GENERAL PROCESS DESCRIPTIONS

There are five basic techniques that can be used to remove salt and other dissolved solids from water: distillation, reverse osmosis (RO), electrodialysis (ED), ion exchange (IX), and freeze desalination. Distillation and freezing involve removing pure water, in the form of water vapor or ice, from a salty brine. RO and ED use membranes to separate dissolved salts and minerals from water. IX involves an exchange of dissolved mineral ions in the water for other, more desirable dissolved ions as the water passes through chemical “resins. The relative percentages of different types of desalination plants worldwide is shown in table 1.

In addition to removing salts and other dissolved solids from water, some of these desalination techniques also remove suspended material, organic matter, and bacteria and viruses; however, they will not produce water where there is none. These techniques were originally developed for treating large quantities of water (i.e., hundreds or thousands of gpd) at a central location, but some have been adapted recently for small scale use in the home. These desalination processes are described briefly below and in more detail in appendix A.

Distillation

Salt- and mineral-free water can be separated from seawater by vaporizing some of the water from the salt solution and then condensing this water vapor on a cooler surface. This is the same phenomenon that occurs when water vapor (or steam) inside a warm house condenses on a cold window pane, or when water vapor condenses to form rain or snow. This separation process is called distillation.

The vaporization of water molecules can be accelerated by heating the brine to its boiling point and/or reducing the vapor pressure over the brine. To maximize the efficiency of the distillation process, the heat given up during condensation is used to heat the incoming feed water, or to reheat the unvaporized brine. Because distillation involves vaporizing water from the salty feed water, the energy required for distillation, as well as its costs, do not increase appreciably with increasing salinity of the feed water. Depending on the plant design, distilled water produced from seawater normally has salt concentrations of 5 to 50 ppm. Between 25 and 65 percent of the feed water is recovered by most distillation plants.

Four major processes are now used to distill water on a commercial or semi-commercial scale. Both “multiple-effect” (ME) (figure 1) evaporation and “multi-stage flash” (MSF) (figure 2) distillation involve boiling the brine in adjacent chambers at successively lower vapor pressures without adding heat. With “vapor compression” (VC) (figure 3) the water vapor from salty feed water is collected and compressed thereby condensing the vapor. “Solar” distillation typically occurs inside a glass

Table 1.—Relative Distribution of Different Types of Desalination Plants Worldwide

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of plants</th>
<th>Percent of total</th>
<th>Capacity (mgd)</th>
<th>Percent of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distillation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSF</td>
<td>532</td>
<td>15.1</td>
<td>1,955</td>
<td>64.5</td>
</tr>
<tr>
<td>ME</td>
<td>329</td>
<td>9.3</td>
<td>145</td>
<td>4.8</td>
</tr>
<tr>
<td>VC</td>
<td>275</td>
<td>7.8</td>
<td>66</td>
<td>2.2</td>
</tr>
<tr>
<td>Membrane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RO</td>
<td>1,742</td>
<td>49.4</td>
<td>709</td>
<td>23.4</td>
</tr>
<tr>
<td>ED</td>
<td>564</td>
<td>16.0</td>
<td>139</td>
<td>4.6</td>
</tr>
<tr>
<td>Other</td>
<td>85</td>
<td>2.4</td>
<td>18</td>
<td>0.6</td>
</tr>
<tr>
<td>Total</td>
<td>3,527</td>
<td>100.0</td>
<td>3,032</td>
<td>100.1</td>
</tr>
</tbody>
</table>

Figure 1.—Conceptual Diagram of a Horizontal-Tube Multiple-Effect (HTME) Distillation Plant

1st EFFECT  2nd EFFECT  3rd EFFECT

Seawater Feed  P₁  P₂  P₃  T₁  T₂  T₃
Steam from Boiler  Vapor  Brine  Vapor  Brine  Vapor
Condensate Returned to Boiler  Pump  Vacuum  Condensed Freshwater  Pump  Vacuum

Notes: 1. This drawing is greatly simplified.
2. A final condenser such as shown on Figure 3-10 is necessary for operation.

Figure 2.—Conceptual Diagram of the Multistage Flash (MSF) Process

The seawater feed increases in temperature as it moves toward the brine heater where sufficient additional heat is added to permit it to flash boil in the first stage.

The freshwater produced by condensation in each stage is flashed in subsequent stages to recover additional heat.

Brine flashes when introduced into the stage which has a reduced pressure, permitting rapid boiling to occur immediately.

A portion of the hot brine is recirculated to the spray nozzles for further vaporization on the tube bundle.

The vapor gems heat energy at a higher temperature and are compressed by the vapor compressor.

A steam jet ejector could replace the vapor compressor where surplus steam is available.

endosure, similar to a greenhouse, where water vapor rising from sun-heated brine condenses on the cooler inside surface of the glass. The droplets of distilled water that run down the glass are then collected in troughs along the lower edges of the glass (figure 4).

**Reverse Osmosis**

With RO, salty water on one side of a semi-permeable membrane is typically subjected to pressures of 200 to 500 lb/sq in. for brackish water, and 800 to 1,200 lb/sq in. for seawater. “Pure” water will diffuse through the membrane leaving behind a more salty concentrate containing most of the dissolved organic and inorganic contaminants (figure 5). Brackish water RO plants typically recover 50 to 80 percent of the feed water, with 90 to 98 percent salt rejection. For seawater, recovery rates vary from 20 to 40 percent, with 90 to 98 percent salt rejection.

**Electrodialysis (ED)**

With this technique, brackish water is pumped at low pressures between several hundred flat, parallel, ion-permeable membranes that are assembled in a stack. Membranes that allow cations to pass through them are alternated with anion-permeable membranes. A direct electrical current is established across the stack by electrodes positioned at both ends of the stack. This electric current “pulls” the ions through the membranes and concentrates them between each alternate pair of membranes. Partially

---

**Figure 4.—Basic Elements in a Solar Still**

BASIC ELEMENTS IN SOLAR DISTILLATION
1) Incoming Radiation (Energy)
2) Water Vapor Production from Brine
3) Condensation of Water Vapor (Condensate)
4) Collection of Condensate

The inside of the basin is usually black to efficiently absorb radiation and insulated on the bottom to retain heat.

Figure 5A.—Principles of Reverse Osmosis

NORMAL OSMOSIS OSMOTIC EQUILIBRIUM REVERSE OSMOSIS

FRESH SALINE WATER WATER WATER

SEMIPERMEABLE MEMBRANE


Figure 5B.—Elements of a Reverse Osmosis System

A membrane assembly is generally symbolized as a rectangular box with a diagonal line across it representing the membrane.

Figure 6.—Spiral Membrane-Cut-Away View With Elements in a Pressure Vessel

Desalted water passes through the membranes on both sides of the porous product water carrier.

CUTAWAY VIEW OF A SPIRAL MEMBRANE ELEMENT

The product water flows through the porous material in a spiral path until it contacts and flows through the holes in the product water tube.

CROSS SECTION OF PRESSURE VESSEL WITH 3-MEMBRANE ELEMENT

desalted water is left between each adjacent set of membrane pairs (figure 7).

Scaling or fouling of the membranes is prevented in most ED units by operationally reversing the direction of the electrical current around the stacks at 15- to 30-minute intervals. This reverses the flow of ions through the membranes, so that the spaces collecting salty concentrate begin collecting less salty product water. Alternating valves in the water collection system automatically direct the flow in the appropriate direction. Typical freshwater recovery rates for ED (reversal) range from 80 to 90 percent of the feedwater volume (65).

**Ion Exchange (IX)**

In this process undesirable ions in the feed water are exchanged for desirable ions as the water passes through granular chemicals, called ion exchange resins. For example, cation exchange resins are typically used in homes and municipal water treatment plants to remove calcium and magnesium ions in “hard” water, and by industries in the production of ultra-pure water. The higher the concentration of dissolved solids in the feed water, the more often the resins will need to be replaced or regenerated. With rising costs for resins and for disposing of regeneration solutions, IX is now competitive with RO and ED only in treating relatively dilute solutions containing a few hundred ppm of dissolved solids.

**Freeze Desalination**

When saltwater freezes, the ice crystallizes from pure water leaving the dissolved salt and other minerals in pockets of higher salinity brine. In fact, freeze desalination has the potential to concentrate a wider variety of waste streams to higher concentrations with less energy than any distillation process (55). Traditional freezing processes involve five steps:

1. precooking of the feed water,
2. crystallization of ice into a slush,
3. separation of ice from the brine,
4. washing the ice, and
5. melting the ice.

New research efforts are attempting to reduce the number of steps, especially the need to wash the ice crystals. Although small scale commercialization of freezing was attempted in the late 1960s, there were still significant operational problems. Only a few isolated commercial freezing plants now exist (figure 8).

**PRETREATMENT OF INCOMING FEED WATER**

The efficiency of desalination equipment can be significantly reduced due to fouling of membrane surfaces with solids (e.g., colloidal material, dissolved organics, bacteria, etc.) and/or the formation of scale (due to the precipitation of dissolved minerals). Consequently, the water fed to desalination units usually requires some type of pretreatment. The level of pretreatment required depends on the desalination process used, and feed water quality.

Pretreatment may include coagulation and settling; filtration; treatment with activated carbon to remove organics; disinfection to kill microorganisms; dechlorination (when chlorine and chlorine sensitive membranes are used); and the addition of acid, polyphosphates, or polymer-based additives to inhibit scaling (67,91). Generally speaking, these are all standard, water treatment techniques. Pretreatment costs may account for 3 percent to 30 percent of the total cost of desalination.
Figure 8. Schematic Diagram of a Freezing Desalination Plant Using the Vacuum-Freezing Vapor-Compression (VFVC) Process

NOTES: 1. The combined freezer (crystallizer) and melter in one vessel is a unit called a hydrocon.  
2. The compressor utilizes thin flexible metal blades. It is built specifically for the high-volume low-pressure conditions found in the VFVC process.

POST TREATMENT OF PRODUCT WATER

Depending on the quality of the product water and its intended use, some post treatment of the product water may be required. For example, distillation and ion exchange can produce water with such a low mineral content that the water may corrode metal pipes. Post treatment processes include carbon dioxide removal, pH adjustment, chemical addition, and disinfection. In some cases desalted water may be blended with water supplies from other sources to improve taste, to extend supplies of desalted water, and to improve the quality of other water (91).

SELECTING THE MOST APPROPRIATE DESALINATION TECHNOLOGY

Selection of the most appropriate technology depends on many site-specific factors including the concentration of organic and inorganic material in the incoming feed water (table 2), the desired quality of the treated water, the level of pretreatment that may be required prior to desalination, the availability of energy and chemicals to treat the water, and the ease with which waste concentrates can be disposed (91). In fact, both RO and ED membranes can be tailor-made based on the feed water composition. Many other factors that must also be considered include availability of construction and operating personnel, waste concentrate disposal, environmental considerations, maintenance requirements, and cost. An engineering study of site-specific conditions within the context of a long-term water resources development plan is usually required prior to selecting a specific process for desalinating or demineralizing large quantities of water.

Table 2.—Desalination Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brackish water</td>
</tr>
<tr>
<td></td>
<td>0-3,000 ppm</td>
</tr>
<tr>
<td>Distillation</td>
<td>s</td>
</tr>
<tr>
<td>Electrodialysis</td>
<td>b</td>
</tr>
<tr>
<td>Reverse osmosis</td>
<td>P</td>
</tr>
<tr>
<td>Ion exchange</td>
<td></td>
</tr>
</tbody>
</table>

KEY: P = Primary application  
s = Secondary application  
t = Technically possible, but not economic