Appendix A

Desalination Technologies

There is no best method of desalination. A wide variety of desalination technologies effectively remove salts from salty water (or extract fresh water from salty water), producing a water stream with a low concentration of salt (the product stream) and another with a high concentration of remaining salts (the brine or concentrate). Most of these technologies rely on either distillation or membranes to separate salts from the product water (USAID 1980, Wangnick 1998 and 2002, Wangnick/GWI 2005). Ultimately, the selection of a desalination process depends on site-specific conditions, including the salt content of the water, economics, the quality of water needed by the end user, and local engineering experience and skills. These processes are described in greater detail below.

Membrane and Filtration Processes

Membranes and filters can selectively permit or prohibit the passage of certain ions, and desalination technologies have been designed around these capabilities. Membranes play an important role in the separation of salts in the natural processes of dialysis and osmosis. These natural principles have been adapted in two commercially important desalting processes: electrodialysis (ED) and reverse osmosis (RO). Both of these concepts have been understood for a century, but commercialization lagged until the technology for creating and maintaining membranes improved. Although they have typically been used to desalinate brackish water, versions are increasingly being applied to seawater, and these two approaches now account for more than half of all desalination capacity. A growing number of desalination systems are also adding filtration units prior to the membranes in order to remove contaminants that affect long-term filter operation. Box 1 lists the characteristics of major filtration and membrane systems.

Box 1: Filtration/Membrane Systems

Microfiltration (MF) membranes are used to reduce turbidity and remove suspended solids and bacteria. MF membranes operate via a sieving mechanism under a lower pressure than either UF or NF membranes.

Nanofiltration (NF) membranes are used for water softening, organics and sulfate removal, and some removal of viruses. Removal is by combined sieving and solution diffusion.

Reverse osmosis (RO) membranes are used for both brackish water and seawater desalination and are capable of removing some organic contaminants.

Ultrafiltration (UF) membranes are used for removal of contaminants that affect color, high-weight dissolved organic compounds, bacteria, and some viruses. UF membranes also operate via a sieving mechanism.

Sources: Heberer et al. 2001, Sedlak and Pinkston 2001, NAS 2004

Electrodialysis

Electrodialysis is an electrochemical separation process that uses electrical currents to move salt ions selectively through a membrane, leaving fresh water behind. The process was commercially introduced in the mid 1950s, providing a cost-effective way to desalinate brackish water and spurring considerable interest in the use of membranes. ED can produce more product water and less brine than distillation processes, can treat water with a higher level of suspended solids than RO, and needs fewer pretreatment chemicals. These systems produce water for industrial and power plant cooling towers, freshwater fish farms, and municipal uses; treat industrial wastes; and concentrate polluted groundwater for further treatment. In one innovative application of ED, a plant in Tenerife, Spain removes salts and sodium from wastewater and uses the product water to irrigate bananas (von Gottberg 1999).

ED works on the principle that salts dissolved in water are naturally ionized and membranes can be constructed to selectively permit the passage of ions as they move toward electrodes with an opposite electric charge. Brackish water is pumped at low pressure between stacks of flat, parallel, ion-permeable membranes that form channels. These channels are arranged with anion-selective membranes alternating with cation-selective membranes such that each channel has as an anion-selective membrane on one side and a cation-selective membrane on the other (Figure A-1). Water flows along the face of these alternating pairs of membranes in separate channels and an electric current flows across these channels, charging the electrodes. The anions in the feed water are attracted and diverted towards the positive electrode. These anions pass through the anion-selective membrane, but cannot pass through the cation-selective membrane and are trapped in the concentrate channel. Cations move in the opposite direction through the cation-selective membrane to the concentrate channel on the other side where they are trapped. This process creates alternating channels, a concentrated channel for the brine and a diluted channel for the product water.

ED membranes are arranged in a series of cell-pairs, which consist of a cell containing brine and a cell containing product water. A basic ED unit or "membrane stack" consists of several hundred cell-pairs bound together with electrodes on the outside. Feed water passes simultaneously in parallel paths through all of the cells to produce continuous flows of fresh water and brine (Strathmann 1992, IDA 1999, Lee and Koros 2002).

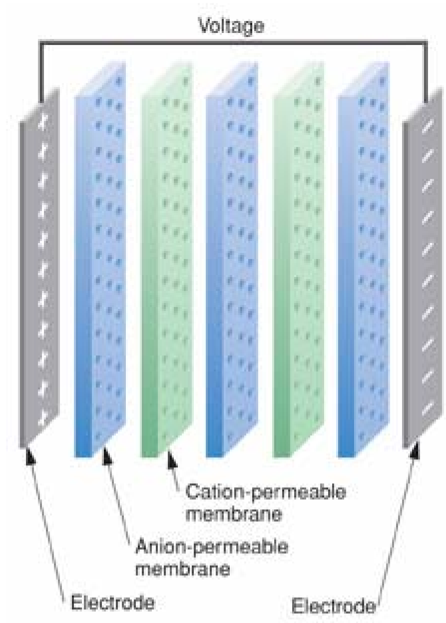

Figure A-1
Schematic of an Electrodialysis Desalination Plant

Source: Lawrence Livermore National Laboratory 2004

Electrodialysis Reversal

In the early 1970s, a modification of ED was introduced – electrodialysis reversal (EDR). An EDR unit operates on the same principle as a standard ED plant except that both the product and the brine channels are identical in construction. Several times an hour, the polarity of the electrodes is reversed, and the brine channel and product water channel flows are switched. Immediately following the reversal of polarity and flow, the ions are attracted in the opposite direction across the membrane stack and product water is used to clean out the stack and lines. After flushing for a few minutes, the unit resumes producing water. The reversal process breaks up and flushes out scale and other deposits in the cells. Flushing also allows the unit to operate with fewer pretreatment chemicals and minimizes membrane fouling.

EDR systems can operate on highly turbid feed water and are less prone to biofouling than RO systems. Experience suggests that EDR can also achieve higher water recovery than RO systems. The major energy requirement is the direct current used to separate the ions in the membrane stack. ED and EDR represent a very minor fraction – less than one percent – of worldwide desalination capacity (Wangnick/GWI 2005).

Reverse Osmosis

Reverse osmosis uses pressure on solutions with concentrations of salt to force fresh water to move through a semi-permeable membrane, leaving the salts behind (Figure A-2). The amount of desalinated water that can be obtained ranges between 30% and 85% of the volume of the input water, depending on the initial water quality, the quality of the product, and the technology and membranes involved.

An RO system is made up of the following basic components: pretreatment, high-pressure pump, membrane assembly, and post-treatment. Pretreatment of feed water is often necessary to remove contaminants and prevent fouling or microbial growth on the membranes, which reduces passage of feed water. Pretreatment typically consists of filtration and either the addition of chemicals to inhibit precipitation or efficient filtering to remove solids. A high-pressure pump generates the pressure needed to enable the water to pass through the membrane (Fisia Italimpianti 1999, IDA 1999).

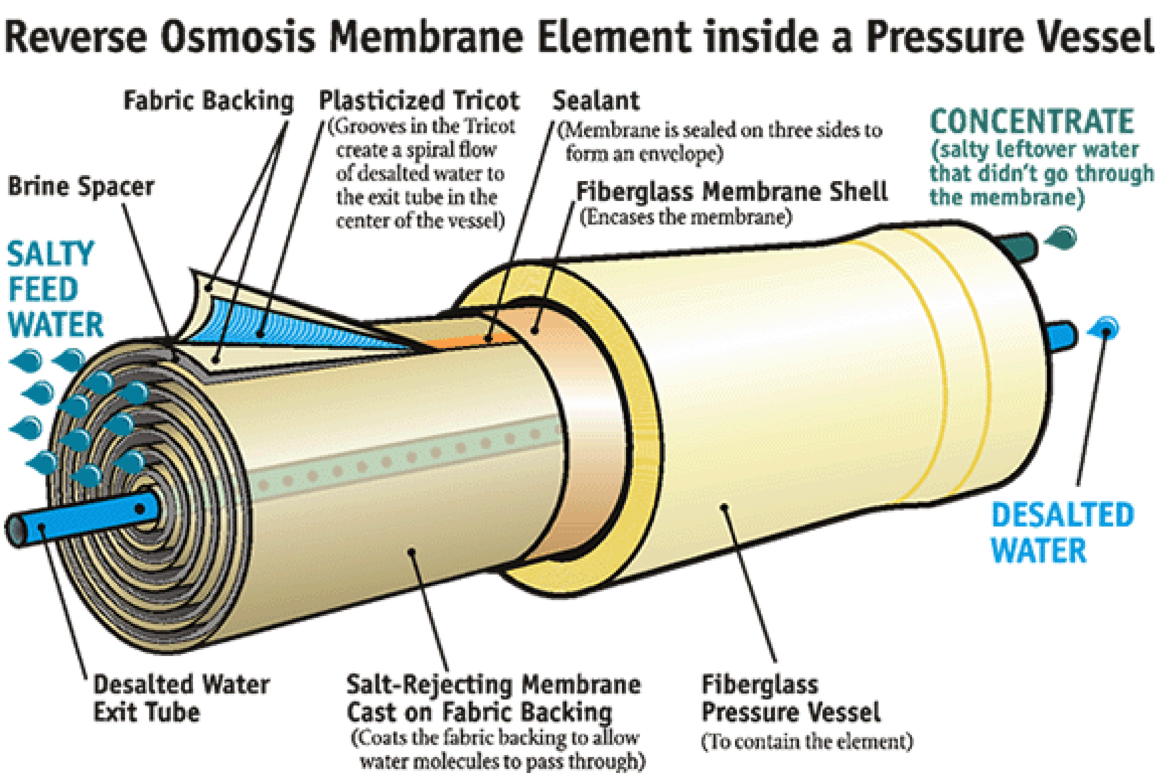

Figure A-2

Schematic of a Reverse-Osmosis Desalination Plant.

Source: U.S. Bureau of Reclamation Undated

The membrane assembly consists of a pressure vessel and a membrane that permits the feed water to be pressurized against the semi-permeable membranes. The membranes are fragile and vary in their ability to pass fresh water and reject salts. RO membranes are made in a variety of configurations. The two most commercially successful membrane configurations are spiral-wound and hollow-fine fiber. Post-treatment prepares final product water for distribution, removes gases such as hydrogen sulfide, and adjusts pH.

The energy requirement for RO depends directly on the concentration of salts in the feed water. Because neither heating nor phase change is necessary for this method, pressurizing the feed water accounts for the major use of energy. As a result, RO facilities are most economical for desalinating brackish water and increase in cost as the salt content of the water increases.

RO has become a relatively mature technology and membrane approaches are experiencing fast growth. Some of the largest new desalination plants under construction and in operation use RO membranes, including Ashkelon in Israel and the new plant at Tuas in Singapore. Ashkelon, the largest RO plant in the world, desalinates seawater for municipal purposes with a capacity of 100 million gallons per day (MGD), or 395,000 cubic meters per day (m^3/d) (Wangnick/GWI 2005).

Among the needed improvements in RO systems are better pretreatment of feedwater to reduce the use of chemicals that often end up in the brine and cause a disposal problem; improved membranes that are more durable and increase the flux of pure water; new approaches to reduce biofouling in membranes; more effective energy recovery and use; and development of less expensive materials (Awerbuch 2004).

Thermal Processes

Approximately 40% of the world's desalted water is produced with processes that use heat to distill fresh water from seawater or brackish water. The distillation process mimics the natural water cycle by producing water vapor that is then condensed into fresh water. In the simplest approach, water is heated to the boiling point to produce the maximum amount of water vapor. Water will boil at 100°C under atmospheric pressure. By decreasing pressure, however, the boiling point can be reduced. At one-quarter of normal pressure, water will boil at 65°C, and at one-tenth of normal pressure it will boil at only 45°C. To take advantage of this principle, systems have been designed to allow “multiple boiling” in a series of vessels that operate at successively lower temperatures and pressures. The concept of distilling water with a vessel operating at a reduced pressure has been applied for well over a century.

Distillation systems are often affected by scaling, which occurs when substances like carbonates and sulfates[1] found in seawater and brackish water precipitate out of solution and cause thermal and mechanical problems. Scale is difficult to remove and reduces the effectiveness of desalination operations by restricting flows, reducing heat transfer, and coating membrane surfaces. Ultimately scaling increases costs. Keeping the temperature and boiling point low slows the formation of scale.

[1]One of the most significant concerns is gypsum, a hydrate of $CaSO_4$ that forms from solution when water approaches about 95°C. Gypsum is the main component of concrete and can coat pipes, tubes, and other surfaces.

Multi-Stage Flash Distillation

Multi-stage flash distillation (MSF) accounts for the greatest installed thermal distillation capacity. Like all evaporative processes, MSF can produce high-quality fresh water with very low salt concentrations (10 ppm or less), from salt concentrations as high as 60,000 to 70,000 ppm total dissolved solids, nearly twice the salinity of seawater. In MSF, evaporation or “flashing” occurs from the bulk liquid, not on a heat-exchange surface, as is the case with other distillation processes (see Multiple-Effect Distillation, below). This minimizes scale and is a major reason MSF has been popular for several decades (Birkett 1999). Until recent advances in membrane technology, MSF was the primary technology used for desalinating seawater.

In MSF distillation, water is heated in a series of stages. Typical MSF systems consist of many evaporation chambers, each with successively lower pressures and temperatures that cause flash evaporation of hot brine, followed by condensation on cooling tubes. The steam generated by flashing is condensed in heat exchangers that are cooled by the incoming feed water. This warms up the feed water, reducing the total amount of thermal energy needed.

Generally, only a small percentage of feed water is converted to water vapor, depending on the pressure maintained in each stage. MSF plants may contain between 4 and 40 stages, but most typically are in the range of 18 to 25. Multi-stage flash plants are typically built in sizes from 2.6 MGD (10,000 m^3/d) to over 9.2 MGD (35,000 m^3/d), with several units grouped together. As of early 2005, the largest MSF plant in operation was in Shuweihat in the United Arab Emirates. This plant desalinates seawater for municipal purposes with a total capacity of 120 MGD (455,000 m^3/d) (Wangnick/GWI 2005).

Multiple-Effect Distillation

Multiple-effect distillation (MED) is a thermal method that has been used successfully for well over 100 years, substantially predating MSF (Birkett 1999). MED takes place in a series of vessels or “effects” and reduces the ambient pressure in subsequent effects. There are 8 to 16 effects in a typical large plant. This approach reuses the heat of vaporization by placing evaporators and condensers in series. Vapor produced by evaporation can be condensed in a way that uses the heat of vaporization to heat salt water at a lower temperature and pressure in each succeeding chamber, permitting water to undergo multiple boilings without supplying additional heat after the first effect. In MED plants, the salt water enters the first effect and is heated to the boiling point. Salt water may be sprayed onto heated evaporator tubes or may flow over vertical surfaces in a thin film to promote rapid boiling and evaporation.

Only a portion of the salt water applied to the tubes in the first effect evaporates. The rest moves to the second effect, where it is applied to another tube bundle heated by the steam created in the first effect. This steam condenses to fresh water, while giving up heat to evaporate a portion of the remaining salt water in the next effect. The condensate from the tubes is recycled.

Although some of the earliest distillation plants used MED, MSF units – with lower costs and less tendency to scale – have increasingly displaced this process. In the past few years, however, interest in the MED process has been renewed and MED appears to be gaining market share. According to the Wangnick/GWI desalting inventory, MED has a 15% share of the thermal market, but 21% share of proposed projects (Wangnick/GWI 2005). MED plants are typically built in units of 0.3 to 3 MGD (1,000 to 10,000 m^3/d) for smaller towns and industrial uses.

Vapor Compression Distillation

Vapor compression (VC) distillation has typically been used for small- and medium-scale desalting units. These units also take advantage of the principle of reducing the boiling point temperature by reducing ambient pressure, but the heat for evaporating the water comes from the compression of vapor rather than the direct exchange of heat from steam produced in a boiler. The two primary methods used to condense vapor to produce enough heat to evaporate incoming seawater are mechanical compression or a steam jet. The mechanical compressor can be electrically driven, making this process the only one to produce water by distillation solely with electricity (Buros 2000).

VC units use a compressor to create a vacuum, compress the vapor taken from the vessel, and condense it inside a tube bundle that is also in the same vessel, producing a stream of fresh water. As the vapor condenses, it produces fresh water and releases heat to warm the tube bundle. Salt water is then sprayed on the outside of the heated tube bundle where it boils and partially evaporates, producing more fresh water. Steam jet-type VC units, also called thermocompressors, create lower ambient pressure in the main vessel. This mixture is condensed on the tube walls to provide the thermal energy (through the heat of condensation) to evaporate salt water on the other side of the tube walls. VC units are usually built in the 0.066 to 0.50 MGD (250 to 2,000 m^3/d) range and used for tourist resorts, small industries, and remote sites.

Other Desalination Processes

Water can be desalted though many other processes including small-scale ion-exchange resins, freezing, and membrane distillation. None has achieved much commercial success, and together they account for less than one percent of total desalination capacity (Wangnick/GWI 2005). Nevertheless, some of these approaches can be effective, and even preferable, under special circumstances.

Ion-Exchange Methods

Ion-exchange methods use resins to remove undesirable ions in water. For example, cation-exchange resins are used in homes and municipal water-treatment plants to remove calcium and magnesium ions in “hard” water. The greater the concentration of dissolved solids, the more often the expensive resins have to be replaced, making the entire process economically unattractive compared with RO and ED. At lower concentrations and for small-scale systems, however, these methods have proven effective. Thus some form of ion exchange is sometimes used for the final polishing of waters that have had most of their salt content removed by RO or ED processes (Birkett 1999).

Freezing

Freeze separation takes advantage of the insolubility of salts in ice. When ice crystals form, dissolved salts are naturally excluded. If the resulting pure ice crystals can be separated from the brine, desalinated water can be produced. Extensive work was done in the 1950s and 1960s on separation technology using freezing of water. In this approach, seawater is cooled to form crystals. Before the entire mass of water has been frozen, the mixture is usually washed and rinsed to remove the salts adhering to the ice crystals. The ice is then melted to produce fresh water. The most efficient freeze methods use vapor-compression freeze-separation systems.

Freezing has some theoretical advantages over distillation, including a lower minimum energy requirement, minimal potential for corrosion, and little scaling or precipitation. Among the disadvantages, however, is the difficulty of handling and processing ice and water mixtures. A small number of demonstration plants have been built over the past 40 years, but the process has never proven commercially feasible. The few demonstration plants built have largely been abandoned. Better commercial success has been achieved in the application of freezing to the treatment of industrial wastes.

Membrane Distillation

Membrane distillation (MD) combines the use of both thermal distillation and membranes and was introduced commercially on a small scale in the 1980s. The process relies primarily upon thermal evaporation and the use of membranes to pass vapor, which is then condensed to produce fresh water.

Thus far, MD has been used in only a few areas. Compared to the more commercially successful processes, MD requires more space and more pumping energy per unit of fresh water produced. The main advantages of MD lie in its simplicity and the need for only small temperature differentials to operate. MD probably has its best application in desalting saline water where inexpensive low-grade thermal energy is available, such as from industries or solar collectors.

Desired Technological Improvements

The technology for desalinating water continues to improve, driven by advances in technology, the need to reduce costs, and commercial competition. Recent reviews recommend that research focus on several areas, which include water quality sensor development, improved filtration, improved heat-transfer materials, and improved intake methods (NAS 2004). See below for a more detailed discussion.

Water Quality Sensor Development

In order to permit more effective application of filters and chemicals and reduce membrane fouling, development of sensors able to quickly and inexpensively analyze water quality and identify pathogens are needed. These improvements apply to all desalination systems, as they would allow more effective post treatment application.

Improved Filtration

Nanofiltration and ultrafiltration membranes are designed to reduce the concentration of certain ions or contaminants early in the desalination process. The use of such filters in other desalination processes can increase overall productivity of both membrane and distillation systems by removing sulfate, calcium, and other compounds in feedwater. Improving these approaches and reducing their cost would help performance of all desalination systems.

Improved Heat-Transfer Materials

Most desalination methods use various heat-transfer surfaces to facilitate the process and reduce costs. Current heat-transfer surfaces are often made of expensive corrosion-resistant materials, such as titanium and high-grade stainless steel. New nonmetallic or polymeric heat-transfer materials could reduce capital costs but additional research is required to produce reliable and effective ones. Improvement in the design of heat-transfer surfaces could also improve operating efficiencies and reduce costs.

Improved Intake Methods

With few exceptions, current intake methods for seawater desalination plants, especially large plants, impinge and entrain substantial amounts of marine life. Intake methods should be improved to reduce the marine impacts of desalination plants.

Membrane Integrity Improvements

Membranes fail for a number of reasons, including oxidation by chlorine and metals and mechanical damage from sediment. These failures are expensive and permit pathogens or contaminants to compromise the quality of the final product. Improvements in membrane durability and integrity would reduce costs and increase system performance.

Membrane Selectivity

"Selective" membranes capable of removing specific contaminants from a water stream would increase the flexibility of a system and potentially reduce costs. Contaminants not targeted for removal, such as algal toxins, may remain in the purified water and pose a human health, economic, and/or environmental risk.

Reduced Membrane Fouling

Innovations in approaches to clean and restore fouled membranes are still needed. The fouling of membrane systems by organic and inorganic materials, including algae and bacteria, reduces membrane life and increases overall costs. Efforts to control fouling, i.e., pretreatment of source water, application of membrane-cleaning chemicals, or operational changes, are costly. Some efforts to develop fouling-resistant elements are underway. The wide variety of feedwater qualities makes it unlikely that complete resistance to fouling will be achieved.

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