The ABCs of Desalting

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INTRODUCTION

Desalting: A Treatment Process

Desalting, as discussed in this booklet, refers to a water treatment process that removes salts from water. It is also called *desalination* or *desalinization*, but it means the same thing. Desalting can be done in a number of ways, but the result is always the same: fresh water is produced from brackish or seawater. Desalting technologies can be used for a number of applications, but the purpose of this booklet is to discuss the use of desalting to produce potable water from saline water for domestic or municipal purposes.

The ability to obtain fresh water from the sea has transformed semi-arid areas like the Virgin Islands, where seawater desalination units were first installed in 1960 *Photo — O.K. Buros*

Throughout history, people have continually tried to treat salty water so that it could be used for drinking and agriculture. Of all the globe's water, 94 percent is salt water from the oceans and 6 percent is fresh. Of the latter, about 27 percent is in glaciers and 72 percent is underground. While this water is important for transportation and fisheries, it is too salty to sustain human life or farming. Desalting techniques have increased the range of water resources available for use by a community.

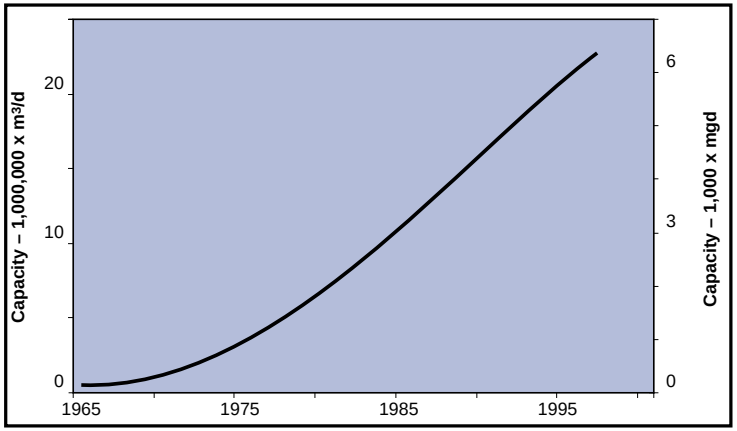
Until recently, only water with a dissolved solids (salt) content generally below about 1,000 milligrams per liter (mg/L) was considered acceptable for a community water supply. This limitation sometimes restricted the size and location of communities around the world and often led to hardship to many that could not afford to live near a ready supply of fresh water. The application of desalting technologies over the past 50 years has changed this in many places. Villages, cities, and industries have now developed or grown in many of the arid and water-short areas of the world where sea or brackish waters are available and have been treated with desalting techniques.

This change has been very noticeable in parts of the arid Middle East, North Africa, and some of the islands of the Caribbean, where the lack of fresh water severely limited development. Now, modern cities and major industries have developed in some of those areas thanks to the availability of fresh water produced by desalting brackish water and seawater.

The Development of Desalting

Desalting is a natural, continual process and an essential part of the water cycle. Rain falls to the ground. Once on the ground, it flows to the sea, and people use the water for various purposes as it makes this journey. As it moves over and through the earth, the water dissolves minerals and other materials, becoming increasingly salty. While in transit and upon arrival in the world's oceans or other natural low spots like the Dead Sea or the Great Salt Lake, a part of the water is evaporated by the sun's energy. This evaporated water leaves the salts behind, and the resulting water vapor forms clouds that produce rain, continuing the cycle.

A major step in development came in the 1940s, during World War II, when various military establishments in arid areas needed water to supply their troops. The potential that desalting offered was recognized more widely after the war and work was continued in various countries. The American government, through creation and funding of the Office of Saline Water (OSW) in the early 1960s and its successor organizations like the Office of Water Research and Technology (OWRT), made one of the most concentrated efforts to develop the desalting industry. The American government actively funded research and development for over 30 years, spending about $300 million in the process. This money helped to provide much of the basic investigation and development



Total installed capacity of desalting facilities
Source — 1998 IDA Inventory

of the different technologies for desalting sea and brackish waters.

By the late 1960s, commercial units of up to 8,000 cubic meters per day (m^3/d) [2 million U.S. gallons per day (mgd)] were beginning to be installed in various parts of the world. These mostly thermal-driven units were used to desalt seawater, but in the 1970s, commercial membrane processes such as electrodialysis (ED) and reverse osmosis (RO) began to be used more extensively. Originally, the distillation process was used to desalt both brackish water and seawater. This process could be expensive and restricted the applications for desalting to municipal purposes. When ED was introduced, it could desalt brackish water much more economically than distillation, and many applications were found for it. This breakthrough in reducing the potential costs for brackish

water desalting was significant because it focused interest, especially in the USA, on the potential to use desalting as a means to provide water for municipalities with limited fresh water supplies.

By the 1980s, desalination technology was a fully commercial enterprise. The technology benefited from the operating experience (sometimes good, sometimes bad) achieved with the units that had been built and operated in the previous decades. By the 1990s, the use of desalting technologies for municipal water supplies had become commonplace.

Commercially Available Desalting Processes

Major Processes

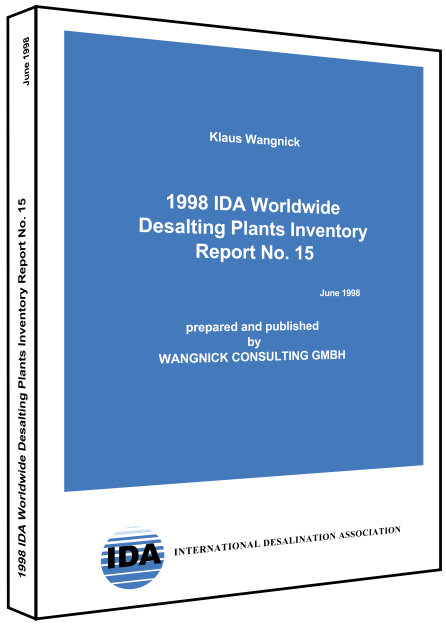
- **Thermal**
  - Multi-Stage Flash Distillation
  - Multiple-Effect Distillation
  - Vapor Compression
- **Membrane**
  - Electrodialysis
  - Reverse Osmosis

Minor Processes

- **Freezing**
- **Membrane Distillation**
- **Solar Humidification**

A variety of desalting technologies has been developed over the years and, based on their commercial success, they can be classified into the major and minor desalting processes shown in the table.

Worldwide Acceptance

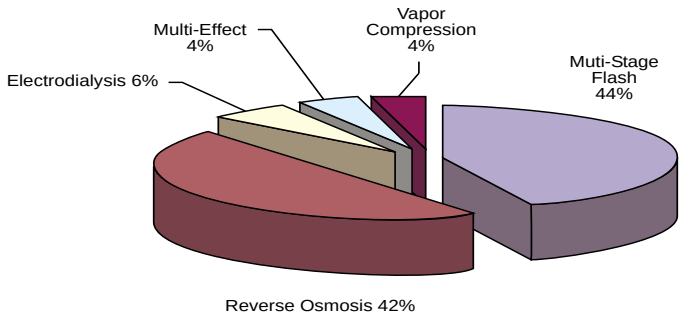


The continual growth of desalination has been monitored over the years through a series of inventories. IDA has sponsored the inventories for over 10 years. The latest one, at the time of printing of this booklet, is an inventory completed in 1998 for IDA by Klaus Wangnick, *1998 IDA Worldwide Desalting Plants Inventory - Report No. 15* (the Inventory). This inventory indicated that the total capacity of installed desalination plants worldwide was 22.7 million m^3/d 6 billion gpd of which about 85 percent was still in operation. This total capacity is an increase of about 70 percent from that reported in the previous edition of *The Desalting ABC's* in 1990. Desalting equipment is now used in over 100 countries. According to the Inventory, 10 countries have about 75 percent of all the capacity. Almost half of this desalting capacity is used to desalt seawater in the Middle East and North Africa. Saudi Arabia ranks first in total capacity (about 24 percent of the world's capacity), with most of it being made up of

seawater desalting units that use the distillation process. The United States of America (USA) ranks second in overall capacity, with about 16 percent. Most of the capacity in the USA consists of plants in which the RO process is used to treat brackish water.

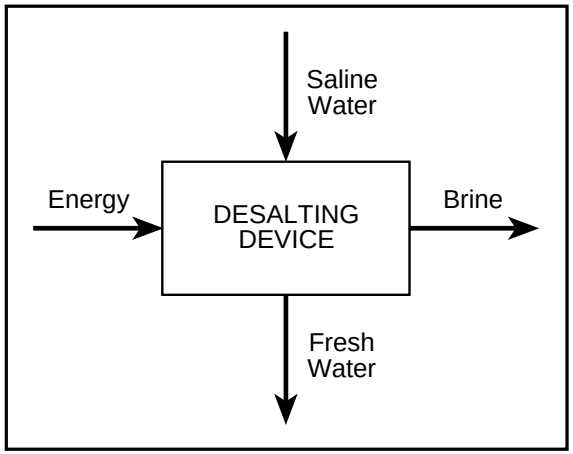
The Inventory indicates that the world's installed capacity consists mainly of the multi-stage flash distillation and RO processes. These two processes make up about 86 percent of the total capacity. The remaining 14 percent is made up of the multiple effect, electrodialysis, and vapor compression processes, while the minor processes amounted to less than one percent.

Based on these data, the installed capacity of membrane and thermal processes is about equal. Since a portion of the older units, which generally were distillation units, are now retired, it is probable that the capacity of operating membrane units exceeds that of thermal.



Installed desalination capacity by process
Source — 1998 IDA Inventory

Desalting Technologies



A desalting device essentially separates saline water into two streams: one with a low concentration of dissolved salts (the fresh water stream) and the other containing the remaining dissolved salts (the concentrate or brine stream). The device requires energy to operate and can use a number of different technologies for the separation. This section briefly describes the various desalting processes commonly used to desalt saline water.

Thermal Processes

About half of the world's desalted water is produced with heat to distill fresh water from sea water. The distillation process mimics the natural water cycle in that salt water is heated, producing water vapor that is in turn condensed to form fresh water. In a laboratory or industrial plant, water is heated to the boiling point to produce the maximum amount of water vapor.

To do this economically in a desalination plant, the applied pressure of the water being boiled is adjusted to control the boiling point because of the reduced atmospheric pressure on the water, the temperature required to boil water decreases as one moves from sea level to a higher elevation. Thus, water can be boiled on top of Mt. McKinley, in Alaska [elevation 6,200 meters (20,300 feet)], at a temperature about 16 °C (60.8 °F) lower than it would boil at sea level. This reduction of the boiling point is important in the desalination process for two major reasons: multiple boiling and scale control.

To boil, water needs two important conditions: the proper temperature relative to its ambient pressure and enough energy for vaporization. When water is heated to its boiling point and then the heat is turned off, the water will continue to boil only for a short time because the water needs additional energy (the heat of vaporization) to permit boiling. Once the water stops boiling, boiling can be renewed by either adding more heat or by reducing the ambient pressure above the water. If the ambient pressure were reduced, the water would be at a temperature above its boiling point (because of the reduced pressure) and would flash to produce vapor (steam), the temperature of the water will fall to the new boiling point. If more vapor can be produced and then condensed into fresh water with the same amount of heat, the process tends to be more efficient.

To significantly reduce the amount of energy needed for vaporization, the distillation desalting process usually uses multiple boiling in successive vessels, each operating at a lower temperature and pressure. Typically 8 tons of distillate can be produced from 1 ton of steam. This process of reducing the ambient pressure to promote additional boiling can continue downward and, if carried to the extreme with the pressure reduced enough, the point at which water would be boiling and freezing at the same time would be reached.

Aside from multiple boiling, the other important factor is scale control. Although most substances dissolve more readily in warmer water, some dissolve more readily in cooler water. Unfortunately, some of these substances, like carbonates and sulfates, are found in seawater. One of the most important is calcium sulfate (CaSO4), which begins to leave solution when sea water approaches about 115 °C (203 °F). This material forms a hard scale that coats any tubes or surfaces present. Scale creates thermal and mechanical problems and, once formed, is difficult to remove. One way to avoid the formation of this scale is to control the

Scaled tubes in a distillation plant
Photo — OK Buros

concentration level of seawater and to control the top temperature of the process. Another way is to add special chemicals to the sea water that reduce scale precipitation and permit the top temperature to reach 110°C.

These two concepts have made various forms of distillation successful in locations around the world. The process that accounts for the most desalting capacity for seawater is multi-stage flash distillation, commonly referred to as the MSF process.

Multi-Stage Flash Distillation

In the MSF process, seawater is heated in a vessel called the brine heater. This is generally done by condensing steam on a bank of tubes that carry seawater which passes through the vessel. This heated seawater then flows into another vessel, called a stage, where the ambient pressure is lower, causing the water to immediately boil. The sudden introduction of the heated water into the chamber causes it to boil rapidly, almost exploding or flashing into steam. Generally, only a small percentage of this water is converted to steam (water vapor), depending on the pres-

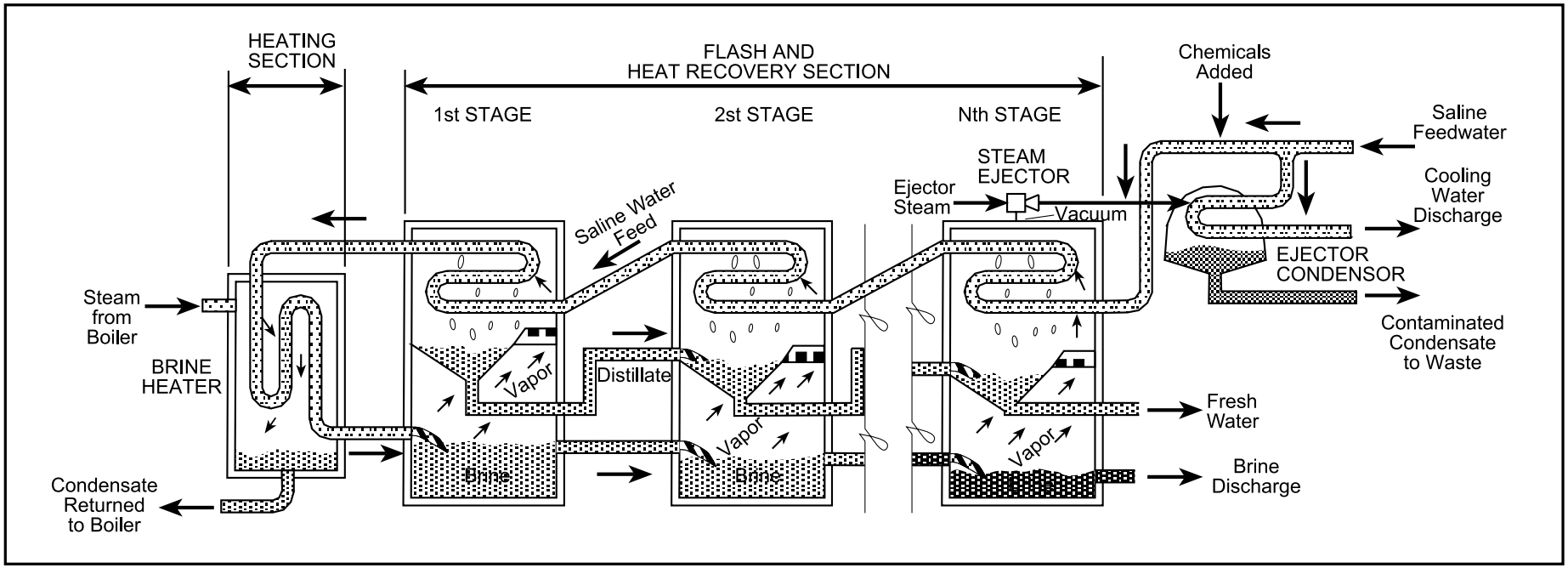


Diagram of a Multi-Stage Flash Plant *USAID*

sure maintained in this stage, since boiling will continue only until the water cools (furnishing the heat of vaporization) to the boiling point.

The concept of distilling water with a vessel operating at a reduced pressure is not new and has been used for well over a century. In the 1950s, an MSF unit that used a series of stages set at increasingly lower atmospheric pressures was developed. In this unit, the feed water could pass from one stage to another and be boiled repeatedly without adding more heat. Typically, an MSF plant can contain from 15 to 25 stages. Adding stages increases the total surface area, thus increases the capital cost in addition to the complexity of operation.

Photo — OK Buros

The vapor steam generated by flashing is converted to fresh water by being condensed on tubes of heat exchangers that run through each stage. The tubes are cooled by the incoming feed water going to the brine heater. This, in turn, warms up the feed water so that the amount of thermal energy needed in the brine heater to raise the temperature of the seawater is reduced.

Multi-stage flash plants have been built commercially since the 1950s. They are generally built in units of about 4,000 to 57,000 m^3/d (1 to 15 mgd). The MSF plants usually operate at the top brine temperatures after the brine heater of 90 - 110 °C (194 - 230 °F). One of the factors that affect the thermal efficiency of the plant is the difference between the temperature of the brine heater exit and the temperature in the last stage on the cold end of the plant. Operating a plant at the higher temperature limits of 110 °C (230 °F) increases the efficiency, but it also increases the potential for detrimental scale formation and accelerated corrosion of metal surfaces.

Desalting research facility in Saudi Arabia
Photo — SWCC

The most significant progress that has been made over the past 10 years is the increase in the reliability of operation. This reliability has been brought about by improvements in scale control, attention to daily operation, automation and controls, and materials of construction. In addition, increases in the size of the basic unit has produced economies of scale in capital costs. Many countries on the Arabian Peninsula, such as Saudi Arabia, the United Arab Emirates, and Kuwait, are highly dependent on MSF facilities to supply water to their urban areas. This dependence, combined with a large installed capacity, has encouraged them to take measures to protect this investment. The water authorities in these countries have invested funds to increase the level of operator training, experimented with anti-scaling methods and chemicals, and generally stabilized the operation of their plants.

Saudi Arabia, Kuwait, Oman, and others have established important desalting research facilities in their countries to support the operation and reliability of their plants, and they have supported overall research on desalting technologies.

Multi-Effect Distillation

The multi-effect distillation (MED) process has been used for industrial distillation for a long time. Traditional uses for this process are the evaporation of juice from sugar cane in the production of sugar and the production of salt with the evaporative process. Some of the early water distillation plants used the MED process, but MSF units, because of a better resistance against scaling, displaced this process. However, starting in the 1980s, interest in the MED process was revived, and a number of new designs have been built around the concept of operating on lower temperatures, thus minimizing corrosion and scaling.

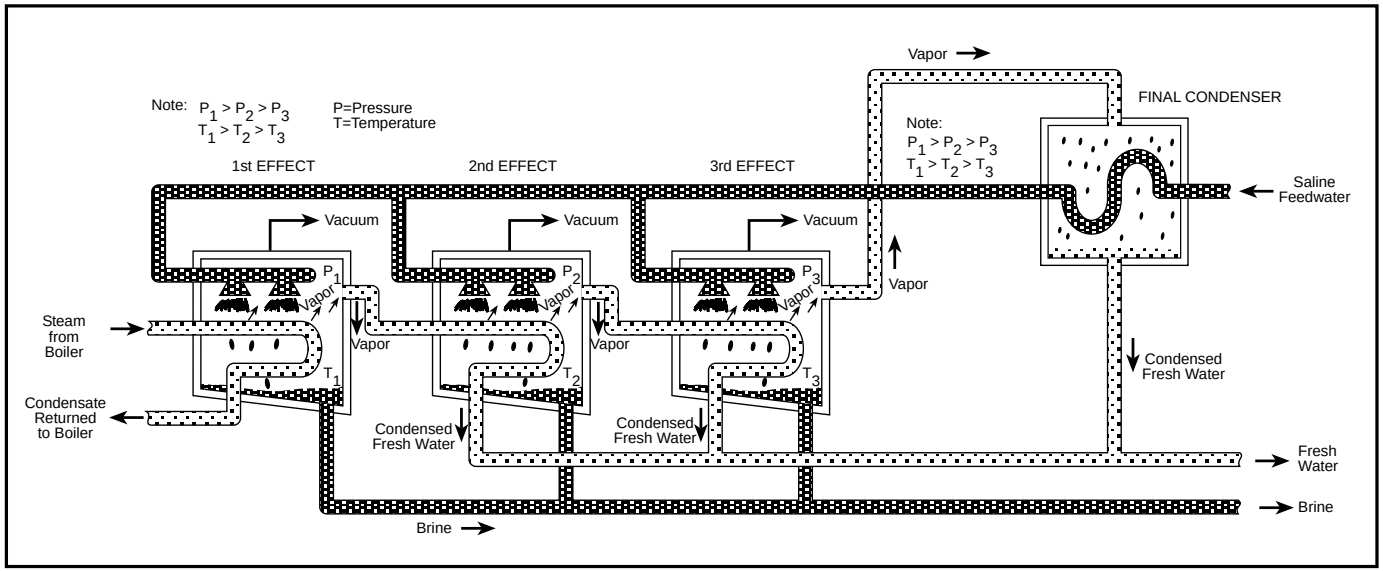


Diagram of a Multi-Effect plant with horizontal tubes. *USAID*

MED, like MSF, takes place in a series of vessels (effects) and uses the principles of condensation and evaporation at reduced ambient pressure in the various effects. This permits the seawater feed to undergo boiling without the need to supply additional heat after the first effect. In general, an effect consists of a vessel, a heat exchanger, and devices for transporting the various fluids between the effects. Diverse designs have been or are being used for the heat exchanger area, such as vertical tubes with falling brine film or rising liquids, horizontal tubes with falling film, or plates with a falling brine film. By far the most common heat exchanger consists of horizontal tubes with a falling film.

There are several methods of adding the feed water to the system. Adding feed water in equal portions to the various effects is the most common. The feed water is sprayed or otherwise distributed onto the surface of the evaporator surface (usually tubes) in a thin film to promote rapid boiling and evaporation after it has been preheated to the boiling temperature on the upper section. The surfaces in the first effect, are heated by Steam from Steam turbines of the power plants or a boiler. The steam is then condensed on the colder heat transfer surface inside the effect to heat. The condensate is recycled to the boiler for reuse. The surfaces of all the other effects are heated by the steam produced in each preceding effect. The steam produced in the last effect is condensed in a separate heat exchanger called the final condenser, which is cooled by the incoming sea water, thus preheating the feed water.

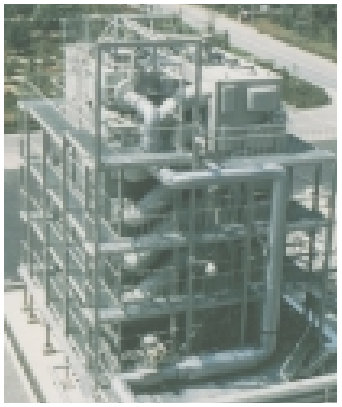
Only a portion of the seawater applied to the heat transfer surfaces is evaporated. The remaining feed water, of each effect, now concentrated and called brine, is often fed to the brine pool of the next effect, where some of it flashes into steam. This steam is also part of the heating process. All steam condensed inside the effects is the source of the fresh water product.

The ambient pressure in the various effects in the MED process is maintained by a separate vacuum system. The thermal efficiency of the process depends on the number of effects with 8 to 16 effects being found in a typical plant.

Three low-temperature MED plants on St. Thomas (V.I). Each plant has a capacity of about 5,000 m³d (1.2 mgd). Photo — OK Buros

MED plants are typically built in units of 2,000 to 20,000 $^{m3/d}$ (0.5 to 5 mgd). Some of the more recent plants have been built to operate with a top temperature (in the

first effect) of about 70 °C (158 °F), which reduces the potential for scaling of seawater within the plant. This in turn increases the need for additional heat transfer areas that add to the physical size of the plants. Most of the more recent applications for the MED plants have been in India, the Caribbean, the Canary Islands and the United Arab Emirates. Although the installed capacity of units using the MED process relative to the world's total capacity is still small, their numbers and popularity have been increasing.

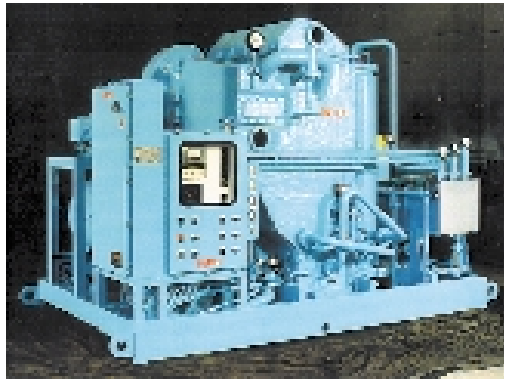


2,000 $^{m3/d}$ (0.5-mgd) vertically stacked MED plant in Japan
Photo — Sasakura

Highly efficient MED plants need a considerable number of effects and large heat transfer areas and are therefore used in cases where energy costs are high. In cases where low cost steam is available. The MED capital costs are significantly reduced. In other MED applications, a vapor thermal compression cycle is usually added to the system. This considerably reduces the number of effects and surface area required for the same capacity.

Vapor Compression Distillation

The vapor compression (VC) distillation process is generally used in combination with other processes (like the MED described above) and by itself for small and medium-scale seawater desalting applications. 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.



A mechanical vapor compression unit
Photo — MECO

The plants that use this process are also designed to take advantage of the principle of reducing the boiling point temperature by reducing the pressure. Steam ejectors (thermal vapor compression) and mechanical compressors (mechanical vapor compression) are used in the compression cycle to run the process. The mechanical compressor is usually electrically or diesel driven, allowing the sole use of electrical or mechanical energy to produce water by distillation.

VC units have been built in a variety of configurations to promote the exchange of heat to evaporate the seawater. The diagram illustrates a simplified method in which a mechanical compressor is used to generate the heat for evaporation. All steam is removed by a mechanical compressor from the last effect and introduced as heating steam into the first effect after compression where it condenses on the cold side of the heat transfer surface. Seawater is sprayed, or otherwise distributed on the other

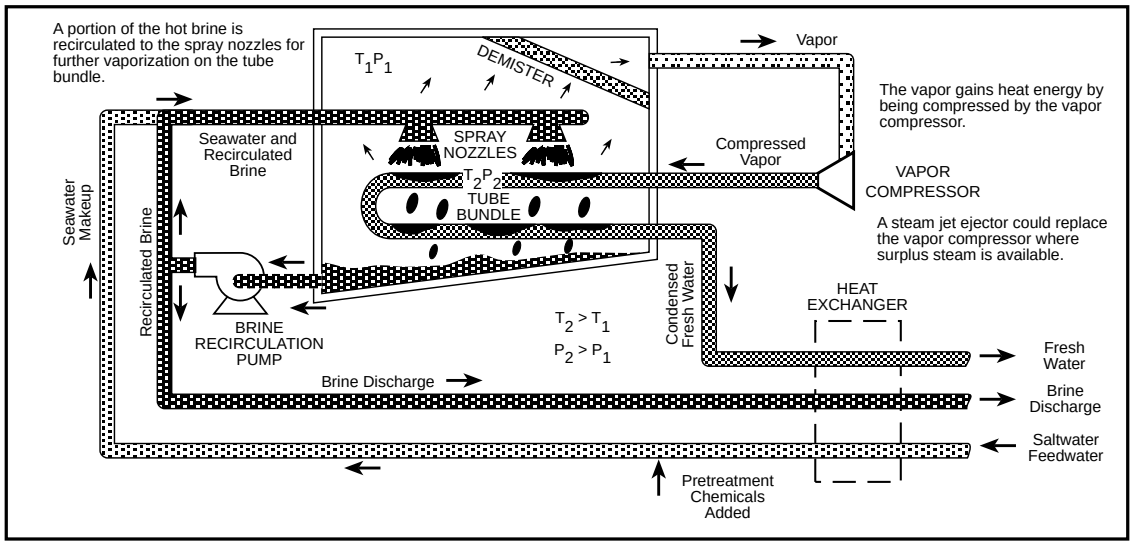


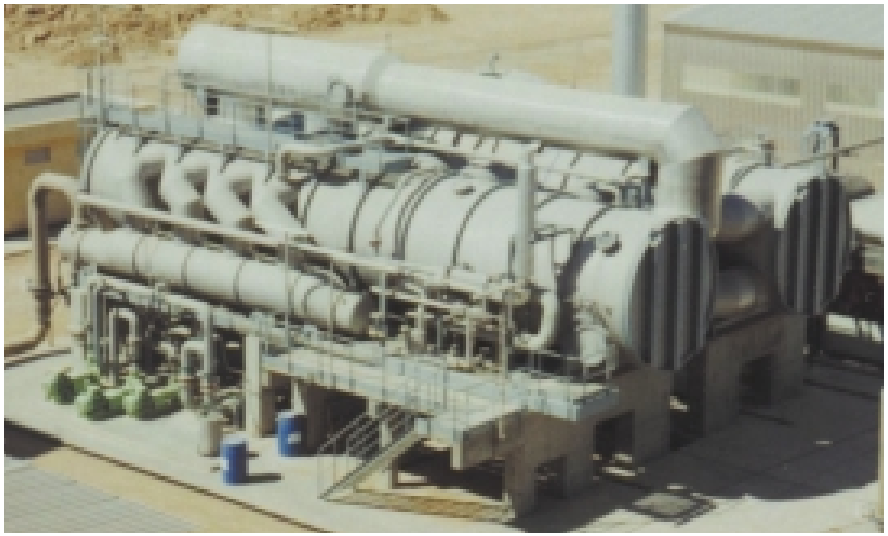
Diagram of a mechanical vapor compression unit *USAID*

side of the heat transfer surface where it boils and partially evaporates, producing more vapor.

In order to use low cost compressors, the pressure increase is limited, and therefore, most smaller plants only have one stage. In newer and larger plants, several stages are used. The mechanical VC units are produced in capacities ranging from a few liters up to 3,000 m^3/d (0.8 mgd). They generally have an energy consumption of about 7 to 12 kWh/m^3 (26 to 45 kWh/1000 gal).

With the steam-jet type VC unit, also called a thermocompressor, an ejector operated using 3 to 20 bar (45 to 300 pounds per square inch [psi]) motive steam removes part of the water vapor (steam) from the vessel. In the ejector, the removed vapor is compressed to the necessary heating steam pressure to be introduced into the first effect. On average, one part of motive steam removes one part vapor from the last effect, thus producing two parts of heating steam. Thermal vapor compression plants are usually built in the 500 to 20,000 11 range.

VC units are often used for resorts, industries, and drilling sites where fresh water is not readily available. Their simplicity and reliability of operation make them an attractive unit for small installations where these factors are desired.

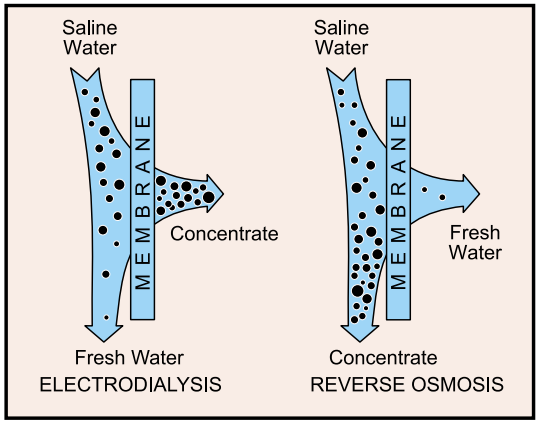


Thermal vapor compression unit in Saudi Arabia
Photo — Weir Westgarth

Membrane Processes

In nature, membranes play an important role in the separation of salts, including both the process of dialysis and osmosis, occurs in the body. Membranes are used in two commercially important desalting processes: electrodialysis (ED) and reverse osmosis (RO). Each process uses the ability of the membranes to differentiate and selectively separate salts and water. However, membranes are used differently in each of these processes.

ED is a voltage-driven process and uses an electrical potential to move salts selectively through a membrane, leaving fresh water behind as product water.



RO is a pressure-driven process, with the pressure used for separation by allowing fresh water to move through a membrane, leaving the salts behind.

Scientists have explored both of these concepts since the turn of the century, but their commercialization for desalting water for municipal purposes has occurred in only the last 30 to 40 years.

Electrodialysis

ED was commercially introduced in the early 1960s, about 10 years before RO. The development of ED provided a cost-effective way to desalt brackish water and spurred considerable interest in the whole field of using desalting technologies for producing potable water for municipal use.

ED depends on the following general principles:

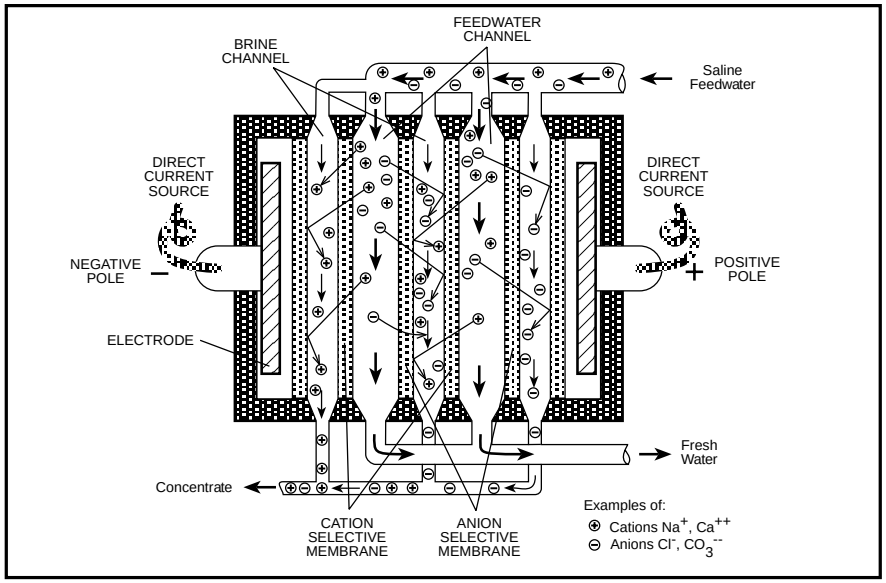
- Most salts dissolved in water are ionic, being positively (cationic) or negatively (anionic) charged.
- These ions migrate toward the electrodes with an opposite electric charge.
- Membranes can be constructed to permit selective passage of either anions or cations.

The dissolved ionic constituents in a saline solution, such as chloride (-) sodium (+), calcium (++), and carbonate (–), are dispersed in water, effectively neutralizing their individual charges. When electrodes are connected to an outside source of direct current like a battery and placed in a container of saline water, electrical current is carried through the solution, with the ions tending to migrate to the electrode with the opposite charge.

For these phenomena to desalinate water, individual membranes that will allow either cations or anions (but not both) to pass are placed between a pair of electrodes.

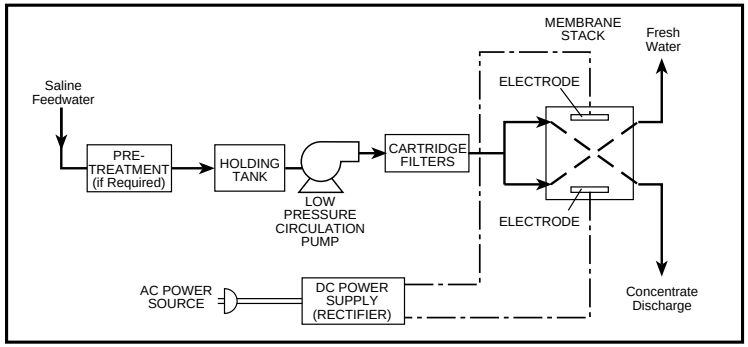
These membranes are arranged alternately, with an anion-selective membrane followed by a cation-selective membrane. A spacer sheet that permits water to flow along the face of the membrane is placed between each pair of membranes.

One spacer provides a channel that carries feed (and product) water, while the next carries brine. As the electrodes are charged and saline feed water flows along the product water spacer at right angles to the electrodes, the anions (such as sodium and calcium) in the water are attracted and diverted through the membrane towards the positive electrode. This dilutes the salt content of the water in the product water channel. The anions pass through the anion-selective membrane, but cannot pass any farther than the cation-selective membrane, which blocks their path and traps the anions in the brine stream. Similarly, cations (such as chloride or carbonate) under the influence of the negative electrode move in the opposite direction through the cation-selective membrane to the concentrate channel on the other side. Here, the cations are trapped because the next membrane is anion-selective and prevents further movement towards the electrode.



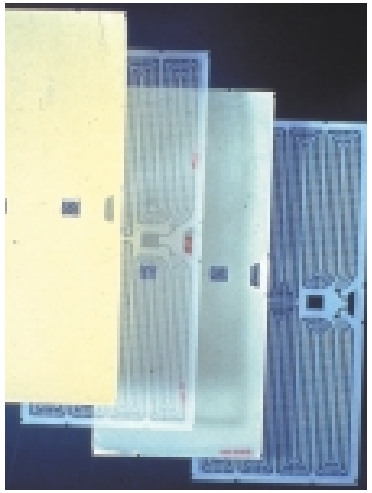
Movement of ions in the electrodialysis process *USAID*

By this arrangement, concentrated and diluted solutions are created in the spaces between the alternating membranes. These spaces, bounded by two membranes (one anionic and the other cationic) are called cells. The cell pair consists of two cells, one from which the ions migrated (the dilute cell for the product water) and the other in which the ions concentrate (the concentrate cell for the brine stream).



Components of an electrodialysis plant *USAID*

The basic ED unit consists of several hundred-cell pairs bound together with electrodes on the outside and is referred to as a membrane stack. Feed water passes simultaneously in parallel paths through all the cells to provide a continuous flow of desalted water and concentrate (or brine) from the stack. Depending on the design of the system, chemicals may be added to the streams in the stack to reduce the potential for scaling.



EDR membranes and spacers
Photo — Ionics

An ED unit is made up of the following basic components:

- Pretreatment train
- Membrane stack
- Low-pressure circulating pump
- Power supply for direct current (a rectifier)
- Post-treatment

The raw feed water must be pretreated to prevent materials that could harm the membranes or clog the narrow channels in the cells from entering the membrane stack. The feed water is circulated through the stack with a low-pressure pump with enough power to overcome the resistance of the water as it passes through the narrow passages. A rectifier is used to transform alternating current to the direct current supplied to the electrodes on the outside of the membrane stacks.

Post-treatment consists of stabilizing the water and preparing it for distribution. This post-treatment might consist of removing gases such as hydrogen sulfide and adjusting the pH.

A 4,000 m^3/d (1mgd) EDR unit, Port Hueneme, USA
Photo — Ionics

In the early 1970s, an American company commercially introduced the electrodialysis reversal (EDR) process. An EDR unit operates on the same general principle as a standard electrodialysis plant except that both the product and the brine channels are identical in construction. At intervals of several times an hour, the polarity of the elec-

trodes is reversed, and the flows are simultaneously switched so that the brine channel becomes the product water channel, and the product water channel becomes the brine channel.

The result is that the ions are attracted in the opposite direction across the membrane stack. Immediately following the reversal of polarity and flow, the product water is dumped until the stack and lines are flushed out and the desired water quality is restored. This flush takes only 1 or 2 minutes, and then the unit can resume producing water. The reversal process is useful in breaking up and flushing out scales, slimes, and other deposits in the cells before they can build up and create a problem. Flushing allows the unit to operate with fewer pretreatment chemicals and minimizes membrane fouling.

ED has the following characteristics that make it suitable for a number of applications:

- Capability for high recovery (more product and less brine)
- Energy usage that is proportional to the salts removed
- Ability to treat feed water with a higher level of suspended solids than RO
- Uneffected by non-ionic substances such as silica
- Low chemical usage for pretreatment

ED units are normally used to desalinate brackish water. The major energy requirement is the direct current used to separate the ionic substances in the membrane stack.

Reverse Osmosis

In comparison to distillation and electrodialysis, RO is relatively new, with successful commercialization occurring in the early 1970s.

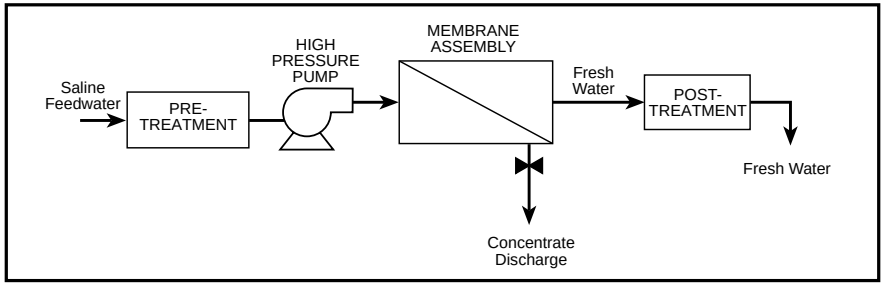
RO is a membrane separation process in which the water from a pressurized saline solution is separated from the solutes (the dissolved material) by flowing through a membrane. No heating or phase change is necessary for this separation. The major energy required for desalting is for pressurizing the feed water.

The world's largest reverse osmosis plant in Yuma, USA. is used to reduce the salinity of the Colorado River 270,000 $^{m3/d}$ (72mgd)

Photo — USBR

In practice, the saline feed water is pumped into a closed vessel where it is pressurized against the membrane. As a portion of the water passes through the membrane, the remaining feed water increases in salt content. At the same time, a portion of this feed water is discharged without passing through the membrane.

Without this controlled discharge, the pressurized feed water would continue to increase in salt concentration,



Basic components of a reverse osmosis plant *USAID*

creating problems such as precipitation of super-saturated salts and increased osmotic pressure across the membranes. The amount of the feed water discharged to waste in the brine stream varies from 20 to 70 percent of the feed flow, depending on the salt content of the feed water, pressure, and type of membrane.

An RO system is made up of the following basic components:

- Pretreatment
- High-pressure pump
- Membrane assembly
- Post-treatment

Pretreatment is important in RO because the membrane surfaces must remain clean. Therefore, suspended solids must be removed and the water pretreated so that salt precipitation or microbial growth does not occur on the membranes. Usually, the pretreatment consists of fine filtration and the addition of acid or other chemicals to inhibit precipitation and the growth of microorganisms.

Hollow fiber membranes being used to desalt brackish water newar Riyadh, Saudi Arabia
Photo — OK Buros

The high-pressure pump supplies the pressure needed to enable the water to pass through the membrane and have the salts rejected. This pressure ranges from 15 to 25 bar (225 to 375 psi) for brackish water and from 54 to 80 bar (800 to 1,180 psi) for sea water.

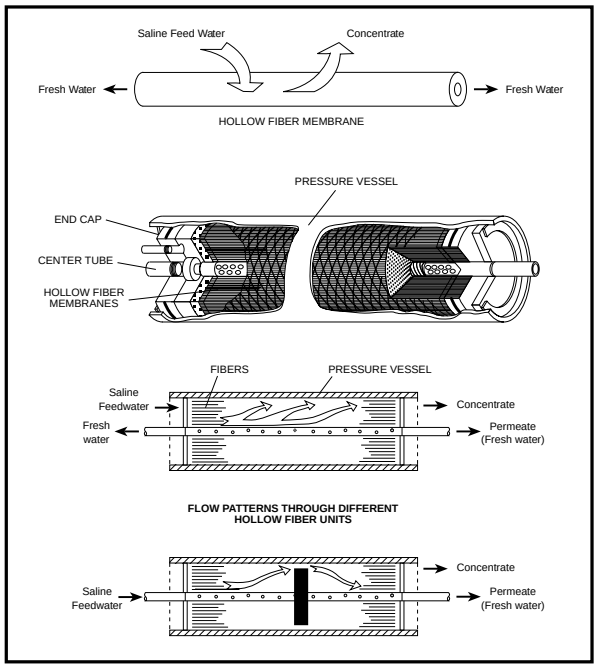
The membrane assembly consists of a pressure vessel and a membrane that permits the feed water to be pressurized against the membrane. The membrane must be able to withstand the entire pressure drop across it. The semi-permeable membranes vary in their ability to pass fresh water and reject the passage of salts. No membrane is perfect in its ability to reject salts, so a small amount of salts passes through the membrane and appears in the product water.

RO membranes are made in a variety of configurations. Two of the most commercially successful are spiral-wound and hollow fiber. Both of these configurations are used to desalt both brackish and seawater, although the construc-

tion of the membrane and pressure vessel will vary depending on the manufacturer and expected salt content of the feed water.

Spiral membrane unit
Photo — Koch Industries

Post-treatment consists of stabilizing the water and preparing it for distribution. This post-treatment might consist of the removing gases such as hydrogen sulfide and adjusting the pH.



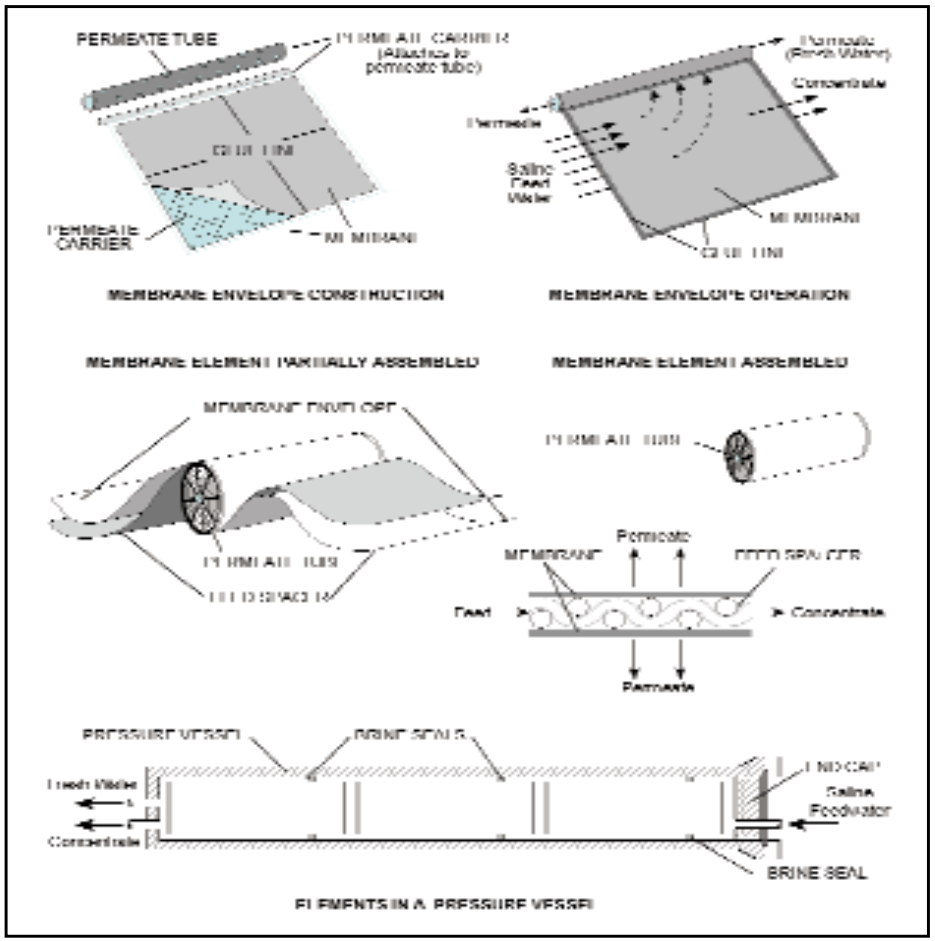
Hollow fiber membrane assembly

Two developments have helped to reduce the operating cost of RO plants during the past decade: the development of more efficient membranes and the use of energy recovery devices. The membranes now have higher water flux (passage per unit area), improved rejection of salts, lower prices, and longer service lives.

Interstage energy recovery unit integrated with the pump
Photo — OK Buros

It is common now to use energy recovery devices connected to the concentrate stream as it leaves the pressure vessel at about 1 to 4 bar (15 to 60 psi) less than the applied pressure from the high-pressure pump. These energy recovery devices are mechanical and generally consist of work or pressure exchangers, turbines, or pumps of some type that can convert the pressure difference to rotating or other types of energy that can be used to reduce the energy needs in the overall process. These can have a significant impact on the economics of operating large plants. They increase in value as the cost of energy increases. Now, energy usage in the range of 3 kWh/m^3 (11.4 kWh/1000 gal) for seawater RO (with energy recovery) plants has been reported.

The other important event in the RO membrane area has been the use of membranes called nanofiltration (NF) that are more porous to the passage of dissolved solids. This process is used to soften water by removing mostly divalent ions (e.g., $Ca^{+2}$and Mg^{+2}). The rejection by NF membranes of monovalent ions like Cl^- is much lower than



Cutaway view of a spiral membrane

Source — USAID and RODI Industries

with RO membranes. They are used even where the feedwater is essentially fresh, although it still contains dissolved solids that cause hardness. Whether the use of NF membranes to perform membrane softening (MS) is considered a desalting process is a matter of how one defines desalting.

However, the development and use of NF membranes are a direct outgrowth from the RO industry. The MS process and NF membranes have revolutionized the water softening industry, and they are moving it from a chemical-based to a largely membrane-based process. Recently NF membranes found an application to effectively soften seawater. The NF softened seawater as a feed to distillation and RO processes offers the potential of significant improvement in seawater desalination costs. This, in turn, has furthered interest in all types of membranes for municipal potable water treatment.

The past ten years have been significant ones for the RO process. Although the process has not fundamentally changed in concept, there have been steady and continuous improvements in the efficiency of the membranes, energy recovery, energy reduction, membrane life, control of operations and operational experience. The result has been an overall reduction in the cost of water produced by the RO process, especially in the desalting of seawater.

Other Processes

A number of other processes have been used to desalt saline waters. These processes have not achieved the level of commercial success that distillation, ED, and RO have, but they may prove valuable under special circumstances or with further development.

Freezing

Extensive work was done in the 1950s and 1960s to develop freezing desalination. During the process of freezing, dissolved salts are naturally excluded during the initial formation of ice crystals. Cooling saline water to form ice crystals under controlled conditions can desalinate seawater. Before the entire mass of water has been frozen, the mixture is usually washed and rinsed to remove the salts in the remaining water or adhering to the ice crystals. The ice is then melted to produce fresh water.

Theoretically, freezing has some advantages over distillation, which was the predominant desalting process at the time the freezing process was developed. These advantages include a lower theoretical energy requirement for single stage operation, a reduced potential for corrosion, and few scaling or precipitation problems. The disadvantage is that it involves handling ice and water mixtures that are mechanically complex to move and process.

There are several different processes that uses freezing to desalt seawater, and a few plants have been built over the past 50 years. However, the process has not been a commercial success in the production of fresh water for municipal purposes. At this stage, freeze-desalting technology probably has better application in the treatment of industrial wastes than in the production of municipal drinking water.

Membrane Distillation

Membrane distillation was introduced commercially on a small scale during the 1980s, but it has had demonstrated no commercial success. As the name implies, the process combines both the use of distillation and membranes. In the process, saline water is warmed to enhance vapor production, and this vapor is exposed to a membrane that can pass water vapor but not liquid water. After the vapor passes through the membrane, it is condensed on a cooler surface to produce fresh water. In the liquid form, the fresh water cannot pass back through the membrane, so it is trapped and collected as the output of the plant.

The main advantages of membrane distillation lie in its simplicity and the need for only small temperature differentials to operate. This has resulted in the use of membrane distillation in experimental solar desalting units.

However, the temperature differential and the recovery rate, similar to the MSF and MED processes, determine the overall thermal efficiency for the membrane distillation process. Thus, when it is run with low temperature differentials, large amounts of water must be used, which affects its overall energy efficiency.

Solar Humidification

The use of direct solar energy for desalting saline water has been investigated and used for some time. During World War II, considerable work went into designing small solar

Solar humidification test units in Mexico
Photo — OK Buros

stills for use on life rafts. This work continued after the war, with a variety of devices being made and tested.

These devices generally imitate a part of the natural hydrologic cycle in that the sun's rays heat the saline water so that the production of water vapor (humidification) increases. The water vapor is then condensed on a cool surface, and the condensate collected as fresh water product. An example of this type of process is the greenhouse solar still, in which the saline water is heated in a basin on the floor, and the water vapor condenses on the sloping glass roof that covers the basin.

Variations of this type of solar still have been made in an effort to increase efficiency, but they all share the following difficulties, which restrict the use of this technique for large-scale production:

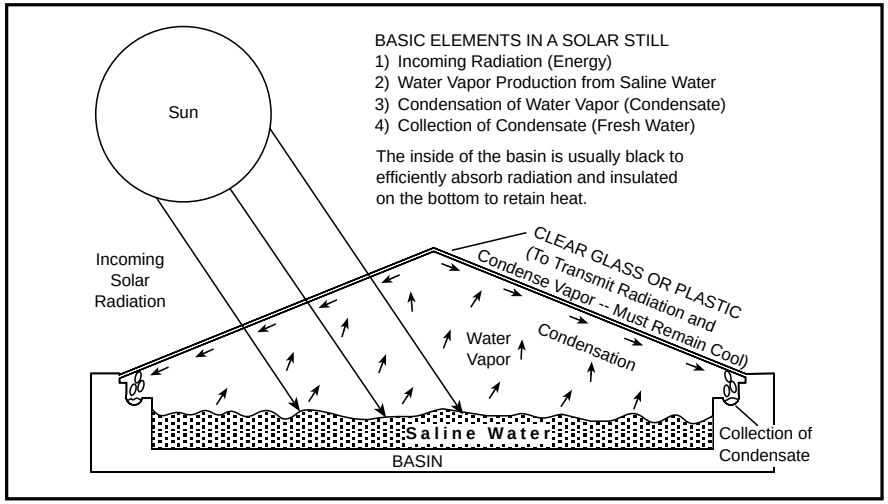


Diagram of a solar still *USAID*

- Large solar collection area requirements
- High capital cost
- Vulnerability to weather-related damage

A general rule of thumb for solar stills is that a solar collection area of about one square meter is needed to produce 4 liters of water per day (10 square feet /gallon). Thus, for a 4,000-m^3/d facility, a minimum land area of 100 hectares would be needed (250 acres/mgd). This operation would take up a tremendous area and could thus create difficulties if located near a city where land is scarce and expensive.

The stills themselves are expensive to construct, and although the thermal energy may be free, additional energy is needed to pump the water to and from the facility. In addition, reasonable attention to operation and routine

Solar still serving a village in Haiti. This still has an area of about 300 m^3 (3,000 ft^2). It was put in operation in about 1967 and was reported as operational in 1998. Photo — Brace Research Institute

maintenance is needed to keep the structure repaired, prevent scale formation caused by the basins drying out, and repair glass or vapor leaks in the stills.

An application for these types of solar humidification units has been for desalting saline water on a small scale for families or small villages where solar energy and low-cost or donated labor is abundant, but electricity is not. A properly constructed still can be quite robust, and solar stills have been reported to operate successfully for 20 years or more. The key is to have users who have a real involvement in its success and have been adequately trained in its construction, operation, and repair. Installing a solar still as a gift for others and then leaving it to its fate will probably result in failure of the operation.

Efforts have been made by various researchers to increase the efficiency of solar stills by changing the design, using additional effects, adding wicking material, etc. In many cases, these modifications have increased production per unit area, but some of these have also increased the complications in operating and maintaining the devices for applications like remote villages. As with any village water supply, technology is only one part of the solution. The successful system will also take into account culture, tradition, and local conditions.

One economic threat to these stills can surface when the local economy has developed to the point where the land area being used for the still becomes too valuable to remain as a water producing area or the value of labor increases. The locals may then consider that it is more economical to replace it with a small RO or VC unit that uses only a fraction of the space and their time.

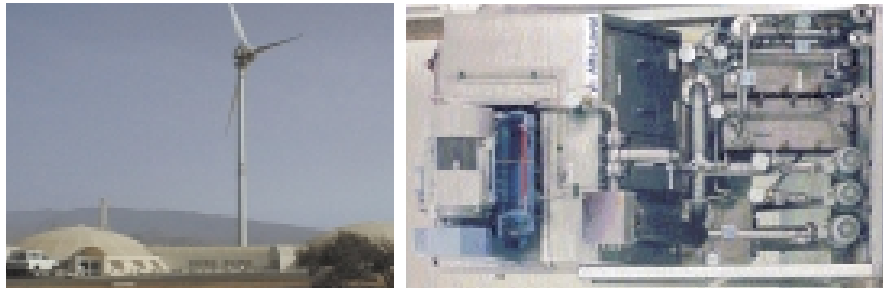
Other Solar and Wind-Driven Desalters

Desalting units that use solar collectors or wind energy devices to provide heat or electrical energy also have been built to operate standard desalting processes like RO, ED, or distillation. The economics of operating these plants

This MED unit in the United Arab Emirates has operated since 1985. The evacuated tube solar collectors in the foreground provide heated water input for the unit. Its design output is 80-m^3/d (0.02 mgd). Photo — A. El-Nasher

tend to be related to the cost of producing energy with these alternative energy devices. Cost tends to be high, but are expected to improve as development of these energy devices continues.

Currently, using conventional energy to drive desalting devices is generally more cost-effective than using solar



The wind turbine produces electricity that is in turn used to drive the mechanical VC unit (top view on right) in Spain.

Photo — Alfa Laval

and wind-driven devices, although appropriate applications for solar and wind-driven desalters do exist. IDA's 1998 Inventory lists about 100 known wind- and solar-powered desalting plants scattered over 25 countries. Most of these installations had capacities of less than 20 m^3/d (0.005 mgd). Due to the difficulty in obtaining this information, the Inventory probably doesn't account for many of the small installations around the world.

As long as conventional energy costs are relatively low and the market for the units small (a large market would tend to bring down costs and increase investment interest), it is not expected that these devices will be developed to any great extent except to fill a small niche market.

Other Aspects of Desalting

Co-generation

In some situations, it is possible to use energy so that more than one use can be obtained from it as the energy moves from a high level to an ambient level. This occurs with co-generation where a single energy source can perform several different functions.

Certain types of desalination processes, especially the distillation process, can be structured to take advantage of a co-generation situation. Most of the distillation plants installed in the Middle East and North Africa have operated under this principle since 1960s and are known in the field as dual purpose plants (water plus power). These

Dual purpose (power-water) facility in Saudi Arabia

Photo — SWCC

units are built as part of a facility that produce both electric power and desalted seawater for use in a particular country.

The electricity is produced with high-pressure steam to run turbines that in turn power electric generators. In a typical case, boilers produce high-pressure steam at about 540ºC (1,000ºF). As this steam expands in the turbine, its temperature and energy level is reduced. Distillation plants need steam whose temperature is about 120ºC (248ºF) or below, and this can be obtained by extracting the lower temperature steam at the low pressure end of the turbine after much of its energy has been used to generate electricity. This steam is then run through the distillation plant's brine heater, thereby increasing the temperature of the incoming seawater. The condensate from the steam is then returned to the boiler to be reheated for use in the turbine.

The main advantage of a co-generation system is that it can significantly reduce the consumption of fuel when compared to the fuel needed for two separate plants. Since energy is a major operating cost in any desalination process, this can be an important economic benefit. One of the disadvantages is that the units are permanently connected together and, for the desalination plant to operate efficiently, the steam turbine must be operating. This permanent coupling can create a problem with water production when the demand for electricity is reduced or when the turbine or generator is down for repairs.

This type of power and water production installation is commonly referred to as a dual-purpose plant. Since many of the oil producing countries of the Middle East and North Africa were engaged in building up their total infrastructure, these types of installations fit in well with the overall development program in these countries.

The size of the water plant that can most efficiently be coupled with a power plant and therefore the ratio of water-to-power production must be consistent with the water-to-power demand in many communities. The dual purpose plant has had a pronounced positive impact on reducing the cost of power and water.

Other types of co-generation facilities benefiting desalination can derive lower-cost steam from heat recovery systems on gas turbine exhausts, heat pumps, or various industrial processes including burning solid wastes in an incinerator.

Concentrate Disposal

The common element in all of these desalination processes is the production of a concentrate stream (also called a brine, reject, or waste stream). This stream contains the salts removed from the saline feed to produce the fresh water product, as well as some of the chemicals that may have been added during the process. It may also contain corrosion by-products. The stream varies in volume, depending on the process, but will almost always be a significant quantity of water.

The disposal of this wastewater in an environmentally appropriate manner is an important part of the feasibility and operation of a desalting facility. If the desalting plant

is located near the sea, the potential for a problem will be considerably less. The major solute in the concentrate stream is salt, and disposing of salt in the sea is generally not a problem. At the same time, care must be taken relative to possible environmental changes related to the receiving waters for the discharge from added constituents, dissolved oxygen levels, and different water temperatures.

A deep disposal well for RO concentrate in Florida. The surge tank for the system is in the background

Photo — R. Bergman

The potential for a more significant problem comes when a desalting facility is constructed inland, away from a natural salt-water body, such as is common for brackish water plants. Care must then be taken so as not to pollute any existing ground or surface water with the salts contained in the concentrate stream. Disposal may involve dilution, injection of the concentrate into a saline aquifer, evaporation, or transport by pipeline to a suitable disposal point. All of these methods add to the cost of the process.

The means of properly disposing of the concentrate flow should be one of the items investigated early in any study of the feasibility of a desalination facility. The cost of disposal could be significant and could adversely affect the economics of desalination. In countries like the USA, with very stringent discharge regulations, the disposal of the concentrate stream can, and has, drastically affected the ability to use desalination as a treatment process.

Hybrid Facilities

Another method of reducing the overall costs of desalting can be the use of hybrid systems. Such hybrid systems are not applicable to most desalination installations, but can prove to be an economic benefit in some cases. A hybrid system is a treatment configuration made up of two or more desalination processes. An example is using both distillation and RO processes to desalt seawater at one facility and to combine the different characteristics of each process productively. Hybrid systems provide a better match between power and water development needs.

An example of a hybrid system could be the use of steam in a dual-purpose plant (electricity and water). The steam is used in a distillation plant to desalt seawater. The product water from the distillation unit has a low level of total dissolved solids, perhaps 20 mg/L. Alongside the distillation plant could be a seawater RO plant that would be run only in off-peak power periods. This would help to stabilize the load on the generator and therefore use lower cost electricity. The RO plant could be designed to produce water with a higher level of total dissolved solids and, thus, also lower its production costs. Thermal and

membrane processes can be linked in more complex manners to increase both efficiency and improve operations. The water from the two processes could then be combined to produce a water that has a reasonable level of total dissolved solids, while reducing the overall unit cost of water.

Economics

Since desalination facilities exist in over 100 countries around the world, specifying exact costs for desalting is not appropriate. What can be said with certainty is that the capital and operating costs for desalination have tended to decrease over the years.

At the same time desalting costs have been decreasing, the cost of obtaining and treating water from conventional sources has tended to increase because of the increased levels of treatment being required in various countries to meet more stringent water quality standards. This rise in cost for conventionally treated water also is the result of an increased demand for water, leading to the need to develop more expensive conventional supplies, since the readily obtainable water sources have already been used.

Many factors enter into the capital and operating costs for desalination: capacity and type of plants, plant location, feed water, labor, energy, financing, concentrate disposal, and plant reliability. In general, the cost of desalted seawater is about 3 to 5 times the cost of desalting brackish water from the same size plant. During the past decade in a number of areas of the USA, the economic cost of desalting brackish water has become less than the alternative of transferring large amounts of conventionally treated water by long-distance pipeline.

In 1999 in the USA, the total production costs, including capital recovery, for brackish water systems with capacities of 4,000 to 40,000 m^3/d (1 to 10 mgd) typically ranges from \$0.25 to \$0.60/m^3 (\$1.00 to \$2.40/1000 gallons). In many recent privatized seawater desalting plants ranging from 4,000 to 100,000 m^3/d (1 to 20 mgd), the total cost of water estimated at \$3 to \$0.75 m^3 (\$12 to \$.80/1000 gallons). These amounts give some idea of the range of costs involved, but the site- and country-specific factors will affect the actual costs.

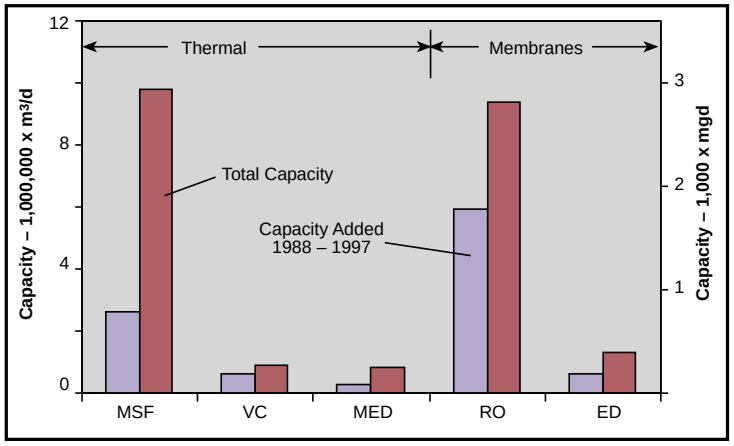
In any country or region, the economics of using desalination is not just the number of dollars, pesos, or dinars per cubic meter, but the cost of desalted water versus the other alternatives. In many water-short areas, the cost of alternative sources of water is already very high and often above the cost of desalting.

Any economic evaluation of the total cost of water delivered to a customer must include all the costs involved. This includes the costs for environmental protection (such as brine or concentrate disposal), distribution and losses in the storage and distribution system.

Desalination in the 1990s

Desalination definitely came of age in the 1990s. Aside from just commercial growth, the concept of using it as a standard tool in water resource development for municipal water supplies has become commonplace. This is a result of the success of the technology, the steady decrease in its overall cost, and the continual pressure on more conventional source of fresh water. Several notable events occurred during this decade.

One was the dramatic increase in the use of RO for all types of desalination applications. These varied from softening water to seawater desalting at costs that continue to drop as steady improvements in the technology are implemented. The growth potential for RO seems tremendous – especially for seawater desalination. Other membrane processes using variants of the RO process, such as NF membranes, are increasingly displacing lime softening processes in the USA and elsewhere. The RO process not only can soften water but also can remove color and disinfection by-product precursors.



Installed capacity in the 10-year period 1987 through 1997
Source — 1998 IDA Inventory

Desalting continued to build itself as a real profession during the 1990s. IDA as the international organization was joined with a number of affiliated national organizations including the American Desalting Association, European Desalination Society, the Indian Desalination Association, the Japan Desalination Association, the Pakistan Desalination Association (Asociacion Espanola de Desalacion y Reutilizacion/Spain) and the Water Science & Technology Association (for the Gulf Countries). In addition, numerous other organizations, such as the American Water Works Association, U.S. Bureau of Reclamation and National Water Research Institute, are regularly sponsoring conferences and workshops on desalination related topics. In 50 years, desalting has turned from an oddity to a full-fledged, recognized technology for supplying municipal drinking water.

As the decade came to a close, the method of specifying desalination facilities began to show some changes. More and more locations were beginning to request developers to design, fund, build, and operate systems, with the municipality paying for the water only as it is produced. This reduces the high front end funding required for a

municipality or authority to increase its water supply. In addition, some of these requests are beginning to leave the choice of desalting technology up to the developer. This is letting the market and technology determine both price and process.

IDA Conferences attract professionals from all over the world to exchange ideas on improving desalting technology. Photo — OK Buros

At the end of the 1990s a number of significant contracts were awarded to developers to fund, design, Build, Operate and either Own (BOO) or eventually Transfer (BOOT) large seawater desalting facilities. These include BOOT contracts for an MSF facility in Abu Dhabi to deliver water, at about \$0.70 to \$0.75/m^3 (\$2.80 to \$3.00/1,000 gal); a 40,000 m^3/d (10 mgd) seawater RO facility in Cyprus to deliver water at about \$0.80 to \$0.85/m^3 (\$3.20 to \$3.40/1,000 gal); and a 100,000 m^3/d (25 gd) seawater RO facility near Tampa, USA, for \$0.45 to \$0.55/m^3 (\$1.70 to \$2.10/1,000 gal).

All of these BOO/BOOT prices that are based on paying for delivered water are influenced by many cost factors which make direct comparisons to each other difficult. These costs include factors such as fuel and electricity cost, as well as financial mechanisms, taxes, labor costs, period of the contract, existing facilities, penalty clauses, location, and contract terms.

Although these costs cannot be directly compared, they do show that there are possible cost advantages that are possible for a water utility when developers are permitted to do their own financing, design, and construction and are paid to essentially deliver water to a customer.

It is anticipted that many more design, build, own and operate or variations of the same can be expected for major desalting facilities in the future.

Summary

Desalination technology has been extensively developed over the past 50 years to the point where it is routinely considered and reliably used to produce fresh water from saline sources. This has effectively made the use of saline waters for water resource development possible. The cost for desalination can be significant because of its intensive use of energy. However, in many areas of the world, the cost to desalinate saline water is less than other alternatives that may exist or may be considered for the future.

Desalinated water is used as a main source of municipal supply in many areas of the Caribbean, Mediterranean, and Middle East. Desalting is also being used or considered for many coastal urban areas in the USA, Asia, and other areas and where it is proving more economical than available conventional sources. The use of desalination technologies, especially for softening mildly brackish waters, is rapidly increasing in the USA.

There is no "best" method of desalination. Generally, distillation and RO are used for seawater desalting, while RO and electrodialysis are used to desalt brackish water. However, the selection of a process should depend on a careful study of site conditions and the application at hand. Local circumstances will always play a significant role in determining the most appropriate process for an area.

The "best" desalination system should be more than economically reasonable in the study stage. It should work when it is installed and continue to work and deliver suitable amounts of fresh water at the expected quantity, quality, and cost for the life of a project.

Publication Information

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Acknowledgments

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The original purpose of *The Desalting ABC's* in 1990 was to provide an up-to-date replacement for the booklet entitled, the *A-B-C of Desalting*, which was published by the U.S. Department of the Interior's Office of Water Research and Technology in about 1977. This second edition updates the booklet based on the events that have occurred in the technology over the past 10 years. The original text for the booklet is based, in part, on a previ-

ous work by the author entitled, *An Introduction to Desalination* (UN, 1987).

For this revised edition, some changes were made in the text, new photos were included, and the drawings were redone using an electronic format. Most of the diagrams are adapted from *The USAID Desalination Manual* and are used courtesy of the U.S. Agency for International Development. RODI Industries allowed the use of the drawings related to spiral membranes. Klaus Wangnick assisted in modifying the drawing of the MED process. The photos are from a variety of sources, including the author's collection, Alfa Laval, Brace Research Institute, Robert Bergman, Dare County Water System, Ali El-Nashar, Ionics Incorporated, Koch Membrane Systems, Mechanical Equipment Company (MECO), Saline Water Conversion Corporation (SWCC), Sasakura Engineering Ltd., U.S. Bureau of Reclamation, and Weir Westgarth. The electronic imaging of many of the photos for the booklet were done courtesy of CH2M Hill International.

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[1] U.S. Gallons are used in this booklet along with metric units 1 U.S. gallon is equal to 3.785 liters; 1 Imperial gallon is equal to 4.536 liters; 1 Imperial gallon is equal to 1.2 U.S. gallons

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