CENTRAL ARIZONA SALINITY STUDY --- PHASE I

Technical Appendix S

Trends in Membrane Technology

INTRODUCTION

The Central Arizona Salinity Study (CASS) was initiated to evaluate the magnitude of the salinity issue in the central Arizona and Tucson areas and to develop an appropriate regional management strategy. Membrane treatment for drinking water and wastewater removes and concentrates impurities, including salts, which must be discharged as a waste product of the treatment process. Municipal and industrial water users in Arizona are currently using membrane technology that produces a salty concentrate. Membrane technology improvements and increasing cost effectiveness could increase membrane use and the associated concentrate discharge. As a result, trends in membrane technology will have an impact on salinity issues in central Arizona. The purpose of this White Paper is to provide a brief overview of trends in membrane technology, its use in central Arizona, and the relation to salinity issues.

CENTRAL ARIZONA SALINITY STUDY OVERVIEW

CASS is evaluating the magnitude of the salinity issue in central Arizona, because salinity is known to be a potential issue related to some water supplies. Salinity in water supplies can reduce agricultural crop yields, impact residential use by causing taste issues and reducing household appliance life, and increase industrial costs for advanced water treatment of process and cooling water. The primary source of salinity in central Arizona and Tucson is the water supply, which includes the Central Arizona Project (CAP), the Salt and Verde Rivers, and the Gila River that average approximately 650, 480, and 600 mg/l total dissolved solids (TDS), respectively.

Average annual salt accumulations are significant. For example in the Phoenix metro areas, approximately 1.5 million tons of salts are imported and 0.4 million tons of salts are exported. This results in an accumulation of an estimated 1.1 million tons of salt per year. Approximately 0.5 million tons of salt accumulate annually in the Pinal County area, and CAP utilization in the Tucson area results in the importation of approximately 65,000 tons annually.

The Maricopa Association of Governments 208 Water Quality Management Plan Update (October 2002) recently reiterated salinity concerns in the region:

> *Another important issue impacting groundwater quality in the MAG planning area is salinity. All waters used for irrigation, urban as well as agricultural, contain salts. Excess irrigation water is applied to irrigated plants to prevent accumulation of salts in the root zone, and surface water and effluent containing dissolved salts are recharged to the groundwater through percolation basins and wells. Much of this salt quantity is being imported to the MAG area in our water supplies from the Salt River and the Central*

Arizona Project (Colorado River). The potential effects and management of salt accumulation in south-central Arizona are addressed in two recent papers: "Accumulation and Management of Salt in South Central Arizona", Bouwer, 1999; and "Where do the salts go?," Cordy and Bouwer, USGS Fact Sheet, June 1999.

The Management Plan summarized the primarily long-term impacts of the shallow groundwater. These impacts include the degradation of water quality in the aquifers utilized for municipal water supplies and increased salinity in the waterlogged and shallow-groundwater areas.

CASS initiated this evaluation of membrane treatment technology, because membranes are currently used in the area and may have increased use in the future. Concentrate has typically been discharged to surface waters, municipal wastewater treatment plants or pumped to deep aquifers via deep well injection. To a lesser extent, other options have been land disposal or evaporation ponds. Apart from the salinity of the concentrate discharge, other issues becoming increasingly important are the contaminants present in the reject stream. In some cases it is becoming necessary to treat the concentrate for these contaminants before disposal.

MEMBRANE TREATMENT PROCESSES

Membrane treatment processes are used for treating potable water, treating wastewater for reclamation and reuse, and treating both industrial process source and wastewater. Membrane technology removes constituents that cannot be effectively removed with conventional treatment such as dissolved solids, organic chemicals, and other inorganic chemicals such as nitrate.

There are five primary types of membrane treatment:

- Microfiltration (MF)
- Ultrafiltration (UF)
- Nanofiltration (NF)
- Reverse osmosis (RO)
- Electrodialysis (ED)

Each of these processes is described briefly as follows:

Microfiltration (MF): a physical separation process applied to removing particulates, typically down to bacterial sizes. Virus removals are relatively low. Organics and other dissolved substances are not removed. Pore sizes are 0.1 μm or greater.

Ultrafiltration (UF): also essentially a physical separation process. Pore sizes are 0.01 μm or greater. UF achieves some macromolecular removal as well as particulates.

Nanofiltration (NF): also called low pressure reverse osmosis. These membranes are designed for selectively removing multivalent ions such as calcium and magnesium – hence the terminology "softening membranes." Monovalent ions are poorly rejected by nanofiltration; therefore, osmotic pressures are relatively low and operating pressures are lower than in RO applications. Nanofilters are increasingly applied for the removal of larger organics, such as color and NOM substances.

Reverse osmosis (RO): RO is a semipermeable membrane process that relies on diffusivity to remove dissolved solids. RO introduces water to the membranes at a pressure that is greater than the osmotic pressure to reject electrolytes into the "reject" flow or concentrate. Monovalent ions – such as sodium and chloride - are typically targeted. Increasingly, trace organic compounds are targeted, including endocrine disruptor chemicals. A newer trend is selective ion removal from groundwater, such as fluoride, nitrate, and arsenic.

Electrodialysis/Electrodialysis Reversal (ED/EDR): ED/EDR is also a semipermeable membrane process, but it removes dissolved solids through polarity-selective membranes that remove dissolved solids through an electrical charge. Application of an electrical charge to the membranes attracts (removes) ions based on polarity and produces a dilute (treated) and concentrated (concentrate) waste stream.

This evaluation focuses on NF, RO, and ED/EDR because these processes remove dissolved organics and salts to produce a concentrate that can contribute to salinity issues in receiving waters. MF and UF primarily remove solids and do not produce similar concerns with reject disposal.

MEMBRANE TECHNOLOGY AT MUNICIPAL AND INDUSTRIAL TREATMENT FACILITIES

The climate and limited water resources in central Arizona puts a priority on the effective use of water supplies. In addition, source water quality and more stringent regulatory requirements have prompted higher levels of treatment for municipal and industrial water and wastewater resources.

Municipal Use

Multiple municipal drinking water and wastewater facilities currently use membrane treatment. Regional municipal facilities were contacted as part of this evaluation to identify the types of current membrane use and anticipated future use (Table 1.)

Industrial Use

Industrial water users must use water efficiently to grow and stay competitive. In addition, specific industries, such as the medical and semiconductor industries, have more stringent requirements for process water and typically need very high quality water. For example, high-tech industries often require “ultrapure” water. As a result, RO is currently being used to provide ultrapure water, which is then typically followed by a polishing treatment step. These water supply and water quality factors led to the current use of membrane technology, specifically NF and RO, by industry in the region. With the current industrial use of RO, concentrate from the treatment process is typically discharged to municipal wastewater treatment facilities.

Industry costs for water supply, treatment, and disposal can be significant, averaging on the order of $15/1,000 gallons (varies with raw water supply). With water supply limitations and emphasis on water conservation, industrial water users need to get the most value from their water supplies. This has led to using NF to treat RO reject to produce more useable water. (RO removes 99% of the salts and NF is used to remove hard salts). This treatment train can be applied if the water supplier caps water supply quantities. Another example of current membrane use to produce more water and reduce costs is the use of UF applied to treated wastewater effluents, to produce reusable water and reduce wastewater volumes. In this example, solids removed by the UF process are dewatered to produce a solid cake for disposal.

Industrial water use can be significant. In 2002, the City of Phoenix supplied 20 million gallons of water to 58 manufacturer and industrial users that were in the top 1,000 water users in the City of Phoenix. In general, manufacturing water users direct about 32% of water to cooling, 29% to water treatment and regeneration (wastewater treatment), and the remainder to process water. Tucson Water indicated that industrial and commercial users utilized approximately 100,000 acre-feet of water in 2000.

Table 1. Current Membrane Use at Regional Municipal Facilities

Treatment Facility	Current Drinking Water Membrane Use	Current Wastewater Membrane Use	Comments
Anthem Community	MF (1 mgd)	MF (0.5 mgd)	Dispose water concentrate to land/irrigation. Dispose wastewater concentrate to recycle.
City of Buckeye	EDR (0.9 mgd)		Dispose concentrate to surface.
City of Chandler	No current membrane use.	Industrial RO (2.8 mgd)	
City of Glendale	UF (1 mgd)		Dispose backwash to WWTP.
City of Mesa	No current membrane use. Water supply: Salt River (100-500 ppb TDS)	No current membrane use.	Don't anticipate need for membranes for water or wastewater treatment.
City of Peoria			
City of Phoenix	No current membrane use.	No current membrane use.	Don't anticipate need for membrane treatment in next 10 years unless costs decrease significantly. Membranes would most likely be considered for wastewater treatment before drinking water treatment.
City of Pine	NF (0.04 mgd)		Dispose concentrate to surface.
City of Scottsdale		MF/RO (12 mgd)	Dispose of concentrate through recycling.
City of Tempe	No current membrane use Water supply: Salt River and limited groundwater	Kyrene WWTP will be upgrading to membrane ultrafiltration to replace the filters and clarifiers	Don't anticipate need for RO membranes unless SRP quality changes or technology becomes a lot less expensive.
City of Tolleson	EDR (1 mgd)		Dispose concentrate to WWTP.
Fountain Hills		MF (2 mgd)	Dispose concentrate to WWTP.
Randolph Park		UF (3.1 mgd)	
State Prison-Lewis	EDR (1.5 mgd)		Dispose concentrate to evaporation pond.
Yuma Desalting Plant	RO (72 mgd)		Dispose concentrate to surface water.

Notes:
Treatment facilities were contacted for this evaluation but at the time of this draft not all facilities had responded to provide the most current information. mgd – million gallons per day

Trends in Membrane Use for Industrial Water Users

For industries to grow in the future, they need more power and water or must increase efficiency of water use and process technologies. Trends in water treatment for industry in central Arizona can be summarized as follows:

- Increasing use of treatment trains with a combination of treatment processes
- Treating wastewater for another use such as cooling water (a consideration for this practice is that if a regulated water or waste stream is mixed with unregulated water, it all becomes regulated).
- As salinity in water supplies increase, industry will continue to add membrane treatment processes and other purification processes to extend water supplies.
- Industry growth is difficult to predict, because it is impacted by many factors, particularly the economy. However, previous industrial growth in Arizona over the past decade has demonstrated an 18% increase in employment from 1991 to 2001; the gross state product grew 246% due to Arizona manufacturers over the same period.

MEMBRANE TECHNOLOGY TRENDS

Trends in membrane technology will have an impact on salinity issues in central Arizona, as a result of increased membrane use and associated concentrate discharge. Membrane technology improvements and increasing cost effectiveness, including higher efficiency in membrane systems, reduced energy and membrane costs, and the development of selective and low fouling membranes could result in an increase in the use of membrane technology.

The recent Desalination Roadmap[1] released by the US Bureau of Reclamation emphasizes that membrane technologies are effective in removing contaminants from impaired waters ranging from natural salts to synthetic chemicals. In addition, the Roadmap states that membrane technology can ‘create’ new water from impaired sources such as brackish groundwater, impaired rivers, and at wastewater treatment plants.

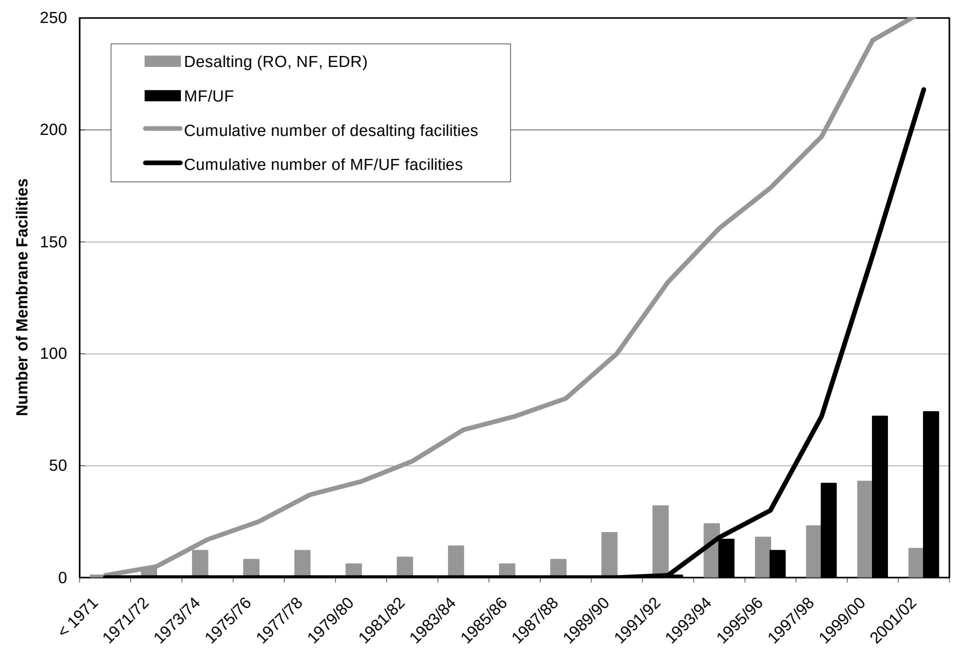
Increase in Membrane Use Nationwide

The use of membrane technology has increased over the past 30 years (Figure 1). In the past 10 years the number of RO, NF, and EDR treatment plants in the U.S. has increased from 132 to 253. During this same period MF and UF treatment plants in the U.S. increased from one to 218. It is difficult to estimate the number of membrane facilities that may be constructed in the future, but it is estimated that an additional 30 new membrane treatment plants will be online in the next two years in the U.S. However, no new membrane facilities are anticipated in Arizona before

[1] U.S. Bureau of Reclamation, Sandia National Laboratories. 2003. Desalination and Water Purification Technology Roadmap - A Report of the Executive Committee.

2004. This may be due to the difficulty of concentrate disposal in this region compared to other areas of the country.

Figure 1. Estimated Number of Membrane Water and Wastewater Treatment Plants in the U.S.



Source: Mickley & Associates, June 2003

Higher Efficiency in Membrane Systems

Ongoing research targeting the structure of membranes will result in higher efficiency in membrane systems. For example, computational fluid dynamics applied to membrane feed channels could result in reduced fouling. Advances in nanofiltration (NF) and reverse osmosis (RO) membrane processes will contribute to the increase in membrane efficiency. Within the next 10 years, it is likely that the size of NF or RO plants will be up to 250 mgd, from 40 mgd today. The main drivers for this development are inadequate fresh water sources, increasing soluble contaminants such as endocrine disruptors, reduced costs, and new, larger module designs. Future membrane research may also lead to oxidant resistant membranes, biofilm resistant membranes, and membranes that can operate in a wider pH range.

Reducing Costs

Significant research has been done on reducing costs in membrane technology. One example is the use of turbine energy recovery devices and pressure work exchangers to reduce energy costs for high pressure RO applications. Another example is the use of larger membrane elements such as the 60-inch long 17-inch diameter elements currently under trial at the Scottsdale Water Campus. Essentially these larger elements could increase the throughput per element by up to six times compared with existing 8-inch elements thereby providing a more compact and less costly installation.

In general, the increasing use of membranes has the indirect effect of reducing costs. For example, current capital costs for a MF or UF 20 mgd treatment facility ranges from $0.20 to $0.30 per gallon per day (gpd). Within 5 to 10 years this could decrease to $0.10 to $0.15/gpd. Similarly, within ten years, reverse osmosis costs could be on the order of $0.25 to $0.45/gpd.

Selective Membranes

Ongoing research is leading to membranes targeted at specific ions or organics, thereby avoiding the more expensive "bulldozer" approach of removing all contaminants in cases where this may not be necessary or desirable. Specific selective membranes allow particular contaminants to be sought out while permitting others to pass through the membrane. As a result, the number of pollutants and their concentrations in the reject stream will be reduced. For brackish and seawaters, selective ion removals are probably not appropriate. In this case, research into low fouling membranes may help to increase recoveries thereby reducing the volume of reject streams.

Advances are continuing in retarding scaling and fouling of membranes. For example, silica scale inhibitors allow operation on waters with relatively high silica contents, which previously was not possible without significantly reducing recoveries.

Advances are also continuing regarding membrane chemistry. For example applications of NF technology have expanded from softening applications to synthetic organic (SOC) removals – particularly in Europe, and for color and/or the removal of DBP precursor materials. Advances in membrane chemistry also target the development of fouling resistant membranes and target the removal of organics. The objective here is to reduce the simultaneous rejection of inorganics, which produces a less aggressive finished water and reduces post treatment costs. The concentrate would also have a lower salinity and be easier to dispose of, for example to surface waters or for discharge to municipal wastewater treatment plants.

In 15 to 20 years, membrane technology may adjust removal capabilities based on the water supply quality and removal needs. Research and development may lead to membranes that can sense a contaminant differential across the membrane and automatically change performance and selectivity.

Improved Concentrate Disposal

Concentrate management includes the disposal, volume reduction, and beneficial use of brine or concentrate, which is primary byproduct of NF, RO, and ED/EDR. Concentrate disposal, reduction, and use will still be issues as the use of these membrane treatment technologies increase. In addition, this may be the deciding factor in the viability of membrane schemes in some cases. Experience at existing membrane treatment plants indicates that on the order of 20 percent of the treated flow can become concentrate discharge. Traditional concentrate disposal options may not be appropriate in all cases. Where possible, ocean disposal or deep well injection may still remain the most viable options. But in other cases, zero liquid discharge (ZLD) options may be the most economical. Potential alternatives for concentrate disposal include the following:

- **Deep well injection**—Concentrate is injected into subsurface formations to contain concentrate without contaminating groundwater. Well depths can range from 1,000 to 8,000 feet. Waste can never migrate out of the injection zone.
- **Discharge to surface water—**Concentrate is discharged through a pipeline to the ocean or other surface waters. Primary costs relate to constructing the conveyance and addressing permitting issues. Regulatory requirements continue to become more stringent to protect the beneficial uses of receiving waters.
- **Evaporation or solar ponds—**These facilities are more appropriate for facilities with smaller flows that are located in climates with high evaporation rates. The ponds can be constructed and maintained at a relatively low cost. However, ponds can be land intensive and require lining.
- **Spray irrigation**—Concentrate is land applied through sprinkler systems. This option requires an irrigation need in the area with vegetation that is tolerant of the concentrate or a diluted concentrate. A backup system for storage must also be in place when irrigation is not feasible (e.g., frozen or saturated ground). Monitoring is also required.
- **Discharge to local wastewater system—**This option requires permitting and fees through the local wastewater treatment plant. The wastewater treatment plant will consider how the discharge will affect treatment processes and its discharge permit.
- **Zero liquid discharge—**These options include **t**hermal brine concentrators, crystallizers, spray dryers, and solid landfill disposal. These options use evaporation to further concentrate the membrane concentrate. This requires a capital investment, as well as potentially high power and labor costs. These options typically require limited area and can enables a more efficient use of water.
- **Beneficial use** (e.g., irrigation, farming, solar pond, cooling water, manufacturing, agriculture, energy recovery, artificial wetland, aquaculture)

Some studies have shown that, in terms of capital costs, extensive pipelines to facilitate ocean disposal and installation of wells for deep well injection may be the highest cost followed by evaporation ponds. ZLD options may represent a lower capital cost amongst these options, but generally represent high O&M costs. ZLD options still require further development to reduce costs and to recover the water lost during the process. Research is currently underway, particularly in Australia, where sequential precipitation of salts may produce commercial products which offset chemical and land disposal costs.

A 2001 study for the U.S. Bureau of Reclamation evaluated cost factors for concentrate disposal and provided tools for estimating preliminary costs[2]. Table 2 summarizes cost considerations for the above concentrate disposal options.

Table 2. Concentrate Disposal Cost Considerations

Deep well injection	Discharge to surface water	Evaporation Pond or Solar Ponds	Spray irrigation	Discharge to local wastewater system	Zero liquid discharge options	Beneficial Use
• Permitting • Pretreatment • Pumping • Well design and construction • Monitoring	• Permitting • Construction of conveyance and outfall • Pretreatment • Dilution water	• Permitting • Land area • Design and construction • Lining • O&M • Disposal • Monitoring • Contaminated ground cleanup	• Permitting • Land area • Conveyance and distribution • Pumping • Storage for nonirrigable periods • Dilution water • O&M	• Pretreatment • Pretreatment permitting • Conveyance • Dilution Water	• Equipment • Power • Additional labor • O&M • Disposal	• Varies depending on end use

Research into concentrate disposal is a key consideration for expanding membrane technologies. The most important improvements need to be made in reducing disposal costs. Research priorities identified in the Desalination Roadmap include discovering beneficial uses of concentrate. Additionally, reducing the quantity of concentrate produced will enable greater use of limited water supplies.

2 Mickley, M. 2001. Membrane Concentrate Disposal: Practices and Regulation. Desalination and Water Purification Research and Development Program Report No. 69 for U.S. Bureau of Reclamation