technologies varies widely. Brine concentrators and crystallizers have been successfully implemented in industrial settings and their performance and costs are well understood. Other technologies, like solar ponds are developmental in nature.

Pressure-driven membrane-based technologies use several strategies to increase recovery. The first approach is to reduce the scaling potential of the concentrate, allowing the use of secondary membranes to operate at high recoveries. Alternatively, raw water quality is substantially modified to reduce scaling potential of the source. A final approach is to use non-spiral wound membrane configurations that are less susceptible to scaling, often in conjunction with spiral wound membranes. Several technologies use a combination of these strategies. Many of these technologies are proprietary and have been demonstrated at small scale.

Electric potential-driven technologies (electrodialysis) use cathodes and anodes to draw ions across ion-exchange membranes, removing ions from the feed stream. This differs from RO membranes which remove water from the feed stream, causing both ionic and non-ionic species to concentrate on the concentrate side of the membrane. With electric potential driven technologies, non-ionic species such as silica are not concentrated and their scaling potential is reduced. These technologies appear to be most suitable when treating low to moderate TDS waters.

Alternative technologies are those which are currently under development and show potential for future use. These include forward osmosis, electrocoagulation, membrane distillation, dewvaporation, and eutectic freeze crystallization. While these technologies have the potential to be more cost effective or environmentally friendly than current technologies, they are not mature enough to warrant testing by this project.

CHAPTER 1.0

INTRODUCTION

Increasing demands for potable water in Colorado and other arid locations in the United States have forced drinking water utilities to consider using water from lower quality sources. These lower quality sources may include brackish groundwater or surface water sources impacted by industrial or municipal discharges. Lower quality sources require the use of advanced treatment technologies such as reverse osmosis (RO) or nanofiltration (NF) membranes to treat the water to a level suitable for human consumption. At present, drinking water utilities have been reluctant to undertake RO or NF membrane projects due to the uncertainty surrounding the availability of feasible disposal options for the concentrate. Wastewater utilities in turn have been reluctant to accept membrane concentrate for treatment in their plants.

Zero liquid discharge (ZLD) is a sustainable disposal option that may represent a long-term solution to concentrate disposal for water utilities that need membrane treatment to produce safe drinking water. It may also help alleviate the pressure wastewater treatment plants are under to accept membrane concentrate streams. The primary barrier to implementing ZLD in Colorado is the lack of cost and performance data developed for drinking water systems under conditions unique to Colorado. A pilot test demonstrating ZLD will help address the technical and financial uncertainties which currently hinder its implementation.

Pilot testing will occur at two existing RO plants, one in Brighton, Colorado and another in La Junta, Colorado. The Brighton plant treats groundwater adjacent to the South Platte River and has an average concentrate TDS of 4,260 mg/L. Based on RO modeling of the existing brine, the constituents that will limit the recovery of Brighton's concentrate are silica and calcium phosphate.

The La Junta plant treats groundwater adjacent to the Arkansas River and has an average concentrate TDS of 7,420 mg/L. Based on RO modeling of the existing brine, the constituent that will limit the recovery of La Junta's concentrate is calcium sulfate.

This literature review begins with a brief overview of available concentrate disposal options followed by an in depth literature review that examines the various high recovery and ZLD technologies currently available for application at these two pilot sites. The various categories of ZLD options include:

- Intermediate Treatment
- Thermal-Based Technologies
- Pressure Driven Membrane Technologies
- Electric Potential Driven Membrane Technologies
- Alternative Technologies (e.g., forward osmosis, membrane distillation, etc.)

CHAPTER 2.0

CONCENTRATE DISPOSAL OPTIONS

Existing disposal options for concentrate are primarily surface water discharge, deep well injection, evaporation ponds and land application (Mickley, 2004). Disposal of concentrate is site specific and the availability of any option depends on the concentrate quality and quantity. Thus, improvement by removing pollutants of environmental concern may facilitate implementation of some disposal options (Nederlof et al., 2005).

2.1 Surface Water and Sewer Discharge

Disposal to surface waters includes discharge to rivers, bays, tidal lakes, brackish canals, or oceans (Bergman, 2007). In the United States, approximately 50% of the existing plants use surface water discharge (Howe, 2004). Economically, ocean disposal is limited to coastal treatment plants with available access. Truesdall et al. (1995) reported that several regulators who responded to a survey on disposal methods noted that surface water discharge permits were becoming more difficult to obtain and the monitoring requirements were becoming more costly. Faced with extensive and costly permit reviews, some plants have avoided surface water discharge in favor of other options (Skehan and Kwiatkowski, 2000).

The major costs associated with surface water discharge are (Jordalh, 2006):

- Engineering costs associated with obtaining discharge permits as well as ongoing water quality testing for compliance and renewal.
- Design and construction costs for post-treatment, conveyance, and outfall structure as well as associated operation and maintenance (O&M) costs.
- Land acquisition costs.

The 2007 Report to the Colorado Water Quality Control Commission reported that in order to dispose of RO/NF concentrate into a surface water, the receiving waterbody plus concentrate must be capable of meeting all water quality goals during low flow conditions. This only occurs when a sufficient low flow is available and/or there are minimal upstream concentrations of contaminants. As a result, surface water discharge in Colorado is not a long term solution for the disposal of RO concentrate.

Dilution or blending of high ionic strength residuals with other wastewaters is another option. In addition, concentrate blended with industrial or municipal wastewaters can undergo further treatment or be disposed of by release to publicly owned treatment works (POTW) (Glueckstern and Priel, 1997; Sethi et al., 2005). The dilution available from the POTW might assist in reducing the contaminant concentrations in the RO/NF waste stream to acceptable levels. This concentrate flow may constitute a new source to the POTW, if not already historically accepted. As such, in order to protect beneficial uses of the receiving waterbody, the Colorado Water Quality Control Division could modify the permit to require an assessment of the need for limits on any constituents not considered in the original analysis. This option, if initially feasible, may not be a permanent solution (Membrane Treatment Workgroup, 2007).

2.2 Deep-Well Injection

Deep-well injection enables concentrate to be pumped into porous subsurface rock formations. Well depths can vary from a few hundred feet to several thousand feet depending on the geological conditions at the site (Glater and Cohen, 2003). Injection well systems generally consist of a pump and a lined shaft (usually 1,000 to 8,000 ft in depth) which is protected by a casing and cement grouting. While considering deep-well injection, the nature of the substrata must be carefully considered in selecting a suitable location for injection (Rhee et al., 1993). Also, the total suspended solids (TSS) content of the concentrate, injection rate, injection pressure, porosity and permeability of the well strata need to be studied for proper design and operation of deep-well injection (Glater and Cohen, 2003). Injection zones must have a total dissolved solids (TDS) level greater than 10,000 mg/L and at least one overlaying, confining layer (Bergman, 2007).

Deep well injection costs depend on the concentrate volume, the distance from the plant to the injection point, well depth, pumping pressure, emergency storage and regulatory monitoring (Glater and Cohen, 2003). Due to concerns about aquifer contamination, injection wells are usually not located where groundwater supply for domestic or agricultural use is significant, in areas vulnerable to earthquakes, or in regions with mineral resources (Ahmed, 2000). Although it is unlikely that dense concentrate discharge will rise into drinking water or irrigation zones, monitoring wells are typically installed to ensure the integrity of the boundaries.

Deep-well injection is a reasonable method for concentrate disposal provided that long-term operation can be maintained, in order to dispose of large volumes of process fluid (Mickley, 2004). Considerations for deep-well injection include selection of a suitable well site, costs involved in conditioning the waste concentrate, possibility of corrosion and subsequent leakage in the well casing, and seismic activity – which could cause damage to the well and uncertainty of the well half-life (Saripalli et al., 2000).

Deep-well injection in Colorado is subject to issuance of an Underground Injection Control permit from the EPA Region VIII, to protect current and future underground sources of drinking water. The ability to use deep well injection for larger facilities may be limited in Colorado, principally due to site-specific incompatible hydrogeologic conditions (Membrane Treatment Workgroup, 2007).

2.3 Evaporation Ponds

Evaporation ponds are most appropriate for small flows and for regions having a relatively warm, dry climate with high evaporation rates, level terrain, and low land costs. (Mickley, 2001). Evaporation ponds have an extensive history of use, are easy to construct, and require less maintenance and operator attention than mechanical systems (Ahmed, 2000). At this time, evaporation ponds are probably the most widespread method of concentrate disposal for inland-based desalination facilities worldwide (Glater and Cohen, 2003).

Evaporation ponds require impervious liners of clay or synthetic membranes to limit potential contamination of underlying potable water aquifers (Ahmed, 2000; Ahmed et al., 2001). Disadvantages include large land requirements and compatible weather patterns, expensive liners, odors, impacts to wildlife (especially birds), and the potential for seepage. The primary environmental concern associated with evaporation ponds is leakage. All current installations are lined with polyethylene or various other polymeric sheets (Glater and Cohen, 2003). To prevent leaks and provide leakage monitoring, polymeric sheets are double lined and leakage sensing probes are installed between layers of pond lining. Design of evaporation ponds is based on the concentrate flow and the estimated brine evaporation rate; solids are usually not removed from the pond. Due to land area requirements, this option may be limited to smaller facilities (Membrane Treatment Workgroup, 2007).

2.4 Land Application

Land application methods for concentrate disposal consist mainly of disposal to creeks and ponds. Percolation ponds or rapid infiltration basins are a viable disposal alternative where the waste will not significantly affect the quality of the groundwater in the receiving area. This option may be employed for discharge over shallow brackish aquifers, usually in areas which border estuaries or tidal creeks (Acquaviva et al., 1997). Application rates are generally high, in the range of 4-80 inches per week (Jordahl, 2006) and are usually applicable for low TDS waters because infiltration is not capable of removing many salts.

2.5 Conclusion

Due to the current regulatory environment, cost of land and hydrogeologic conditions, disposing of concentrate without further treatment or volume reduction is of limited feasiblity in Colorado. The following chapter discusses a number of options for reducing the volume of concentrate to the point where disposal (likely through the use of evaporation ponds) becomes feasible.

CHAPTER 3.0

BRINE VOLUME MINIMIZATION AND ZLD TECHNOLOGIES

3.1 Intermediate Treatment

Intermediate treatment is used to remove sparingly soluble salts that inhibit the recovery of concentrate. As the name implies, these technologies are used in-between the primary RO step and the final brine minimization technology. The intermediate step can be accomplished with multiple technologies including lime softeners, pellet softeners (also known as fluidized bed crystallizers), nanofiltration, and activated alumina, all of which are discussed in more depth below.

3.1.1 Lime Softening

In lime softening, lime slurry is added to the brine to raise the pH and precipitate calcium carbonate and magnesium hydroxide. Calcium is removed as calcium carbonate while silica is removed by co-precipitation with magnesium hydroxide (Gabelich et al., 2011). Metals (such as barium) are also removed by co-precipitation (Gabelich et al., 2011). Lime softening has been primarily used in the industrial sector as an intermediate treatment followed by a secondary RO system (Subramani et al., 2011). The advantage of using a lime softening system for intermediate treatment is primarily due to the high removal rates of scale forming ions. Drawbacks include large sludge volumes and difficulties achieving accurate control of pH conditions in the contactor.

3.1.2 Pellet Softening

In the case of pellet softening, sodium hydroxide is added to the brine and fed to a reactor system consisting of sand pellets. Calcium carbonate precipitation occurs on the sand particles which act as seed crystals. Saturated calcium carbonate crystals are removed from the bottom and can be used as a saleable product.

In a pilot-study, energy savings and costs associated from using a pellet reactor to treat brackish water RO concentrate were determined to be 50% lower than disposing brine directly to an evaporation pond (Bond and Veerapaneni, 2008). In this study, the primary RO was operated at 85% recovery. The concentrate from the primary RO was passed through a pellet reactor and NaOH and $Na_2Al_2O_4$ were added to the bottom of the reactor. The reactor was loaded with quartz or garnet sand to a fixed bed height of 400 to 500 mm. The pellet reactor was used to remove calcium and silica from the primary RO concentrate. The pellets in the reactor were used as nucleation sites for $CaCO_3$ crystals to grow on. When the pellet size increased due to growth of crystals, spent pellets were removed from the bottom and fresh sand was added from the top. The pellet rector system was backwashed on a daily basis. The effluent from the reactor was discharged to the secondary RO. Costs and energy estimates were made by assuming discharge of secondary RO concentrate to a brine concentrator and finally to evaporation ponds. Results from the study indicated that the cost of desalination and energy consumption to achieve ZLD can be significantly reduced by using secondary RO for treatment of concentrate. Costs could be reduced 50-70% and energy consumption could be reduced by 60-75% when compared to conventional thermal ZLD approach (Bond and Veerapaneni, 2008).

3.1.3 Nanofiltration

Nanofiltration (NF) membranes are designed to effectively remove divalent ions, such as calcium, magnesium and sulfate while minimizing pressure requirements by allowing smaller monovalent ions to pass through the membrane. The removal of scaling ions combined with the lower energy requirements, makes NF a viable technology for water softening.

3.1.4 Activated Alumina

Activated alumina is used primarily for the removal of silica (Bouguerra et al., 2007). The nature of silica in solution had a significant influence on its removal. Adsorption was strongly dependant on pH and adsorbent dose. A maximum of 90% silica removal was achieved at a pH of 8.0-8.5. However, the effect of sulfate, fluoride, and nitrate did not significantly decrease the amount of silica removed.

To evaluate silica removal in the pH range 8-9, tests were conducted to study adsorption onto different forms of aluminum. The forms of aluminum tested were activated alumina, sodium aluminate, and alum (Bond and Veerapaneni, 2007). Both sodium aluminate and alum were found to be effective for silica removal, but these chemicals had an opposite effect on alkalinity. In the case of sodium aluminate, alkalinity was added to the water. In the case of alum, alkalinity was consumed from the water. Specifically, for each mole of sodium aluminate used, two equivalents of alkalinity were added to the water. In contrast, for each mole of alum used, six equivalents of alkalinity were consumed. Hence selection of chemical was based on maintaining the target pH range.

Adsorption with activated alumina for primary RO concentrate was tested at four different sites (Bond and Veerapaneni, 2007). Activated alumina was found to be very effective for silica removal, reducing silica concentrations from 100 mg/L to less than 5 mg/L. In addition, reduction of calcium and barium concentrations were observed. Analysis of test results with Freundlich isotherm model indicated that the bed service time for silica removal would be 17 to 40 hours. The frequency of media regeneration that would be required and the associated volume of liquid waste generated were deemed impractical.

3.2 Thermal-Based Technologies

Thermal-based technologies use heat to separate water from the concentrate stream, in order to reduce overall volume of the concentrate stream. Some technologies also provide additional recovery, such as brine concentrators and crystallizers. With other technologies (WAIV, solar ponds, spray dryers, EVRAS), the water is not captured and therefore does not increase the system recovery.

3.2.1 Brine Concentrators

Brine concentrators consist of vertical tube bundles with brine evaporating from a thin film on the inside of the tubes. The brine absorbs heat from condensing water vapor on the outside of the tubes and the latent heat of vaporization transfers from the water vapor through the tube wall to the thin brine film on the inside of the tube (Mickley, 2006). Following heat-exchange, this stream can be used further by returning it upstream to the membrane treatment process. A schematic of brine concentrator is provided by Mackey and Seacord, 2008.

Brine concentrators are oftentimes designed to operate in a slurry mode where calcium sulfate is added to the recycle to provide nucleation sites for the precipitation of scale to prevent scaling of heat transfer surface. Some important issues associated with brine concentrator are as follows (Mickley, 2006).

- Brine concentrators are typically capable of concentrating brine by as much as 40 to one without any scaling problems, where the waste stream from the concentrator is typically 2-10% of the feed water flow.
- The TDS of the reject stream can be as high as 250,000 mg/L.
- Concentrators can produce high quality water (TDS less than 10 mg/L).
- Typical brine concentrator capacity ranges from 10 to 700 gpm.

There are about 75 brine concentrators in operation worldwide and approximately 10 of these systems are used for RO concentrate management in industrial plants (Mickley, 2006). Brine concentrator recovery depends on the feed water quality, but typically ranges from 90-98% of the feed concentrate stream. Brine concentrators are energy-intensive, requiring approximately 70-100 kWh of energy per 1,000 gallons concentrate treated.

As part of the Las Vegas Valley Shallow Groundwater Study performed by Black and Veatch, an economic evaluation on RO concentrate disposal to evaporation pond, compared to brine concentrator coupled with evaporation pond was conducted. That study (Stanford et al., 2010), found that just the land cost (344 acres) associated with disposal through evaporation ponds alone cost $11.29 per 1,000 gallons. A brine concentrator coupled with a crystallizer would cost $4.15/kgal while a brine concentrator with evaporation ponds was the most economic option at $3.1/ kgal (Stanford, et al., 2010).

3.2.2 Brine Crystallizers

Brine crystallizers are typically vertical cylindrical vessels with heat input from vapor compressors or an available stream supply. A schematic of brine crystallizer is provided by Mackey and Seacord, 2008. Feed brine is mixed with recirculating brine and pumped to a shell-and-tube heat exchanger where the brine is heated by vapor from the compressor, and as water evaporates, salts precipitate out of the concentrated solution. Brine crystallizers are oftentimes employed with brine concentrators. Crystallizers typically require approximately 200-250 kWh of energy per 1,000 gal treated brine, which is approximately three times the energy required by brine concentrators (Mickley et al., 2006).

3.2.3 Wind Aided Intensified Evaporation (WAIV)

Several technologies in various stages of development have been shown to increase evaporation rates of evaporation ponds. Examples include implementation of vertical wetted packing towers that utilize wind in the drying process (Gilron et al., 2003), otherwise known as Wind-Aided Intensification of Vaporization (WAIV). An illustration of WAIV is shown in Figure 3-1. In WAIV the concentrate is sprayed over vertical transport surfaces to reduce the pond footprint. The evaporation surface usually consists of woven nettings, non-woven geotextiles, or tuff (volcanic rock) arranged in trays (Sethi et al., 2006). Packing of surface is optimized to achieve enhanced evaporation. Materials with no internal surfaces (netting) are less susceptible to plugging than those with internal surfaces (non-woven geotextiles). By utilizing such surfaces in arrays with large lateral dimensions, wind can be exploited while it is still less than saturated with vapor. The WAIV method has been reported to increase the evaporation capacity per area footprint by a factor of 10 or more (Sethi et al., 2006). The technology is characterized with low energy costs and reduced footprint and land area requirement, compared to traditional evaporation ponds. Other developments include use of water cannon to pressurize the water prior to pond discharge or solar powered reservoir circulators (Sethi et al., 2006).

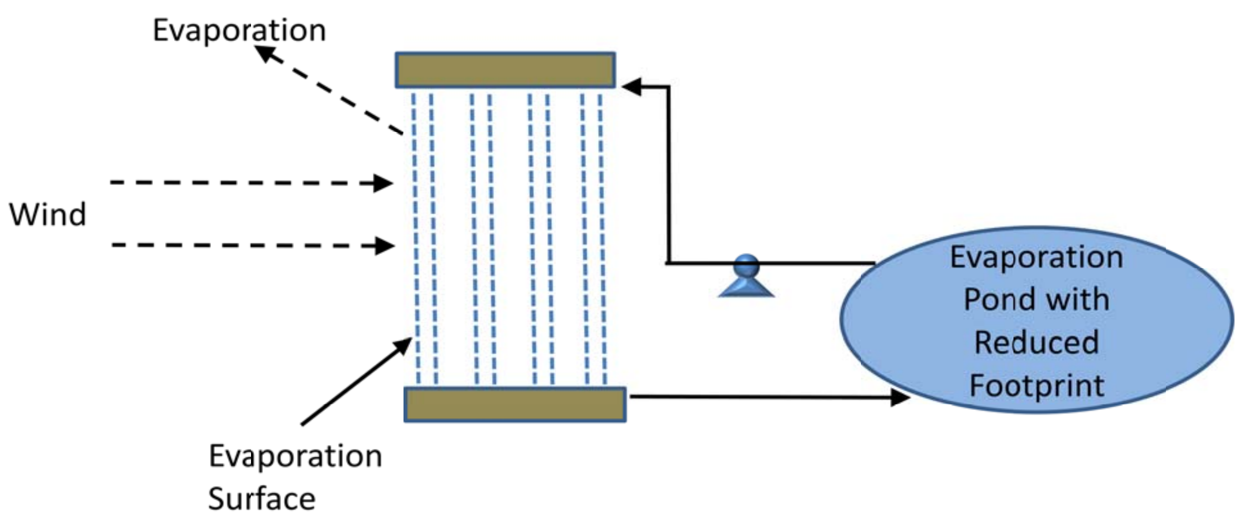

Figure 3-1. Illustration of WAIV Technology.
Adapted from Sethi et al., 2009.

3.2.4 Salinity Gradient Solar Pond – Brine Concentrator and Recovery System

Salinity gradient solar ponds (SGSP) allow for the storage of brine in a manner that also provides storage for waste heat. The waste heat can then be used to provide energy for various applications, including operation of the desalination systems. An example of SGSP coupled with desalination system for ZLD application is shown in Figure 3-2. The brine from the RO system is treated using a second stage thermal desalination process. The brine from the thermal desalination system is then fed into the third stage brine concentrator and recovery system (BCRS). The salt slurry from the BCRS is then fed to SGSP. The hot brine from the ponds can use a thermal source to evaporate the water to be desalted at low pressure in an evaporator (Kalagirou, 2005).

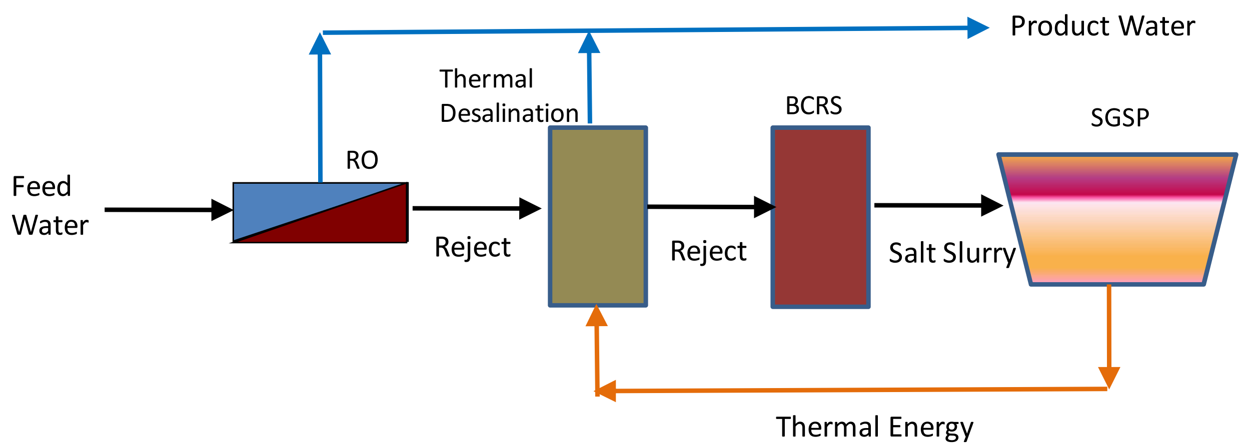

Figure 3-2. Schematic of Zero Liquid Discharge System Using Salinity Gradient Solar Pond and Brine Concentrator and Recovery System.
Adapted from Lu et al., 2001.

Solar ponds conserve heat by reducing the heat losses that would occur if the less dense heated water were allowed to rise to the surface of the pond and lose energy to the atmosphere by convection and radiation (Kalogirou, 2005). An illustration of a salinity gradient solar pond (SGSP) is shown in Figure 3-3. The objective of the solar pond is to create a stagnant and insulating zone in the upper part of the pond to contain the hot fluid in the lower section of the pond. In a solar pond there are three distinct zones. The upper zone is the surface zone and is a convecting zone (UCZ); it is of low salinity and is close to ambient temperature. The UCZ is typically 0.3 m thick, which is a result of wind-induced mixing and surface flushing. This zone is kept as thin as possible by using wave-suppressing surface meshes and placing wind-breaks near the pond. The middle zone is the insulation zone and is a non-convecting zone (NCZ). In the NCZ, both salinity and temperature increase with depth. The vertical salt gradient in the NCZ inhibits convection and provides thermal insulation. The lower section of the pond is the storage zone and is the lower convecting zone (LCZ). In the LCZ, the salinity is high (typically 20% by weight) and the temperature is high (70-80^{o}C). Heat stored in the LCZ can be utilized to supply heat energy throughout the year.

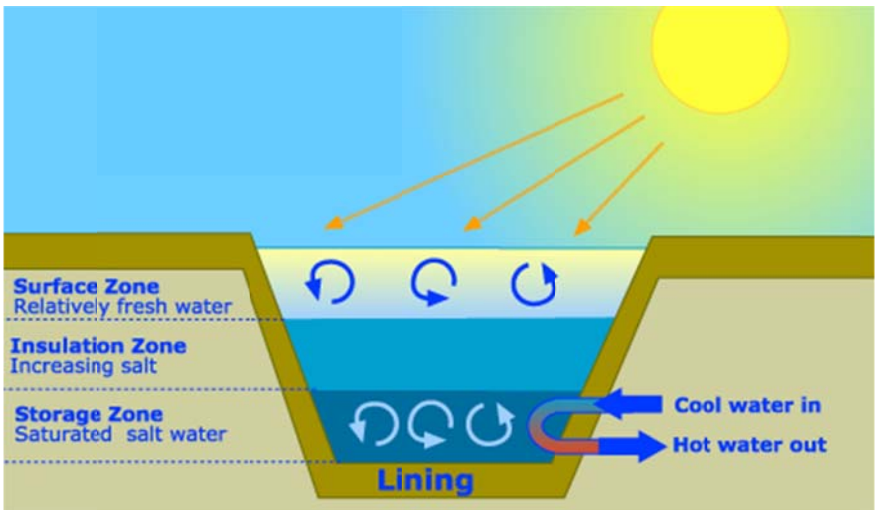

Figure 3-3. Schematic of Solar Pond.
Energy Education of Texas, 2011.

Electric power generation from solar ponds has been evaluated in Israel (Tabor, 1981). The analysis included a 1500 m^2 solar pond used to operate a 6 kW Rankine cycle turbine-generator and a 7000 m^2 solar pond for producing 150 kW of peak power. Both the solar ponds were operated at about 90^{o}C.

When evaluating solar ponds, several factors need to be considered. Since solar ponds are horizontal solar collectors, site location should be at low to moderate northern and southern latitudes ($\pm$ 40^{o}). The water table should be at least a few meters below the bottom of the pond to minimize heat losses, since the thermal conductivity of the soil increases greatly with moisture content. Lining material that will minimize transport to the underlying aquifers must be used. Most solar ponds constructed today consist of a reinforced polymer material 0.75-1.25 mm in thickness.

3.2.5 Spray Dryers

Spray dryers are comprised of a vertical drying chamber and a centrifugal atomizer through which the concentrate slurry is sprayed (Mackey and Seacord, 2008). The dry solids are blown by hot air through a bag filter, where they are collected. The moist air is exhausted out the top of the bag and the solids are collected in a hopper below. Associated equipment for the spray dryer include conveyance pipe to the dryer, an atomizer, spray drying chamber, a bag filter and a solids storage chamber (Mackey and Seacord, 2008). Spray dryers are typically more economical to operate than brine crystallizers at flow rates below 10 gpm (Mickley, 2006). Advantages of a spray dryer include: concentration of slurries to solids waste, feasible in areas where other low cost options are not available and a small footprint. Disadvantages of a spray dryer for concentrate management are the high capital costs and high energy requirements (> 200 kWh/1000 gal) (Mackey and Seacord, 2008).

3.2.6 Evaporative Reduction and Solidification (EVRAS)

The EVRAS process is an evaporative system similar to a cooling tower that relies on water temperature, surface area and airflow (RPSEA, 2009). The EVRAS is a patented technology provided by Intevras Technologies, LLC, a Texas based privately held company. A schematic of the technology is available from Intevras, 2011). The technology is used for brine treatment and utilizes low-grade waste heat to concentrate and/or crystallize large volume of brine streams. EVRAS is an evaporative system and fresh water is not recovered. Without waste heat available onsite, the process is energy intensive. The EVRAS system has primarily been used in industrial applications with limited applications in the municipal sector. The advantages of the system include (RPSEA, 2009):

- Use of low temperature waste heat
- TDS insensitive
- Corrosion resistant and minimal scaling problems
- Simplicity in operation and minimal maintenance
- No blow-down or discharge

3.2.7 Comparison of Thermal-Based Technologies

A comparison of thermal-based technologies is listed in Table 3-1. All the thermal-based technologies are energy intensive. Reducing RO brine volume will be critical for reducing the costs of using thermal-based technologies. Technologies for reducing the brine volume are discussed in detail in the next two sections.

Table 3-1. Comparison of Thermal-Based Technologies for Brine Management.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
Brine Concentrator/ Brine Crystallizer	Recoveries range between 90-98%. In combination with evaporation pond or other technologies, ZLD is achievable.	Brine Concentrator: 70-100 kWh/1,000 gal	Brine concentrator + crystallizer: $4.15/kgal. (Stanford, B.D., et al., 2010)	Well developed technology.	High capital costs.
		Brine Crystallizer: 200-250 kWh/1,000 gal	Brine concentrator + evaporation pond: $3.1/ kgal. (Stanford, B.D., et al., 2010)	TDS of brine to be treated can be as high as 250,000 mg/L. High quality water (TDS of < 10 mg/L) is produced.	High energy consumption.
Wind Aided Intensified Evaporation (WAIV)	All water is evaporated and hence "lost" to atmosphere.	Data not available. Overall energy consumption will be higher than evaporation ponds due to additional pumping energy requirements.		Compact and modular design.	Higher capital and O&M costs when compared to evaporation ponds. If the technologies are used together, the reduced pond size may reduce costs.
				Reduced footprint by 10 times compared to evaporation pond.	Sludge disposal required periodically.
Salinity Gradient Solar Pond (SGSP) – Brine Concentrator and Recovery System (BCRS)	In combination with other technologies, ZLD is achievable.	Data not available. Thermal energy from SGSP is re-used for process needs.		Thermal energy from the SGSP is used to heat the feed water of thermal processes.	Large footprint requirement.
				Electric power generation is possible with SGSP.	Plant site must be in a region receiving high solar radiation.

Spray Dryers	All water is evaporated and hence "lost" to atmosphere.	> 200 kWh/1,000 gal		Cheaper to operate than brine crystallizers at flow rates below 10 gpm.	High capital costs.
				Feasible in locations where low-cost options are not available for brine treatment.	High energy consumption.
Evaporative Reduction and Solidification (EVRAS)	All water is evaporated and hence "lost" to atmosphere.	Data not available. Energy consumption will be lower when waste heat is available.		Process is insensitive to TDS of brine to be treated.	Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment.
				Corrosion resistant and minimum scaling problem.	

3.3 Pressure Driven Membrane Technologies

Membrane-based technologies modify the traditional RO membrane system such that scaling potential is reduced, allowing the secondary membrane process to operate at high recovery rates.

3.3.1 Dual Reverse Osmosis with Intermediate Demineralization

In this approach the feed water passes through a primary RO followed by an intermediate demineralization step (as introduced in Section 3.1) before being fed to a secondary RO system. (Bond and Veerapaneni, 2007; Gabelich et al., 2011; Subramani et al., 2011). The intermediate demineralization removes scaling precursors (such as calcium, magnesium, barium, silica, etc.) to allow a secondary RO to be used to increase the overall recovery. The concentrate from the secondary RO can be further treated with a brine concentrator and finally sent to an evaporation pond to achieve zero liquid discharge. The permeate from the primary and secondary RO and the distillate from the brine concentrate can be blended as product water. Unlike thermal desalination, the use of RO membranes to treat concentrate requires chemical treatment to remove constituents that would inhibit membrane performance. An illustration of the process is shown in Figure 3-4.

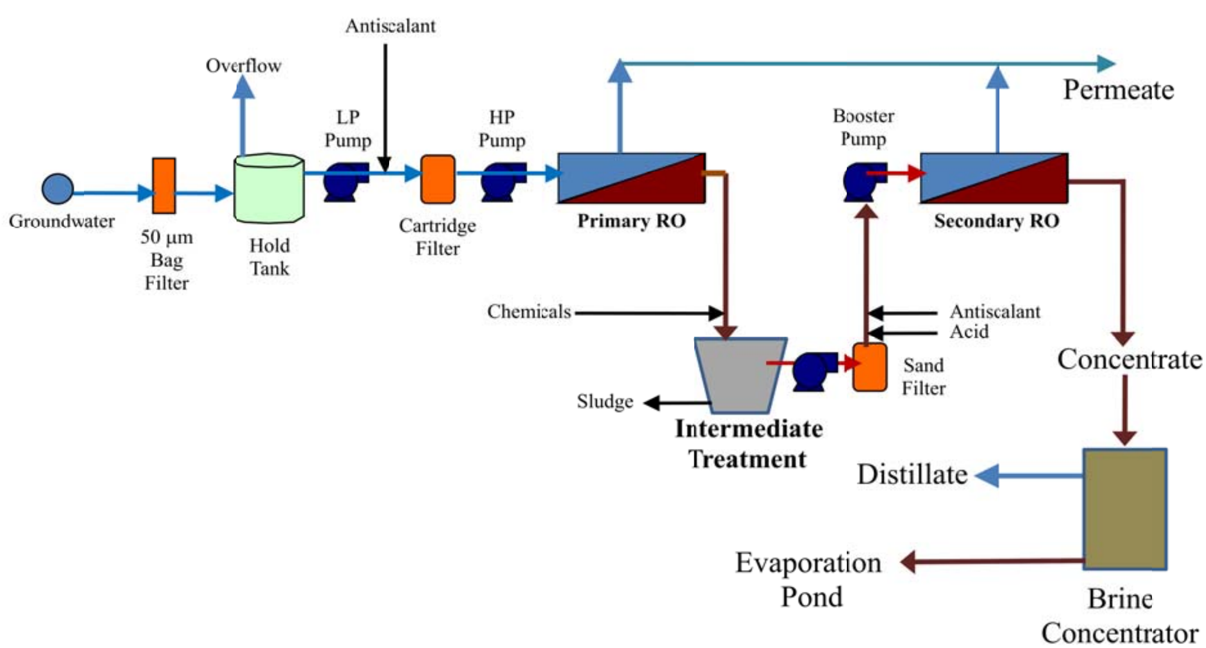

Figure 3-4. Process Schematic for Desalination with Zero Liquid Discharge Using Secondary RO Membranes. Adapted from Subramani et al., 2011.

A schematic of dual RO with pellet softener is shown in Figure 3-5. Concentrate from a primary RO system is treated with lime or sodium hydroxide in a pellet reactor. Sand is fed to the pellet reactor to serve as nucleation sites for the precipitation of calcium carbonate. The pellet softener is used to reduce the concentration of calcium (removed as calcium carbonate) and silica (co-precipitated with magnesium hydroxide). The saturated calcium carbonate pellets from the softener can be used as a saleable product. The treated water from the pellet reactor is filtered and further treated using a secondary RO system to enhance the feed water recovery. The final brine from the secondary RO can be passed through a brine concentrator and finally to an evaporation pond to achieve zero liquid discharge.

In a pilot-study, energy savings and costs from using a pellet reactor to treat brackish water RO concentrate was determined to be 50% lower, than disposing brine directly to an evaporation pond (Bond and Veerapaneni, 2008). In this study, the primary RO was operated at 85% recovery. The concentrate from the primary RO was passed through a pellet reactor and NaOH and $Na_2Al_2O_4$ were added to the bottom of the reactor. The reactor was loaded with quartz or garnet sand to a fixed bed height of 400-500 mm. The pellet reactor was used to remove calcium and silica from the primary RO concentrate. The pellets in the reactor were used as nucleation sites for $CaCO_3$ crystals to grow on. When the pellet size increased due to growth of crystals, spent pellets were removed from the bottom and fresh sand was added from the top. The pellet rector system was backwashed on a daily basis. The effluent from the reactor was discharged to the secondary RO. Costs and energy estimates were made by assuming discharge of secondary RO concentrate to a brine concentrator and finally to evaporation ponds. Results from the study indicated that the cost of desalination and energy consumption to achieve ZLD can be significantly reduced by using secondary RO for treatment of concentrate. Costs could be reduced 50-70% and energy consumption could be reduced by 60-75% when compared to conventional thermal ZLD approach (Bond and Veerapaneni, 2008).

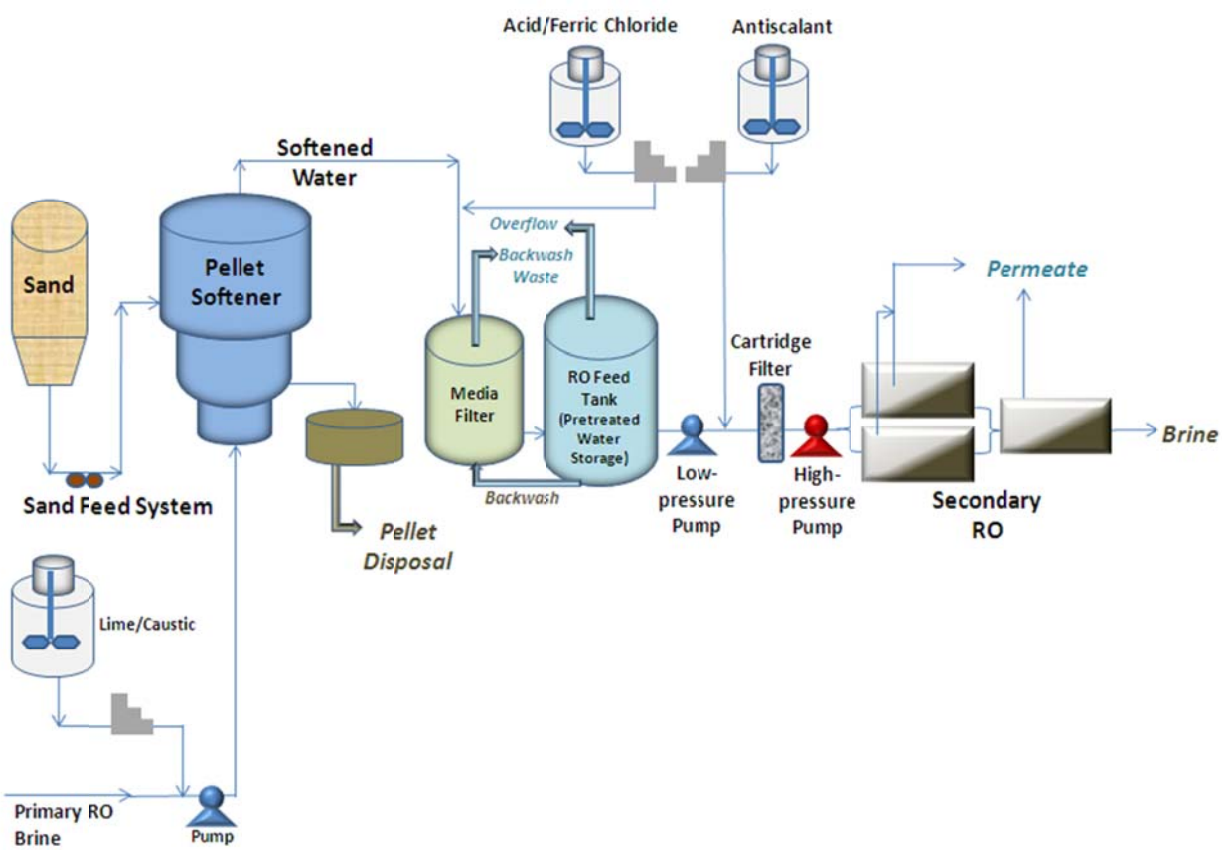

Figure 3-5. Schematic of Concentrate Volume Minimization Process using Pellet Softener and Secondary RO. Adapted from Bond and Veerapaneni, 2008.

3.3.2 Dual Reverse Osmosis with Intermediate Biological Reduction (IBR)

In this approach, sulfate present in the primary RO brine is reduced biologically. The treated primary RO brine is further treated using a secondary RO to enhance the overall feed water recovery (Williams and Pirbazari, 2003). A schematic of the process is shown in Figure 3-6.

The biological reduction step primarily removes anions such as sulfate and carbonate via biological treatment and air stripping. Sulfate is reduced to sulfide by sulfate reducing bacteria after addition of an electron donor (such as acetate or ethanol). The reaction is favorable under anaerobic conditions (Williams and Pirbazari, 2003). Sulfides and carbonates are subsequently air stripped under acidic conditions. Following gravity thickener and filtration, the treated brine is fed to a secondary RO system.

A combined recovery of 95% and higher has been reported for brackish water treatment using this approach (Williams and Pirbazari, 2003). Advantages of the treatment scheme include the utilization of well-established treatment processes and relatively low additional energy requirements for treatment of brine. Drawbacks of the treatment scheme include the addition of chemicals and biological treatment, production of sludge from the solids removal process and footprint and costs associated with additional unit processes (Sethi et al., 2009).

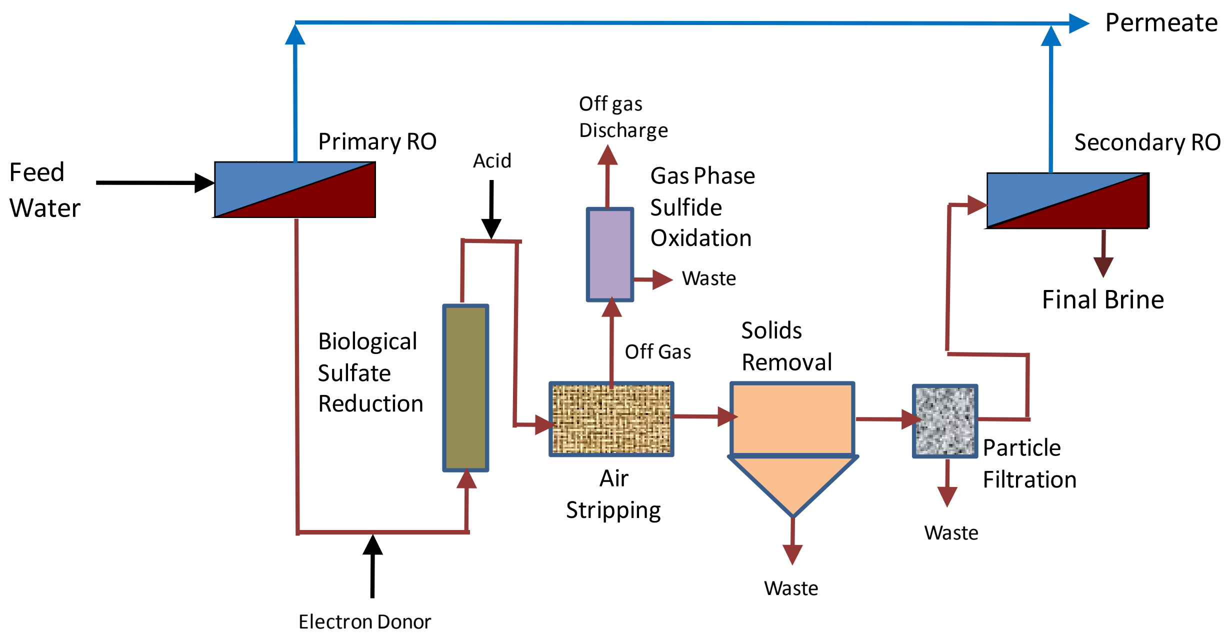

Figure 3-6. Schematic of Dual RO with Intermediate Biological Reduction.
Adapted from Williams and Pirbazari, 2003.

3.3.3 Seeded Slurry Precipitation and Recycle (SPARRO)

The seeded slurry precipitation and recycle RO technology uses crystals to precipitate scaling compounds (Juby and Schutte, 2000). A schematic of the SPARRO process is shown in Figure 3-7. Seed crystals are introduced in a tubular RO membrane to precipitate scaling compounds on the seeds. A slurry of seed crystals are circulated within the RO system. The seed crystals serve as nucleation sites instead of the membrane surface. The SPARRO process is primarily used to precipitate calcium sulfate and other calcium salts and silicates that begin to precipitate when the solubility limits are exceeded. Gypsum crystals are used to precipitate calcium sulfate. The feed water to be desalted is mixed with a stream of recycle concentrate containing seed crystals and fed to the RO process. The concentrate with seed crystals is processed in a cyclone separator to separate the crystals (Juby and Schutte, 2000). The combined recovery of the process has been reported to be greater than 90% (Sethi et al., 2006). The SPARRO technology has been reported to have relatively low energy costs. Drawbacks of the technology include the use of tubular RO membranes, footprint and additional chemicals (Sethi et al., 2006).

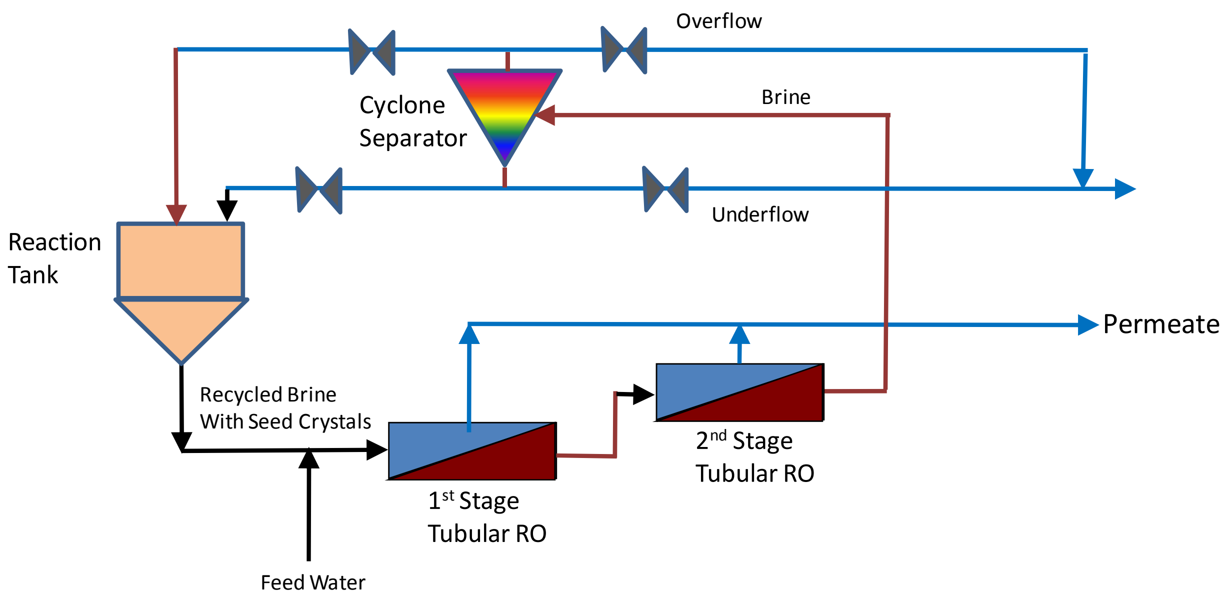

Figure 3-7. Schematic of SPARRO Process.
Adapted from Juby and Schutte, 2000.

3.3.4 High-Efficiency Reverse Osmosis (HERO)

HERO is a patented technology and consists of a hardness and alkalinity removal step, a degasification step to remove carbon dioxide and caustic addition to increase the pH of the RO feed water (Mukhopadhyay, 1999). A schematic of the HERO process is shown in Figure 3-8. For brackish water treatment, the process combines a dual RO system with chemical pretreatment of primary RO, intermediate ion exchange treatment of primary RO brine, and high pH operation of secondary RO (Jun et al., 2004). The secondary RO system operates as a "high efficiency" system due to ion exchange pretreatment and high pH operation.

The brine from the primary RO is treated using weakly acidic cationic (WAC) exchange resins to remove divalent ions (such as calcium). The carbon dioxide from the brine is removed and pH is raised above 10 to allow operation of the secondary RO at high recoveries. Operation of the secondary RO at high pH results in higher rejection of the membranes. The solubility of silica is also increased at high pH and allows the RO system to operate at high recoveries on brackish water with high silica concentrations.

The combined recovery of the process is estimated to be greater than 90% for brackish water with typical target recovery rates of approximately 95% (Sethi et al., 2009). Advantages of the technology include the use of well-established unit processes, negligible potential of silica or calcium carbonate scaling, higher rejection of ions and less frequent cleaning. Limitations of the process include dealing with a proprietary technology, additional chemical and ion exchange treatment, production of sludge from the chemical treatment process and higher footprint (Sethi et al., 2009).

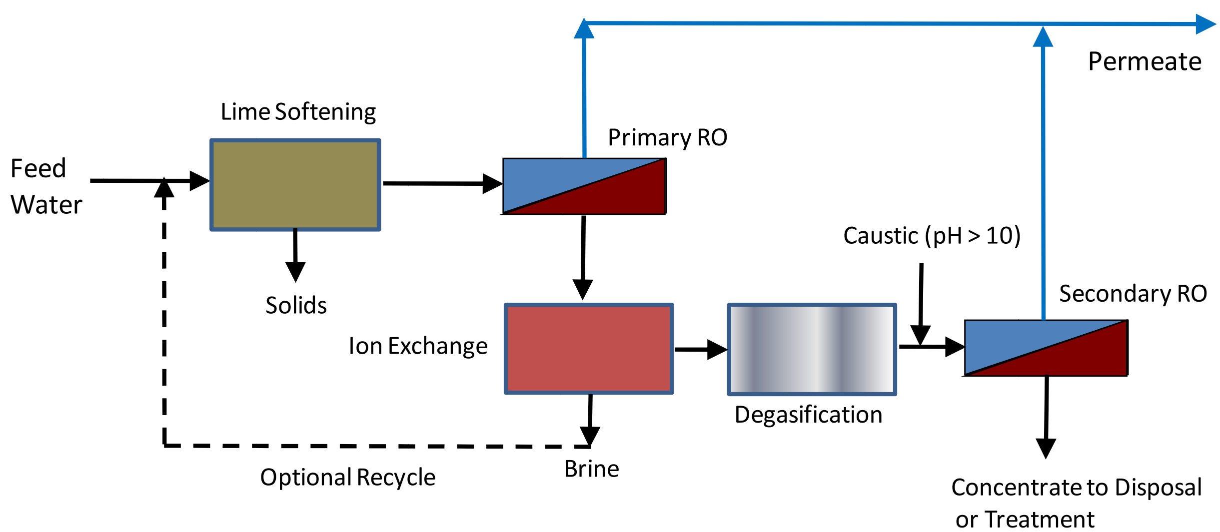

Figure 3-8. Schematic of HERO Process.
Adapted from Jun et al., 2004.

3.3.5 High-Efficiency Electro-Pressure Membrane (HEEPM)

HEEPM is a patented technology consisting of an ED stack design and spiral wound RO system (EET, 2011). A schematic of HEEPM is shown in Figure 3-9. The ED design significantly reduces the energy requirement and allows processing to high salinities. Salinities in excess of 200,000 mg/L have been achieved (EET, 2011). In this configuration, both ED and RO are used taking feed from the same working tank. The product water from the ED stack and RO concentrate are returned back to the working tank. The final system waste is from the ED stack and the product water is from the RO system. The processing arrangement minimizes ED membrane area relative to ED-only systems while maximizing recovery relative to RO-only systems (Mickley, 2008).

The HEEPM system is applicable to batch, semibatch, or continuous flow arrangements. The advantages are high for batch processing, where the arrangement allows for maintaining a lower feed concentration to the RO system while the batch volume is being reduced due to the treatment (Mickley, 2008). The purpose of the ED stack is to keep the RO feed TDS at a relatively constant level over the high recovery processing time. The combination of ED and RO has been shown to be cost effective (Mickley, 2008).

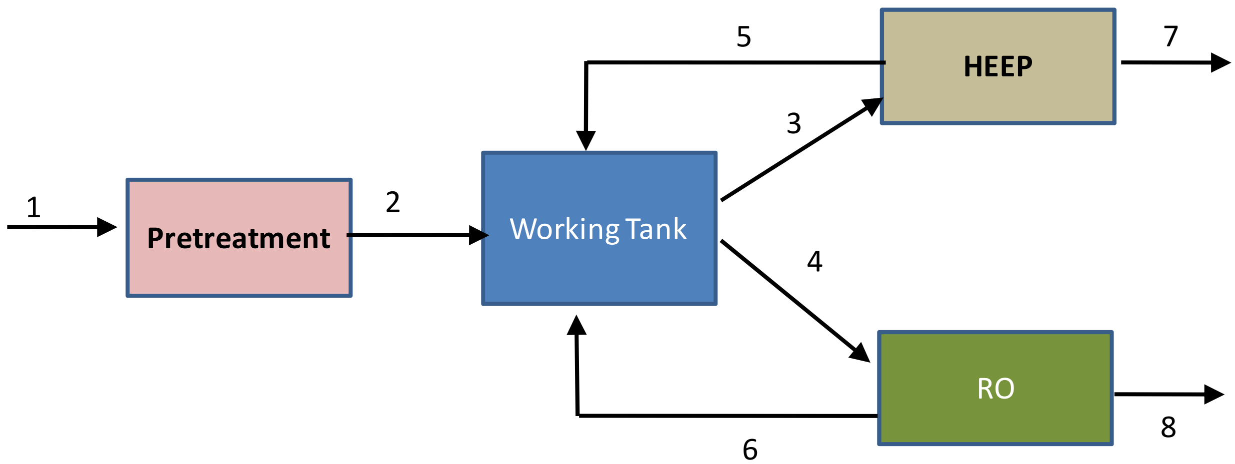

Figure 3-9. Schematic of HEEPM Technology.
Adapted from Mickley, 2008.

Note:

1. Raw water	2. Treated water from pretreatment step	3. Feed to ED unit	4. Feed to RO unit
5. Product stream from HEEP unit	6. Concentrate from RO unit	7. Waste stream from HEEP	8. Product stream from RO unit

3.3.6 Advanced Reject Recovery of Water (ARROW)

ARROW is a patented technology licensed by O'Brien & Gere that allows for high recovery treatment (Mickley, 2008). A schematic of the technology is shown in Figure 3-10. In the ARROW configuration, instead of typical chemical precipitation before the RO process or in between stages, precipitation is performed in the back-end (i.e., in the reject of second stage RO) (Mickley, 2008). The primary benefit of the configuration is the reduction of brine volume that needs to be chemical treated, leading to lower foot print. In the chemical precipitation step, scale forming ions (such as calcium) and silica are removed by raising the pH of the brine stream from the second stage RO system. The treated brine after chemical precipitation is filtered and recycled back in between the first and second stage RO. Feed water recoveries greater than 95% have been reported for the ARROW configuration (Mickley, 2008).

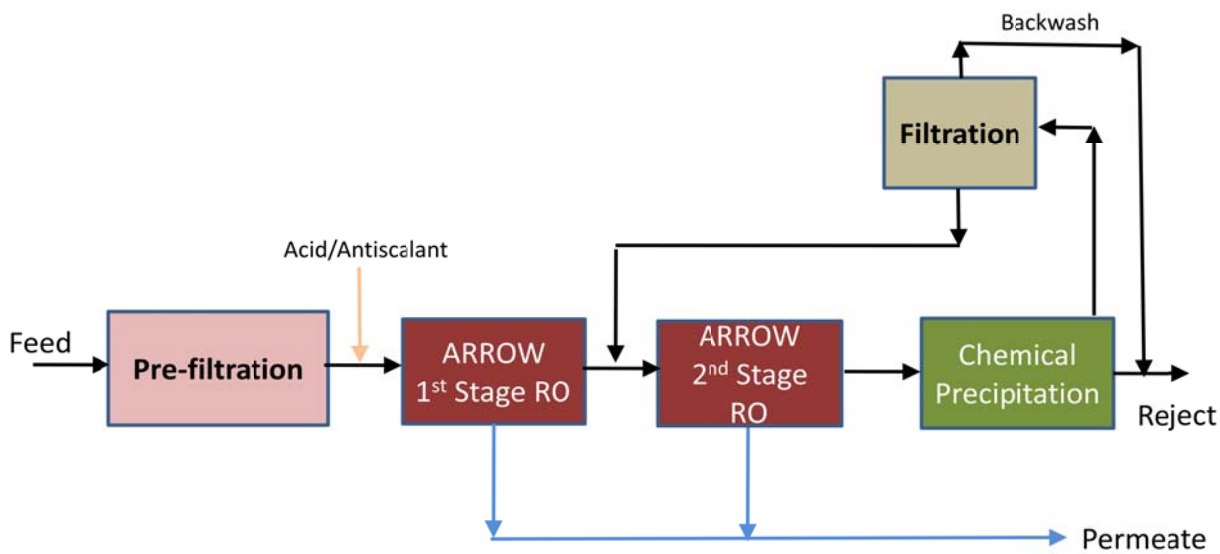

Figure 3-10. Schematic of ARROW Technology.
Adapted from Mickley, 2008.

3.3.7 Optimized Pretreatment and Separation (OPUS)

OPUS is a patented technology from Veolia Water (Veolia, 2011). A schematic of the OPUS technology is available from Veolia, 2011. Similar to the HERO process, OPUS consists of multiple treatment processes consisting of degasification, chemical softening, media filtration, ion exchange softening, cartridge filtration and RO. OPUS technology has primarily been used for industrial water treatment with high silica content for achieving high feed water recoveries. The pretreatment processes ahead of the RO are designed for the removal of hardness, metals and suspended solids in the feed water. The RO process operates at high pH to eliminate fouling due to organics and simultaneously achieving high rejection (Veolia, 2011).

3.3.8 Vibratory Shear Enhanced Process (VSEP)

The Vibratory Shear Enhanced Process (VSEP) is a vibrating membrane system manufactured by New Logic Research, Inc. (Emeryville, CA). The unique feature of this system is the application of torsional oscillation (~ 50 Hz) at a membrane surface which has been purported to produce shear up to ten times greater than typical crossflow membrane systems

(New Logic Research, 2011). The result is that colloidal fouling and polarization of the membrane due to concentration of rejected materials are greatly reduced.

The basic components of the VSEP system are a drive system, membrane module, torsion spring and vibration control system. The system can be fitted with various types of membranes including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Unlike traditional membrane systems which are configured as hollowed fiber (MF/UF) or spiral wound (NF/RO) VSEP membranes are stacked vertically in a “plate and frame” configuration. Similar to conventional RO systems, VSEP can be operated in two stage configuration to increase recovery (New Logic Research, 2011).

Initial applications of the VSEP process have been limited to mainly chemical processing and industrial use; however, several recent studies have evaluated the technology’s ability to reduce RO concentrate volume. A study was conducted at the Big Bear Area Regional Wastewater Agency (BBARWA) located in Big Bear Valley, CA (Lozier, et al., 2006) to compare various brine treatment technologies (including VSEP) to reduce the volume of brine produced from a proposed 1.2 MGD WTP employing RO. This study included a short term pilot study of a two-stage VSEP system and the authors reported the system operated with estimated cleaning frequencies of two times per week while operating at a recovery of 85% and feed TDS concentration of approximately 2,800 mg/L. The flux rate for these tests was not reported. The study also showed the VSEP achieved the following rejection of dissolved and organic contaminants: TDS (93%), sulfate (99%), TN (83%), TOC (91%) and boron (56%). Lastly, the authors emphasized that additional water quality analysis would be necessary to determine if VSEP permeate or blend of VSEP permeate with RO permeate could meet California Department of Health Services (CDPH) groundwater discharge requirements.

In another study, VSEP was assessed for brine treatment at an existing water treatment plant in California (Johnson, 2006). This study utilized a two-stage VSEP system configured with “tight” NF membranes to treat brine from a brackish groundwater membrane plant. The authors reported the VSEP system achieved 98% feed water recovery while operation in batch-mode. During operation the membrane flux ranged from an initial value of 144.5 gfd to ending value of 11.47 gfd with average flux of 65.2 gfd. The flux decreased as the concentration of dissolved solids increased in the VSEP concentrate.

Another study performed by MWH used VSEP for treating primary RO concentrate (MWH, 2008). A schematic of the treatment scheme is shown in Figure 3-11. The primary RO was operated at a recovery of 75% and was used to treat brackish groundwater with a TDS of about 1200 mg/L. The VSEP system was operated at 75% recovery and overall recovery of the RO-VSEP system was about 94%. Due to high silica concentration in the RO concentrate, pH adjustment by addition of acid was performed as pretreatment for the VSEP unit. A range of initial flux ranging from 30 gfd to 65 gfd was used for the study. The flux decreased linearly with time due to accumulation of barium sulfate and silica colloids on the VSEP membrane. Chemical cleaning frequency was estimated to be about three to four times per week. Cost estimates developed from pilot study information described above show the capital and O&M costs of a 160,000 gpd VSEP system operating on RO brine at 85% feed water recovery to be $2,087,000 and $279,000/yr, respectively. Details of the cost estimate are provided by Lozier et al. (2006). Advantages of VSEP system are smaller footprint and higher flux. Limitations include higher chemical cleaning frequency and high capital costs.

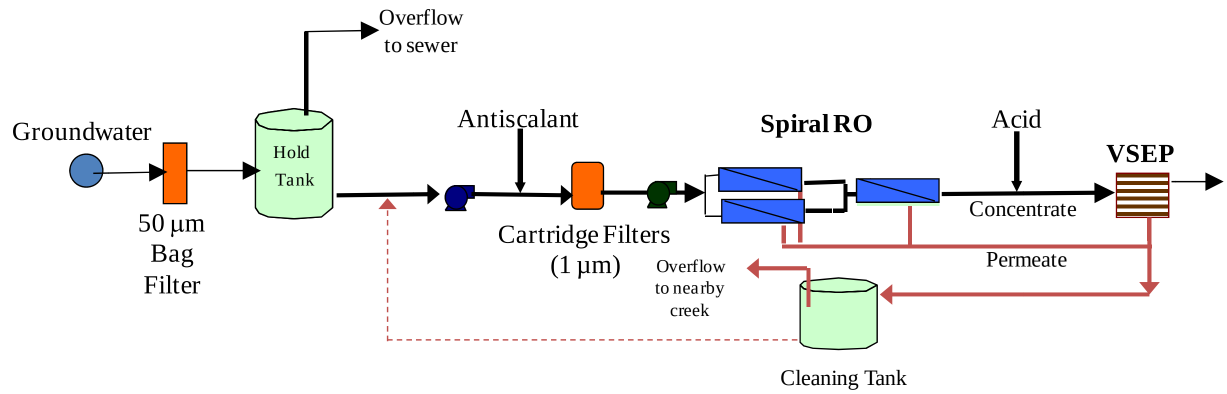

Figure 3-11. Schematic of VSEP System Used for RO Concentrate Treatment.
Adapted from Subramani et al., 2011.

3.3.9 Disc Tube (DT) Filtration

The DT system consists of commercial flat sheet membranes installed in a plate and frame configuration similar to a VSEP system but without the system vibration. The module consists of a fiber glass housing and can withstand pressures up to 1000 psi (PALL, 2011). The module consists of unique crossflow construction with stacked membrane discs. The disc membrane stack is housed in an 8-inch (diameter) pressure vessel and assembled on a center tension rod using stainless steel end flanges. The extremely short feed water path across the membrane surface, followed by a 180^{o} flow reversal greatly reduces concentration polarization on the membrane surface, reducing fouling and scaling potential (PALL, 2011). The DT module is capable of operating at high particulate loading (2500 ppm). The DT module has been primarily used for industrial water treatment and limited applications exist for the municipal water sector.

In a recent study, pretreated produced water was passed through a dual nanofiltration (NF) and RO system (Subramani et al., 2011). A DT system was used to treat the concentrate from the first pass NF system to enhance the feed water recovery. A schematic of the treatment scheme is provided in Figure 3-12. The feed water recovery of the first pass was increased to more than 91% with the use of a DT system for treating the brine from spiral wound NF membranes. Similar to the VSEP system high flux (20 gfd) was achievable using the DT system for concentrate volume minimization. The DT system fouled due to the presence of organics in the NF brine stream but chemical cleaning completely recovered the initial flux. Advantages of DT system are smaller footprint and higher flux. Limitations include higher capital costs and frequent cleaning.

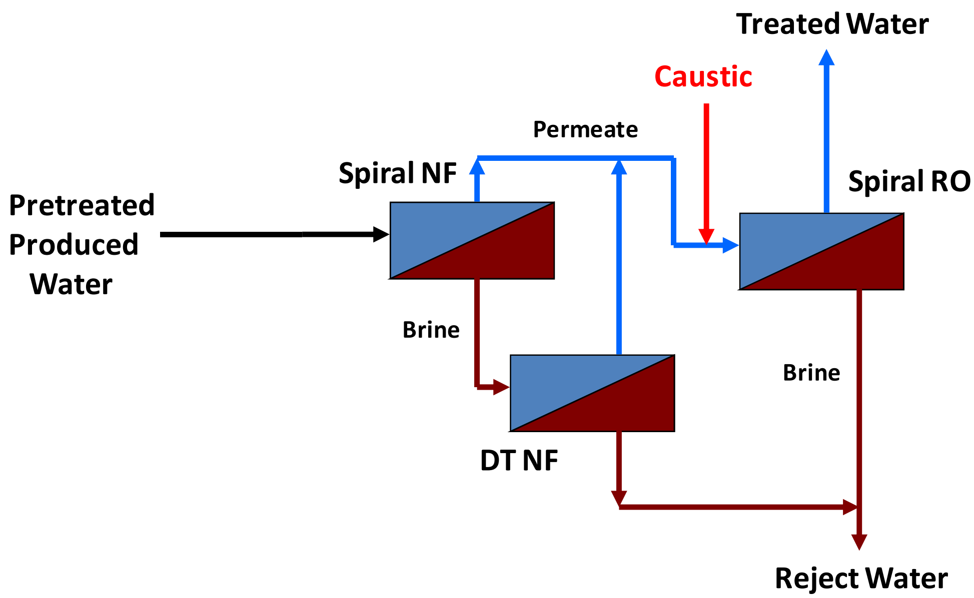

Figure 3-12. Schematic of DT Filtration Module used for Concentrate Volume Minimization. From Subramani et al., 2011.

3.3.10 Comparison of Membrane-Based Technologies

A comparison of membrane-based technologies for brine volume minimization is provided in Table 3-2. Dual RO with pellet softener is a promising technology for reducing the concentration of calcium in the brine thus reducing the scaling potential of calcium sulfate resulting in enhanced recovery (applicable for La Junta, Colorado). The advantage of using pellet-based reactors for brine softening over chemical softening techniques is the production of saleable salt products such as calcium carbonate or magnesium hydroxide. The SPARRO process is also applicable when calcium sulfate supersaturation is an issue in the brine but the technology has been tested primarily at the pilot-scale and full-scale applications are limited. Membrane-based technologies such as HERO, HEEPM, ARROW, and OPUS have been proven to result in high feed water recoveries but are patented and consist of numerous processes resulting in high costs.

Table 3-2. Comparison of Membrane-Based Technologies for Brine Management.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
Dual RO with Intermediate Chemical Demineralization	Overall recovery is expected to vary from 90-98% for brackish water treatment. The recovery of primary RO will be 60-85%. The recovery of secondary RO is expected to vary from 50-80%.	Data not available. Energy consumption expected to higher than brackish water RO treatment due to chemical precipitation and secondary RO.		Combination of well developed and established technologies.	Increased chemical dosage and sludge disposal required.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
				Good for removal of calcium from brine. Prevention of saturation of gypsum, calcite, barite and silica in the secondary RO to increase recovery.	Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment.
Dual RO with Pellet Softener (PS) or Fluidized Bed Crystallizer (FBC)	Overall recovery is expected to vary from 90-98% for brackish water treatment. The recovery of primary RO will be 60-85%. The recovery of secondary RO is expected to vary from 50-80%.	Data not available. Energy consumption expected to higher than brackish water RO treatment due to fluidized reactor and secondary RO.		Combination of well developed and established technologies.	Increased chemical dosage and sludge disposal required.
				Good for removal of calcium from brine. Prevention of saturation of gypsum, calcite, barite and silica in the secondary RO to increase recovery. Production of saleable salts.	Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment.
Dual RO with Intermediate Biological Reduction (IBR)	Overall recovery is expected to vary from 90-98% for brackish water treatment. The recovery of primary RO will be 60-85%. The recovery of secondary RO is expected to vary from 50-80%.	Data not available. Energy consumption expected to higher than brackish water RO treatment due to biological reactor and secondary RO.		Good for removal of calcium from brine. Prevention of saturation of gypsum in the secondary RO to increase recovery.	Increased chemical dosage and sludge disposal required.
					Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
					Process performance is dependent on acclimation of sulfate reducing bacteria. Pilot-scale data is not available.
Seeded Slurry Precipitation and Recycle (SPARRO)	Expected recovery vary between 90-95%.	Data not available. Energy consumption expected to higher than brackish water RO treatment due to use of tubular membranes and high cross flow velocity.		Good for removal of calcium from brine. Prevention of saturation of gypsum in the secondary RO to increase recovery.	Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment.
High Efficiency RO (HERO)	Expected recovery vary between 90-98%.	11-19 kWh/1,000 gal		Combination of well developed and established technologies. Prevention of saturation of gypsum, calcite, barite and silica in the RO to increase recovery.	Patented technology. Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment. High capital and O&M cost.
High Efficiency Electro-Pressure Membrane (HEEPM)	Expected recovery vary between 95-99%.	Data not available. Energy consumption expected to higher than brackish water RO treatment due to use of electrodialysis and RO.		Combination of well developed and established technologies. Lower membrane area requirement for ED process.	Patented technology. Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment. High capital and O&M cost.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
Advanced Reject Recovery of Water (ARROW)	Expected recovery vary between 95-99%.	Data not available. Energy consumption expected to higher than brackish water RO treatment due to use of chemical softening and RO.		Combination of well developed and established technologies.	Patented technology. Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment.
Optimized Pretreatment and Separation (OPUS)	Expected recovery vary between 90-98%.	Data not available. Energy consumption expected to similar to HERO technology.		Combination of well developed and established technologies.	Patented technology. Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment. High capital and O&M cost.
Vibratory Shear Enhanced Process (VSEP)	Expected recovery greater than 93% in combination with primary RO.	Data not available. Energy consumption expected to higher than brackish water RO treatment due VSEP applied pressure.	Capital: $2,087,000 (160,000 gpd VSEP system operating on RO brine at 85% feed water recovery, Lozier et al. 2006)	Effective for operation of water with high suspended solids and organics content.	Patented technology. Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment. High capital and O&M cost.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
Dist Tube (DT) Filtration	Expected recovery greater than 93% in combination with primary RO.	Data not available. Energy consumption expected to higher than brackish water RO treatment due DT applied pressure.		Effective for operation of water with high suspended solids and organics content.	Patented technology. Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment. High capital and O&M cost.

3.4 Electric Potential Driven Membrane Technologies

Electric potential driven technologies use cathodes and anodes to draw ions across ion-exchange membranes, removing ions from the feed stream. This differs from RO membranes which remove water from the feed stream, causing both ionic and non-ionic species to concentrate on the concentrate side of the membrane. With electric potential driven technologies, non-ionic species such as silica are not concentrated and their scaling potential is reduced.

3.4.1 Electrodialysis (ED) and Electrodialysis Reversal (EDR)

Electrodialysis (ED) uses an electrical potential to attract dissolved ions through ion-exchange membranes that are virtually impermeable to water; in this process, desalination occurs by the movement of anions and cations, not the water, across the membrane (Malmrose et al., 2004). Cations are attracted to the negative cathode and pass through the cation transfer membranes only. Meanwhile, anions are attracted towards the positive anode and pass through anion transfer membranes only. The membranes are periodically cleaned by either CIP or disassembling the stack. These membranes are made of ion-exchange resins woven into sheet form and reinforced with synthetic fiber cloth and are resistant to chlorine, acid, and base degradation. Electrodialysis reversal (EDR) is similar to ED, however scaling potential is further reduced by reversing the DC voltage three to four times per hour.

Because non-ionic precipitates (e.g., silica) are not concentrated during the ED/EDR process, they can be more effective than pressure driven membranes for waters with high silica content. An EDR pilot-scale facility in Buckey, AZ treated RO concentrate with TDS of 8,000 mg/L to improve the overall recovery (RO+EDR) to approximately 97% (Reahl, 2006); other reports indicate combined recoveries in the range of 95-98%. EDR processes can typically increase TDS to approximately 80,000 mg/L (Dalan, 2000). There are few full-scale applications of EDR processes for concentrate treatment from brackish water RO process. Reahl (1990) described three RO-EDR plants:

- The first was located at an industrial plant; EDR was selected over vapor compression to treat 100 gpm RO concentrate based on capital costs, O&M costs, and system reliability. Because EDR does not remove SiO_2, a lime reactor clarifier was used to treat the EDR waste prior to disposal to a settling pond and subsequent recycle to the RO system. Recovery through the EDR was 85% and the antiscalant (Flocon) concentration in the EDR feed was reported to be 15 mg/L and the design feed TDS was approximately 8,000 mg/L and the concentrate TDS was 45,000 mg/L. The energy use by the EDR system was 15 kWh/1,000 gallons treated concentrate with 25 gallons/day HCl.
- The second was an EDR system treating 23 gpm RO concentrate (40,000 mg/L of TDS) to 5 gpm (130,000 mg/L of TDS) prior to discharge to solar pond. The reclaimed water was feed back into the RO process
- The third RO-EDR system was located at a gallium-arsenide chip manufacturing plant with the reclaimed water used for cooling tower make-up and the EDR waste was trucked away (ultimate disposal not described)

ED was used to treat concentrate from a seawater reverse osmosis membrane in Panoche Water District, San Jaoquin Valley, California (Davis, 2006). The SWRO system was operated at 50% recovery and the concentrate contained significant amounts of sodium chloride and potassium bromide, which were removed by the ED system. A portion of the sodium chloride depleted stream was recycled to the RO system and the remaining volume was processed for magnesium hydroxide recovery. The sodium chloride in the ED brine was recovered by brine crystallization and evaporation. The bromine rich concentrate after sodium chloride recovery can be treated with chlorine to oxidize Br^- to Br_2. After recovery of sodium chloride and magnesium hydroxide, and bromine, the residual solution was evaporated to dryness to produce road salt.

The estimated energy consumption in this instance was approximately 15 kWh/1,000 gal of treated water (Reahl, 2007). The upper limit of Langelier Index in an EDR treating brine has been reported to be 3.0 if acid is used for pH depression (Reahl, 1990).

3.4.2 Electrodialysis Metathesis (EDM)

Due to the presence of sparingly soluble salts on the concentrate side of an ED/EDR membrane, recovery can be limited when species such as calcium sulfate are present in the feed water. In order to reduce the scaling potential on the concentrate side, a new configuration of the technology was developed. EDM utilizes four ion-exchange membranes in a repeating unit cell (Davis and Rayman, 2008). An illustration of membrane arrangement and transport of ions in EDM is shown in Figure 3-13. As with ED/EDR, the system consists of anion exchange (A) and cation exchange (C) membranes in an alternating fashion. When electric field is applied in the cell, cations migrate through the cation exchange membrane and anions migrate through the anion exchange membrane. Where EDM differs from ED/EDR is in the addition of a sodium chloride feed, supplied adjacent to the feed water cell, allowing for the formation of species that are more soluble than those formed in ED/EDR processes.

For example, if the feed water contains calcium sulfate, calcium ions would migrate through the cation exchange membrane while sulfate ions would migrate through the anion exchange membrane. In the adjacent cells (fed with sodium chloride), sodium ions would migrate through the cation exchange membrane while chloride ions would migrate through the anion exchange membrane. One resulting brine stream would contain sodium sulfate and the other would contain calcium chloride, which are substantially more soluble than calcium sulfate. The solubility of sodium sulfate (Na_2SO_4) formed in the EDM system is 15-35 times more soluble than calcium sulfate. Thus, by utilizing EDM for RO brine treatment, the feed water recovery of the system can be enhanced significantly.

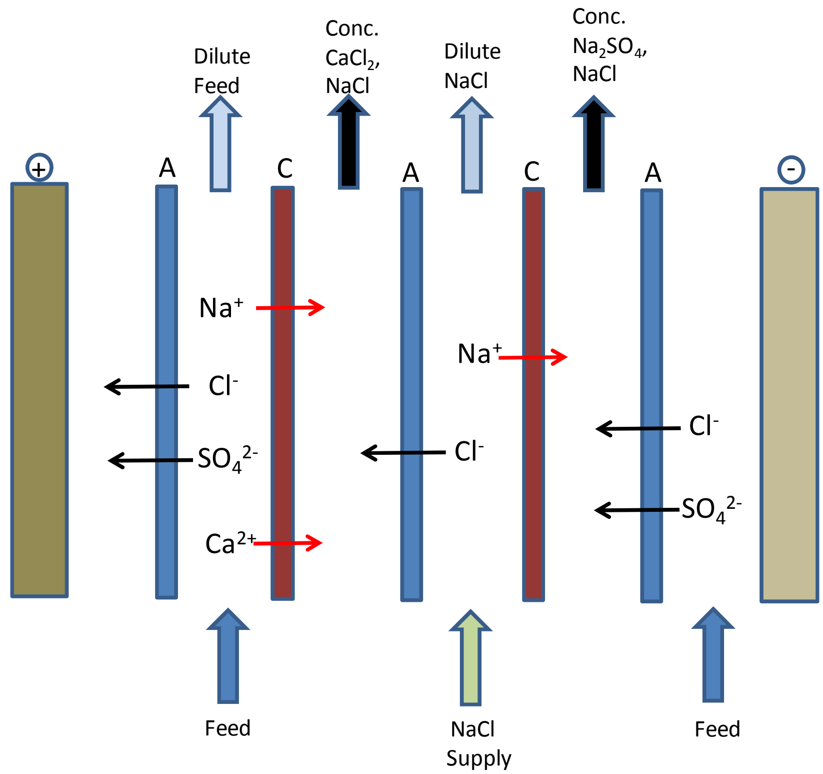

Figure 3-13. Membrane Arrangement and Transport of Ions in Electrodialysis Metathesis. "A" represents anion exchange and "C" represents cation exchange membranes. Adapted from Davis and Rayman, 2008.

In one study, the EDM process was used to remove calcium sulfate from the RO concentrate and recycle the calcium sulfate depleted water back to the RO for increased recovery (Davis and Rayman, 2008). The pilot facility was used to treat irrigation drainage water with high levels of selenium. The EDM produced two streams, one rich in calcium chloride and the other rich in sodium sulfate. Both streams were subsequently mixed to precipitate calcium sulfate. The supernatant from the precipitation process was processed by electrodialysis to recover sodium chloride.

In another study (Bond et al., 2011), EDM was used to treat RO concentrate. An illustration of the treatment scheme used is shown in Figure 3-14. The EDM system effectively separated the concentrate into two streams of highly soluble salts, silica and TOC were not rejected by the EDM and were largely unaffected and posed no problem to the ion selective membranes. More than 99% recovery was achieved in the EDM system while treating RO brine and feed water recovery decreased with an increase in TDS of the RO brine. The relationship between EDM recovery versus TDS is shown in Figure 3-15. A recovery of 97% was obtained at 1,400 mg/L TDS. The recovery decreased to 87% at 5,300 mg/L TDS and 76% at 27,700 mg/L TDS (Bond et al, 2011). Similarly, the energy consumption of the EDM process increased with TDS. Energy consumption of EDM and conventional thermal processes is compared in Figure 3-16 (Bond et al, 2011). EDM was found to be less expensive when the feed water to the system consisted for TDS less than 5,000 mg/L. When the feed water TDS was more than 15,000 mg/L, thermal processes were found to be less expensive.

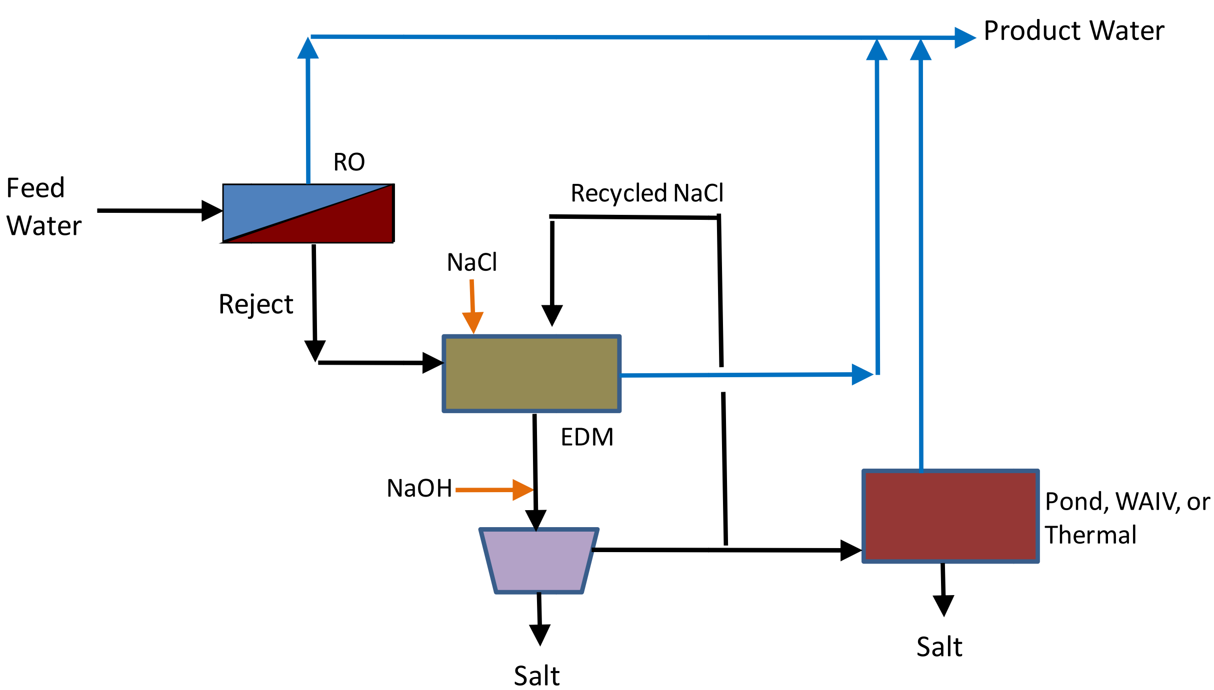

Figure 3-14. Schematic of EDM used for RO Brine Treatment.
Adapted from Bond et al., 2011.

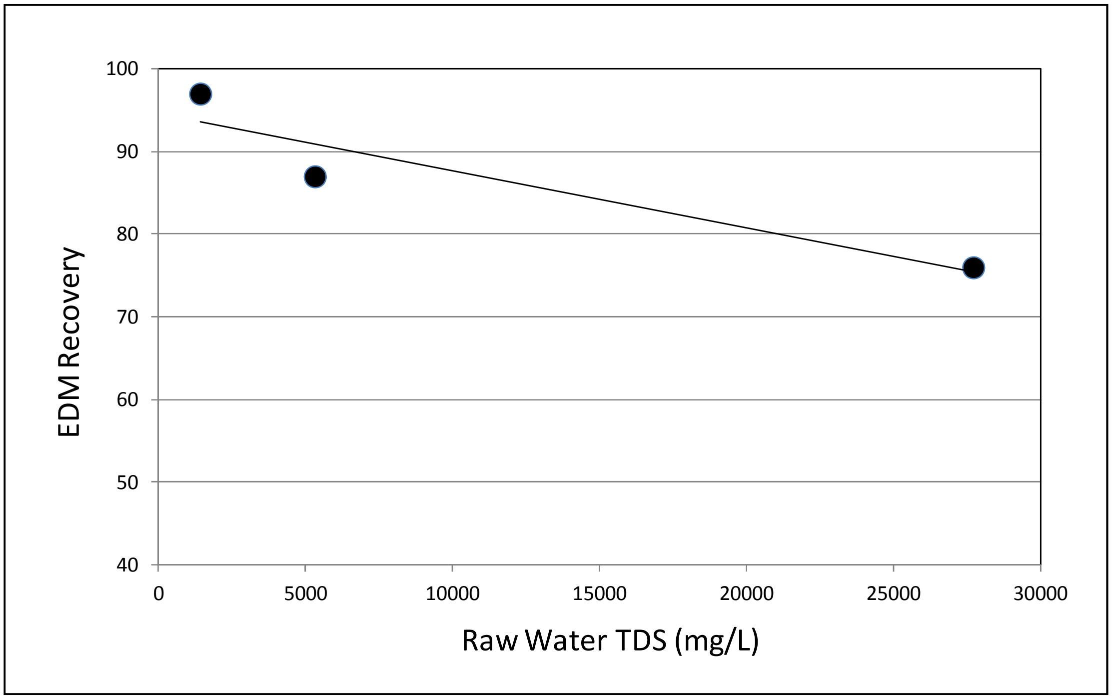

Figure 3-15. EDM Recovery Versus Raw Water TDS.
Adapted from Bond and Veerapaneni, 2007.

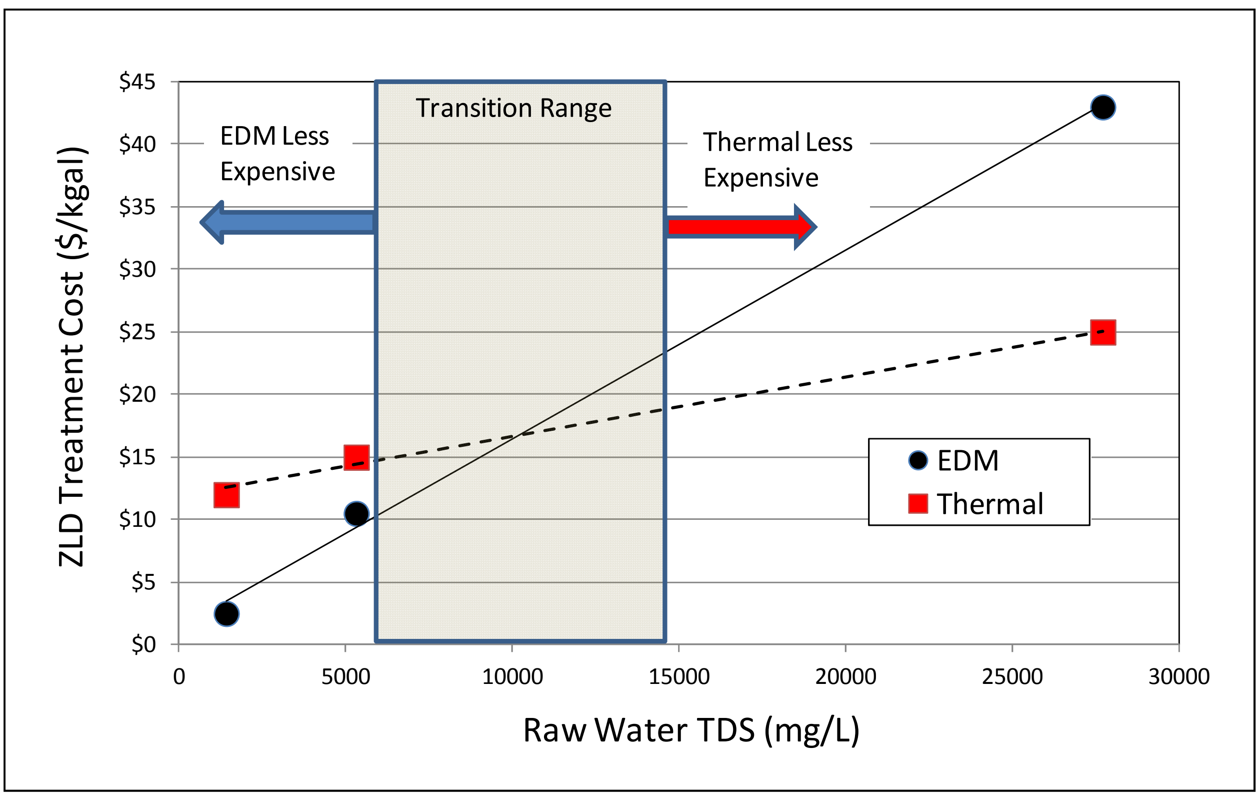

Figure 3-16. Comparison of EDM Treatment Costs with Thermal Processes.
Adapted from Bond et al., 2011.

In the case of ED and EDR systems, the recovery is limited by calcium sulfate, calcium carbonate, barium sulfate and other sparingly soluble salts (Bond, 2010). For EDM systems, the recovery is limited only by sodium sulfate. Since silica is uncharged at neutral pH conditions, silica present in the RO brine does not pose restrictions on the feed water recovery and is passed through the system without being concentrated. Thus, the advantages of using EDM for RO brine treatment are as follows:

- High product water recovery
- Potential to develop reusable salts
- Reduced concentration of all ions without chemical addition or production of solid waste
- Membrane fouling potential due to silica does not increase through the process

However, if the EDM product water is recycled to the head of the primary RO system (as recommended by the manufacturer), silica build up in the system can occur. In this case, silica removal system (such as a purging or use of an NF membrane) would be required.

3.4.3 Comparison of Electric Potential Driven Technologies

Comparison of electric potential driven technologies is provided in Table 3-3. Among the technologies, EDM has been proven to be a promising technology to treat brine when calcium sulfate supersaturation is an issue (La Junta, Colorado). Very high recoveries have been achieved using this technology but the costs depend on the TDS of the brine to be treated. EDM was found to be more cost efficient than thermal-based technologies only when the TDS is less than 5,000 mg/L (Bond et al., 2011).

Table 3-3. Comparison of Electric Potential Driven Technologies for Brine Management.

Technology	Recovery	Energy Consumption	Advantages	Limitations
Electrodialysis (ED) and Electrodialysis Reversal (EDR)	Expected recovery greater than 95% in combination with primary RO.	15 kWh/1,000 gal while treating water with 7,000 mg/L TDS.	Effective for operation of water with silica content. Higher limits for LSI (> 3) and gypsum scaling compared to RO.	Energy cost increases with TDS of water.
Electrodialysis Metathesis (EDM)	More than 99%. Recovery reduces with increase in TDS.	45 kWh/1,000 gal while treating water with 10,000 mg/L TDS.	Effective for operation of water with high calcium sulfate saturation. Less expensive than thermal processes whtn TDS is less than 5,000 mg/L. Production of saleable salts.	Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment. More expensive than thermal processes when TDS of water is > 15,000 mg/L.

3.5 Alternative Technologies

Technologies that are currently under development are categorized as alternative technologies and are described in the following sub-sections.

3.5.1 Forward Osmosis (FO)

Forward osmosis (FO) is the net movement of water across a selectively permeable membrane driven by a difference in osmotic pressure across the membrane (Cath et al., 2006). A schematic of the FO process is shown in Figure 3-17. When solutions of different solute concentrations are separated by a semi-permeable membrane, the solvent (i.e., water) will move across the membrane from the lower solute concentration side to the higher concentration solute side (i.e., "draw solution"). The driving force for this movement is the osmotic pressure gradient across the membrane caused by the differences in solute concentrations.

The main advantage of using FO in water treatment is lower energy consumption because no external pressure is required. The FO process may also demonstrate a lower membrane-fouling propensity than pressure-driven membrane processes. The main challenges, however, exist in the manufacture of high performance FO membranes and the selection of easily separable draw solutions with a high osmotic pressure (Cath et al., 2006). In addition, the water flux in FO process is often much lower than the flux expected from the bulk osmotic pressure difference and membrane permeability. This is often attributed to concentration polarization (CP), especially internal CP (McGutcheon et al., 2006). Consequently, the hydraulic configurations of forward osmosis process need to be optimized to minimize CP and membrane fouling.

Forward osmosis has been studied for a variety of applications such as volume minimization of sanitary landfill leachate (York et al., 1999), concentration of fruit juices (Petrotos et al., 1998), desalting (McGinnis, 2002; Cath et al., 2005; McCutcheon, et al., 2005; McCutcheon et al., 2006) and emergency water supply equipment (Cohen, 2004)). MWH recently completed a proof of concept study to assess the feasibility of using FO for concentrate volume minimization (Adham et al., 2007). One of the main issues to be resolved with FO is the development of a membrane suitable for this application; conventional membrane support layers result in high resistance and contribute to fouling/cleaning issues. To date there are no full scale facilities using FO for concentrate volume minimization.

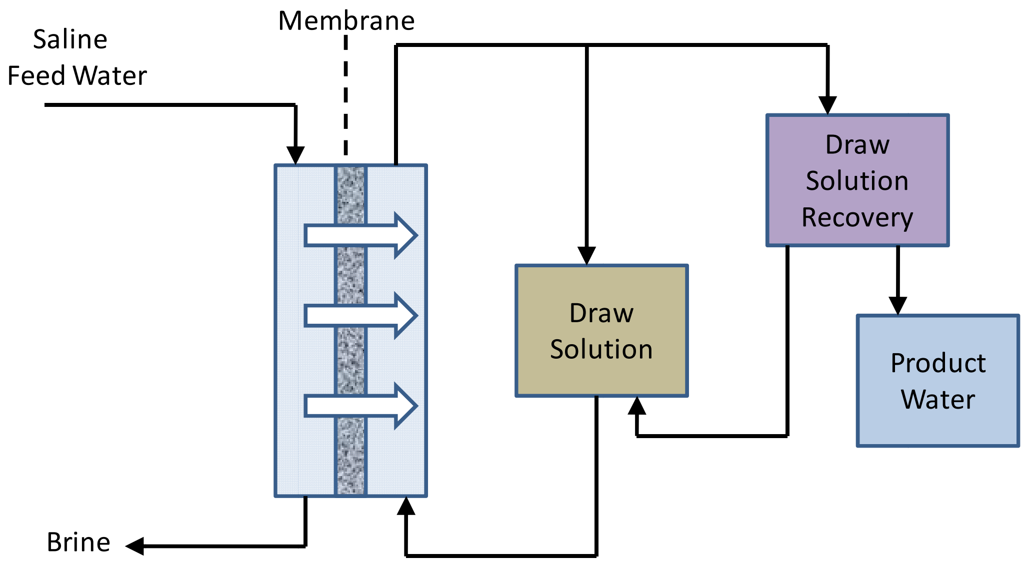

Figure 3-17. Schematic of Forward Osmosis Process.
Adapted from McCutcheon et al., 2005.

3.5.2 Electrocoagulation (EC)

Electrocoagulation involves an electrolytic reactor with electrodes (either aluminum or iron) and a separation tank. RO concentrate is passed through a reactor and coagulation/ flocculation occurs with the aluminum or iron dissolved from the electrodes. Simultaneously, hydrogen gas bubbles are generated at the cathode (Baudequin et al., 2011). In the process, the metal anode dissolution is accompanied by hydrogen gas bubble, which captures the flocs and causes floatation of the suspended solids and removes contaminants. Similar to dual RO with intermediate chemical demineralization, electrocoagulation has been used in the past to treat the primary RO concentrate to remove scaling precursors such as barium, calcium, magnesium, strontium and silica (Subramani et al., 2011). More than 90% removal of scaling precursors was achieved when the pH was increased to more than 10. After filtration of the electrocoagulated water, a secondary RO with seawater membranes was used to increase the overall feed water recovery. Using a combination of primary RO, electrocoagulation and secondary RO more than 93% feed water recovery was achieved for desalination of brackish groundwater. Advantages of using electrocoagulation for brine treatment include high removal rates of scale forming ions and metals. Limitations of the process include high operation and maintenance cost associated with electrode replacement and limited full-scale studies conducted in the past.

3.5.3 Membrane Distillation (MD)

Membrane distillation (MD) is an evaporation process driven by the difference between the partial pressure of a solution contacting one side of a porous hydrophobic membrane and its partial pressure on the other side of the membrane (Song et al., 2007). A schematic of MD process is shown in Figure 3-18. Evaporation occurs at the solution surface if the vapor pressure at the solution side is greater than the vapor pressure at the condensate side. Membrane distillation units are available in a number of configurations, but direct contact membrane distillation is the most suitable for desalination. In this process, hot brine is passed on one side of a porous hydrophobic membrane as a colder aqueous distillate stream flows on the other side.

The hydrophobic membrane allows water vapor to penetrate through while repelling the liquid water (Sirkar and Li, 2003). Diffusion of water vapor evaporated from the hot brine at the brine-membrane interface takes place through the gas-filled hydrophobic membrane pores; the water vapor is condensed in the cold distillate membrane interface. The driving gradient for vapor production has been enhanced by heating the feed water and hence increasing the vapor pressure (Sethi et al., 2006).

MD is advantageous because it can be coupled with low grade heat sources such as solar, waste heat, or geothermal energy. In addition, MD performance is only weakly influenced by the concentration polarization phenomena, so high concentration values (up to saturation) can be fed into the process. Integrated systems of RO/MD, where MD is used to treat the concentrate from RO membranes, have been studied (Criscuoli and Drioli, 1999). Polymers such as polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidenefluoride (PVDF) are commonly employed in the preparation of membranes for MD applications (Curcio and Drioli, 2005). Fouling of MD membranes is due to biological activity, particulates and colloids, or precipitation of concentrated salts.

By coupling RO and MD, the overall recovery factor can be increased to near 90% in some cases. A detailed energetic and exergetic analysis carried out on an integrated NF/RO/MD system (Criscuoli and Drioli, 1999) showed that 13 kWh/m^3 are required to drive the plant, but this value decreases to 2.6 kWh/m^3 if low grade thermal energy is available. The combined use of a gas-liquid membrane contactor, a conventional precipitator, and a membrane crystallizer was successfully applied to NF concentrate treatment in a study by Drioli et al. (2004). Calcium carbonate was removed up to 89%; 35.5 kg of NaCl and 8.4 kg MgSO4. $7H_2O$ per cubic meter of NF retentate were obtained. In addition, the amount of water condensed in the distillate side at the membrane crystallizer allowed to increase the NF recovery factor from 64-95%.

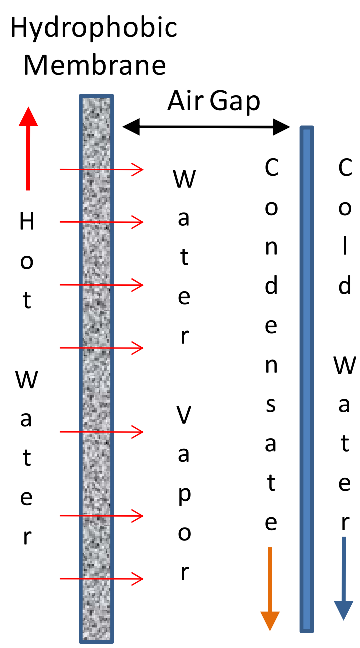

Figure 3-18. Schematic of Membrane Distillation of Process.

3.5.4 Saltworks

Saltworks process involves a thermo-ionic system that can operate on waters with feed water TDS range of 20,000 to 80,000 mg/L (Saltworks, 2011). A schematic of the process used for treating RO brine is shown in Figure 3-19. The thermo-ionic process uses ion exchange membranes in an arrangement resembling an EDR system. However, in the thermo-ionic system, energy contained within a concentrated salt solution, rather than external power, is used for the desalination process. The hypersaline solution is produced in a special evaporative unit that operates at a temperature 10°C warmer than the ambient wet bulb temperature (Saltworks, 2011). The system utilizes a proprietary ion exchange membrane. Besides solar heat or other low-grade heat sources for the evaporative unit, the only external energy requirement is the electricity needed to operate the circulation pumps and fans. The remaining energy for the desalination process is produced by the hypersaline solution. For achieving ZLD, the thermo-ionic system is used to treat RO brine. Discharge from thermo-ionic system is processed in a salt maker which produces solid salt. Powered with low grade heat only 10°C warmer than ambient temperature, the system operates at a fraction of the electrical energy consumption of conventional crystallizers (Saltworks, 2011). Limited applications and data are available on the process and commercialization is expected by 2012.

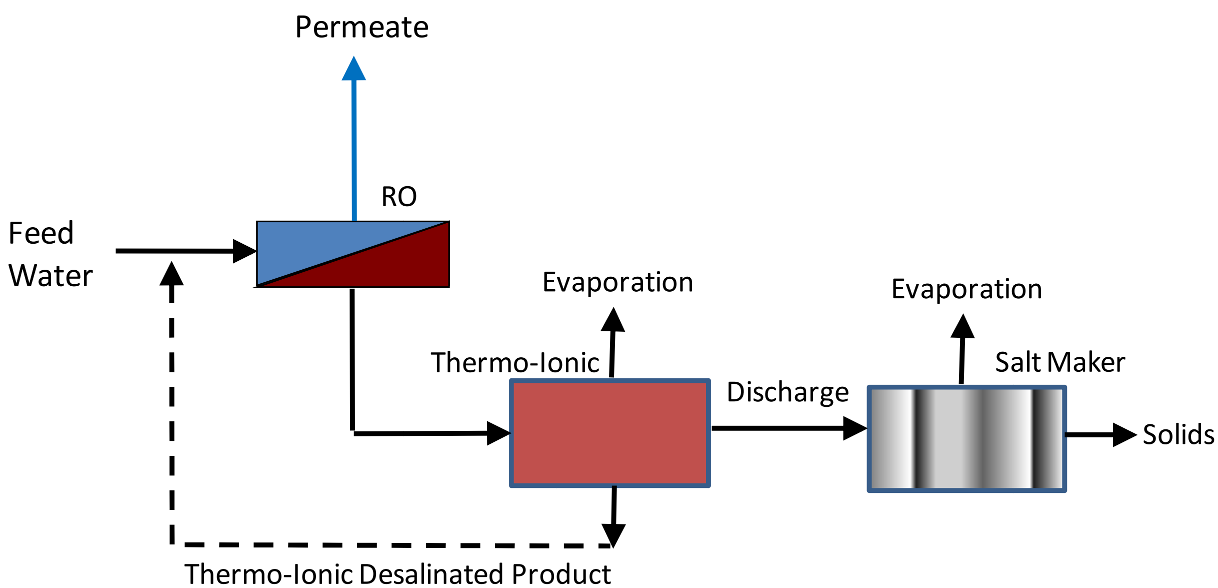

Figure 3-19. Schematic of Thermo-Ionic Desalination Process.
Adapted from Saltworks, 2011.

3.5.5 Dewvaporation (DV)

Dewvaporation is a process where brackish water is evaporated by heated air and subsequently deposits fresh water as dew on the opposite site of a heat transfer wall. The energy needed for evaporation is supplied by the energy released from dew formation. Dewvaporation employs an innovative heat-driven process using air as a carrier gas and operation at atmospheric pressure throughout the housing which is typically a tower structure (Hamieh et al., 2001). An advantage to this process is that scaling in minimized because evaporation occurs at the air-liquid interface and not at the heat transfer wall. Non-traditional heat sources include solar and waste heat.

Reported recoveries for dewvaporation range from 82-85% for brackish water applications (Sethi et al., 2006). This technology is still in development, but it is expected to find application with small-scale systems. A 10,000-gpd dewvaporation pilot unit treating RO concentrate generated from a wastewater treatment plant is being planned at Phoenix, Arizona (Jordahl, 2006) with the intention of treating RO concentrate TDS from 5,000-200,000 mg/L thereby reducing the brine volume production to approximately 2% (i.e., 98% overall recovery). To date there is no reported full-scale application of the dewvaporation process. The reported operating cost of the dewvaporation is $3.5/1000 gallons when using natural gas as heat source and $12/1000 gallons when using vapor compression evaporators as the heat source (Jordahl, 2006).

3.5.6 Eutectic Freeze Crystallization

Desalination by freezing is categorized as a crystallization processes. While desalination by freezing has been proposed as a method for several decades, only demonstration projects have been built to date (Qiblawey, 2008). Freezing is a separation process related to the solid-liquid phase change phenomenon. When the temperature of saline water is reduced to its freezing point, ice crystals of pure water are formed within the salt solution. These ice crystals can be washed and re-melted to obtain pure water. In a direct freezing process, the refrigerant is mixed directly with the brine. In an indirect process, the refrigerant is separated from the brine by a heat transfer surface. The process is essentially a conventional compressor-driven refrigeration cycle with the evaporator serving as the ice freezer, and the condenser as the ice melter. Eutectic freeze crystallization is an extension of the freeze crystallization process and utilizes the density differences between the ice and the salt produced to ensure effective separation (Randall et al., 2011). The process is operated at the eutectic point, where both ice and salt crystallize. The process is capable of producing potable water as well as pure salt with lower energy consumption than evaporative crystallization (Randall et al., 2011). Using the eutectic freeze crystallization process for treating RO brine, 97% conversion of concentrate as pure water was achievable with pure calcium sulfate and sodium sulfate salt products (Randall et al., 2011).

3.5.7 Comparison of Alternative Technologies

Comparison of alternative technologies is provided in Table 3-4. Although the technologies shown promise for brine management, they are in their developmental stages and more data on pilot-scale operation is necessary.

Table 3-4. Comparison of Alternative Technologies for Brine Management.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
Forward Osmosis (FO)	Expected recovery greater than 90% in combination w/ primary RO.	1 kWh/1,000 gal to 3 kWh/1000 gal (membrane alone).		Energy efficient than RO when waste heat is available.	Limited full-scale applications for municipal water treatment.
				No limit on TDS of water.	Limited pilot testing data available.
				No feed pressure requirements	
					Less fouling and hence less cleaning required
Electro-coagulation (EC)	Expected recovery greater than 90% in combination with primary and secondary RO.	Data not available. Energy consumption expected to higher than brackish water RO treatment due precipitation step with primary and secondary RO.		Prevention of saturation of gypsum, calcite, barite and silica in the RO to increase recovery.	Emerging technology.
					Primarily been used for industrial water treatment. Limited full-scale applications for municipal water treatment.
Membrane Distillation (MD)	Expected recovery greater than 90% in combination with primary and secondary RO.	50 kWh/1,000 gal. With waste heat ~ 39 kWh/1,000 gal.		No applied pressure requirement.	Emerging technology.
					Pilot or full-scale data not available.
Saltworks	Expected recovery greater than 99% in combination with RO.	Data not available.		Use of renewable solar energy for evaporation.	Emerging technology.
				Production of saleable salts.	Pilot or full-scale data not available.

Technology	Recovery	Energy Consumption	Cost	Advantages	Limitations
Dew-vaporation	Expected recovery greater than 80% when used alone for brackish water treatment.	Data not available.	Natural gas: $3.5/1000 gallons Vapor compression evaporators: $12/1000 gallons (Jordahl, 2006).	No applied pressure requirement.	Emerging technology. Limited full-scale applications for municipal water treatment.
Eutectic Freeze Crystal-lization	Expected recovery greater than 97%.	Data not available.		No applied pressure requirement.	Emerging technology. Limited full-scale applications for municipal water treatment.

CHAPTER 4.0

SUMMARY OF FINDINGS

A literature review was performed to evaluate brine volume minimization and zero liquid technologies. Technologies were categorized as thermal-based, membrane-based, electric potential driven and alternative. The summary of the findings is provided below:

- Thermal-based technologies reviewed were brine concentrators, brine crystallizers, wind aided intensified evaporation, salinity gradient solar pond – brine concentrator and recovery system, spray dryers and evaporative reduction and solidification. Except for evaporative reduction and solidification, all other thermal-based technologies have been used for municipal water treatment.

- Thermal-based technologies have been primarily used for complete ZLD treatment. Capital costs, energy and footprint requirements must be considered while selecting a thermal-based technology. Reducing RO brine volume will be critical for reducing the costs of thermal-based technologies.

- Membrane-based technologies reviewed were dual RO with intermediate demineralization using chemical softening and pellet softener, dual RO with intermediate biological reduction, SPARRO, HERO, HEEPM, ARROW, OPUS, VSEP, and DT filtration.

  - Dual RO with pellet softener is a promising technology for reducing the concentration of calcium in the brine and thereby reducing the scaling potential of calcium sulfate resulting in enhanced recovery. Pellets softener is also effective in reducing the concentration of silica. Based on the water quality obtained on the RO brine from Brighton, barium sulfate and silica were found to be limiting the recovery of the RO process. For the La Junta plant, calcium sulfate was determined to limiting the feed water recovery. Thus, application of a pellet softener followed by a secondary RO system could be a promising option to evaluate at Brighton and La Junta.

  - The SPARRO process is also applicable when calcium sulfate supersaturation is an issue in the brine but the technology has been tested primarily at the pilot-scale and full-scale applications are limited. Membrane-based technologies such as HERO, HEEPM, ARROW, and OPUS have been proven to result in high feed water recoveries but are patented and consist of numerous processes resulting in high costs.

- Electric potential driven technologies reviewed were ED, EDR, and EDM. EDM has been proven to be a promising technology to treat brine when calcium sulfate supersaturation is an issue. Thus, EDM would be a promising candidate to evaluate at La Junta plant where calcium sulfate is limiting the feed water recovery. For EDM, the costs depend on the TDS of the brine to be treated. Based on the water quality (TDS) of RO brine at Brighton and La Junta the use of EDM would be applicable for both sites for RO brine management.

- Alternative technologies reviewed were forward osmosis, electrocoagulation, membrane distillation, Saltworks, dewvaporation and eutectic freeze crystallization. Although the technologies show promise for brine management, they are in their developmental stages and more data on pilot-scale operation is necessary.

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