Using Desalination Technologies for Water Treatment

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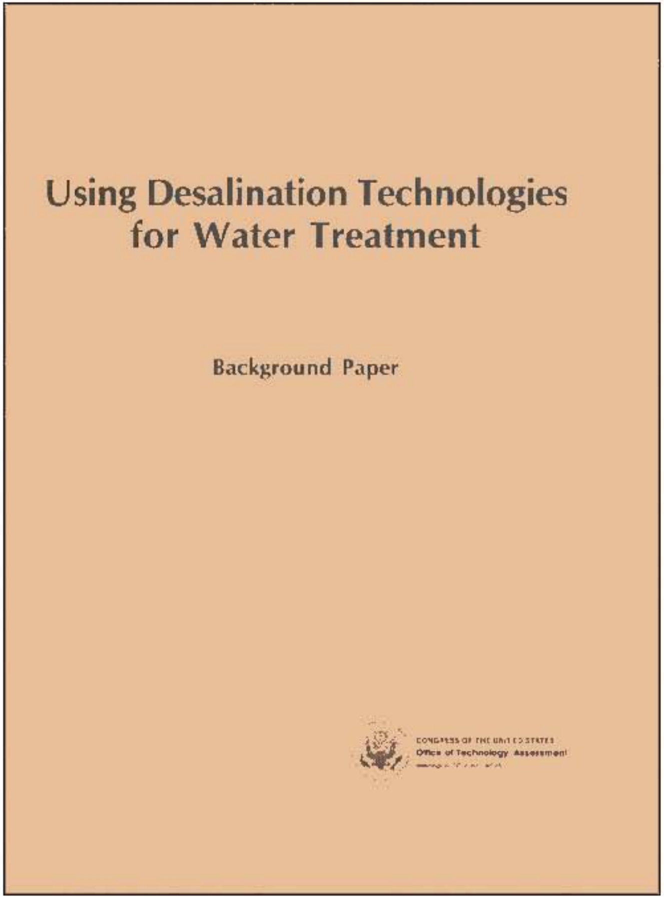

Using Desalination Technologies for Water Treatment

Background Paper

CONGRESS OF THE UNITED STATES
Office of Technology Assessment
[illegible]

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Foreword

Technologies that were originally developed to desalinate water are widely applied in this country to remove contaminants other than salt from freshwater supplies. Of the many available desalination technologies, two membrane processes—reverse osmosis and electrodialysis —are most widely used in the United States. Such widespread use would not have been possible without the advances made in membrane technology over the last two decades, due largely to federally sponsored research and development.

In the past when water was found to be contaminated, a new supply of uncontaminated water was developed. But, most renewable supplies of clean freshwater have now either been tapped or are not readily available for development. OTA'S study "Protecting the Nation Groundwater from Contamination' also found that the frequency of groundwater contamination is increasing. Therefore, the need to decontaminate surface and groundwater supplies of freshwater will undoubtedly increase in the future. The need for treatment will be further increased as water quality regulations are developed under the Clean Water and Safe Drinking Water Acts.

This study provides a technical assessment of traditional desalination techniques that can be used for water treatment. These techniques include distillation, as well as more recently developed membrane processes. As part of this effort OTA held a one-day workshop on July 29, 1987, with desalination and water treatment experts to review the initial draft of this background paper and to discuss other areas of interest. The conclusions of these discussions are invluded in this background report.

OTA is grateful for the input from the workshop participants and the desalination community at large. The preparation of this report would have been much more difficult without such support. As with all OTA studies, the content of this report is the sole responsibility of OTA.

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NOTE: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the workshop participants. The workshop participants do not, however, necessarily approve, disapprove, or endorse this background paper. OTA assumes full responsibility for the background paper and the accuracy of its contents.

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Abbreviations

AID	–(U.S.) Agency for International Development
CWJA	—Clean Water Act
degrees C	—degrees Centigrade
degrees F	—degrees Fahrenheit
DOI	—Department of the Interior
ED	—electrodialysis
EPA	—(U.S.) Environmental Protection Agency
GAC	—granular activated carbon
gpd	—gallons per day
IX	—ion exchange
lb/sq. in.	—pounds per square inch
ME	—multiple effect (distillation)
mgd	—million gallons per day
MSF	—multi-stage flash (distillation)
NPDES	—National Pollutant Discharge Elimination System
OWRR	—Office of Water Resources Research
OSW	—Office of Saline Water
OWRT	—Office of Water Research and Technology
ppm	—parts per million
POE	—point-of-entry
POU	—point-of-use
R&D	—research and development
RO	—reverse osmosis
SDWA	—Safe Drinking Water Act
USGS	—U.S. Geological Survey
VC	—vapor compression (distillation)

Conversion Factors

To convert from:	To:	Multiply by:
cubic meters	U.S. gallons	264
U.S. gallons	cubic meters	0.0038
millions of U.S. gallons	acre-feet	3.07
acre-feet	millions of U.S. gallons	0.33
dollars/1 ,000 gallons	dollars/acre-foot	325
parts per million	milligrams per liter	1
degrees Fahrenheit	degrees centigrade	0.56 X (°F – 32)

Contents

Page

Chapter 1

Introduction

OVERVIEW

General Trends

Over the last few decades desalination technologies have been used increasingly throughout the world to produce drinking water from brackish groundwater and seawater, to improve the quality of existing supplies of fresh-water for drinking and industrial purposes, and to treat industrial and municipal wastewater prior to discharge or reuse. In the early 1950s there were about 225 land-based desalination plants worldwide with a combined capacity of about 27 million gallons per day (mgd). There are now about 3,500 plants worldwide with a production capacity of about 3,000 mgd. As the demand for freshwater increases and the quality of existing supplies deteriorates, the use of desalination technologies will increase.

Seawater distillation plants dominated the early desalination market, which was primarily overseas. However, due to lower energy requirements, a desalination process called reverse osmosis (RO)[2] now appears to have a slightly lower cost than distillation for seawater desalination (unless a dual purpose electric power/desalination plant is being built). For brackish water desalination, RO and another desalination process called electrodialysis (ED) are both competitive. Other desalination technologies are used less widely due to their rudimentary development and/or higher cost. However, there is no single desalination technology that is considered “best’ for all uses. The selection of the most appropriate technology depends on the composition of the feed water (prior to desalination), the desired quality of the product water, and many other site-specific factors. Desalination technologies cannot produce water where there is none.

Brackish water can be most economically desalinated on a large scale (e. g., 1 mgd, or larger) at well-operated, centralized RO or ED plants at an overall cost (including both capital and operating costs) of about $1.50 to $2.50 per 1,000 gallons; for seawater, large scale distillation and RO both cost about $4 to $6 per 1,000 gallons.[3] Although there are no developing desalination technologies that will generate major reductions (e. g., 50 percent) in water treatment costs, industry experts believe that the costs of RO and ED should continue to decrease as membranes, treatment equipment, and operational procedures are improved. Future cost reductions for distillation processes will probably be modest.

Domestic Use of Desalination Technologies

Relative to many areas of the world the United States has plentiful, and therefore inexpensive, supplies of freshwater. Since the colonization of the United States, the use of freshwater has generally increased along with our population growth and industrial development. As water use increases and the availability of renewable supplies decreases, the cost of developing new supplies of surface and groundwater increases. These trends will probably continue. Water pollution also requires increasing levels of water treatment, including the use of some desalination technologies. In some areas of the country (e. g., southern California) it may be cheaper to use desalination technologies to treat either brackish water or irrigation drainage water than to develop new supplies of surface water (via reservoirs and diversions).

As the cost of developing and treating water supplies increases, the use of desalination technologies will probably increase in this country in the following six areas:

1. RO and ED of brackish groundwater will supply drinking water for some small to midsize inland communities in the water-limited ***West***

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[1] See box A on p. 2 for definitions of scientific terms.

[2] Different desalination technologies are described briefly in ch. 2 and in more detail in app. A.

[3] Under less-than-ideal operating conditions these costs may be higher. Unless otherwise stated all dollar values in this report are given in terms of 1985 dollars.

and for some rapidly growing, mid-size communities along our coasts.

2. A few large municipalities in the West will increasingly use RO or ED to demineralize and treat wastewater from sewage treatment plants (and perhaps from irrigation operations) for direct or indirect reuse as drinking water.
3. With more stringent Federal regulations on drinking water, public and private suppliers throughout the United States will increase their use of RO, ED, and perhaps a desalination process called ion exchange, at centralized plants to remove contaminants (e. g., dissolved minerals, heavy metals, dissolved organics, and pathogens) from both surface water and groundwater supplies.
4. As water quality regulations become more stringent, industries may increase their use of RO, ED, and other water treatment processes to remove potentially toxic contaminants from wastewater prior to reuse or discharge.
5. Small RO and distillation units will be used increasingly in homes for “point-of-use' treatment of drinking water in response to individual concerns about water quality.
6. Industries will continue to use desalination technologies to treat the water used in the manufacture of various products, such as paper, pharmaceuticals, and food products.

Box A.—Definition of Scientific Terms

Brackish water—in this report, water containing significant levels (i. e., greater than 500 ppm) of salt ***and/or*** dissolved solids, but 1ess than that found in seawater (35,000 ppm dissolved solids). Less brackish water (i.e., containing between 500 ppm and 3,000 ppm dissolved solids) mayor may not require desalination depending on the water use; moderately brackish water (i. e., containing between 3,000 ppm and 10,000 ppm dissolved solids) usually requires desalination prior to use; highly brackish water (i.e., containing between 10,000 ppm and 35,000 ppm dissolved solids) would probably require a level of treatment comparable to seawater.

Desalination-processes used to remove salt and other dissolved minerals from water. Other contaminants in water (e. g., dissolved metals, bacteria, and organics) may also be removed by some desalination processes.

Freshwater—water with levels of dissolved salt and other minerals that are low enough (typically less than 500 ppm) to make desalination unnecessary for most uses. However, depending on its quality, freshwater may have to be treated in some way prior to use.

Ions—positively or negatively charged atoms or groups of atoms that are often found dissolved in water. Cations are positively charged; anions are negatively charged.

Potable water—water suitable for drinking that generally has less than 500 ppm of dissolved minerals (including salt).

Product water—the freshwater produced from a desalination operation.

Seawater—water that is withdrawn from the ocean (with about 35,000 ppm salt and dissolved solids).

Waste concentrate—salty wastewater that is produced by desalination operations and must be disposed of. Salt concentrations in waste concentrates can exceed 50,000 ppm.

Much of the development of desalination technologies in the past three decades was sponsored by the U.S. Government. In fact, since 1952 the Federal Government has spent just over $900 million (in 1985 dollars) in support of desalination research, development, and demonstration projects. Federal funding for most desalination research was discontinued in 1982. This research program was primarily responsible for the development of reverse osmosis, and for many advances and improvements in distillation technologies. The United States still holds a technological advantage in some, but not all, areas of desalination. U.S. industry investment in desalination R&D is now probably about $5 million to $10 million per year.

There are now about 750 desalination plants in the United States with a combined production capacity of about 212 mgd. This water is used primarily for industrial uses, and secondarily for drinking water. There are desalination plants in 46 States and on two island territories. Between 70 and 80 percent of this capacity is provided by RO (33). The amount of desalinated water produced in this country is equivalent to about 1.4 percent of the

15,000 mgd that is consumed[4] for domestic and industrial purposes. The use of desalination technologies for treating fresh, brackish, and contaminated water supplies will continue to increase in the United States. However, large-scale seawater desalination will probably not be cost-effective in this country for some years to come.

Overseas Use of Desalination Technologies

In predominantly arid regions of the world, and especially in the Middle East, where conventional sources of fresh water (e. g., rivers, lakes> reservoirs or groundwater) are not readily available, seawater desalination will continue to supply drinking water. In some countries, desalinated water may also be used for government subsidized agricultural operations where self-sufficiency and national security are primary objectives. However, desalinating irrigation water for traditional open-field agriculture will probably not be economically competitive in the foreseeable future anywhere in the world. In the absence of free market constraints (e. g., government subsidies), it is usually more cost-effective to import crops from water-rich agricultural regions.

In most lower-tier developing countries the vast majority of water will continue to come from essentially salt-free surface and groundwater supplies. It is estimated that about half of the people in these countries do not have adequate (e. g., disinfected) drinking water supplies; about 70 percent have inadequate sanitation facilities. Water treatment, if there is any, generally involves the use Of more conventional technologies, such as sedimentation, filtration, and disinfection. However, relatively small desalination plants may be of particular value for tourist hotels, construction sites, and certain isolated communities that have no other readily available sources of freshwater. In very remote areas small solar stills or solar-powered desalting units may be an appropriate desalting alternative.

The majority of industrialized countries are located in temperate zones where supplies of freshwater are adequate. Therefore, desalination technologies will be used in these countries primarily for industrial purposes, and secondarily for treating drinking water.

Scope of This Study

This report provides a state-of-the-art evaluation of technologies that were developed to desalinate water. Many of these same technologies can also be used to remove contaminants other than salt from water supplies. Water treatment techniques that remove contaminants other than salt and/or dissolved minerals are beyond the scope of this study. The policy implications associated with the use of desalination technologies are briefly addressed in the chapter discussing future prospects for desalination in the United States.

Generalizations about the capabilities and uses of desalination technologies have been made to the extent possible, recognizing that there are exceptions to most generalizations. Selecting the most appropriate desalination technology for a particular use depends on many site-specific factors that must be evaluated in detail by qualified engineers and scientists. In other words, this paper should not be used as the only source of information when evaluating different desalination technologies for a specific use.

HISTORICAL BACKGROUND

The hydrologic cycle provides the Earth with a continuous supply of fresh, and for the most part, distilled water. The sun drives the cycle by providing the energy to evaporate water from the ocean and from water bodies on land. This water vapor, which accumulates as clouds, condenses in the cooler upper atmosphere and falls to the Earth's surface in the form of rain or snow.

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[4] Water may be withdrawn from a supply, used for some purpose such as cooling, and then discharged directly or indirectly into a water body so that it can be reused later. Water is consumed when it is withdrawn, used up perhaps in a manufacturing process, and is not available for reuse.

Man has distilled freshwater from seawater for many centuries. Egyptian, Persian, Hebrew, and Greek civilizations all studied various desalination processes. Aristotle and Hippocrates both advocated the use of distillation in the 4th century B.C. (37). During the 1700s both the United States and British navies were making simple stills from pots and by the mid- 1800s small stills were being built into shipboard stoves. By the turn of the century various types of land-based distillers were being used in several arid parts of the world (4).

By the 1940s all major naval vessels and passenger ships had their own stills. During World War II the U.S. Navy built a 55,000 gallons per day (gpd) distillation plant on Johnston Island (87) and several smaller stills on other Pacific islands. Prior to 1953 there were only about 225 land-based desalination plants worldwide with a combined capacity of about 27 mgd (24). In the late 1950s desalination took on added importance with the construction of several large distillation plants in the Middle East where freshwater supplies are extremely limited.

As the demand for freshwater increased and production costs decreased in the 1960s, the use of desalination increased, especially in arid regions of the world. The development of nuclear power at this same time also brought visions of inexpensive electricity to power distillation plants (90). It was hoped that in the coming decades "dual purpose' reactors would produce power and distill seawater at costs ranging from $0.35 to $1.00 per 1,,000 gallons; abundant supplies of distilled water would "make the deserts bloom and the cities thrive' (23,32,70). However, the optimism of the 1960s mellowed considerably in the 1970s when it became evident that the costs of desalination using nuclear power would be much higher than many had expected.

The costs of distillation were significantly reduced during the 1960s through advances in plant design, heat transfer technology, scale prevention, and corrosion resistance. Worldwide desalination capacity grew from about 60 mgd in the early 1960s to about 1,000 mgd supplied by 1,500 plants in the late 1970s (22,24,33,87). Although distillation plants dominated the early desalination market, RO and ED began to take over an increasing market share in the early 1970s (33,50).

In 1986 there were 3,500 desalination plants in 105 countries worldwide (operating or under construction) with a combined capacity of about 3,000 mgd.[5] Almost 60 percent of this capacity is located in the Middle East. Saudi Ar'abia alone has about 800 plants that produce a total of about 915 mgd, or about 30 percent of the world's desalinated water. Saudi Arabia's 40-unit Al Jubail II is the world's largest desalination facility in operation with a capacity of almost 250 mgd. The United States and its territories have about 750 plants that account for about 10 percent of the world's capacity.

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[5] This total capacity for the world includes all the desalination plants ever built; the older plants since retired have not been subtracted from this total. Therefore, the actual total is probably about 10 percent to 15 percent less than the 3,000 mgd. For the total desalination capacity in the United States it was assumed that plants built prior to, and after 1970, had operating lifetimes of 10 years and 15 years, respectively. Also, the United States total does not include the 72 mgd RO plant at Yuma, AZ, which is not yet operational.

GENERAL WATER USE IN THE UNITED STATES

Sources of Fresh and Brackish Water

Precipitation within the 48 contiguous states averages nearly 30 inches a year, or about 4.2 billion mgd. The majority of this precipitation falls in the East. In fact, most areas of the United States west of the Great Plains receive less than 20 inches of rainfall a year; during periodic droughts rainfall is even less. In addition to this renewable supply, about 150 trillion gallons of freshwater are stored in surface lakes and reservoirs (89). and 200 to ***600*** times this amount is stored in aquifers of fresh groundwater (56,89).

Potentially developable brackish aquifers are known to occur in many parts of the United States (25). However, limited data suggest that brackish groundwater is quite a bit less abundant than fresh groundwater. Furthermore, the occurrence of brackish aquifers varies considerably from one region of the country to another. The presence of brackish groundwater may be particularly important in those arid and semiarid areas of the country where existing supplies of freshwater are scarce and/or largely utilized. These areas are found in the following western States: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North and South Dakota, Oklahoma, Oregon, Texas, Utah, Washington, and Wyoming.

Water Consumption (69)

According to data collected in 1980, about 450 billion gallons of fresh and saline water, or about 2,000 gallons/person, are withdrawn from surface and groundwater supplies each day for various commercial and domestic uses. Much of the freshwater that is withdrawn is discharged after use into adjacent surface supplies for subsequent reuse in downstream areas. However, about 100,000 mgd of freshwater are actually consumed (e. g., via plant transpiration, evaporation, etc.) and are not readily available for reuse. Consumptive uses of water include:

- ***Irrigation:*** About 81 percent (i. e., 81,000 mgd) of freshwater consumed in this country irrigates about 58 million acres of farmland, mostly in the West. About 60 percent of this water comes from major surface water diversions; the rest comes from groundwater aquifers.
- ***Industry:*** About 8 percent (i. e., 8,000 mgd) of all freshwater is consumed by industry. The level of water treatment required by industry depends on its particular use and the location of the industry. Most industries that require large volumes of processing water are located where water supplies are naturally abundant.
- ***Domestic Use:*** Over 200,000 public water systems in the United States sell about 34,000 mgd to more than 200 million customers for domestic use, for public and municipal use, and for some industrial and commercial uses. Average domestic use in this country is believed to be between 120 and 150 gpd per person (85). About 7 percent (i. e., 7,000 mgd) of all freshwater consumption is for domestic uses.
- ***Rural Use:*** There are about 40 million people living in rural areas of the United States. About 90 percent of all rural water systems depend on groundwater from about 12 million private wells for drinking water, livestock, and other uses (besides irrigation). Rural use accounts for 4 percent (i. e., 4,000 mgd) of all freshwater consumption.

Water Quantity/Water Quality Linkage

Only about 20 percent of water withdrawn for use is actually consumed. The rest is generally discharged into rivers, lakes, and estuaries as wastewater or irrigation return flows, and can be subsequently reused at downstream locations. Each time water is reused it can be expected that the concentration of pollutants (including salt) in the discharged water will increase. Water quality problems tend to be greater where the frequency of water reuse is high, such as in water-limited areas of the West, and along waterways adjacent to heavily industrialized areas.

In coastal areas most freshwater aquifers become increasingly brackish as they extend offshore. If the rate at which fresh groundwater is withdrawn exceeds the rate of freshwater recharge, more brackish water from offshore will move inland and progressively increase the salt concentration in the aquifer. Depending on the aquifer configuration and the brackish water withdrawal rates, increasing salinity levels in coastal wells may occur over a period of months to many years. Saltwater intrusion has been a significant problem for Long Island, NY, Florida, southern California, and several other coastal areas.

FUTURE WATER SUPPLY NEEDS

A comparison of past analyses of water use indicates that both water withdrawals and water consumption in the United States gradually increased through 1980. More recent data collected for 1985 indicate that both water withdrawals and water consumption have decreased somewhat since 1980. This shift may be due to more eflicient use of water, decreased precipitation over the last 5 years, a shift toward less water intensive industries in this country, and/or increased accuracy of the data collected (68).

Despite this apparent decrease in water use over the last 5 years, the demand for water will probably continue to increase over the next several decades. In fact, water demand exceeds available supplies during periodic droughts and in many water-limited areas of the country (e. g., most of the West). Droughts occur more frequently in the West. In areas of the country, where readily available supplies of surface and groundwater have already been developed, dams and other water diversions are becoming more expensive and time consuming to construct and often meet with opposition due to potential environmental impacts. For example, the Two Forks Project, a dam on the South Platte River southwest of Denver, has been in the planning process for about 10 years. Although $37 million has been spent on planning and preparation of an environmental impact statement, the project has yet to be approved (35). Water from this project is projected to cost about $10 per 1,000 gallons. As the cost of developing new supplies of water increase, the level of water treatment and reuse will also increase,

Chapter 2

Overview of Desalination Technologies

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.

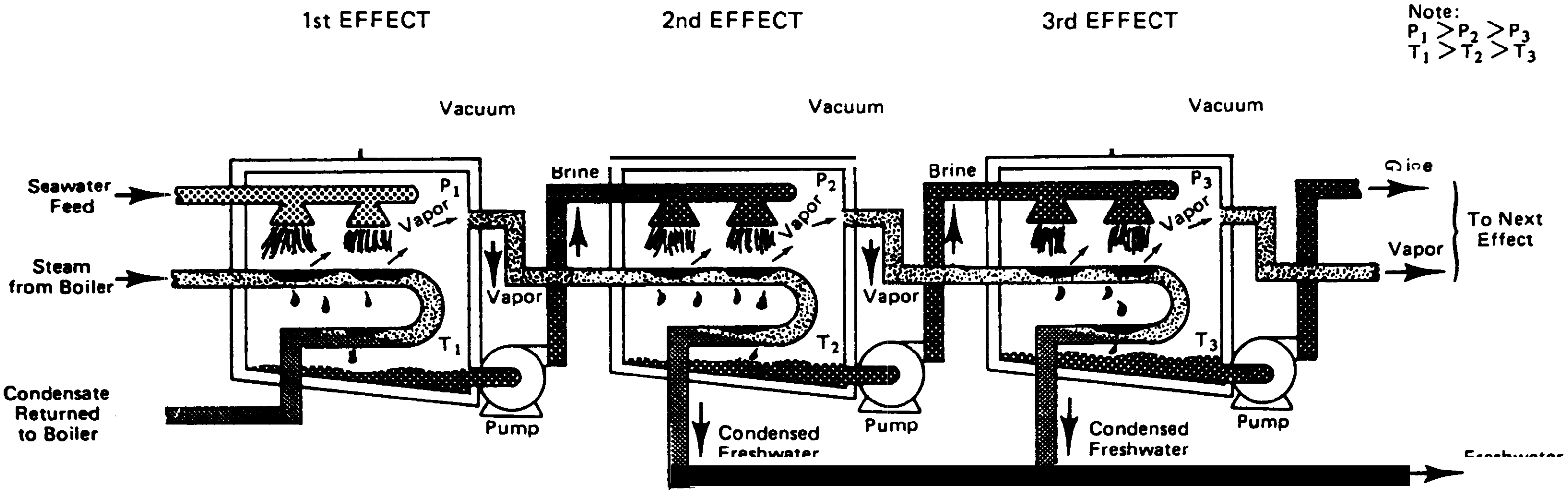
Four major processes are now used to distill water on a commercial or semi-commercial scale. Both “multiple-effect’ (ME) (figure 1) evaporation and “multi-stage flash’ (MSF) (figure 2) distillation involve boiling the brine in adjacent chambers at successively lower vapor pressures without adding heat. 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 I.—Relative Distribution of Different Types of Desalination Plants Worldwide

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

SOURCE: International Desalination Associate’s desalination plant inventory, 1987.

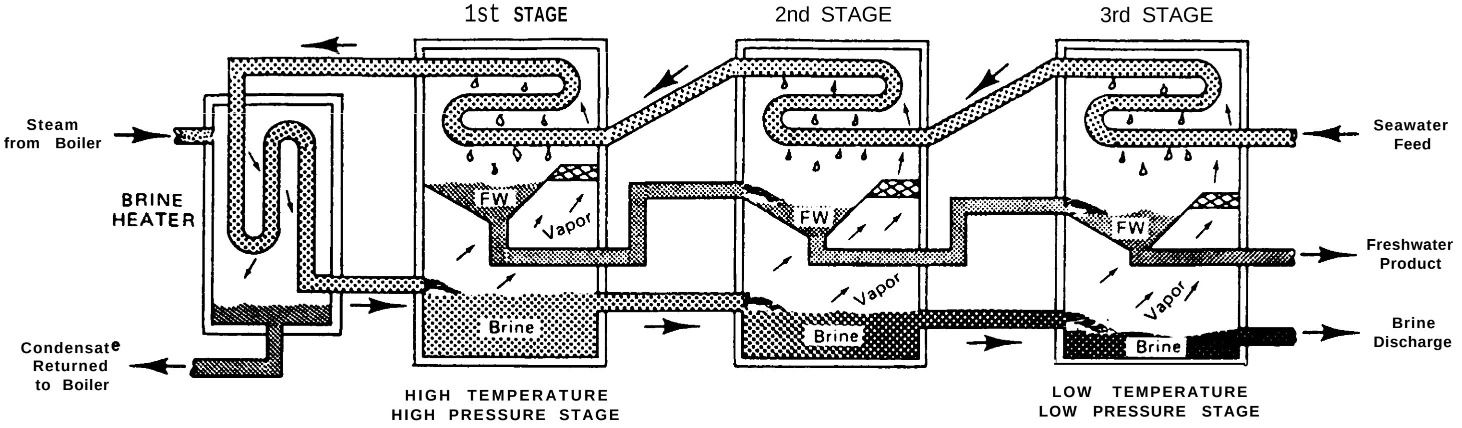
Figure 1.—Conceptual Diagram of a Horizontal-Tube Multiple-Effect (HTME) Distillation Plant



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

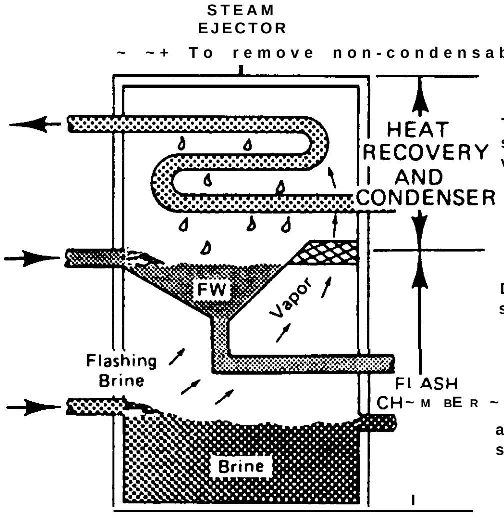
SOURCE: O.K. Buros, et al. "The USAID Desalination Manual," U.S. Agency for International Development, Washington, DC, prepared by CH2M Hill International Corp., August 1980.

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



Note. For simplicity, no heat rejection section is shown In this diagram–see Figure 315.

FW = Freshwater



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.

Tube bundle which serves as a heat recovery and condenser section. Incoming seawater inside the tubes is heated by vapor condensing on the outside of the tubes.

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

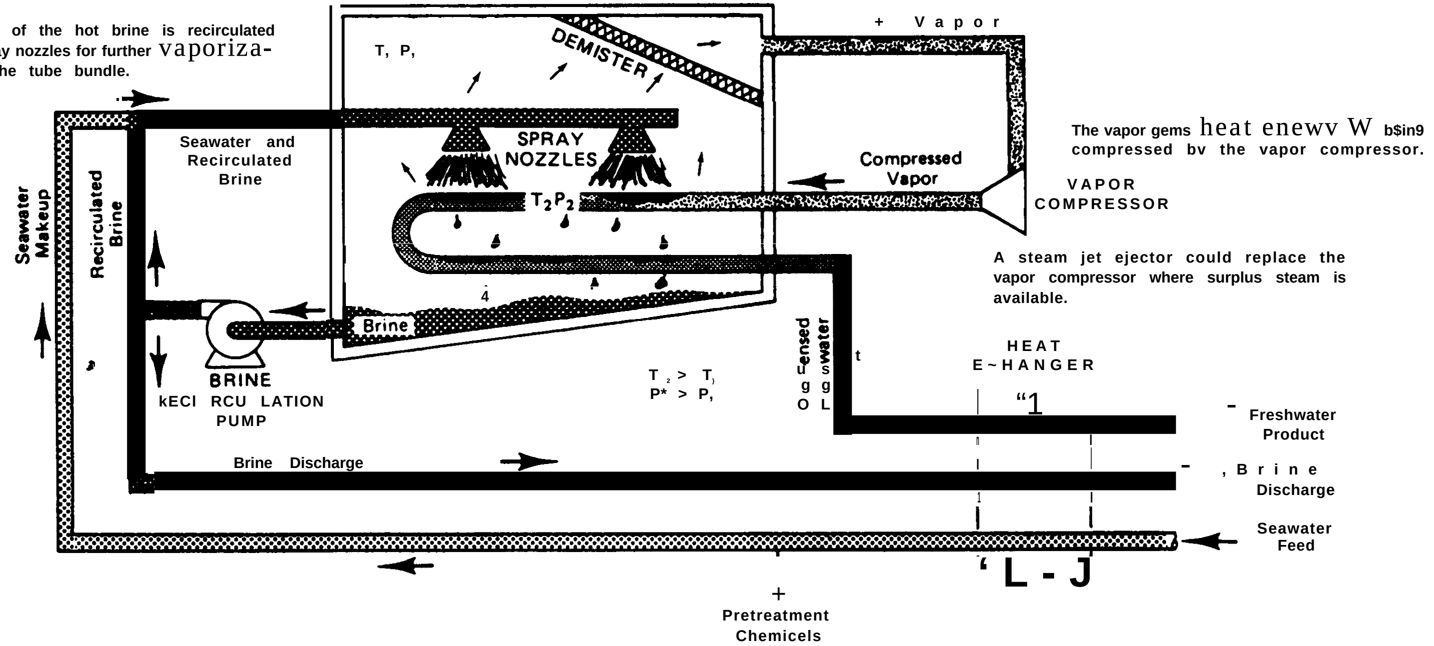
Demister-Usually screening or wire mesh which removes saltwater droplets entrapped in the vapor.

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

rine moves to the next stage to be flashed again to produce additional vapor and transfer heat to the heat-recovery section.

SOURCE: O.K. Buros, et al., “The USAID Desalination Manual,” U.S. Agency for International Development, Washington, DC, prepared by CH2M Hill International Corp., August 1980.

Figure 3.—Simplified Flow Diagram for a Spray-Film Vapor-Compression Process



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

The vapor gains heat energy by being compressed by the vapor compressor.

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

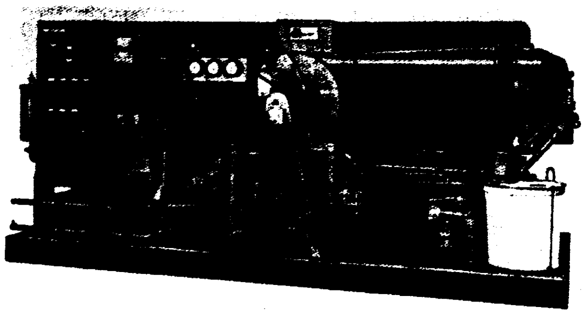


Photo Courtesy of Aqua-Chem, Inc.

This type of electric-driven spray film vapor compression unit is used for facilities such as hotels, industrial plants, and power stations. It is generally available in capacities from 2,500 to 30,000 gpd [9.5 to 114 m^3/d]

SOURCE: O.K. Buros, et al., “The USAID Desalination Manual,” U.S. Agency for International Development, Washington, DC, prepared by CH2M Hill International Corp., August 1980.

enclosure, 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

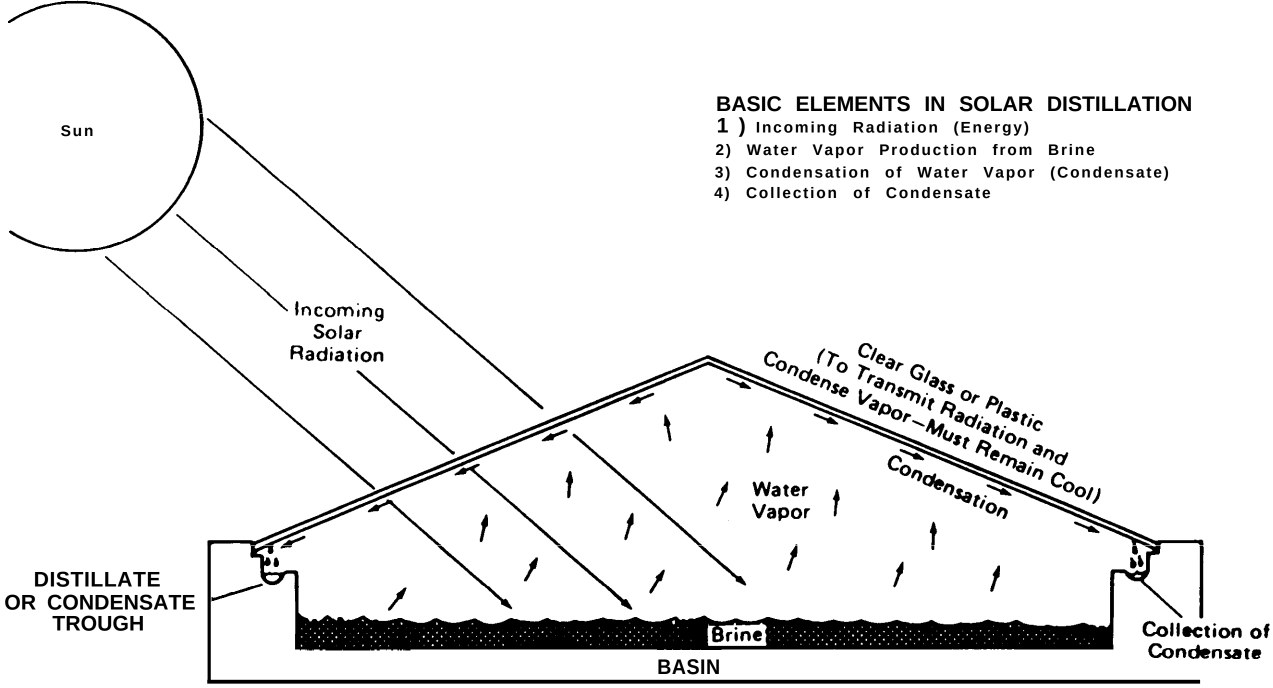
With RO, salty water on one side of a semipermeable membrane is typically subjected to pressures of 200 to 500 lb/sq in. for brackish water, and 800 to 1,200 lb/sq in. for seawater. "Pure" water will diffuse through the membrane leaving behind a more salty concentrate containing most of the dissolved 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.

RO membranes are manufactured commonly in the form of hollow, hair-like fibers; or several alternating layers of flat-sheet membranes and open "spacer" fabric which is rolled into a spiral configuration (figure 6). Membrane selection depends largely on feed water characteristics and membrane costs.

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

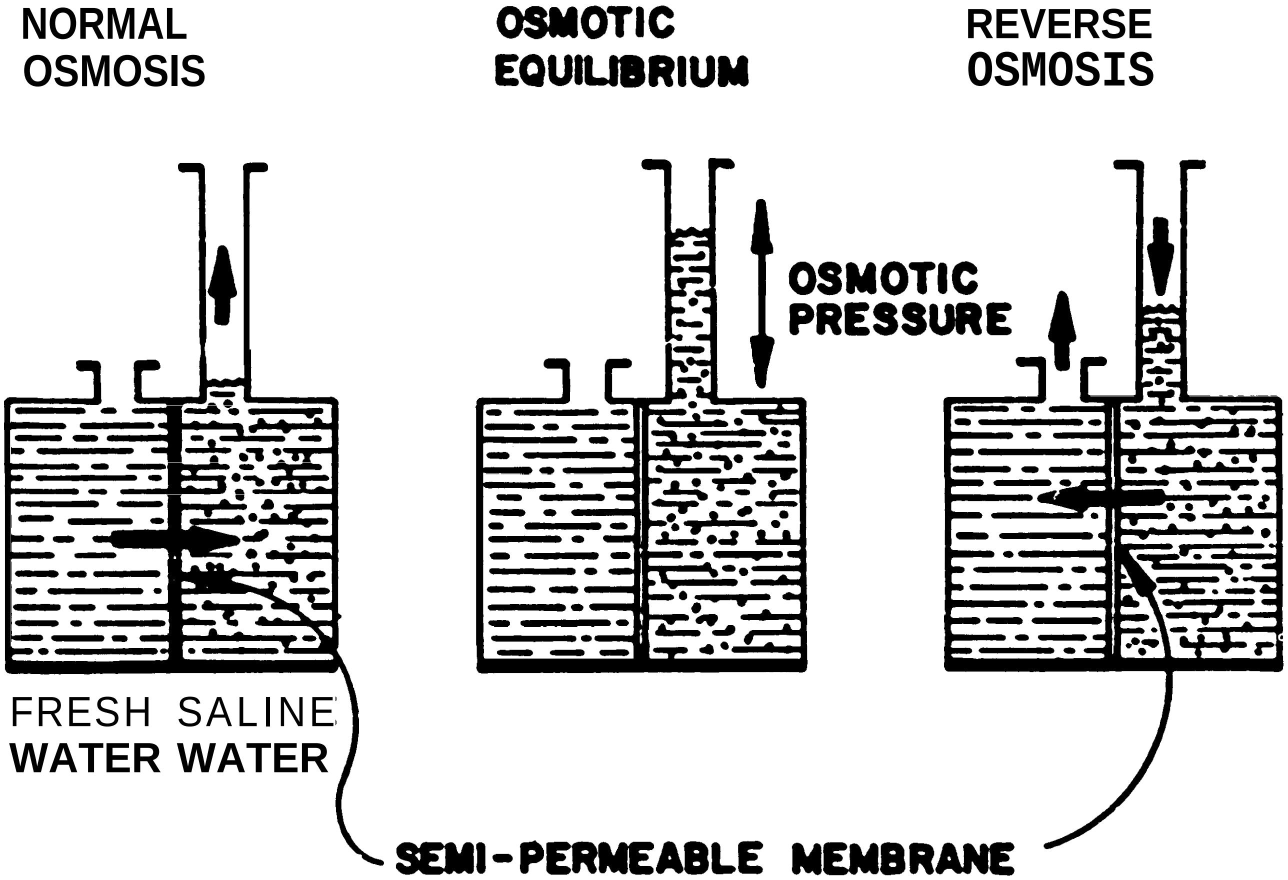
Figure 4.—Basic Elements in a Solar Still



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

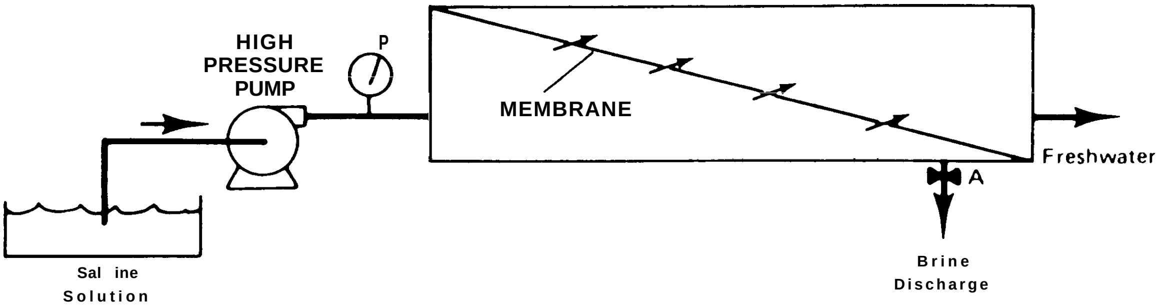
SOURCE: O.K. Buros, et al., "The USAID Desalination Manual," U.S. Agency for International Development, Washington, DC, prepared by CH2M Hill International Corp., August 1980.

Figure 5A.—Principles of Reverse Osmosis



SOURCE: S.L. Scheffer, H.D. Holloway, and E.F. Miller (R.M. Parsons Co.), "The Economics of Desalting Brackish Waters for Regional, Municipal and Industrial Water Supply in West Texas," Office of Saline Water, R&D Progress Report 337, 1967.

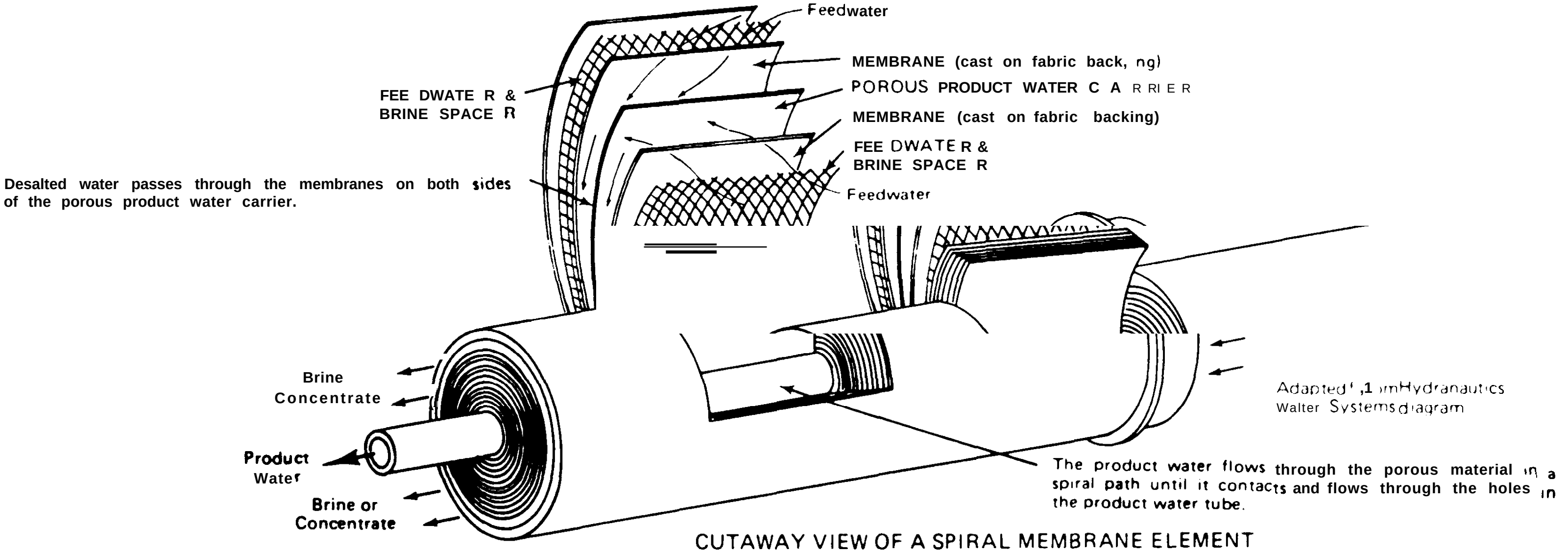
Figure 5B.—Elements of a Reverse Osmosis System



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

SOURCE: O.K. Buros, et al., "The USAID Desalination Manual," U.S. Agency for International Development, Washington, DC, prepared by CH2M Hill International Corp., August 19S0.

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

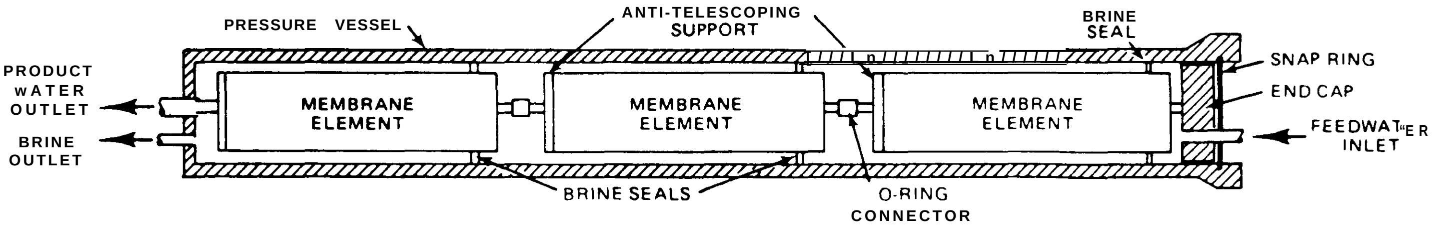


Desalted water passes through the membranes on both sides of the porous product water carrier.

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.

Adapted from Hydranautics Water Systems diagram

CUTAWAY VIEW OF A SPIRAL MEMBRANE ELEMENT

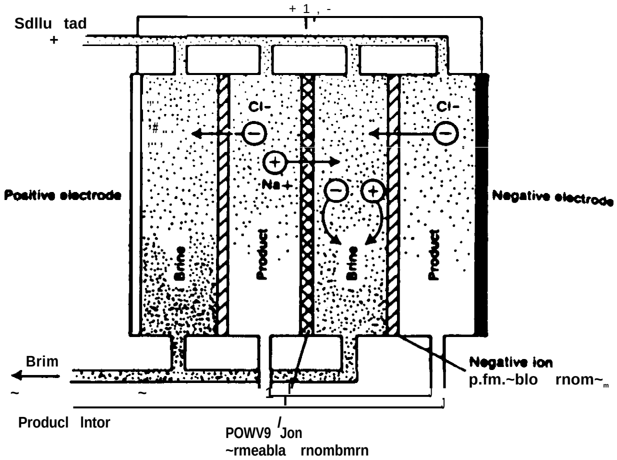


CROSS SECTION OF PRESSURE VESSEL WITH 3-MEMBRANE ELEMENT

SOURCE: O.K. Buros, et al., "The USAID Desalination Manual," U.S. Agency for International Development, Washington, DC, prepared by CH2M Hill International Corp., August 1980.

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

Figure 7.–Electrodialysis (ED)



SOURCE: O.K. Buros, et al., "The USAID Deaallnation Manual," U.S. Agency for International Development, Washington, DC, prepared by CH2M Hiii International Corp., August 1980.

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.

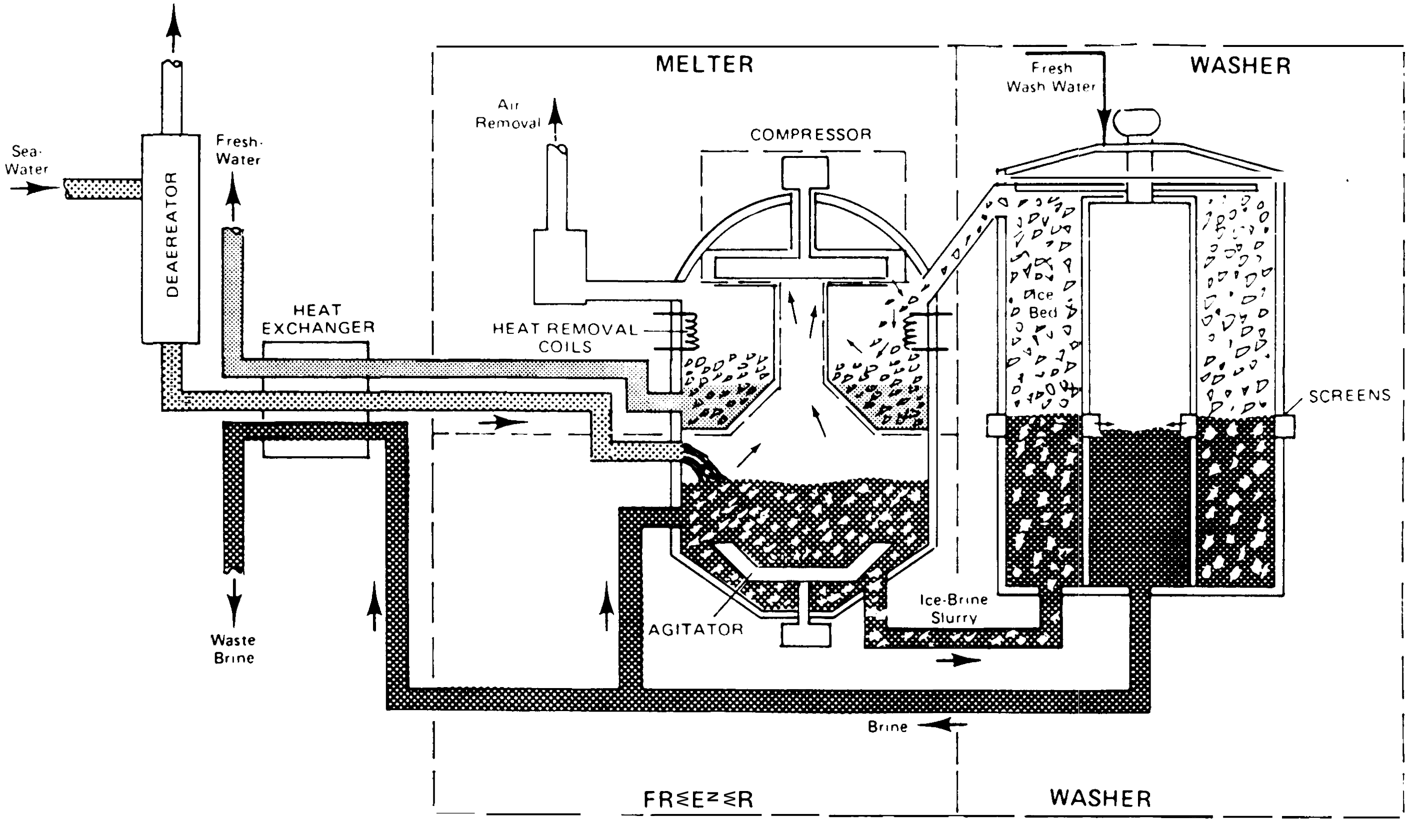
New research efforts are attempting to reduce the number of steps, especially the need to wash the ice crystals. Although small scale commercialization of freezing was attempted in the late 1960s, there were still significant operational problems. Only a few isolated commercial freezing plants now exist (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: The combined freezer (crystallizer) and melter in one vessel is a unit called a hydroconverter.
2. The compressor utilizes thin flexible metal blades. It is built specifically for the high-volume low-pressure conditions found in the VFVC process.

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SOURCE: O.K. Buros, et al., "The USAID Desalination Manual," U.S. Agency for International Washington, DC, prepared by CH2M Hill International Corp., August 980.

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

Technique	Typical applications			
	Brackish water		Seawater 35,000 ppm	Higher salinity brines
	0-3,000 ppm	3,000-10,000 ppm		
Distillation		s	P	P
Electrodialysis	b		t	P
Reverse osmosis	P	;	P	s
Ion exchange	P			

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

SOURCE: Office of Technology Assessment, 19S7.

Chapter 3

Domestic Applications

The United States has about 750 desalination plants (with individual capacities greater than 25,000 gpd) with a combined capacity of about 212 mgd, or about 1.4 percent of the 15 billion gallons of freshwater consumed each day for domestic and industrial purposes. Between 70 percent and 80 percent of this capacity is provided by reverse osmosis plants located in 44 States. Although this country ranks second in the world in the number of desalination plants, it ranks fourth in capacity with almost 10 percent of world production. The largest non-Federal plant in the United States is the RO plant operated by the city of Cape Coral, Florida (33). About 70 percent of the desalination plants in this country are used for industrial purposes. There are also more small RO units (i. e., producing less than 25,000 gpd) than large plants in the United States, but their combined capacity is relatively low. These units are used by hospitals, small industries, pleasure boats, merchant ships, off-shore drilling rigs, and the military.

Desalination technologies can be cost-effective not only to obtain freshwater from brackish and seawater, but also to remove contaminants from drinking water supplies, sewage wastewater, industrial feedwater and wastewater, and irrigation drainage water. In fact, desalination technologies may be more widely applied in this country to decontaminate water than to remove salt. As problems and concerns about water quality increase in the future, the use of desalination technologies, along with other water- treatment techniques, will increase. Legal, environmental, and sociopolitical factors in some areas of the country may also encourage the desalination of brackish groundwater, rather than transfer of surface waters from other counties or States. Therefore, desalination should be included as a viable option in any evaluation of water-supply alternatives.[2]

The current and potential uses of desalination technologies for desalination and water treatment are evaluated in the following discussion.

INDUSTRIAL FEED- AND PROCESS-WATER TREATMENT

Industry consumes about 8 billion gallons of freshwater per day (69). Although water requirements vary significantly from one use to another, high-quality water is needed for manufacturing many products including textiles, leather, paper, pharmaceuticals and other chemicals, beverages, and dairy and other food products. In fact, the majority of desalination capacity in the United States is used by industries to treat feedwater, processwater, or wastewater prior to its discharge or reuse.

Water treatment for different industries varies, but typically involves conventional water treatment techniques (e. g., filtering, softening, etc.). More sophisticated water treatment systems used by industries incorporate RO, ED, IX, or a combination of these and other treatment processes. For example, ultra-pure, deionized water is used by the electronics industry for manufacturing integrated circuits and pharmaceuticals, and for medical applications, electroplating, electric power ***generation,*** and some petroleum processes (42,55).

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[1] There are many tens of thousands of desalination plants with individual capacities of less than 25,000 gpd. The combined capacity of these smaller plants is probably small relative to the combined capacity of larger plants.

[2] Over the long-term desalination could become very important if predictions of global warming and other climate modifications resulting from increased levels of atmospheric carbon dioxide prove to be true. For example, increased desertification could create severe water shortages in semiarid and warmer regions of the world, and elevated sea levels could increase the degree of saltwater intrusion in many coastal aquifers.

INDUSTRIAL WASTEWATER TREATMENT

There are over 200,000 industrial facilities and commercial establishments that discharge an estimated 18 billion gallons of wastewater daily. About three-fourths of this wastewater is discharged into adjacent waterbodies, while the remaining quarter is discharged into municipal sewage treatment systems (52). Desalination technologies can be used to remove and concentrate contaminants in wastewater, thereby reducing potential problems associated with its disposal or reuse.

Although not widely used now for treating industrial wastewater, the attractiveness of RO, ED, and other desalination techniques will probably increase as regulatory restrictions on wastewater discharges become increasingly stringent under EPA's National Pollutant Discharge Elimination System. This trend will also intensify as the cost of membrane processes decreases. Especially in areas where water supplies are limited, industries will increasingly treat and reuse their wastewater (42,55). In some states, ''zero discharge' requirements have forced some industries to use VC distillation in combination with RO to minimize or eliminate wastewater discharges.

In some cases, industries (e. g., photographic, electroplating, pulp and paper, etc.) may use desalination technologies to recover valuable chemicals. However, recovery of potentially useful material from wastewater is often not economic because of low material concentrations in the wastewater. Furthermore, the adverse economic effects of faulty wastewater treatment and recovery processes can be significant. If recovery is practiced, industries generally favor segregating, treating, and reusing waste streams from individual processes rather than treating the combined flow from all processes. Whether or not desalination technologies would be used in such recovery processes would depend primarily on the nature of the waste streams (55).

DRINKING WATER PRODUCTION

About 140, or 20 percent, of the desalination plants (with capacities of greater than 25,000 gpd) in the United States are used to treat brackish groundwater for municipal drinking water supplies. Florida alone has a total of about 70 such plants.[3] Most of these systems rely on RO. With future improvements and cost reductions in membrane technologies, desalination will become increasingly attractive for supplying drinking water to some small (e.g., with populations of 10,000) to midsized (e.g., with populations of a few hundred thousand) communities in the West and along our coasts where brackish groundwater supplies are often adequate and waste concentrate disposal is economically feasible.[4] However, high costs may limit the use of seawater desalination in the United States for some time to come.

Many large metropolitan areas in the United States (i.e., with populations of greater than a million) have fewer problems obtaining adequate supplies of drinking water at reasonable costs, than smaller communities. There are several reasons for this. First, there are significant economies-of-scale associated with developing large supplies of water from conventional sources (e.g., reservoirs, freshwater aquifers, etc.) even if this involves transporting the water over long distances, and treating it prior to use. These costs are normally less than comparable costs associated with desalinating brackish groundwater. Second, many metropolitan areas are located on major rivers or near larger surface supplies of freshwater. Finally, many larger cities have factored future water supply needs into long-term growth scenarios,

In the West, rapidly growing metropolitan areas are having increasing problems finding freshwater as available surface and groundwater supplies are

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[3] Florida also has another 42 municipal plants with production capacities of less than 25,000 gpd.

[4] These numbers are based in part on an unpublished evaluation of potential sites for demonstrating different desalination techniques conducted by the Office of Water Research and Technology in the late 1970s. A 1 mgd plant will supply the water needs for about 7,000 people using just under 150 gpd over a typical year. In some areas of the country and during hot, dry weather domestic water peak demand may be another 30 percent higher (26).

developed for other purposes. Some cities are gaining the rights to additional water through the purchase of irrigated farmland. Some, such as Tucson, have implemented conservation programs. Many cities reuse sewage water from their municipal treatment plants for landscape irrigation; several cities recharge their drinking water aquifers with well-treated sewage water.

Desalinating Existing Water Supplies

About 1,000 smaller municipal water systems and probably many more private systems in arid or semi-arid regions of the country rely on water supplies—typically groundwater—with concentrations of salt and other dissolved solids (e. g., magnesium/calcium sulfates and carbonates) that can reach 2,000 or 3,000 ppm. In many cases this water is not treated prior to delivery (1 1,36). Most brackish groundwater is especially suited to desalination because it usually has low levels of naturally occurring organics, and it tends to be of more uniform quality than surface waters (36).

Desalination costs decrease significantly as the capacity of desalination plants increases to a few million gallons per day.[5] For some small to mid-size communities with ample supplies of brackish groundwater, the use of desalination technologies will become increasingly attractive for three reasons. First, the costs of membrane processes will probably continue to decrease over the next decade or so in response to technical and nonstructural improvements, and continued industry competition. Second, the costs of developing conventional supplies of freshwater will increase as nearby sources are used for other purposes, and environmental and legal complications increase. For example, in some parts of southern Florida it is now more economical to desalinate and treat relatively small volumes of brackish groundwater using RO or ED than to import fresh surface water from inland areas (19). Groundwater desalination also avoids potential political problems associated with transferring water from other political jurisdictions. And third, increasingly stringent drinking water regulations will probably require increased levels of water treatment,

For small towns with populations of a few thousand people, water treatment costs (whether conventional processes or desalination) are unusually high. Furthermore, many small towns with poor quality drinking water are located in economically depressed areas, leaving them unable or unwilling to pay for water treatment. Some economies-of-scale may be realized if several adjacent communities jointly treat their water at a common plant. Smaller utilities (i.e., serving fewer than 500 customers) may be eligible for technical and financial assistance from the Federal and some State governments. Extremely small towns and those families with private wells may have to resort to private point-of-use treatment or bottled water if existing drinking water supplies are inadequate or of low quality.

Smaller desalination plants may be used for water supplies on oil rigs and at remote construction sites in coastal areas of the United States to supply drinking water. Vapor compression units could be used for seawater distillation, and RO and ED units for desalinating groundwater from brackish aquifers or seawater wells.

Incrementally Developing Drinking Water Supplies Via Desalination

Many rapidly growing communities, particularly mid-sized coastal communities, are now experiencing or anticipate drinking water shortages as their populations grow. In many cases small increments of capacity from conventional water sources (e. g., small diversions, additional wells, etc.) can be developed relatively cheaply. However, in other cases developing conventional supplies may require developing large-capacity reservoirs. A large increment of capacity may have lower costs per volume of water, but the full capacity may not be needed until many years later. In some cases, surface water supplies can not be developed soon enough to meet rising demands. If brackish water supplies are available, it may be more economical to develop several increments of desalination capacity over time, rather than developing larger than necessary water supplies from conventional sources.

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[5] Domestic water use in the United States is about 120 to 150 gallons of water per person per day. So, a plant producing 3 mgd would supply the water needs of about 20,000 people,

Supplementing Water Supplies During Droughts Via Desalination

During droughts and other unpredictable emergencies that might occur once every 10 or 20 years, drinking water supplies can be limited for many months. Unfortunately, reserve capacity, whether it is provided through desalination or conventional sources, is very expensive if it is used only during emergencies or when water supplies fall below a critical level (but before an emergency situation arises).[6] Conservation seems to be the most appropriate and economical method for dealing with most unpredictable, short-term shortages. Although conservation does provide some elasticity in water demand, the more water that is conserved during normal use, the less elastic the demand will be during times of shortage. In some cases cross-connections with neighboring communities can alleviate any short-term water disruptions.

Further Treatment of Surface Water Supplies

With increasing population and industrial growth in this country over the last 200 years the quality of surface supplies has gradually declined, thereby increasing the need to treat water before it is used. In fact, the 1986 amendments to the Safe Drinking Water Act will require increasing levels of water treatment to meet more stringent water quality standards now being developed by EPA. In response to these regulations public utilities will be increasing their use of RO, ED, and perhaps IX (in addition to, or in place of, other conventional water treatment processes) to remove dissolved minerals, heavy metals, low-molecular-weight dissolved organics (some of which are transformed to trihalomethanes, or THMs, during chlorination), and microorganisms.

Decontaminating Groundwater

About 50 percent of this country's population uses groundwater for all or a portion of its potable water. Recent studies show that groundwater can easily be contaminated by migrating chemicals from a variety of sources including landfills, surface impoundments, septic tanks and cesspools, injection wells, mining activities, livestock feed lots, and the use of pesticides, herbicides, and fertilizers on agricultural lands. Although only an estimated 1 to 2 percent of the Nation's groundwater is known to be contaminated with potentially toxic chemicals (51), the levels of contamination maybe somewhat higher near large metropolitan centers, industrial areas, and agricultural regions. In addition, groundwater contamination is likely to increase with time as previously disposed of chemicals continue to spread throughout our aquifers.

In the past when groundwater has been found to be contaminated, water has often been acquired from uncontaminated sources. However, as different sources of clean water are used for other purposes RO, ED, and perhaps IX, may be used increasingly to remove organic and inorganic contaminants from groundwater supplies.

MILITARY USES

The U.S. Navy has used shipboard distillation units for drinking water and boiler feed water for the last several decades. However, RO units are now being tested on several classes of ships in our fleet. The Navy is also evaluating the technical and economic feasibility of using RO instead of, or in combination with, ion exchange for the pier-side production of potable water and boiler feedwater at some of its land-based facilities. A preliminary evaluation indicates that RO could be the preferred alternative at 10 of 15 naval bases studied (45). Small 25 gpd RO units operated with hand pumps are now being developed by the Navy for use on its life rafts (88).

Both the Army and the Marine Corps have upgraded the water production capabilities of some

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[6] For example, in a New York City study of options for supplying water during periodic droughts it was assumed that a 300 mgd desalination plant would begin operating when the water supply in the city's reservoirs dropped below 50 percent of their total storage capacity. The plant would stop operating when the storage capacity reached 80 percent. Even under these conditions the plant would be used only about 20 percent of the time at a very high cost (53).

field and hospital units with the acquisition of 900 skid-mounted RO units with water production capacities of about 15,000 gpd. In addition, the Army is now developing a trailer-mounted 70,000 gpd unit. These units are capable of processing untreated freshwater, brackish water, seawater, and water contaminated with nuclear, biological, and chemical warfare agents. Along with RO, these units incorporate other possible treatment processes including coagulation of suspended material, filtration, disinfection, and ion exchange. The smaller units can be dropped by parachute; the larger units can be airlifted or transported on a ship. The Army has also developed a water purification barge consisting of two 300,000 gpd RO units capable of treating brackish or seawater and pumping the treated water ashore while anchored 2,000 feet offshore (44).

POINT-OF-USE/POINT-OF-ENTRY, OR AT-HOME, WATER TREATMENT

About 44 million people in the United States obtain their drinking water from private water supplies, the bulk of which comes from wells. Some of this well water, especially in arid and semiarid regions of the United States, is brackish. Many small water supply systems and private wells are also contaminated with bacteria (49). The occurrence of potentially hazardous industrial and agricultural chemicals in drinking water aquifers is also on the increase (51). For many small public and private systems with brackish (or contaminated) drinking water, treating water with RO or ED at a centralized facility may be either impractical or prohibitively expensive.

Alternatives to treating contaminated groundwater at a centralized plant include developing new wells or surface water sources, connecting to neighboring water supplies of higher quality, hauling water from nearby sources, purchasing bottled water for drinking and cooking, point-of-entry (POE) treatment as water enters the home, or point-of-use (POU) treatment of drinking and cooking water with small distillation or RO units in the home (60). In this latter area, the Water Quality Association estimated that 1985 residential sales of POU treatment devices at more than $700 million (85). Considering the increased level of public concern about drinking water quality, it is quite likely that POU, and perhaps POE, water treatment will increase in the coming years.

Ion exchange water "softeners' have been used for many decades for POE treatment of water containing large quantities of dissolved calcium and/or magnesium. With these units the calcium and magnesium is replaced by sodium as the water flows through the chemical resins in the water softener; however, the total mineral content of the water remains the same. Soft water reduces the amount of calcium carbonate precipitation inside a home's water pipes and faucets. However, there is some question about possible adverse health effects (e. g., increases blood pressure) associated with drinking high-sodium water. Whole-house water softening units cost between $300 and $1,000 (depending on their capacity), plus the cost of installation and periodically changing the resins.

Dissolved minerals and many other inorganic/organic contaminants can be removed from drinking/cooking water by RO or distillation of the tap water. These counter top, under-the-sink, or standalone units typically cost from about $80 to $800, depending on the sophistication and capacity of the unit (which typically range from 5 to 15 gpd). Most contaminants and dissolved solids can be removed by RO units; however, the effectiveness of the units decreases with time. These units require from 5 to 10 gallons of water for each gallon of water processed. Water production costs range from .$0.06 to $0.25 per gallon. small distillation units ako remove most contaminants and dissolved solids. Electricity costs for distillation typically run about $0.25 per gallon.[7]

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[7] After purchasing the unit, the monthly cost for a family of four using two gallons of water per day for drinking and cooking at a cost of $0.25 per gallon would be about $1 5/month. Bottled water generally costs about $1 per gallon, or about $60/month for a family of four. In Washington, D.C. municipal drinking water for a family of four costs about $24/month.

Granular activated carbon (GAC) water filters can be used for POE treatment, or attached to a faucet spigot for POU treatment of cold water. GAC filters will remove some particulate material and many organic contaminants (especially, low-molecular weight, volatile organics, including trihalomethanes) and chlorine from water.[8] But, GAC filters have little, if any, effect on salt and other dissolved minerals and inorganic contaminants.[8] Faucet filters cost about $20 per unit; falter elements that should be replaced on a monthly basis cost about $5 per element. Under-the-sink and whole-house GAC filters can cost as much as a few hundred dollars depending on their size; replacement frequency depends on the filter size and the level of water use.

All types of POU treatment units require some periodic cleaning and/or parts replacement, which is usually performed by the homeowner. The lack of control over monitoring for treatment effectiveness and assuring routine maintenance is a major concern that regulatory agencies have about POU treatment. In fact, EPA regulations (for volatile organics) state that POU treatment systems may be used by public water systems only on a temporary basis (or perhaps over a longer term under an extended EPA exemption) to avoid unreasonable public health risks from polluted water. But, POU treatment can be used at the discretion of homeowners who are particularly concerned about the quality of their water. In fact, the market for POU water treatment equipment is growing at a rate of about 15 to 20 percent per year.

Where centralized water treatment costs are prohibitive, EPA does allow a utility to install water treatment equipment in homes or commercial buildings at the water's POE. However, it is presently unclear how much POE treatment will be used in the future. GAC may be used to remove dissolved organic contaminants and chlorine, but GAC has little effect on other types of contaminants, Distilling or treating all incoming water with RO is prohibitively expensive; RO also produces a great deal of waste water which would need disposal. Furthermore, water with a very low mineral content, regardless of the technique used, can corrode metal pipes. IX is now only used in homes for water softening. All POE equipment would also require periodic maintenance by the utility operating the water system.

MUNICIPAL WASTEWATER TREATMENT

Wastewater from sewage treatment plants is one of the largest potential sources of water where freshwater supplies are limited. In fact, about 60 to 90 percent of potable water delivered to city residents in the United States is discharged into sewage collection systems. After it has been treated to remove contaminants and to kill pathogens, the water can then be reused for potable purposes, agricultural and landscape irrigation, industrial reuse, and streamflow augmentation.

If municipal wastewater were used for groundwater recharge or directly reused for potable purposes, RO or ED could be used to remove the 200 to 500 ppm of salt and other dissolved solids that are typically added to water by domestic use. Other treatment processes that could also be used include: chemical addition, flocculation, lime clarification and recarbonation, equalization, multimedia fitration, ammonia stripping, granular activated carbon adsorption, ultra-filtration, and disinfection with chlorine and/or ozone. The reclamation of municipal wastewater for agricultural, industrial, and other municipal uses is supported by the Federal Government[10] as well as some States.

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[8] Breathing volatilized organics while showering is thought to be a major exposure pathway for low molecular weight organics in water. If further research proves this to be the case, then POE water treatment with GAC may become increasingly important.

[9] GAC provides surfaces for bacterial growth when water is not running through the filter. Although considerable bacterial growth can occur, pathogens are apparently not released at infectious doses. In fact, in a 2-year EPA study people using GAC filters did not show any significant increase in gastrointestinal illnesses over non-users. However, it is recommended that users run water through GAC filters for 30 seconds prior to water use to flush out any bacteria (60).

[10] Under Section 201 of the Clean Water Act EPA encourages the construction of revenue-producing facilities that reclaim municipal wastewater. In addition, under Section 1444 (a)(2) of the Safe Drinking Water Act EPA can support projects investigating and demonstrating the health implications involved in the reclamation, recycling, and reuse of waste waters for potable purposes. For example, EPA contributed $7 million to support Denver's $30 million wastewater treatment test facility and research program.

The potential for advanced treatment and reuse of municipal wastewater was recognized in the early 1960s (15). For example, the City of New York estimated that 100 million gallons of potable water could be obtained by further treating effluent from an existing secondary sewage treatment plant (16, 53). Treated wastewater from sewage has been used as potable water in emergencies in Chanute, Kansas, and Ottumwa, Iowa, and on a continuous basis since the late 1960s by the city of Windhoek, Nambia (48). Whether reclaiming municipal wastewater is economical would depend largely on site-specific conditions.

Indirect reuse of treated municipal wastewater for potable purposes is becoming increasingly attractive to many municipalities, especially in the West. For example, in 1977 the Orange County Water District began injecting treated waste water from a sewage treatment plant into its water supply aquifer to prevent the intrusion of saltwater, and to allow indirect reuse of the treated water. In addition to other treatment processes, the District uses a 5-mgd RO plant as an integral part of its overall 15 mgd treatment and injection operation (l). There are many other communities throughout the country that indirectly reuse some treated wastewater which is mixed with stream flows and storm runoff. These combined flows enter drinking water reservoirs or specially constructed basins where the water percolates into drinking water aquifers.

Treatment and direct reuse of municipal wastewater for potable purposes is also being explored. In 1985 the Denver Water Department completed construction of a l-mgd treatment facility, which includes RO, to demonstrate direct wastewater reuse for potable purposes. Current treatment costs are about $2.50 per 1,000 gallons. If this facility can be operated successfully from a health, safety, and economic standpoint over the next 4 to 8 years, Denver will consider building a full-scale facility for treating up to 100 million gallons of wastewater per day. This could provide over 15 percent of Denver's water needs (40,46). Many countries and cities throughout the United States are closely tracking Denver's experiences. However, significant public reluctance to drink treated wastewater may delay direct reuse.

DESALINATING IRRIGATION WATER

About 81 percent of all water that is consumed in the United States goes for irrigation, most of it in the West. Each time river water is used for irrigation salt is leached from the soil as the excess water migrates into surface and groundwater supplies. In many cases, the salty water is intercepted by subsurface drainage systems, which may empty back into rivers. More salt is added to many rivers in the West from natural, salty seeps. For example, the salinity of the Colorado River increases from about 50 ppm in its headwaters, to approximately 750 ppm at Hoover Dam near Las Vegas, NV, to about 850 ppm at Imperial Dam near Yuma, AZ. High concentrations of salt in irrigation water typically lead to reduced crop yields; poor germination of seeds; stunted plant growth; increased fertilizer requirements; the necessity to plant less profitable, more salt-tolerant crops; and the eventual loss of farmland due to salt build-up (30).

In theory, irrigation water could be desalinated (prior to use) to improve its quality and to increase crop yields. Studies of hypothetical situations conducted in the late 1960s and early 1970s indicated that the market value of crop yields did increase significantly as the salinity of the irrigation water decreased. For example, in one study crop yields ranged in value from about $270 per acre-foot for low quality water (i.e., 1,500 ppm dissolved solids) to about $870 for water of highest quality (i. e., 50 ppm). However, desalination costs ranged from about $500 per acre-foot for 1,500 ppm water to $1,100 per acre-foot for 50 ppm water, or about $1.60 to $3.50 per 1,000 gallons. In the vast majority of cases the costs of desalination greatly exceeded the calculated value of increased crop yields (38).[11]

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[11] The estimated cost of desalinating irrigation water depends largely on assumptions used in the calculations. Some papers written in the late 1960s and early 1970s indicated that the cost of desalinated water would be "at least an order of magnitude greater than the value of the water to agriculture. Other papers were much more optimistic. Part of this optimism was usually reflected in overly optimistic assumptions used in calculating hypothetical costs and benefits (79,93). For example, some models assumed low cost power from dual-purpose nuclear plants, Federal financing at interest rates of 3 3/4 percent,

In the early 1970s research conducted in the San Joaquin Valley, California, demonstrated the technical feasibility of using ED and RO to desalinate agricultural drainage water (from irrigation operations) containing 3,000 to 7,000 ppm of dissolved solids (38). Over the last few years the California Department of Water Resources has continued studying different alternatives for treating agricultural drainage water at a test facility at Los Banes, in the San Joaquin Valley (88). Current estimates for costs of desalinating agricultural drainage water, including disposal, range from about $2 to $4.50 per 1,000 gallons (3). These costs greatly exceed present costs of irrigation water in the West which typically range from less than $0.01 to about $0.15 per 1,000 gallons. (See box B in ch. 4.)

In another related area, the Westlands Water District in the San Joaquin Valley is now exploring the technical and economic feasibility of using biological treatment techniques to remove selenium, and other contaminants (but not salt) from some of its agricultural drainage water that formerly flowed into Kesterson Reservoir, a wildlife refuge (92). The centerpiece of this District-financed, 4-year, $6.6 million drainage water treatment project, is a 0.5-mgd prototype selenium removal plant that is scheduled to operate for 18 months beginning sometime in 1989. The treated water will be disposed of in concentrate ponds operated by the State of California to produce solar energy. According to present plans, untreated irrigation drainage water will also be injected at a rate of 1 mgd into saline aquifers located at a depth of about 5,000 to 6,000 feet (27).

To meet our treaty obligations to Mexico, the Bureau of Reclamation is constructing a 72-mgd RO plant at Yuma, AZ, to desalinate irrigation drainage water before it is discharged into the lower Colorado River for later use in Mexico. This plant is described in more detail in chapter 8 on international involvement in desalination.

Because of the large volumes of water required for normal open-field irrigation, desalinating salty river water for irrigation purposes, or desalinating irrigation drainage water for agricultural reuse is generally not economical at this time in the United States, except possibly for high-value crops grown in greenhouses.[12] In other words, it costs more to grow crops under typical agricultural conditions with desalinated water than they are worth on the market. In most cases, it is more economical to import crops from regions of the country where water is naturally more abundant.[13] Because of the many water-rich agricultural regions of the United States, desalinating irrigation water will probably not be economical for agriculture in this country for the next few decades (at the very least), except in highly specialized situations. It is also doubtful whether most irrigators in the West can afford to develop new surface water supplies given the current market conditions without some level of government assistance.

If the cost of developing new water supplies from other surface sources greatly exceeds the cost of desalinating irrigation drainage water, it may be economical for some metropolitan areas to desalinate and decontaminate irrigation drainage water for potable purposes. For example, several municipalities in southern California are now considering the possible use of treated agricultural drainage water to supplement existing drinking water supplies.

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desalting facility lifetimes of 30 years, 100-year lifetimes for associated facilities, and irrigation efficiencies and crop yields that were higher than average.

[12] Using desalinated water for open field irrigation is generally not economical at this time anywhere else in the world. However, desalinated water is used for irrigation purposes in some areas of the world (e.g., Saudi Arabia). In most of these situations the water is subsidized by the government for reasons of national security and economic independence.

[13] Researchers in this country and overseas are cultivating naturally salt-tolerant plants, developing salt-tolerant plants through plant breeding and biotechnology, and developing marketable products from these plants. Although such efforts may marginally increase the potential use of high salinity river water or irrigation wastewater, the full potential of such research is not known at this time.

Chapter 4

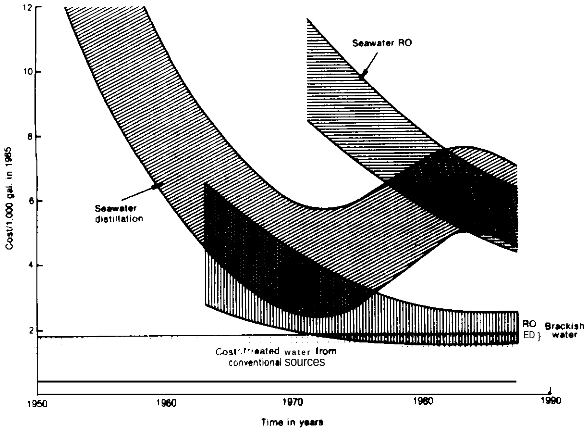
Desalination Costs

DESALINATION COST TRENDS (IN 1985 DOLLARS)

Cost is a primary factor in selecting a particular desalination technique for water treatment. Desalination costs have decreased markedly in the last few decades (figure 9). For example, typical distillation costs in the 1940s and 1950s ranged from $15 to $20 per 1,000 gallons. By the early 1960s distillation costs had dropped to about $5.50 to $9 per 1,000 gallons (39).[1]

Recent cost analyses[2] indicate that distillation and seawater reverse osmosis (RO) now have comparable costs of approximately $4 to $6 per 1,000 gallons (88) under near-optimum operating conditions. If the desalination equipment is not operated efficiently, these latter costs can increase to as much as $10 per 1,000 gallons. Some marginal reductions in distillation costs may be realized from improvements in plant designs, fabrication techniques, heat exchange materials, scale control techniques, and plant automation. Cost reductions are most likely to occur for multiple effect and vapor compression units. Distillation costs will fluctuate more than RO with changing energy costs. Cost variability is discussed in box B.

Figure 9.—Approximate Desalination Costs



Desalination costs (including capital and operating costs) for distillation and RO over the last 40 years for plants producing 1 mgd to 5 mgd of "polished" water ready to drink. Costs may be higher than the cumes indicate when desalination equipment is not operated efficiently. The increasing distillation costs during the 1970s primarily reflect rising capital and energy costs.

SOURCE: Lamb, 19S2; U.S. Off Ice of Saline Water, 1971; Koalzer, 1972; U.S. Bureau of Reclamation, 1972; Robinson et al., 19S3; Schroeder, 1978; U.S. General Accounting Office, 1979; TouPs, 19S2; Reed, 1982; Bechtel Group, 19S3; United Natlona, 1985; Leitner, 19S7 (IVDR), and discussions with desalination experts. (See Bibliography.)

Box B.—Variability of Costs

It is important to recognize that desalination costs vary significantly depending on:

- the size and type of the desalination plant (figure 10),
- the plant location,
- the source and quality of incoming feed water,
- labor costs,
- availability of construction and maintenance materials,
- Waste concentrate disposal costs,
- energy costs,
- financing costs and options,
- the reliability of the plant, etc.

Desalination costs in developing countries can be higher than they are in the United States, because of transporation costs, the need for spare parts in more remote regions of the world, more extensive site development, and added management costs (77). All cost estimates in this chapter are approximate and given in terms of 1985 dollars.

Detailed evaluations are required to determine the cost effectiveness of particular processes for a specific location. A particular desalination process should neither be selected nor rejected based on the costs provided in this report. Also, when comparing costs of desalination with costs of conventional treatment plants it is important to recognize that desalination plants typically have an operating lifetime of 15 to 20 years. Conventional water treatment plants often last 30 to 40 years, and sometimes longer.

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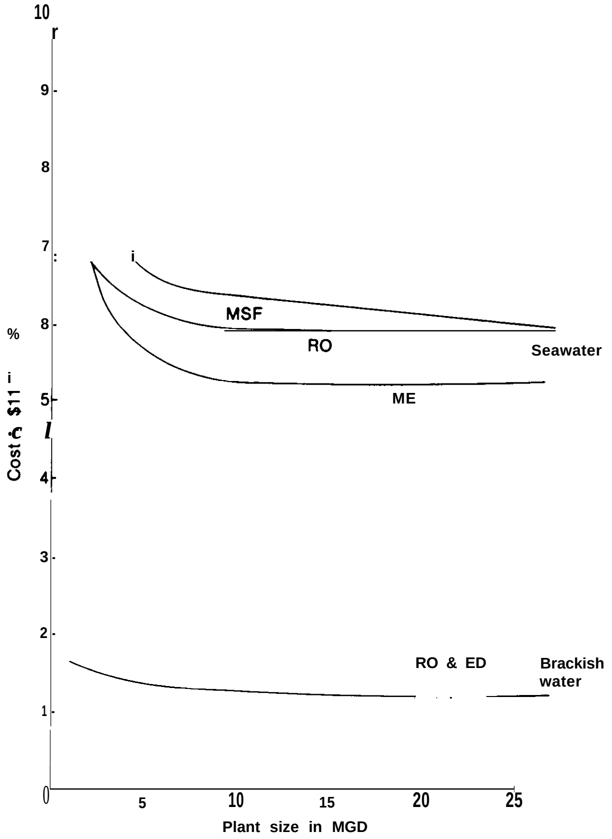
[1] All costs are given in 1985 dollars.

[2] Based on cost analyses performed by Wade, Heaton, and Boulter of Ewbank Preece in 1985, and Leitner in 1987 and reported in the Water Desalination Report.

Figure 10.—Desaiination Costs v. Plant Size



This graph shows how the cost of “polished” product water decreases with size of plant for all desalination processes. Although it is also clear that the costs of desalinating seawater are about 5 times comparable costs for brackish water, this graph should not be used as evidence that one desalination technique is more cost effective than another for seawater and brackish water.

SOURCE: S.A. Reed, “Deealting Seawater and Brackish Water 1981 Cost Update,” DE82020482, ORNU TM-8191, Office of Water Resaarch and Technology, Washington, DC, August 1982; and United Nations, “Progress Report on the International Drinking Water Supply and Sanitation Decade,” 1985.

The costs of desalinating brackish water using RO have dropped from about $5 per 1,000 gallons in 1963 (62) to about $1.50 to $2.50 per 1,000 gallons today. Costs for brackish water electrodialysis (ED) are generally comparable to those for RO. When low pressure RO membranes are used to remove dissolved solids and trihalomethane precursors (via nanofdtration), treatment costs are reduced by about $0.50 per 1,000 gallons.[3] According to industry experts, the costs of membrane processes should continue decreasing in line with improved membrane plant performance (e. g., decreased water pressure requirements, increased rejection of salt, longer operating lifetimes, improved energy recovery, and plant automation), and improved economics associated with larger scale production of membranes.

There do not seem to be any newly developing desalination technologies that will produce major reductions in overall water treatment costs, which are described in box C.

BRACKISH WATER RO AND ED

RO and ED are generally the most economical processes for desalinating brackish water with salinities of less than 10,000 ppm. ED tends to be more economical than RO at-salinities of less than ***3,000*** ppm, and less economical than RO at salinities greater than 5,000 ppm. Overall costs depend to a large extent on pre- and post-treatment requirements. Both capital and operating costs for brackish water plants tend to be very high for sma.ll-capacity plants (e. g., several hundred thousand gpd); however, costs decrease significantly as plant capacities increase to 3 mgd. Beyond 3 mgd overall costs decrease only slightly with increasing plant size (12).[4] For example, projected water production costs (per gallon) of a 100-mgd RO plant are

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[3] These costs include capital and operating costs for plants producing from 1 to 5 mgd of ‘polished’ water, ready to drink. All desalination costs in this section include plant construction (typically amortized over 20 years), pretreatment, desalination, waste brine disposal, and maintenance. They do not include costs associated with planning, land acquisition, well drilling or reservoir construction, water storage, or distribution. Because costs depend so much on site-specific conditions, the costs in this report should not be used to determine which desalination or traditional water treatment process is most economical for a specific application.

[4] There are significant economies of scale for operating costs and some economies of scale for capital costs associated with RO plants as their capacity increases up to about 3 mgd. For larger plants there are modest economies of scale for operating costs and almost no economies of scale for capital costs (12).

Box C.—Freshwater Costs

As the demand for freshwater increases, so will its cost. However, water in the United States is inexpensive relative to its cost in many other parts of the World. For example, costs for publicly supplied water in metropolitan areas of the United States average about $1.25 per 1,000 gallons for water treatment and delivery. Typical rates for municipal water (delivered to the home) range from $0.50 to $2.00 per 1,000 gallons (14), with a low of $0.10 per 1,000 gallons to a high of $22 per 1,000 gallons (71).

In Washington, D. C., potable water costs approximately $1.35 per 1,000 gallons; about half of this cost is for treatment, and half for delivery. Collection and treatment of sewage cost about $2.50 per 1,000 gallons. A family of four, each using 150 gallons of water per day, has a monthly water/sewer bill of about $70/month (at $3.85 per 1,000 gallons).

According to some estimates 3 to 6 percent of the U.S. population consistently buys bottled water. In southern California, one of every three families has bottled water in their home (85). Sales of bottled water in this country have grown from $100 million in 1975 to almost $1.3 billion in 1986. Assuming a cost of about $0.85 for a gallon of bottled water, a family of four each using about gallon of water per day for drinking and cooking would spend about $50/month on bottled water.

In the west irrigation water supplied by federally sponsored water diversions generally costs farmers between $0.01 and about $0.18 per 1,000 gallons (10,58), and groundwater costs between $0.05 and $0.08 per 1,000 gallons. The costs paid by farmers for water from Federal water projects may be heavily subsidized by the government. Capital costs are typically repaid over a 50-year period without interest. Yearly payments are often further reduced by selling electricity generated from multipurpose dams, and/or by using such low-cost electricity for pumping operations. Western farmers pay only about 17 percent of the actual cost of water supplied by Bureau of Reclamation projects (58).

Costs for developing new supplies of surface water in the west vary significantly from region to region. For example, in California the estimated cost of water from proposed projects averages almost $5 per 1,000 gallons (10). In 1987 the Army Corps of Engineers estimated that water from the proposed Two Forks Project south of Denver would cost about $10 per 1,000 gallons. In many areas of the west it is now cheaper to use desalination technologies to treat either brackish water or irrigation drainage water than to develop new supplies of surface water.

Rising water costs reflect:

1. increasing costs associated with developing new surface supplies,
2. an increasing need to remove pollutants from exisiting supplies of surface water and groundwater in response to Federal and State drinking water and wastewater discharge standards,
3. an increasing need to minimize environmental impacts associated with water development projects, and
4. increasing legal costs that may be associated with obtaining the "water rights" to surface supplies.

The cost of groundwater also increases as the water levels in aquifers are drawn down.

only 10 percent less than water costs of a 10-mgd plant (91).

In some coastal areas the salinity of brackish groundwater may increase over time if continued pumping increases the level of saltwater intrusion. This could significantly increase desalination costs. It is therefore important to determine the sustained yield and long-term quality of brackish water aquifers. Financing community drinking water systems is discussed in box D.

Box D.—Financing Community Drinking Water Systems (14)

There are an estimated 59,000 water supply systems in the United States (table 3). The relatively few systems that serve metropolitan areas are quite large; most systems are small. For example, the largest 1 percent of all systems serve over 40 percent of the population, whereas the smallest 65 percent serve less than 3 percent of the population.

Table 3.—MunicipaL Water SuppLy Systems

	Number of systems (thousands)	Population served in percent
Publicly owned systems	26	71
Privately owned systems	16	13
Ancillary systems	17	1
Private wells	N/A	15
No piped water	N/A	1

N/A - Not applicable.

SOURCE: EPA Office of Drinking Water, "Survey of Operating and Financial Characteristics of Community Water Systems," prepared by Temple, Baker, & Sloan, Inc., 1982.

Traditionally local governments have assumed primary responsibility for financing and operating water supply systems through tax-exempt municipal bonds, retained earnings from the sale of water, one-time fees, and the sale of stock and/or taxable bonds. For example, public, non-Federal expenditures to build, operate, and maintain water supply systems amount to about $4 to $5 billion.

Federal assistance for water supply systems came from several sources in 1986: $290 million through the Farmer's Home Administration (exclusively for rural communities); $225 million through the Department of Housing and Urban Development, the Economic Development Administration, and the Appalachian Regional Commission; and $190 million for water supply projects through the Corps of Engineers and the Bureau of Reclamation. Also, Federal tax revenues are lowered due to the tax-exempt status of State and local bonds. State aid of about $500 million (in 1984) is available in the form of direct State spending, support from State-chartered financial institutions and State bonds, and financial management assistance.

Most utilities and private water systems can finance their own operations, which may include the use of desalination technologies. However, very small systems, particularly those in rural areas, may have to rely on creative financing or available State/Federal assistance.

SEAWATER DESALINATION

Desalinating seawater—using either distillation or RO—can be from three to as much as seven times more expensive than brackish water RO or ED. Distillation costs are high, regardless of the salt content, due to the large amounts of energy required to vaporize water; RO (and ED) costs are higher for seawater because more salt must be extracted.

By the early 1980s the costs of desalinating seawater using RO or distillation (for plants larger than about 5 mgd range) had become roughly comparable—about $4 to $6 per 1,000 gallons (7,57,67). So, the selection of a desalination process must be based on other considerations. For example, the capital costs associated with distillation are generally higher, that.ime required for plant construction typically longer, and the operational costs closely tied to energy costs, On the other hand, the level of solids removal is somewhat higher for distillation. Also, up until very recently there had been much more operational experience with large distillation plants than RO plants.

Dual-purpose plants (for power production and desalination) can lead to distillation cost reductions of 20 to 30 percent compared to the overall cost of separate power and desalination plants. In these plants the exhaust steam from the power plant is reused to provide the energy for desalination, thus reducing fuel consumption. To minimize potential shutdowns of the desalination plant during power outages, dual plants should be provided with auxiliary standby equipment, and ample spare parts, and constructed in the form of independently operating, multiple units. Saudi Arabia has three large desalination complexes that use dual purpose plants *(77)*.[1]

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[1] Many of the low cost estimates for distillation made in the 1960s assumed that very large, dual purpose (i. e., power/water) nuclear plants (some using breeder reactors) would be constructed with low, long-term rates of financing. These assumption have proved to be quite optimistic by today's standards.

MUNICIPAL WASTEWATER TREATMENT

Over the last two decades the reuse of treated water from sewage treatment plants has increased significantly, especially in water-limited areas of the United States. In addition to using RO to demineralize wastewater, the effluent from the secondary treatment process has to be subjected to several other treatment processes to remove suspended material and dissolved contaminants, and to kill pathogenic microorganisms prior to reusing the treated water for potable purposes. The total cost of RO and other required conventional treatment processes probably falls between the costs of desalinating brackish and seawater—in the range of $2 to $4 per 1,000 gallons depending on the size of the treatment plant. For example, Denver's l-mgd test plant for treating wastewater from its sewage treatment plant costs about $2.50 per 1,000 gallons to operate. Treating the effluent from secondary treatment plants for non-potable uses (e. g., agricultural and landscape irrigation) tends to be much less costly.

HIDDEN COSTS ASSOCIATED WITH USING SALTY WATER

In any evaluation of desalination costs it is important to consider the "hidden" costs associated with using water with a high salt or mineral content. For example, it is estimated that every ppm of salt in Colorado River water at the Imperial Dam causes about $39,000 of agricultural damage (i. e., in terms of decreased yield) in the lower Colorado Basin. About 85 percent of this damage occurs in the Imperial Valley of Southern California. Collective damage to industrial and municipal users is estimated to be about $280,000/ppm (80).

Using highly mineralized and/or salty water can also generate substantial costs to homeowners for corrosion or scaling of pipes and plumbing fixtures, for softening water, and for buying bottled drinking water. For example, surveys in the 1960s of communities using highly mineralized water indicated that household costs (excluding bottled water costs) were increased by about $135 to $430 per year (5,29,54).

Chapter 5

Environmental Considerations

The primary or direct impacts from desalination are typically associated with the disposal of the waste concentrates produced during desalination and the disposal of sludges from the pretreatment of incoming feed water. Both types of impacts are briefly described in the following paragraphs. It is important to remember that the construction and operation of a desalination facility can create many other secondary or indirect impacts that may be associated with transporting raw water to the plant, generating electric power, etc. Indirect impacts are not covered in this chapter, but should be considered in planning specific projects.

WASTE CONCENTRATES

All desalination processes produce a high-salinity waste concentrate that must be disposed of. The fraction of feedwater that becomes wastewater depends on the desalination process used (table 4), the plant design, the feedwater composition, and the type of concentrate treatment required prior to disposal. The amount of waste concentrate can be minimized by further desalinating the waste concentrate(s) produced from the first stages of desalination. The greater the percentage of feed water recovered, the smaller the amount of concentrate that must be disposed of, but the higher the concentration of salt and other dissolved chemicals in the concentrate. The moderately elevated temperature of waste concentrates may also cause potential ecological changes in the immediate vicinity of concentrate discharges in marine environments. The composition of the waste concentrates generally makes them unsuited for most subsequent industrial, municipal, or agricultural uses.

Waste concentrates from brackish water reverse osmosis (RO) and electrodialysis (ED) plants have been disposed of in a number of ways including: pumping into lined evaporation ponds, injection into underground rock formations, spreading on unusable arid land, or discharging through a pipeline into sewers, rivers, or the ocean. The waste concentrate from seawater RO and distillation plants would probably be discharged into adjacent marine environments. All disposal options require site specific evaluations of costs and potential environmental impacts. To date the problems associated with the disposal of waste concentrates have generally not been significant enough to override a decision to build a desalination plant. However, with increasingly stringent environmental and regulatory programs, the disposal of wrote concentrates could become a primary consideration in siting future plants. Disposal costs could conceivably make some proposed desalination operations uneconomical.

When evaluating several alternatives for increasing supplies of freshwater, it is important to evaluate the potential environmental problems associated with the development of conventional sources of freshwater. For example, diversions from lakes and rivers may reduce natural flows and adversely impact the environment. This may cause interregion-

Table 4.-Waste Concentrate Generation[a]

Process	Percent recovery of feed water	Percent disposed as waste concentrate
Brackish water RO1	50 to 80	20 to 50
Seawater RO	20 to 40	60 to 80
ED	80 to 90	10 to 20
Distillation	25 to 65	5 to 75

[a] In determining the amount of waste concentrate requiring disposal, the percentage of salt rejected during desalination must also be considered. If the salt rejection rate after one pass through the system Is too low, the product water from the first pass may have to be treated again. Sequential processing could Increase the amount of concentrate requiring disposal as well as the overall cost of the desalination operation.

SOURCE: Office of Technology Assessment, 19s7.

al political controversy that effectively limits opportunities to develop additional freshwater supplies for growing metropolitan areas, particularly in the arid and semi-arid West.

Land Disposal

Concentrate disposal can be a very significant problem in inland areas where the disposal options are generally limited to evaporation ponds (lined with an impervious material to prevent seepage), or to deep injection wells. Disposal costs may range from 5 to 33 percent of the total cost of desalination depending on the characteristics of the waste concentrate, the level to which the concentrate must be treated prior to disposal, the means of disposal, and the nature of the disposal environment (64). With any type of land disposal there are risks of groundwater contamination.

Deep well injection of waste concentrates into subsurface strata several thousand feet deep is often used in inland areas. Costs for deep well injection can range from $0.10 to $1.15 per 1,000 gallons (6,37) of desalinated water (in 1985 dollars). These costs are usually cheaper than disposal in properly constructed, lined evaporation ponds (6,64). Concentrate injection wells are currently classified by the Environmental Protection Agency (EPA) as Class V wells (i.e., wells for non-hazardous wastes that do not fall in any of the other four classes of wells), for which there are no Federal restrictions on well location or concentrate concentration. However, most States that regulate Class V wells require a hydrogeological study to prevent contamination of freshwater aquifers.

Concentrate disposal ponds are used typically in climates where evaporation rates are high relative to precipitation, and land costs are low. In Texas, costs for evaporation ponds range from about $0.05 to $0.25 per 1,000 gallon of desalinated water produced (37). In some cases, it maybe advantageous to treat or to further concentrate waste concentrates prior to disposal. Concentrating the waste streams from several percent total dissolved solids to a solid using solar evaporation costs $1.15 to $1.85 per 1,000 gallons of desalinated water (6). If desalination techniques (e. g., VC) are used to further concentrate the waste concentrate, processing costs can be as high as $4 to $5 per 1,000 gallons. Evaporation ponds must comply with Federal and State waste disposal laws. Since concentrate ponds and solid salt deposits are both potential sources of long-term pollution, some contaminants in the waste concentrates may preclude the use of evaporation ponds in some areas.

Some experimental work with waste concentrates suggests that in the future it may be economical to extract minerals from the waste concentrates or to generate electricity in specially constructed concentrate ponds. The technical and economic feasibility of generating electricity in concentrate ponds is being explored by the State of California in conjunction with the Westlands Water District's selenium removal project in the San Joaquin Valley. (See section on desalting irrigation drainage water in ch. 3 on uses.) In another 3-year, $500,000 pilot project located near El Paso, TX, a solar salt gradient pond has been constructed to generate electricity for a 5,000-gpd MSF distillation unit for freshwater production. Project funding has been provided primarily by the Bureau of Reclamation, with added support from the Texas Energy and Natural Resources Advisory Council, and the El Paso Electric Co. (88).

Marine Disposal

Concentrate disposal is generally a less significant problem in coastal, marine environments due largely to the high levels of concentrate dilution that typically occur. However, with seawater RO and distillation, some organisms may be adversely impacted by the increased salinity of the wastewater and/or by higher concentrations of pretreatment chemicals or natural contaminants in the effluent. Moderately elevated temperatures of distillation effluents, which run about 10° to 15° F (i.e., 5° to 8° C) above feed water temperatures, mayor may not be a potential concern depending on the organisms near the point of concentrate discharge. Laboratory bioassays using marine organisms from the proposed discharge area can be used to indicate the potential toxicity of desalination effluents (13,43).

In well-mixed, open marine environments, noticeable impacts are typically restricted to within several hundred feet of the discharge. Environments that are semi-enclosed, or inhabited by sensitive or high-value organisms should be avoided if possible. In many cases potential impacts can be mitigated by using a diffuser at the end of the discharge pipeline to increase mixing of the waste concentrate with surrounding marine waters. Regardless of the potential impacts, direct discharges of waste concentrates into estuaries or the ocean would probably require a National Pollutant Discharge Elimination System (NPDES) under the Clean Water Act and State permits as well. For example, most coastal States require permits for any development in their coastal zones.

Other Disposal Options

In some cases, the waste streams from small desalination plants may be disposed of in adjacent rivers if such disposal practices have insignificant impacts. Such discharges would probably require a NPDES and State permits. Under current regulations, it is unlikely that a permit would be required for waste concentrate disposal in sewers, unless the salt concentrations were high enough to adversely affect either the sewage treatment process or the environment where the treated sewage water was discharged.

PRETREATMENT SLUDGES

Desalination plants that draw their feed water from untreated surface supplies usually have to pretreat the incoming water to remove suspended particulate, colloidal material, and some dissolved minerals. Generally, pretreatment techniques used prior to desalination are the same as those used to treat municipal drinking water supplies. In other words, the pretreatment sludges generated from desalination operations are usually quite similar to the sludges produced by municipal drinking water plants.

The sludges from pretreatment operations may contain chemicals that are classified as hazardous by EPA. Coal-fired boilers used for distillation may also produce fly and bottom ash that might be considered hazardous. Depending on the composition of any wastes, desalination plants may be subject to licensing, monitoring, and reporting requirements under the Resource Conservation and Recovery Act,

Chapter 6

Desalination Industry

DEVELOPING INTERNATIONAL MARKETS UP TO 1980

The very limited desalination market of the 1950s was dominated by European manufacturers, who controlled about 70 to 80 percent of the market. The desalination industry in the United States began developing in the mid-1950s in concert with the federally funded desalination R&D program. By the mid-1960s U.S. manufacturers had built about 45 percent of the distillation plants then operating; the Europeans had about 50 percent of the market (86). With the ongoing desalination R&D program supported by the U.S. Government, the U.S. industry was generally considered to be at the forefront of desalination technology throughout the 1960s and into the 1970s.

U.S. Government funding for desalination R&D peaked in 1967 at over $100 million (in 1985 dollars), and steadily decreased about 40 percent over the next 6 years until 1973 when program funding was all but eliminated. The American desalination industry was adversely impacted by this sudden withdrawal of Federal support. Furthermore, American overseas sales during the early 1970s began to suffer from intense competition from many aggressive, service-conscious Japanese and European companies, some of which were and still are indirectly supported by their respective central governments. The U.S. Government desalination R&D program was partially revived in the late 1970s, and funded at a relatively low level (i.e., $10 million to $15 million per year) until the early 1980s when funding for desalination and other water resources research was largely eliminated.

CURRENT INTERNATIONAL MARKETS

Desalination plant sales worldwide continued to increase throughout the 1960s and 1970s, and peaked at an annual high of just over 460 million gallons per day (mgd) of plant capacity in 1980. From 1981 through 1985 plant sales averaged about 180 mgd (86). This moderating trend primarily reflects the declining sale of large distillation and reverse osmosis (RO) plants (i.e., greater than 3 mgd) in the Middle East and Libya in response to falling oil revenues. Also, the working environment for plant suppliers in some Middle Eastern countries has become less attractive over the last few years with the advent of increasingly stringent contractor performance requirements, delayed contract payments, and other bureaucratic irritations (88), Future markets will probably be stabilized by the need to replace aging plants. Rising tensions in the Middle East may also have a potentially large impact on plant construction.

Almost 60 percent of all desalination capacity[1] is now located in the Arabic peninsula. Saudi Arabia accounts for about 30 percent of the world's capacity followed by Kuwait with just over 11 percent, and the United Arab Emirates with about 11 percent. The United States has almost 10 percent of the world's capacity. Although multi-stage flash (MSF) distillation accounts for about 65 percent of the world's desalination capacity (followed by RO at 23 percent), in terms of the number of plants, only 15 percent are MSF. (Of the remaining plants, 49 percent are RO, 16 percent ED, and 20 percent other.) In other words, most MSF plants are quite large (i. e., in excess of 1 mgd); RO plants tend to be of smaller capacity, but more numerous. Seawater is used to feed most MSF plants, whereas brackish water is used with most RO and electrodialysis (ED) plants. The median size of all desalination plants larger than 25,000 gallons per day is about 3.0 mgd (86).

Although MSF distillation plants have dominated the market since the early 1960s, RO plants are capturing an increasing share of the desalination market. For example, in 1986 about 48 percent of the ***contracted*** desalination capacity was for RO plants; about 35 percent was for MSF distillation.

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[1] Desalination plant inventories include all plants with capacities in excess of 26,000 gpd, or 100 cubic meters/day.

Multiple effect evaporation units and electrodialysis accounted for about 5 and 4 percent of the market, respectively. The largest percentage of the world's RO capacity—about 35 percent—is installed in the United States; Saudi Arabia has about 30 percent (86).

Over the last three decades over 166 different manufacturers have installed plants in 105 countries (33). In fact, the number of plant suppliers increased by 22 percent between 1984 and 1986 as the market shifted away from large MSF plants to smaller RO plants. Over the last decade the manufacture of desalination plants worldwide has been dominated by European, Japanese, and U.S. firms —each group accounting for about 30 percent of the plants in operation. Japaese and European plant manufacturers, who specialize in building larger distillation plants, have been most severely impacted by the declining desalination market in the Middle East since 1980.

Total domestic and overseas sales of desalination plants and equipment by U.S. industry from 1981 through 1985 were probably worth between $200 million and $250 million per year.[2] U.S. manufacturers supplied about 45 percent of the plant capacity in the very competitive, but considerably reduced, 1986 market (86).

CURRENT DOMESTIC MARKETS

Based on sales figures from 1981 to 1985, domestic sales of desalination plants and equipment by U.S. industry are probably worth about $35 million per year.[3] Even with an increased share of the world's desalination market in 1986, U.S. manufacturers have been hit hard by stiff competition and declining profits. Over the last 5 years the domestic desalination industry has experienced great change within an overall trend toward fewer, but generally larger companies. Some firms have been acquired by larger chemical corporations involved in water treatment and/or process separation. A few firms have been acquired by larger companies, and then later sold. Declining profits have forced other firms to file for bankruptcy, or to go out of business (88).

The U.S. desalination market continues to be dominated by sales of small, U.S.-manufactured RO, ED, and vapor compression (VC) units for commercial and military uses, and small to moderate-sized RO plants to coastal communities. However, there are concerns about potential international competition in the U.S. market, especially from the Japanese. There have been some efforts to expand the use of membranes in various industries; however, major investments are often required to develop such markets in industries where other technologies have been long used. Many representatives from the desalination industry believe that demonstration projects are needed to break such reliance on traditional water treatment technologies.

With worldwide sales of between $200 million and $250 million per year the desalination industry in the United States may spend from $5 million to $10 million per year on research and development,[4] compared to an average of $30 million

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[2] Annual sales of desalination plants worldwide over the last 5 years have been about 180 mgd in plant capacity per year. According to the 1987 plant inventory by the International Desalination Association, about three-fourths of these plants use seawater for feed; most of the remaining plants use brackish water. The capital cost for seawater plants is about $5 per installed gallon of capacity; $2 for brackish water:

- Seawater plants: 135 mgd/yr x $5/gal. = $675 million
- Brackish water plants: 45 mgd/yr x $2/gal. = $90 million

Worldwide desalination plant sales would then be about: $765 million/yr. U.S. sales (about 30 percent of worldwide sales) are about: $230 million/yr.

[3] Domestically the United States has about 10 percent of the world's desalination capacity. This means that about 18 mgd of desalination capacity is added to our inventory each year. Most of this is for brackish water RO. At $2/gal of installed capacity, this amounts to about $36 millon/yr in domestic plant sales. The remaining $194 million of the U.S. industry market would represent overseas sales.

[4] An informal survey of industry experts was taken to determine the level to which U.S. industry supports desalination research, applications, and engineering. These estimates ranged from $2 million to $20 million annually. The $5 to $10 million estimate used in the text above is based on the assumption that about 3 percent of worldwide sales of the U.S. industry (i. e., 3 percent of approximately $230 million) is invested in R&D. (This assumed percentage is the approximate percentage of sales invested by the FilmTec Corp. a few years ago when it was still a publicly owned stock company.) This produces an estimate of about $7 million per year for R&D expenditures. A

per year (in 1985 dollars) in R&D during the 30-year, federally funded desalination program. Due to the low or negative profit margins associated with the intensely competitive worldwide market, larger industry investments in R&D are unrealistic at this time. Much of the present research effort is probably applied research—rather than basic research—directed toward the development of specific products (e. g., chlorine-resistant membranes, low-pressure membranes, etc.), or improving plant efficiencies (e. g., energy recovery systems, etc.). Most ongoing R&D takes place within the framework of individual companies; there are no industry-coordinated research efforts being conducted at this time.

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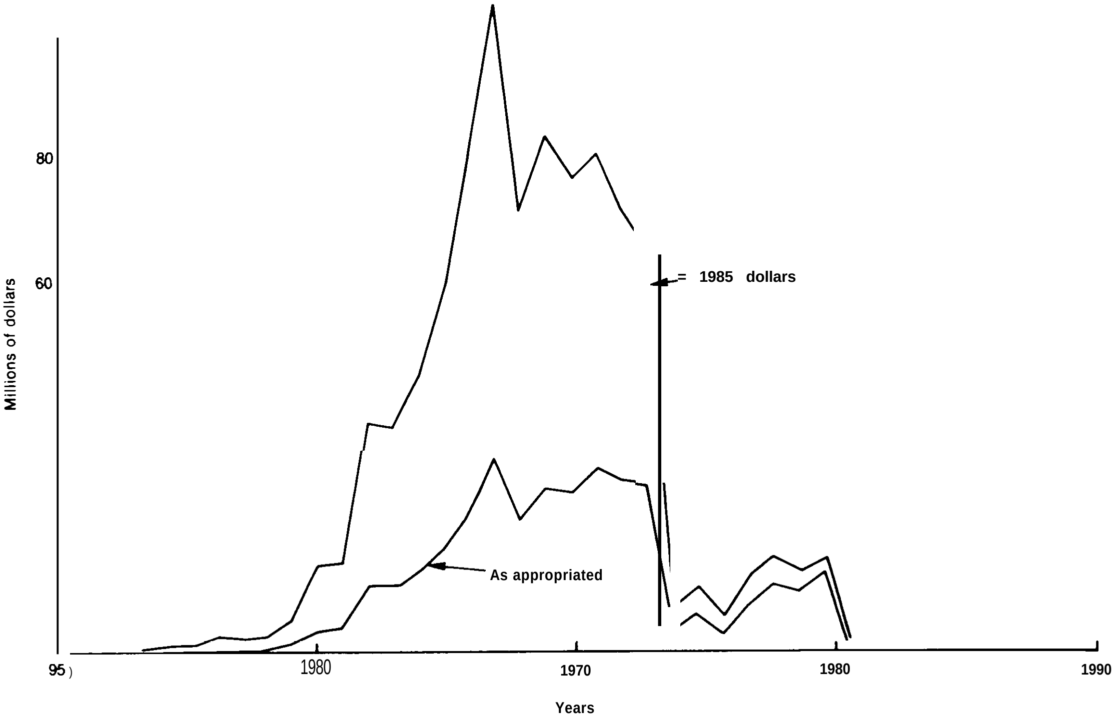
range of $5 million to $10 million per year is used in the text to indicate the level of uncertainty associated with this estimate. Unfortunately, the information required to verify this estimate is not readily available.

Chapter 7

Government Involvement in Desalination

Between 1952 and 1982 Federal funding for desalivation research, development, and demonstration averaged about $30 million per year (in 1985 dollars). Annual funding levels are provided in figure 11, and appendix B. This research program was primarily responsible for the development of reverse osmosis (RO), and for many advances and improvements in distillation technologies. Any future Federal funding for R&D could lead to further improvements in membrane technology and desalination plant operations. Innovative applications of these technologies to complex treatment problems could also be advanced by demonstrations.

Figure 11.—Yearly Federal Funding for Desalination R&D



SOURCE: U.S. General Accounting Office, "Deealting Water Probably Will Not Solve the Nation's Water Probleme, But Can Help," GAO/CED-79-80, May 1979.

PAST FEDERAL INVOLVEMENT

In accordance with the Saline Water Conversion Act (Public Law 82-448), research was initiated in the Department of Interior in 1952 to promote the development of economical processes for desalinating brackish water and seawater for municipal, industrial, agricultural, and other uses. Much of the interest in desalination came from arid and semiarid Western States who were becoming increasingly aware of their vulnerability to periodic droughts. Funding was set for multi-year periods with the intention of reducing Federal support when desalination technology became commercially available.

During the early 1950s Federal officials were optimistic that economic desalination technologies could be developed over a relatively short period of time to provide ample supplies of freshwater for the arid and semi-arid areas in the United States and for the rest of the world. In 1955 research funding was increased and a new Office of Saline Water (OSW) formed within the Department of Interior (DOI). During this same time period the proponents of nuclear power were advocating the use of nuclear power for desalination. In the 1960s and 1970s OSW built pilot-scale desalination plants and other test facilities at five sites: Freeport (TX), San Diego (CA), Roswell (NM), Webster (SD), and Wrightsville Beach (NC). In fact, the MSF plant built in San Diego was later moved to our navy base at Guantanamo Bay, Cuba, in the mid- 1960s where it operated for about 20 years (9).

Added impetus for desalination R&D was provided by the Water Resources Research Act of 1964, which provided funding not only for OSW, but also for more general water resources research through Interior's Office of Water Resources Research (OWRR). During the mid to late 1960s the OSW sponsored a great deal of basic and applied research into all desalination processes, with special emphasis on developing membranes and improving the efficiency of distillation processes. Federal support for the desalination program peaked in 1967 with a funding level of over $100 million (in 1985 dollars). The technology developed under this program was made freely available throughout the world through workshops and the wide distribution of published reports. Thus, by the late 1960s and early 1970s this R&D program had established the United States in a technological leadership role for desalination throughout the world.

The Federal Government's desalination efforts were reinforced in 1971 with reauthorization of the Saline Water Conversion Act (Public Law 92-60). Funding for research grants and contracts during the early 1970s was about $70 million per year. However, in 1974 the desalination research and testing program was cut to about $7 million resulting in significant reductions in ongoing research, development, and testing. This program cutback came in the wake of the 1973 oil embargo which significantly increased distillation costs and increased the need for energy research (9). In addition, the visions of cheap nuclear power were quickly fading and recent commercialization of RO seemed to reduce the need for Federal support. In 1974 the OSW and the OWRR were administratively integrated into the OffIce of Water Research and Technology (OWRT) (81).

The western drought of 1976-77 stimulated a renewed Federal interest in the application of science and technology to the water resources problems facing the nation and individual States. This increased interest led in turn to the passage of the the Water Research and Conversion Act of 1977 (Public Law 95-84) and the Water Research and Development Act of 1978 (Public Law 95-467). Desalination research in OWRT was expanded somewhat with a focus primarily on membrane improvement for RO and ED, and secondarily on further development of other basic desalination processes, such as freezing. In addition to providing renewed funding for basic desalination research, Public Law 95-467 authorized the construction of five small desalination plants in the United States to demonstrate desalination technology where there was a need to supplement existing drinking water supplies.

By 1980 Alamagordo (NM), Virginia Beach (VA), and Grand Isle (LA) had been selected out of a field of 37 as sites for federally supported demonstration plants. Under this program the Federal Government was to pay for the design and construction of the plants, as well as the first 3 years of their operation; State and/or local government agencies were responsible for providing on a cost-sharing basis (of 15 percent to 35 percent) the land, utilities, feed water for desalination, and waste concentrate disposal. After 3 years the plants were to be deeded to the local agencies as part of their water supply systems. Plant design studies were initiated, but funding for this part of the program was withdrawn in 1981.

The OWRT was restructured in 1981 and then abolished (along with most of its funding) by the Secretary of Interior in 1982. The remaining Saline Water Conversion Research and Development Program was transferred to the Bureau of Reclamation in the Department of the Interior, and management of the remaining test facilities at Wrightsville Beach, NC, and Roswell, NM, was turned over to the local governments in 1983. Since Federal funding for the three demonstration plants was also abolished at this time, there was not enough financial backing at State and local levels to continue plant construction. Consequently, none of the plants were ever completed. In 1985 all water resources research, including desalination research and development, was shifted to the U.S. Geological Survey (USGS) in DOI.

The Federal Government now supports some desalination research under Section 105 of the Water Resources Research Act of 1984 (Public Law 98-242) administered by the USGS. Federal funding for these projects amounts to a few hundred thousand dollars per year; an equivalent level of support is provided for each project by non-Federal organizations. Federal funding for all water research under Section 105 grants will decrease from $4.4 million in fiscal year 1987 to $1.8 million in fiscal year 1988 (88). Section 106 of the Act provides for projects to develop and demonstrate desalination technologies; however, no funds have been appropriated by the Federal Government for such activities in the last 3 years. The military also spends a few million dollars per year for basic R&D on particular field uses of desalination.

The Department of Energy (DOE) and the Commerce Department's National Bureau of Standards (NBS), have a joint program, called the NBS/DOE Energy Related Inventions Program, that supports the development of energy-saving inventions, which could include desalination technologies. NBS provides a detailed evaluation of proposals for possible funding by DOE's Inventions and Innovative Programs. About $2.5 million is available each year for grants supporting about 20 new inventions per year. Since 1975 about 400 inventions have been recommended for funding; 250 have received fimding. One desalination concept was recommended, but never funded.

Section 5 of the 1980 appropriations bill (Public Law 96-336) that provided funding for construction of the Yuma Desalting Plant (described in ch. 8) also provided authority to expend 5 percent of the authorized funding for evaluating and improving desalination technology. The test facility at the Yuma plant is partially used for further developing desalination technology, primarily RO, but not for basic research.

Title III of the Water Resources Development Act of 1986 (Public Law 99-662) provides funding for research into problems related to the drawdown of the Ogallala Aquifer beneath the High Plains States east of the Rocky Mountains. Section 304 of Title III could be used to fund some desalination-related research. Up to $13 million has been authorized for all Title III research, including $2.2 million for Section 304, but no funds have yet been appropriated. Such research would be directed by the USGS.

FEDERAL LAWS INDIRECTLY RELATED TO DESALINATION

During the 1960s there was growing evidence that many aquatic environments were becoming polluted as a result of population increases, and industrial growth and development. In light of this situation Congress passed numerous bills in the 1970s regulating the disposal of certain types of waste and protecting different disposal environments. The Safe Drinking Water and Clean Water Acts are most directly related to desalination.

Through the Safe Drinking Water Act (SDWA) of 1974 the Environmental Protection Agency (EPA) and/or States have the authority to regulate the quality of public drinking water supplies, including those that rely on desalinating brackish groundwater. Private systems, most of which get their water from underground sources, are not regulated under the SDWA. Although the States retain the primary control over the use of groundwater, EPA grants are now available for partially funding State programs that protect sole source aquifers and wellhead areas supplying public water systems. EPA's enforcement powers to regulate underground injection wells have also been strengthened and streamlined.

In 1986 the SDWA was amended to increase the level to which EPA and States will be regulating public drinking water supplies. Current EPA guidelines recommend that drinking water supplies have less than: 500 ppm of total dissolved solids, 250 ppm for both chloride and sulfate ions, and 100 ppm calcium carbonate for hardness. Since these guidelines are not enforceable, these levels can legally be exceeded. However, over the next 3 years EPA will be developing standards for over 80 other contaminants. For those water quality parameters that can not be easily measured by utilities, EPA can specify treatment techniques, rather than a numerical standard. Considering these increasingly stringent water quality standards, it is quite likely that the use of various desalination technologies for centralized water treatment and for point-of-use/point-of-entry treatment will probably increase in the coming years.

Desalination demonstration projects could be considered for funding under the SDWA. Under Section 1444 EPA can make grants for State-approved projects that will: 1) demonstrate a new or improved method, approach, or technology, for providing a dependable safe supply of drinking water to the public; or 2) investigate the health implications associated with the treatment and reuse of wastewater for potable purposes. Grants are limited to two-thirds of the cost of construction and three-fourths of any other costs. Priority is given to projects where there is a known or potential health hazard. This section also makes Federal loan guarantees available to private lenders for upgrading small public water systems.

Under the Clean Water Act (1972) desalination plants that discharge wastewater into the Nation's surface waters are required to have a National Pollutant Discharge Elimination System, or so called NPDES, permit. Under NPDES, industrial and municipal dischargers are required to use the best available technology for cleaning up wastewater prior to its discharge into adjacent waterways. The regulation of industrial discharges may indirectly encourage the use of desalination technologies for removing dissolved solids in wastewater prior to its discharge or direct reuse. Also, desalination plants would probably need a NPDES permit to discharge their waste concentrate into waterways or marine environments.

STATE AND MUNICIPAL INVOLVEMENT

Whereas the Federal Government has traditionally been most active in developing large water resource projects and regulating water quality, States have traditionally retained control over the use of existing surface water and ground water supplies through State water laws and regulations. All States have agencies that typically evaluate the quality and quantity of their water resources and have developed plans for meeting the fhture needs of the State. Forty-eight States (and territories) have developed federally approved programs for regulating drinking water. Thirty-six States have developed federally approved programs for regulating industrial and municipal discharges into waterways under the NPDES program (52). States also have primary responsibility for protecting groundwater under the SDWA. Some States regulate underground injection wells that might be used for waste concentrate disposal.

In cases where water use involves several States, multi-State organizations are often formed. For example, the Salinity Control Forum was organized by the seven States in the Colorado River Basin (i.e., Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) to reduce the input of salt and other minerals to the Colorado River. 1 In addition to adopting numerical standards for total dissolved solids at three dam sites along the

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[1] The Colorado River, which has an average flow of about 14 million acre-ft per year, provides about 12.7 million acre-ft of water to about 2.5 million people living within its basin and to another 16 million people that live outside the basin in adjacent areas and States. The total amount of water used approximately equals its supply; however, the 55 million acre-ft of water in the river system's storage reservoirs delays by a few years any supply shortages from droughts (31).

From its point of origin in the Rocky Mountains, the Colorado River picks up about 10 million tons of salt as it moves through the 7 basin States toward the Gulf of California (30). Salt concentrations of about 50 ppm near the river's headwaters increase to about 800 to 900 ppm in the lower reaches of the river. About 38 percent of the salinity in the Colorado (at the Hoover Dam) is contributed by diffuse natural sources of salt, and another 37 percent comes from irrigation drainage water. The remaining salt is contributed by evaporation and riparian plant transpiration (13 percent), natural point sources of salt (10 percent), exports of freshwater out of the basin (3 percent), and discharges from municipal and industrial discharges (1 percent).

Agriculture in the United States and Mexico is the major user of the Colorado's water. Irrigation development in the Colorado Basin began gradually in the late 1800s, but increased significantly during the early 1900s as major federally financed reservoirs were completed. There are now about 4 million acres of agricultural land that are irrigated by Colorado River water.

river,[2] the basin States have placed effluent limitations on industrial and municipal effluents (under NPDES), encouraged salinity control measures for area-wide planning, and developed plans for reducing salt and mineral inputs to the Colorado River.

Agencies operated by muncipal governments are beginning to take a more active role in desalination as the importance of reverse osmosis and electrodialysis for treating drinking water increases. Municipal development of new sources of drinking water, especially for smaller communities, is often supported directly or indirectly by State agencies.

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[2] In response to an EPA regulatory requirement, water quality standards for total dissolved solids were established by the Forum and later adopted by the basin States for three major diversion points in the lower Colorado River: 723 ppm below Hoover Dam, 747 ppm below Parker Dam, and 879 ppm at Imperial Dam.

Chapter 8

International Involvement With Desalination

INTERNATIONAL APPLICATIONS

Most freshwater supplies throughout the world have been developed using conventional means, such as direct diversions, dams, or reservoirs for surface water, and wells for groundwater. Treatment of this water varies from none at all to the removal of suspended material and/or dissolved minerals causing hardness, and disinfection. Overall costs for water are generally less than $0.95 per 1,000 gallons. In the vast majority of cases, water from conventional sources, if it is available, will cost less than water produced by desalination (77).[1]

The development of distillation, reverse osmosis (RO), and electrodialysis (ED) over the last 30 years have made desalination a reliable and widely accepted technology throughout the world where conventional sources of water are limited. There are now about 3,500 plants in 165 countries worldwide with a total capacity of about 3 billion gallons per day (gpd) (33). This capacity could increase in the future with the development of extensive reserves of brackish groundwater found in northern and western Africa, Australia, Canada, southern and western Europe, Mexico, the Middle East, and South America (11,36).

Unfortunately, neither desalination nor any other non-conventional technology will provide inexhaustible and inexpensive supplies of freshwater. They all require sizable capital investments, trained support staff, continued long-term maintenance, and low-cost energy. For these reasons desalination is most viable in middle- to high-income countries. Costs of desalinated water are still beyond the reach of most rural communities in poorer countries. Even with projected decreases in the cost of reverse osmosis, this situation will probably not change substantially in the foreseeable future (77).

Additional technical information and a process for selecting desalination plants, especially for overseas locations, can be found in the Desalting ***Handbook for Planners*** (11), and the ***USAID Desalination Manual (8).***

Middle East

Because of limited freshwater supplies and the availability of oil revenues, the Middle Eastern countries of Saudi Arabia, Kuwait, the United Arab Emirates, Qatar, and Bahrain have the world's greatest collective experience with desalination. For example, Saudi Arabia has a desalination capacity of about 900 million gallons pm day (mgd) (86); its capital of Riyadh alone uses about 270 mgd, or about 10 percent of the world's desalinated water (20).[2] Seawater distillation has been used to meet most drinking water requirements ever since the 1950s; however, over the last decade RO has been used increasingly for treating water from brackish aquifers and seawater wells.

In Middle Eastern countries desalinated water is used primarily for domestic, and industrial purposes. In a few countries (e. g., Saudi Arabia, Israel) it may be used for agricultural purposes. Although it may be more economical to import the crops that are irrigated with desalinated water, such operations are often undertaken for reasons of self-sufficiency and national security. In most cases desalination is heavily or entirely supported by the central governments. The market for desalination in the Middle East is now relatively ‘‘soft’ due to falling oil prices and currently stable water demand,

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[1] Transporting freshwater in tankers from water-rich to water-poor regions of the world may also have some potential, especially during emergencies caused by unexpected droughts. For example, drinking water has been barged 60 miles from Puerto Rico to St. Thomas in the Virgin Islands for about $15 to $20 per 1,000 gal. At present, several water shipping schemes are operating and more are envisioned. In most of these cases, water from Europe is shipped to arid areas around the Mediterranean Sea or Persian Gulf (77). However, national strategies for self-sufficiency weigh heavily against reliance on long-distance transport of permanent water supplies.

[2] In Saudi Arabia about 73 percent of its 915 mgd capacity is provided by MSF distillation; RO accounts for 23 percent; and others, 4 percent (77). The Saudis have a unique network of water distribution pipes that extend from the Red Sea about 500 miles inland. Unlike the other Middle Eastern countries, the Saudis have in the past contracted for more MSF than RO units because of the experienced MSF work-force available within the country.

Arid Islands

There are many islands throughout the world that have limited freshwater supplies, but because of their natural beauty, mild climate, and strategic location have been developed for tourists and/or military bases. Over time these islands have become more and more dependent on desalination of seawater and brackish groundwater, if it is available. For example, the Virgin Islands, Bahamas, Marshalls, Netherlands Antilles, Antiqua, Ascension, Bermuda, Cayman, Canary Islands, Malta, and Cebu (in the Philippines) depend on desalination to produce some or all of their municipal water supplies. Curacao (Netherland Antilles) has been using desalination since 1928. Both the Netherlands Antilles and the Virgin Islands produce more desalinated water than such countries as Great Britain, Mexico, Australia, Israel, and Germany.

The water produced on these islands is usually used within city limits where there are adequate supplies of fuel or electricity and a water distribution system. In many urban and rural areas on islands throughout the world (e.g., Marshall Islands, Bermuda) roof catchment systems are still used to collect and store freshwater.

Other Arid Countries

In countries where desalination is affordable, but not yet in widespread use, it is usually more practical, from an economic and security standpoint, to build and maintain small decentralized RO or ED plants supplied by brackish groundwater, than to distill the water at a large centralized facility and pipe it to outlying areas. For example, resorts along the Mediterranean and the Caribbean Seas typically use small seawater RO plants. A number of small rural communities in Mexico also use brackish water RO to satisfy most of their drinking water needs. The modular construction of RO and ED plants also allows for incremental expansion of capacity as the demand increases. Vapor compression (VC) distillation plants can also be cost-effective.

In some arid countries desalination capacity has expanded considerably over the last decade. For example, between 1957 and 1979 Mexico built 35 plants with a combined capacity of 1.1 mgd. Through the combined efforts of the government, industry, and tourist resorts, Mexico now has 79 operating desalination plants. Since 1980, industry has built most of the plants and is presently the largest producer of desalted water in Mexico.

In very remote areas small solar stills (described in app. A) may be an appropriate alternative (77).[3] For example, solar stills had been used for short periods of time in Australia, Greece, and Mexico up until 1980, but were phased out of use when other sources of freshwater were developed.

Industrialized Countries

Other than the United States which has almost 10 percent of the world's desalination capacity, there are very few industrialized countries using desalination to any large degree. This is probably because the majority of the industrialized countries are located in temperate zones where there are adequate supplies of freshwater. As in the United States, desalination technologies are used in most industrialized countries primarily for industrial purposes, and secondarily for drinking water.

Since drinking water and wastewater discharge standards are often changed overseas as laws in the United States are amended and/or standards developed, the use of desalination technologies may increase in many industrialized countries.

Lower Tier Developing Countries

In most developing countries water for domestic, industrial, and agricultural uses comes from surface and groundwater supplies. Water treatment, if there is any, generally involves conventional treatment (e. g., sedimentation, fdtration, and disinfection) of surface water supplies. The level of water treatment is typically much lower than it is in industrialized countries. Drinking water is often delivered through leaky pipelines to standpipes that serve several hundred people in a neighborhood. In many developing countries the demands for drinking water exceed existing supplies, especially in cities with rapidly growing popula-

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[3] **More information on solar stills can be found in the** *Manual on Solar Distillation of Saline Water (83)* **and U.S. Agency for International Development's** *Fresh Water from the* **Sun (18).**

tions. As of 1983, 52 percent of the population in developing countries had water supplies that were considered adequate in terms of quantity and quality (i. e., disinfection); 29 percent had adequate sanitation facilities. As expected, water supply improvements generally occur first in urban areas (78).

Unfortunately, the technology of industrialized nations can not be easily transferred to many developing countries. Necessary construction materials are often lacking; the electricity required to operate water treatment facilities may be in short supply; and the infrastructure required for municipal water treatment (e. g., knowledgeable administrators, trained workers, ready availability of supplies and equipment, etc.) often does not exist. These inadequacies are compounded by the fact that once the water is used there is often no systematic and sanitary method for collecting and/or disposing of waste water. In fact, indoor plumbing is more often the exception rather than the rule; the nearest field, gutter, or water body may be the only available disposal option.

Small scale, portable RO units are routinely used by the military in remote areas of the world to provide potable water. These same units could be used in urban and peri-urban areas of developing countries to supplement existing supplies of potable water by desalinating and treating seawater, polluted surface water, or brackish groundwater. However, to do this would require dependable energy supplies, trained personnel to operate the units, and a logistical system to supply spare parts for the life of the project. Also, the water from these units costs in excess of $10 per 1,000 gallons.

For these reasons, desalination is usually either too expensive or too impractical for general use in most developing countries. In fact, desalination costs in developing countries will generally be at least twice as much as they are in the United States. In addition to technical and economic constraints associated with desalination, there can be sociological problems when relatively sophisticated technologies are introduced into villages where age-old traditions have prevailed (77).

U.S. GOVERNMENT INVOLVEMENT IN INTERNATIONAL ACTIVITIES

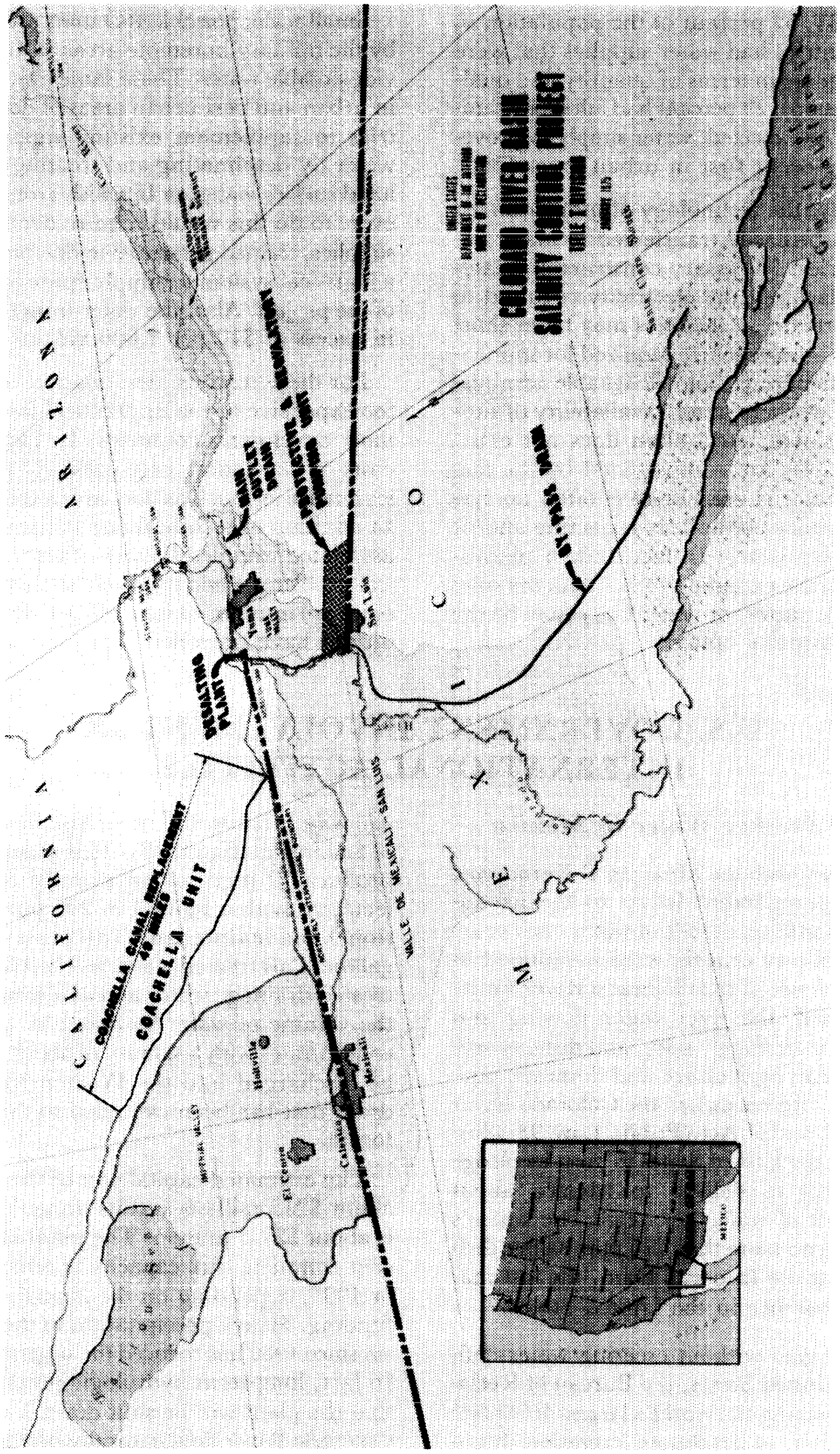
Supplying Fresher Water to Mexico

In a 1944 treaty with the Mexican Government, the United States agreed to deliver to Mexico approximately 1.5 million acre-ft of water each year. However, no salinity criteria were mentioned in the treaty. As the use of the Colorado River for irrigation increased, the river water flowing into Mexico became increasingly salty, and decreasingly useful for Mexican agriculture and domestic purposes. In 1974 Congress passed the Colorado River Basin Salinity Control Act (Public Law 93-320). This act allowed the United States to meet its pledge (in Minute 242) to deliver to Mexico about 1,360,000 acre-ft of water per year. The water's salinity would be no more than 115 ppm saltier than water arriving at the Imperial Dam, the last major diversion structure in the United States.

To meet this goal without creating water deficiencies in the United States, the Bureau of Reclamation is constructing the world's largest RO plant at Yuma, Arizona, to desalinate irrigation drainage water that would otherwise flow into the Gulf of California (figure 12). This plant is designed to produce 72 mgd, or an average of 67,000 acre-feet/year with a salinity of 295 ppm at an operational and maintenance cost of about $1 per 1,000 gallon. This treated water will be blended with untreated drainage water and as a result will increase the volume of water by about 10 percent. Waste concentrates with a salinity of about 9,800 ppm will be discharged into the Wellton-Mohawk bypass drain that has been extended to the Gulf of California.

The estimated capital cost of the Yuma plant is about $215 million and its annual operating cost is about $27.5 million. The plant is about 80 percent complete; full capacity is scheduled for 1992 or 1993, depending on the availability of Federal funding. Heavy precipitation in the Colorado Basin since 1980 has reduced the urgency for the plant. In fact, long-term hydrologic predictions indicate that the plant will be shut down 1 year in 4 when Colorado River flow naturally provides ample sup-

Figure 12.—Colorado River Basin Salinity Control Project



SOURCE: U.S. Department of the Interior.

plies of freshwater to Mexico after United States water uses are met. However, a 1 -mgd test facility at the plant will be operated on a full-time basis to evaluate the performance of new membranes and pretreatment techniques (75,76).

Other measures are also being undertaken to meet water quality standards established for diversions in the United States, to reduce the salinity of Colorado River water entering Mexico, and to improve irrigation efficiency. First, 49 miles of the Coachella (drainage) Canal in the Imperial Valley of California has been lined to reduce the seepage and loss of water. Second, the Wellton-Mohawk bypass that formerly carried irrigation drainage water into the lower Colorado upstream of the Morelos Dam has been extended through Mexico almost to the Gulf of California. Third, 21 wells were developed in southern Arizona to supply an additional 160,000 acre-feet of water per year to meet our obligation to Mexico. Another 10 wells may be added in the future. Finally, the Soil Conservation Service, with Bureau of Reclamation funding and oversight, implemented a program to reduce the generation of drainage water by increasing the efficiency of on-farm irrigation.

There are other rivers in the world's arid zones that present problems in international relations similar to those created by the development of the Colorado River. Eventually, desalination may play a greater role in resolving similar issues of water use elsewhere in the world.

Cooperative Technical Programs

In 1965 the United States and Israel jointly initiated a feasibility study for a dual-purpose nuclear plant located on the Mediterranean Sea, including the construction of a prototype desalination plant. In 1975 the United States and Israel began jointly constructing a 5-mgd distillation plant near the city of Ashdod, south of Tel Aviv. The plant was to test the practicality of coupling desalination to power generation, either from conventional, nuclear, or geothermal sources. Experts from the Office of Water Research and Technology worked with the Israelis and represented U.S. interests through an agreement with the U.S. Agency for International Development (9). This U.S.-supported work has helped to position Israel in direct competition with U.S. desalination firms.

During the early- 1960s the United States was also involved in the development of desalination in Saudi Arabia. At the request of the Saudis, the Department of the Interior (DOI) evaluated the feasibility of constructing a 5-mgd dual-purpose desalting plant at Jeddah. Burns & Roe, Inc., began designing a 2.5-mgd plant in 1966; actual construction began in 1968. Although funding for plant construction was provided by Saudi Arabia, the United States was allowed to use data developed from plant operations to further the development of desalination technology (9).

During the mid- 1970s the United States was involved in several other activities with the Saudis. First, DOI provided technical expertise to the U.S. Army Corps of Engineers on the design of a distillation plant at the Saudi Naval Base near Jeddah. This plant was completed in 1976. **Second,** DOI also agreed to help the Saline Water Conversion Corp., Saudi Arabia, establish a Research, Development, and Training Institute capable of handling 750 students to be trained in desalination plant operation at the Al Jubail desalination complex. Construction of the Institute, which began in 1982, was completed in 1987. The Institute has laboratory facilities, a power plant, and desalting equipment. **Third,** projects were also initiated to develop the technology for building and operating single unit, multi-stage flash (MSF) distillation plants with capacities of up to 66 mgd. Presently there are three to four Bureau of Reclamation personnel working cooperatively in Saudi Arabia. Funding for all these projects has been provided by the Saudis (9).

From the mid-1950s through the early 1980s technical information from the federally supported desalination research and development program was freely transferred to other countries of the world through published technical papers and international conferences. Production licenses on patented desalination technologies were also given to other countries by the United States. Special programs for exchanging information on desalination and other water resource issues were established with several countries, including Mexico and Japan.

Chapter 9

Future Prospects for Desalination in the United States

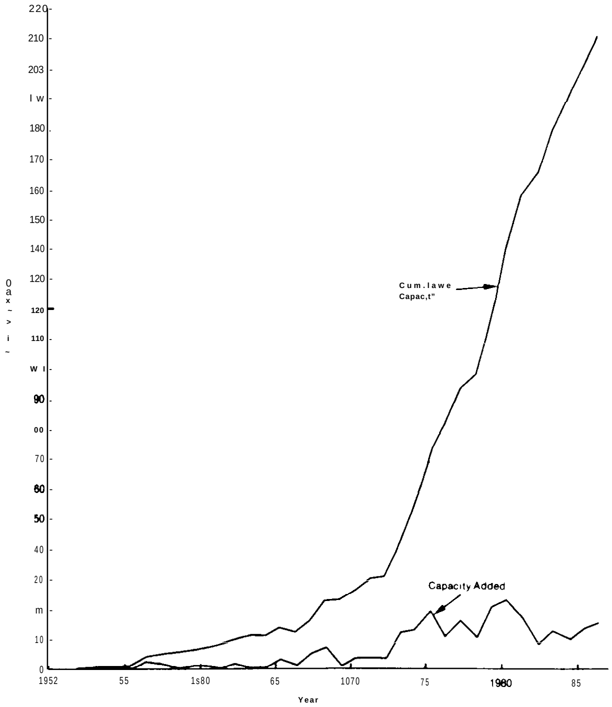
INCREASING USE OF DESALINATION TECHNOLOGIES

The use of desalination technologies for water treatment will probably continue to increase throughout the world. In the United States reverse osmosis (RO) will probably undergo the most expanded use, primarily for desalting brackish groundwater for potable purposes, and for treating municipal and industrial process water. How much desalination is used in the future will depend largely on the:

- decreasing viability of alternatives (other than desalination) for increasing freshwater supplies*;
- decreasing cost of membrane desalination processes;
- increasing demand for drinking water, especially in rapidly growing coastal and western communities;
- increasing need to treat and/or to remove potentially toxic contaminants from surface and ground water supplies;
- increasing stringency in regulatory programs covering drinking water, and wastewater discharges (i. e., the NPDES program);
- increased use of treated irrigation drainage water for drinking water in the West; and
- increased application of RO and other membrane processes to various industrial processes.

Trends associated with these factors indicate that the use of desalination technologies, and especially RO, will probably increase in the United States in the future (figure 13). Exactly how much this increase will be is unknown.

Figure 13.–Desalination Capacity in the U.S. and Territories Over the Last Two Decades



SOURCE: Office of Technology Assessment (data frOm K. Wangnick, "IDA Worldwide Plant Inventory," 19S7).

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[1] There are several alternatives that could be used to increase or extend existing supplies of freshwater, but most have significant limitations. Conservation, especially in agricultural irrigation, has the greatest potential for extending present supplies of freshwater (82). However, conservation only occurs on a sustained basis if there are regulatory and/or financial incentives (e. g., higher water cost), and if existing institutional mechanisms are changed to encourage water conservation. Most easily accessible aquifers have already been tapped and many major aquifers, especially those in arid regions, are being depleted faster than they are being recharged from surface supplies. Most favorable dam sites on U.S. rivers have already been used. In addition, there are many major financial and institutional obstacles to large-scale transfers of water from water rich parts of the country. Further research into other options for increasing or extending water supplies (e. g., weather modification, towing icebergs, etc.) will allow an improved evaluation of their potential (63).

NON-TECHNICAL BIAS AGAINST DESALINATION TECHNOLOGIES

An institutional bias favoring "tried and true" conventional water treatment techniques has probably restrained to some extent the use of desalination technologies in this country, especially in the area of municipal water treatment. For example, EPA typically will not include innovative or "unproven' technologies in designating "best available technologies. Conventional technologies are also preferred by consulting engineers who design treatment plants, by water utilities that build plants, and by state agencies with responsibility for public health. Even equipment manufacturers are reluctant to invest their capital in new technologies that may not sell simply because they are new (85). Finally, it may take engineering schools many years to integrate new water treatment technologies into teaching curicula and text books.

This institutional bias against new technologies tends to be most significant when the technologies are first introduced. This was probably the case for RO in the 1970s. Although some institutional bias against desalination technologies undoubtedly still exists, its significance has probably decreased. For example, according to the latest inventory of desalination plants (33), desalination technologies are now used in 46 States and on the Marshall and Virgin Islands; RO is used by municipalities and/or industries in 44 States and on the Virgin Islands. Since only 20 percent of the desalination plants (with capacities of greater than 25,000 gpd) in the United States are used to treat municipal drinking water supplies, the bias against new technologies may be more of a problem for municipal water treatment than for industrial applications,

POTENTIAL AVENUES FOR FEDERAL SUPPORT OF DESALINATION

The desalination industry in most parts of the world is still adjusting to the moderating demand for desalination capacity that has occurred over the last 5 years. The U.S. industry seems to be consolidating into fewer companies, within an extremely competitive market. The low profit margins associated with the manufacture and sale of desalination equipment do not provide much capital for research, development, and marketing of new technological developments. Also, while Federal research support for desalination R&D has faded during the 1980s, many overseas firms are apparently receiving support from their respective governments.

When informally and randomly polled, industry representatives and desalination experts held widely divergent opinions about the appropriate level of Federal involvement in desalination. However, considering that the industry is presently unable to sponsor significant amounts of R&D (see ch. 6), most industry representatives believe that the Federal Government should increase its direct support of desalination R&D and/or demonstration projects, Sharing of R&D costs with the industry is an option that might be explored. Federally supported R&D would not only benefit all municipal and industrial users of desalination technology in the United States, but it would also improve the competitiveness of United States desalination firms overseas.

Some industry representatives and desalination experts do not favor direct Federal support for desalination R&D and/or demonstration projects. If R&D is left to the private sector, the level of R&D and its focus will be controlled largely by the market demand for desalination technologies. In this situation, R&D costs are indirectly paid for by domestic and foreign users of the technologies, particularly those who might be the first to apply new technological developments. Some industry representatives are particularly concerned that proprietary developments stemming from government-supported R&D would have to be widely shared.

Statistics can be developed to favor either position on Federal support. Opponents of increasing Federal support for desalination would point out that desalination now accounts for only 0.2 percent of **all** freshwater consumed in the United States for domestic, agricultural, and industrial uses. Supporters of increasing Federal involvement would point out that the amount of desalinated water produced in this country is equivalent to about 1.3 percent of the 15 billion gallons of fresh water that is consumptively used each day for domestic and industrial uses. This percentage is likely to grow over time. A research program funded at $30 million per year would add only about $0.0004 to the cost of each gallon of desalinated water used in the United States every year. But, this amounts to about $0.40 per 1,000 gallons, or about 20 percent of the approximate cost of $2 per 1,000 gallons for desalinated brackish water. However, the primary issue is probably not how much research should be conducted, but who should pay for it—the Federal Government or the users of desalination?

If the Federal Government were to become more actively involved in the development of desalination technologies, demonstration projects could be supported through Section 106 of the Water Resources Research Act, which has had no funding since passage of the Act in 1984. Alternatively, demonstration projects could be considered for funding under Section 1444 of the Safe Drinking Water Act (see ch. 7). Such demonstration projects of desalination technologies would further highlight their economic viability for water treatment.[2] If demonstration projects are sponsored by the Federal Government, it might be most appropriate to build plants in small communities that have poor quality drinking water and limited financial resources. Seminars and workshops, structured around these demonstration plants, could reduce any resistance to employing desalination technologies by engineers, Federal and State regulators, and local government officials.

The government might also support desalination through other avenues. For example, the 1 million gallons per day test facility at the Federal Government's Yuma plant, which will be operated full-time for membrane testing, could be used both for Bureau of Reclamation and private testing of membranes. Alternatively, the government and industry could jointly develop a small test facility where individual companies could test new desalination equipment and membranes without having to share any proprietary equipment designs. The government could also accelerate the application of newly developed desalination (and other water treatment) technologies through low-level, long-term support of university educational programs and workshops concerned with desalination and other innovative water treatment technologies.

At present Federal involvement with desalination is split among three Federal agencies. A small amount of desalination R&D is sponsored through the water-related research grants program of the U.S. Geological Survey, Department of Interior (DOI). Overseas activities and construction/operation of the Yuma RO plant are managed by the Bureau of Reclamation (DOI). The Office of Drinking Water at Environmental Protection Agency follows developments in RO and other desalination technologies as they relate to drinking water. However, no agency is responsible for tracking and periodically reporting on the overall development status and costs associated with all desalination technologies, or for disseminating current and reliable information about desalination technologies. For example, considering the growing concern about the quality of drinking water, information on point-of-use water treatment alternatives might be extremely useful to consumers, especially those living in rural locations where water quality is poor.

Some desalination experts, citing the increasing size of the Federal budget deficits, believe that the primary avenue for Federal involvement will come through the regulation of potentially toxic pollutants. In other words, the market for membrane processes will be indirectly driven by the continuing development of increasingly stringent standards for drinking water, industrial wastewater discharges, hazardous waste disposal, and perhaps irrigation drainage water discharges. If additional Federal support for desalination research, development,

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[2] There are three other possible sources of Federal funding for desalination-related projects:

1. The Federal Government now supports a few hundred thousand dollars worth of desalination research each year under Section 105 of the Water Resources Research Act (Public Law 98-242) administered by the U.S. Geological Survey.
2. Under Section 201 of the Clean Water Act EPA can support the construction of revenue-producing facilities that reclaim wastewater from sewage treatment plants. For example, the EPA contributed $7 million to support Denver's $30 million wastewater treatment test facility and research program.
3. The Department of Energy (DOE) and the Commerce Department's National Bureau of Standards (NBS), have a joint program, called the NBS/DOE Energy-Related Inventions Program. This program provides about $2.5 million in grants per year for the development of energy-saving inventions, which could include desalination technologies.

and/or demonstration was considered by Congress, it is likely that any proposed programs would have to compete with other national priorities. A drought in the West would tend to elevate the priorities associated with desalination and other water-related issues.

Appendix A
Desalination Technologies

Distillation

The evaporation of water molecules from a brine can be accelerated by heating the brine to its boiling point—100° C. at normal atmospheric pressure. Boiling occurs at lower temperatures if the vapor pressure over the brine is reduced. Since reducing the vapor pressure is less costly than adding heat to the brine, commercial distillation processes usually involve boiling the brine at successively lower vapor pressures without adding heat. Most volatile substances (e. g., many potentially toxic synthetic organics) and a very small amount of salt in the brine will also be carried along with the water vapor (91).

Condensation of the water vapor to "distilled" water occurs when the energy required for vaporization—the ' 'heat of vaporization'—is given up by the water vapor when it comes in contact with a cooler surface. To maximize the efficiency of the distillation process the heat given up during condensation is used to heat incoming feed water, or to reheat the remaining brine. This can be done by condensing water vapor on one side of a metal surface and simultaneously transferring the heat given up during condensation to the cooler brine (or feed water) on the other side of the metal surface.

Distillation plants typically have very high capital costs. With the exception of solar stills, plant designs are typically quite complicated. To withstand exposure to high temperatures, and corrosive brines and chemicals, high-cost metals, such as titanium and copper-nickel alloys, are typically used. Operating a distillation plant (except solar stills) and attendant pretreatment systems requires highly skilled workers, continuous monitoring of plant operating conditions, and maintenance every few months. Otherwise, major and very costly breakdowns can easily occur.

Four major processes used to distill water on a commercial or semi-commercial scale are discussed below.

Multiple-Effect (ME) Evaporation

In this process incoming feed water is heated and then passed through a series of evaporators, or "effects. In the first effect, water vapor is given off by the hot brine, which lowers the brine temperature. The brine is then transferred to the second effect, where it comes in contact with one side of a series of tubes. The water vapor produced in the first effect is also transferred to the second effect where it condenses on the other side of the tubes. The heat produced during condensation is transferred back to the brine, thereby boiling and further evaporating the brine in the second effect. The vapor pressure in each succeeding effect is lowered to permit boiling and further evaporation at successively lower temperatures in each effect.

ME desalination was the first seawater distillation process to be developed for large-scale applications (2). In fact, by 1900 simple 2- to 4-effect stills were available for commercial use (91). In 1958 a plant having five 6-effect units with a total capacity of 2.5 million gallons per day (mgd) was constructed. This was the largest plant of this type built. An average ME plant recovers a volume of freshwater that is between 40 percent to 65 percent of volume of salty feed water. The remaining concentrate is discharged as waste (77). ME units account for about 5 percent of the world's distillation capacity and have been used very successfully on many Caribbean islands (33).

Multi-Stage Flash (MSF) Distillation

In this process incoming feed water is first heated in a brine heater before it enters the first chamber, or stage. The brine boils violently and a small portion instantaneously "flashes" into water vapor. As the brine passes through successive stages operated at continually lower temperatures and vapor pressures, more and more of the brine flashes into steam. The water vapor produced is then condensed on the outside of tubes conveying incoming brine to the brine heater. The distilled water produced in each stage often passes through each succeeding stage and is allowed to "reflash'; this allows the transfer of additional heat to the incoming feed water.

A typical MSF plant may have 20 to 50 stages. On the one hand, many stages increase the overall efficiency of heat recovery in the plant and decrease its operating costs. On the other hand, more stages increase the capital cost of the plant. In most recently built MSF plants, 50 to 75 percent of the waste concentrate from the last stage is mixed with the incoming feed water to increase the heat recovery and decrease the amount of water needing pretreatment. Unfortunately, this also increases the corrosion and scaling (i. e., precipitation of inorganic minerals) in the plant due to the increased salt concentration in the circulating brine. An average MSF plant recovers a volume of fresh water that is between 25 percent to 50 percent of the volume of incoming feed water (77).

MSF distillation was developed in the late 1950s; the first commercial plant was built in 1957 in Kuwait (77).

In the early 1960s a MSF plant was built in San Diego (CA) and moved in the mid- 1960s to our navy base at Guantanamo Bay, Cuba, where it operated for about 20 years. Since the late 1960s MSF plants have dominated the commercial distillation market (91). Because of the significant economies of scale achieved by large-capacity plants, and the extensive design and operational experience gained over the last three decades, MSF plants, found in 55 countries, now account for almost two-thirds of the world's desalination capacity, or about 2 billion gpd. Individual units as large as 10 mgd are now being built. In fact, a MSF multi-plant complex with a total capacity of almost 300 mgd was completed in Saudi Arabia in the early 1980s (33,77).

Vapor Compression (VC)

In the two previous distillation processes reduced vapor pressure over the brine is used to enhance its vaporization. In VC units water vapor is collected and compressed. This compression causes the vapor to condense on one side of a tube wall. The heat given off during condensation is then transferred (through the tube walls) back to the feed water to enhance its evaporation. In this process the major energy input is provided by the compressor, which not only compresses the vapor, but also reduces the vapor pressure in the vaporization chamber. Energy may also be required to heat the incoming feed water during start-up (91).

During World War II the United States performed considerable work on VC for use on ships and at isolated bases around the world. VC units now account for about 2 percent of the world's capacity with unit sizes generally being less than 0.1 mgd. These units are typically diesel-powered and may be used on ships, offshore oil rigs, at remote construction sites, and at resort hotels in water-limited regions of the world (28,33,77).

Solar

Solar distillation units can have many configurations, but the most common one is referred to as a greenhouse still. In this unit saline feed water is supplied continuously or intermittently to a pool of water inside an airtight, glass enclosure, similar to a greenhouse. The black pool bottom absorbs the solar energy and heats the water. Water vapor rising from the brine condenses on the cooler inside surface of the glass. The droplets of water vapor then run down the glass into troughs along the lower edges of the glass which channel the distilled water to storage tanks. After about half of the feed water has evaporated the remaining waste concentrate must be discarded to minimize precipitation of salt.

Ever since the advent of commercially produced glass sheets in the second half of the 19th century, solar stills have been used in extremely remote, sunny areas of the world. One of the first successful commercial solar stills covering 4,500 sq. meters (48,000 sq. ft.), was built in Las Salinas, Chile, in 1872 and operated for 40 years (17). This still produced 6,000 gpd (18). Over the last two decades about 35 solar stills have been built in a dozen different countries throughout the world (41). Solar stills typically have ratios of capital cost to operating cost of four to one; for most other distillation units this ratio is two to three.

Although solar stills are relatively easy to build and operate, there are few, if any, economies-of-scale associated with larger plants (37). For example, the largest solar stills yet tested have produced only a few thousand gallons of water per day. A well-designed solar still can produce 2 to 4 liters (or quarts) of water per square meter of basin area. Overall costs for water produced by solar stills range from about $50 to $80 per 1,000 gallons (77). The Indian Institute of Technology in New Delhi, India has apparently developed a portable still that is about half the cost of similar units now on the market (88).

In the 1960s the Federal Office of Saline Water in the DOI extensively investigated various solar still designs, including glass-covered basins, inflatable plastic basins, tilted wicks and trays, and all-plastic double tubes (72). Although the program was terminated in 1970 when it was concluded that the high capital costs could not be reduced significantly, the program did produce design data that has been used in numerous solar stills built in various parts of the world since 1970 (77).

Solar energy has recently been used to heat water prior to distillation or to provide electricity from photovoltaic cells for other types of experimental and small-scale RO, ED, and distillation plants discussed in this chapter, However, these plants tend to be smaller, more expensive to operate, and must be equipped with auxiliary power sources to operate at night or during cloudy weather. Such systems appear to have potential only in remote, sunny areas of the world (21 ,77,88).[1]

Reverse Osmosis (RO) (42)

If waters with different salinities are separated by a semi-permeable membrane, "pure' water from the less salty brine will diffuse or move through the membrane until the salt concentrations on both sides of the membrane are equal. This process is called osmosis. With RO, salty feed 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.[2] "Pure' water will diffuse through the

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[1] The development of desalination units powered by other alternative energy sources (e. g., wind, ocean wave energy, salt ponds, etc.) is in it infancy (8).

[2] Normal atmospheric pressure is 14.7 lb/sq in,

membrane leaving behind a more salty waste concentrate (91).

About 10 gallons of water will pass through a square foot of membrane each day. The higher the operating pressure, the greater the flow of product water. The percentage of incoming feedwater that is recovered as product water after one pass through an RO module ranges from about 15 to 80 percent; however, this percentage can be increased if necessary by passing the waste water through sequential membrane elements (8). Brackish water RO plants typically recover 50 to 80 percent of the feed water, with 90 to 98 percent of the salt being rejected by the membrane. Recovery rates for salt water RO plants vary from 20 to 40 percent, with 90 to 98 percent salt rejection. The water is usually processed at ambient temperatures.

Membranes, which are usually made of cellulose acetate, aromatic polyamide, polyimide, polysulfones, or thin film composites, can last as long as 7 years depending on the composition of the membrane used and the quality of the feed water. Membranes used for seawater generally have to be replaced every 3 to 5 years. Membranes can be designed to remove particular inorganic and organic contaminants, such as trihalomethanes. Low pressure membranes have decreased the pressure requirements for some RO operations by up to 50 percent, The efficiency of RO operations will undoubtedly increase and costs decrease as membranes are improved. Such improvements may involve increased rejection of salt; increased membrane resistance to compaction, chlorine, and microorganisms; and large-scale production of standardized RO elements. RO is being used increasingly in the emerging area of nanofiltration of water.

Reverse osmosis can remove from brines not only dissolved solids, but also organic material, colloidal material, and some microorganisms. RO is typically used for brackish water with salt concentrations ranging from 100 to 10,000 ppm; however, membrane developments over the last decade have made it economically possible to use reverse osmosis for seawater (7,77). RO consumes only one-third to one-half of the energy required for MSF distillation (7,12,61). In addition to using RO for desalinating drinking water, it is also used extensively by industries and municipalities to treat feedwater (including water softening), and to treat wastewater prior to disposal or reuse.

Membranes are manufactured in three basic configurations: half-inch, hollow tubes; hollow, hair-like fibers; or several alternating layers of membranes and “spacer’ materials that are rolled into a spiral configuration, or stacked in a sandwich form. The latter two configurations are now the most commonly used for commercial applications (77). The membranes are sealed into tubular plastic, pressure vessels, called elements. The elements used for most plants measure 4 to 12 inches in diameter and 1 to 4 feet in length, and are assembled in parallel and in series in steel racks.

RO plants usually consist of a series of standard-sized modules each with a capacity of about 2,000 gpd (77). Plant design, construction, and operation are all relatively straightforward, especially for brackish groundwater. Pretreatment of the incoming feedwater is usually necessary, especially for seawater; otherwise, clogged membranes will require more frequent replacement, thereby significantly increasing the expense of the operation.

During the first few thousand hours of operation, the processing capacity of a RO plant may decrease by up to 25 percent due to membrane compression (i. e., densification) at higher pressures, and/or membrane deterioration. Another 20 percent of the capacity can be lost due to membrane fouling. Most of this latter capacity can be regenerated by periodically (e. g., every 1,000 hours of operation) flushing a hot cleaning solution through the filter elements (1).

The feasibility of RO was demonstrated in the laboratory in the mid-1950s and field tested in the mid-1960s at a seawater conversion plant near San Diego, CA. The first municipal brackish water RO plant built in Greenfield, IA, in 1971 had a capacity of 150,000 gpd (47). The development and demonstration of RO was heavily supported by the Federal desalination research program during this early period and throughout the 1970s. In fact, most desalination experts agree that without this Federal support RO would certainly not have been developed to its current level of sophistication.

There are now about 1,750 major RO plants in over 63 countries with a combined capacity of about 700 mgd.; just over 35 percent of this capacity is in the United States (86). In fact, Florida alone has about 70 reverse osmosis plants (larger than 25,000 gpd) that are supplementing existing supplies of drinking water. A “typical’ municipal RO plant has a capacity of between 0.2 and 0.6 mgd (77). Smaller RO units with capacities of 10,000 to 70,000 gpd are also now being manufactured for various commercial and military uses. Low-capacity under-the-sink units are being sold for point-of-use water treatment for the home.

Electrodialysis (ED)

ED is a process that uses a direct electrical current to remove salt, other inorganic constituents, and certain low molecular weight organics from brackish water with concentrations of dissolved solids up to 10,000 ppm. ED tends to be more economical than RO at salinities of less than 3,000 ppm, and less economical than RO at salinities greater than 5,000 ppm. Seawater ED is not yet commercially available (2,65).

With this technique several hundred flat, ion permeable membranes and water flow spacers are vertically assembled in a stack. Half of the membranes allow positively charged ions, or cations, to pass through them. The other half-anion-permeable membranes—allow negatively charged ions to pass through them. The an+ ion permeable membranes are alternately placed between the cation-permeable membranes. Each membrane is separated from the adjacent membrane in the stack by a polyethylene flow spacer. This assemblage of one cation membrane, a flow spacer, one anion membrane, and another flow spacer comprise the cell pair, which is the basic building block of an ED cell.

An electrical current (powered by an external d.c. electric power source) is established across the stack by electrodes positioned at both ends of the stack. Brackish water is pumped at low pressures (e. g., 50 to 70 lbs/sq. in.) into the 0.04-inch flow spacers between each membrane. The cations pass through the cation-permeable membranes and anions through the anion-permeable membranes, thereby concentrating between each alternate pair of membranes. Between each set of membrane pairs adjacent to the concentrating compartments, the brackish water is partially desalinated. ED will not remove uncharged molecules (55).

Partially desalted water is passed through additional ED stages until the desired desalination is achieved. Typical salt removal varies from 40 to 50 percent for a single stage plant (i.e., one pass through a single stack) and, 65 to 75 percent and 82 to 88 percent removal for 2- and 3-stage plants, respectively (65). The amount of electricity required for ED, and therefore its cost, increases with increasing salinitiy of the feed water. ED systems typically operate more efficiently at elevated temperatures of up to 110 degrees F (91).

Scaling or fouling of the membranes, the most common problem encountered with ED, is prevented in most ED units built since the mid- 1970s by operationally reversing the direction of the electrical current through the stacks at 15- to 30-minute intervals. This process is called electrodialysis reversal, or EDR, and is an automatic, self-cleaning electrodialysis process. Polarity reversal reverses the flow of ions through the membranes, so that the spaces collecting concentrated brine begin collecting less salty product water. Alternating valves in the water collection system automatically direct the flow in the appropriate direction depending on the direction of the current. Typical freshwater recovery rates for EDR now range from 80 percent to 90 percent of the feedwater volume (65).

ED plants are constructed and operated in much the same way as RO plants. Similarly, some pretreatment may be required; however, EDR typically requires much less pretreatment of incoming feed water than other desalination processes. If scaling and/or clogging of the membranes becomes a problem, effective chemical cleaning is achieved by circulating a solution through the membrane stacks. The membrane stacks may also be disassembled and the membranes cleaned by hand. Although this is time consuming, it avoids the frequent replacement of membranes. Under proper operating conditions ED membranes are guaranteed for up to 5 years, but may have an effective life of 10 years or more (55,77,91).

Extensive laboratory work on ED occurred in the 1930s and 1940s. It was commercialized for desalting brackish water supplies in the 1950s using sheet membranes made from ion-exchange resins. At this time ED has significant economic advantages over distillation for desalinating brackish water. ED was first used in the United States in 1958 to supply freshwater to Coalinga, California. Four years later a 650,000 gpd plant was constructed in Buckeye, Arizona. Several hundred ED plants with a combined capacity of about 140 mgd (86) are now operating in over two dozen countries where they are used primarily for industrial purposes and for municipal drinking water. A typical ED plant can range in size from 0.05 to 0.5 mgd. The largest installation is an 8 mgd plant in Iraq (55,65,77,91).

One American company (Ionics, Inc.) continues to dominate the market for ED units throughout the world. However, several Japanese firms have been involved in further developing the ED process. The U. S. S. R., China, and India have also been experimenting with the ED process and various unit designs (77).

Ion Exchange

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 to remove calcium and magnesium ions in “hard' water. However, special resins are available for adsorbing organics. A 1981 survey of public water supply systems by the American Water Works Association found almost 50 systems that use IX for water softening. Many homeowners also have IX units for softening water prior to use. For industries requiring extremely pure water, ion exchange resins are often used after RO or ED to “polish” the water by removing specific ions from water and wastewater.

Treating water with ion exchange resins is relatively simple to do. The primary cost is associated with periodically regenerating or replacing the IX resins. The higher the concentration of dissolved solids in the feed water, the more often the resins will need to be replaced or regenerated with other chemicals (e. g., strong acids, bases, or high concentration chemical solutions). Also, any organics in the water may foul some resins, thereby reducing their exchange capacity. Reliable cost estimates for different IX processes are not widely published, but appear to be very ion- and process-dependent (55). In general, IX becomes competitive with RO and ED only in treating relatively dilute solutions containing a few hundred ppm of dissolved solids. IX is rarely used for salt removal on a large-scale (e. g., for municipal water treatment).

The only municipal water treatment plant in this country using IX for treatment other than water softening was built in Burgettstown, Pennsylvania, in 1972. In this case, the 500,000-gpd plant processes drinking water supplies that have been contaminated by acid mine drainage (91). IX units can also be used where small amounts of freshwater are needed, such as on spacecraft.

Freeze Desalination

When salty water freezes, the ice crystallizes from pure water leaving the dissolved organic and inorganic solids (e.g., salt) in liquid pockets of high salinity brine. Traditional freezing processes involve five steps: precooking of the feed water, crystallization of ice into a slush, separation of ice from the brine, washing the ice, and melting the ice. Although freshwater can be obtained quite easily from ice where seawater freezes naturally, the engineering involved in constructing and operating a freeze desalination plant is quite complicated.

Freeze desalination has the potential to concentrate a wider variety of wastes streams to higher concentrations with less energy than any of the distillation process discussed above (55). In fact, the energy requirements for freezing and reverse osmosis are comparable. Pretreatment of incoming feed water is not necessary and corrosion is much less of a problem with freezing due to the low operating temperatures. Some equipment development required for freeze desalination has occurred over the last 30 years, and the technical feasibility of freeze desalination has been established; however, a considerable amount of research and development still remains before this technology can be used commercially on a large scale (34).

One variation of the freezing concept with some potential involves spraying seawater, or contaminated freshwater, into the air when winter temperatures fall below 29° F for significant periods of time. The partially frozen spray is collected in a reservoir where the pure ice accumulates and the unfrozen saltwater drains back into the sea. Costs are likely to run about $1.50 to $3.00 per 1,000 gallons, even for small scale applications (i. e., less than 1 mgd). This variation on freeze desalination can only be used in colder winter climates (73). However, very recent work using low energy refrigeration systems may allow use of this technique in any climate, with preliminary cost estimates of $1.50 per 1,000 gallons for feed water with a solids concentration of 1,000 ppm and about $2.00 per 1,000 gallons for seawater (74).

New Concepts

There are several new concepts and/or variations on existing concepts that may have some potential. Among these are: hybrid desalination plants that optimize the use of capital and energy resources by combining various desalination processes (e. g., RO and distillation); computerization of desalination operations; three-stage ion-exchange “Desal” process (55); “Delbuoy” concept that uses ocean waves to power RO equipment; “Puraq” liquid-liquid extraction of pure water using a polymeric solvent; “Gravacutron’ vacuum distillation process; distillation units coupled with ocean thermal energy conversion plants, etc. The potential of these concepts for economically purifying water is not known.

Appendix B

Federal Funding for Desalination Research

Year	Yearly funding in millions (as appropriated)	(1985 dollars)
1953	0.2	0.6
1954	0.4	1.4
1955	0.4	1.4
1956	0.6	2.2
1957	0.6	2.0
1958	0.7	2.6
1959		4,3
1960	: : ;	13.0
1961	3.8	13.7
1962	9.8	35.4
1963	9.6	34.8
1964	11.9	43,6
1965	16.2	57.5
1966	22.5	78.3
1967	29.9	101.9
1968	20.8	68.2
1969	25.6	80.4
1970	25.0	74.4
1971	28.6	78.3
1972	27.0	68.8
1973	26.9	63.7
1974	3.6	7.4
1975	5.9	10.2
1976	3.4	5.6
1977	7.6	11.9
1978	11.0	15.5
1979	10.1	12.9
1980 (Budget request)	12.4	14.5
1981	3.0	3.3
Total	322.3	907.8

SOURCE: U.S.General Accounting Office, ”WaterIssues Facing the Nation:An Overview/’ (81}Burton, J.S. “History of the Sallne Water Conversion and Focused Water Research, Development, and Demonstration Programs:’(9)

Appendix C

Present Desalination Costs in the United States

	Plant size (mgd)	Overall cost (1985 dollars/1,000 gal.)
Brackish water:		
Reverse osmosis . . .	**1**	**1.67**
	3	**1.41**
	5	**1.33**
	10	**1.23**
	25	**1.21**
Electrodialysis . . . . (reversing).	**1**	**1.72**
	5	**1.47**
	10	**1.37**
	25	**1.26**
Seawater		
Distillation		
Multi-stage flash .	1[a]	9,73
	5[a]	6.78
	10[a]	6.50
	25[a]	6.10[b]
Multiple-effect . . .	1	8.31
	5[a]	5.70
	10[a]	5.36
	25[a]	5.36[b]
Reverse osmosis . . .	**0.01**	13.42
	0.1	9.88
	1	7.40
	3	6.64
	5[a]	6.36
	10[a]	6.03[c]
	25[a]	5.96’

theoretical costs since no plants of this size are operating in the United States

[b] approximated from Reed (57).

[c] extrapolated cost

SOURCE: United Nations, “The Use of Nonconventional Water Resources in Developing Countries,” (77); edopted from Reed, S.A., “Desaiting Seawater and Brackish Water: 19S1 Cost Update,” (57).

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