DESALINATION
FOR URBAN WATER SUPPLY

JULY 1991

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BOYLE ENGINEERING CORPORATION
BAKERSFIELD, CALIFORNIA

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Ronald Esau
William Mills Jr.
Anson Moran
W. E. Seegmiller
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Lester Snow
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Lyle N. Hoag, Executive Director

Report Reviewers:

Walter J. Bishop
Byron Buck
Keith Carns
Jeanne Duncan
C. C. Gelatt
John Gregg
Lyle N. Hoag
Penny Lawbaugh

BOYLE ENGINEERING CORPORATION

Ernest O. Kartinen, Jr., Principal Author

Thomas S. Maddock

David L. Hardan

Ian Watson

FOREWORD

This study was commissioned by CUWA to examine the range of factors involved in considering seawater desalination for urban use. It provides an overview of desalination as an additional water supply option; advantages and disadvantages are both presented.

Desalting oceanwater may be an excellent complementary water supply for seaside areas, such as Santa Barbara and the Monterey Peninsula, where access to the principal aqueducts is limited. This option also may become an important supplementary source for major metropolitan coastal areas where freshwater supplies are no longer adequate.

Designed as a semitechnical review of the technology's state of the art as it applies to urban water use, this report is written for those who are informed on water supply issues and who are interested in understanding the technical as well as the economic aspects of desalination.

California Urban Water Agencies

DESALINATION FOR

URBAN WATER SUPPLY

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DESALINATION FOR URBAN WATER SUPPLY

INTRODUCTION

This compendium is designed to explain the various desalination processes, their characteristics, and the factors that affect their feasibility for supplementing urban water supply. It was written for non-technical readers who know about water supply issues and want to know more about desalination.

Desalination is the process of removing salt from brine, particularly sea water, to get fresh water. Like any technology, its use is driven by necessity and depends on practical considerations relative to other potential sources of water. Most of California's urban centers are located on the Pacific Coast where seawater is abundant. These urban areas are now experiencing water shortages in California's five-year drought, and anticipate long term shortages because of rapid population growth and lack of other water resources. As a result, there is increasing interest in desalination as a possible source of supplemental water. Because of this interest, California Urban Water Agencies (CUWA) commissioned this report to furnish background for understanding desalination options and the state of the art.

Water from any source containing minerals (dissolved solids) can be desalted. Source waters could be the ocean, brackish waters in swamps, marshes, or inland seas, waste waters, including agricultural drainage, domestic, or industrial, or highly mineralized groundwaters. Generally, the saltier the source water, the more costly and energy-intensive the treatment needed to get high quality fresh water, unless a distillation process is used. (The thermal energy required for distillation is unaffected by salinity.)

This report discusses desalination processes used to reduce the total dissolved solids (TDS) concentrations in three types of source water:

1. Hard waters, which generally contain large concentrations of magnesium, calcium, sulfate, and/or bicarbonate.

2. Brackish waters, which are usually hard and may have TDS levels up to several thousand parts per million, or milligrams per liter (mg/L). The TDS Secondary Drinking Water Standard recommended by the California Department of Health Services for municipal water supplies is 500 mg/L.

3. Sea water, with TDS's ranging from about 34,000 mg/L in the Pacific Ocean off California to 44,000 mg/L in the Red Sea.

HISTORY OF DESALINATION

Desalination has been understood in principle since Greek sailors in the 4th Century BC used an evaporation process to desalinate sea water. The difficulty of developing practical methods to do so is evident in the limited worldwide use of desalination on any large scale in the intervening centuries.

Generally, sea water desalination has been used only in circumstances where freshwater sources were not economically available. The greatest impediment to developing practical technology to desalinate sea water has been the large energy requirements of the processes.

The first large, land-based seawater-desalting plant was built in Kuwait in 1949. Its capacity of 1.2 million gallons per day (MGD) was increased to 5 MGD in 1958. By the early 1970's, large-scale desalination plants were in operation or under construction in the U. S., the U.S.S.R., Israel, Egypt, Saudi Arabia, Mexico, Italy, Spain, and many other countries.

Desalination capacity worldwide has increased dramatically in the last 20 years. In 1960, worldwide desalination plant capacity was about 50 million gallons per day (MGD). By 1970, total capacity had reached about 200 MGD and, by 1990, almost 3,500 MGD. For comparison, this is about twice the amount deliverable by the California State Water Project (SWP) to municipal and industrial (M&I) users.

A survey conducted by the International Desalination Association in 1990 revealed that the following types of desalination processes were being used worldwide:

TABLE 1

RESULTS OF 1990 DESALINATION PLANT SURVEY

Processes	% of World Capacity	MGD Capacity
Distillation		
Multi-Stage Flash (MSF)	56	1,950
Multi-Effect Distillation (MED)	5	180
Mechanical Vapor Compression (MVC)	3	110
Subtotal	64	2,240
Membrane		
Reverse Osmosis (RO)	31	1,080
Electrodialysis Reversal (EDR)	5	160
Subtotal	36	1,240
	100	3,480

Distillation has been the most widely used desalination process, but recent improvements have been made in membrane processes.

In the last five years, reverse osmosis (RO) has been used in about 85% of the new desalination plants constructed. Of the 1,080 MGD of installed RO capacity, about 85% is for brackish water, and 15% is for sea water.

DESALINATION IN CALIFORNIA

Until recently, desalination has not been used in California to supply municipal drinking water. Desalination plants treat sea water to supply industrial water for processes at

Chevron's Gaviota Oil and Gas Processing Plant and at three Pacific Gas and Electric Company (PG&E) power plants at Moss Landing, Morro Bay, and Diablo Canyon. A 0.15 MGD sea water RO plant began operation in mid-1991 on Santa Catalina Island. Most other desalination plants in the state treat brackish groundwater, domestic wastewater, or agricultural drainage.

Because of the drought, this situation is changing. A number of California communities are considering desalting brackish water or sea water for municipal use.

The Marin Municipal Water District is considering desalination of San Francisco Bay water which exhibits TDS's ranging from brackish to sea water concentrations depending on the season and rainfall. The Marin District operated a RO plant for three months to demonstrate the feasibility of a 5 MGD (expandable to 10 MGD) RO plant.

Monterey Peninsula Water Management District is conducting a site evaluation and feasibility study for possible construction of a 3 to 8 MGD sea water desalination plant. One potential site is at a large power plant where steam is available. Therefore, RO and two distillation processes, Mechanical Vapor Compression (MVC) and Multi-Effect Distillation (MED), which requires steam, are being studied.

Other potential sea water desalination projects include the City of Santa Barbara which has authorized construction of a RO desalination plant to produce 7500 acre feet per year (AFY), at least as a short term solution to their water shortages. The San Diego County Water Authority and the Metropolitan Water District of Southern California (MWDSC) are also investigating the feasibility of sea water desalination to supplement existing water supplies. The City of Morro Bay has awarded a contract for a 0.6 MGD sea water RO plant to be completed in the summer of 1991.

Brackish water desalination is being considered by MWDSC, Orange County Water District, and several other agencies in California.

The California Legislature is considering six bills on the subject of desalination, some to provide funding and low-cost power, and others for research.

DESALINATION PROCESSES

The three most common methods of desalination used today are:

(1) Distillation (thermal) processes,

(2) Membrane processes, and

(3) Ion exchange.

This paper discusses two of the three types of desalination processes; distillation and membrane. Ion exchange (IX), the third process type, is not cost effective for desalting if the TDS exceeds about 1000 mg/L. IX can, however, "target" specific mineral contaminants (such as nitrate) for removal.

Selecting the appropriate desalination process for a particular situation requires consideration of a number of factors. Each of these factors affects the capital and operating and maintenance (O&M) costs of a desalination plant. These factors include the source water quality, pretreatment requirements, "recovery" (percentage of feed water recovered as product water), equipment size, energy requirements, chemical requirements, product water quality goal, post-treatment requirements, waste disposal, and the plant utilization factor (PUF).

Distillation (Thermal) Processes

Distillation processes use heat to desalt water by evaporating and condensing the water vapors. (See Figure 1.) The salts remain in that portion of the feed water not evaporated. Hence, the product water (condensed vapor) is essentially salt-free. The heat may come from an external energy source such as a boiler or from the compression of water vapor. Distillation processes used for desalination recover and re-use a portion of the heat required to vaporize the feed water to decrease overall energy requirements.

DISTILLATION

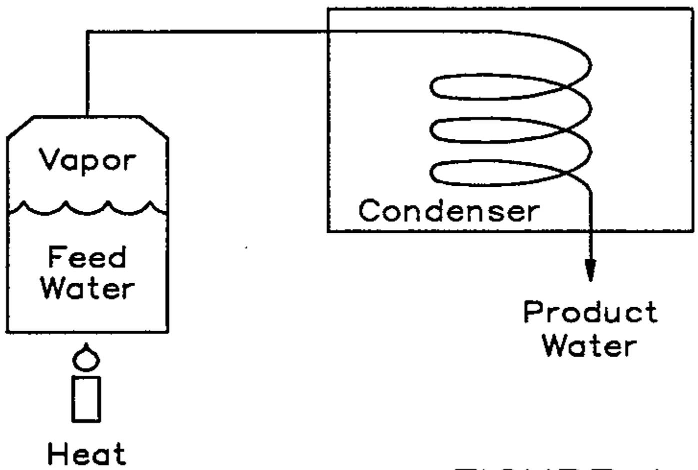


FIGURE 1

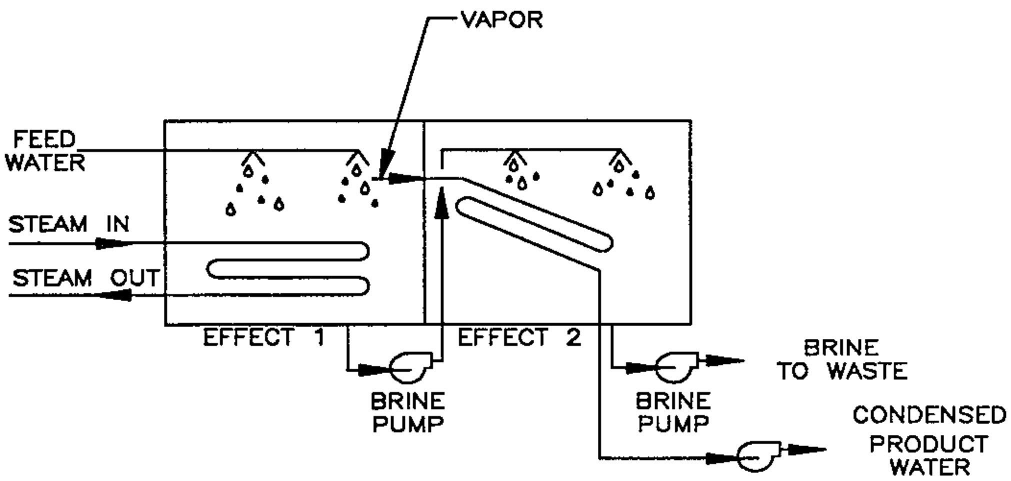
Thermal desalination plant equipment tends to be much larger than membrane desalination equipment for a given plant capacity. However, distillation plants do not have the stringent feed water quality requirements of membrane plants. But, due to their relatively high operating temperatures, scaling (precipitation of minerals from the feed water being desalted) can occur. Scale can generally be controlled by chemical inhibitors and by operating at temperatures of less than about 200° F. Since this temperature is less than the boiling point of water, a partial vacuum must be induced to lower the boiling point. Distillation plants tend to have high energy requirements, making energy a large factor in overall water cost. Distillation process product water recoveries range from about 15% to 45%, depending on the process.

Thermal processes produce very low TDS product water (less than 25 mg/L). Thermal processes may concentrate volatile organic carbon contaminants (VOCs), such as pesticides, insecticides, etc., in the product water, thereby increasing the likelihood that the allowable Maximum Contaminant Level (MCL) for VOC's may be exceeded.

Multi-Stage Flash (MSF) plants, the desalination process with the most installed capacity (see Table 1), are expensive to build and operate. The recovery from a MSF sea water desalination plant is only about 15% -- the least recovery of any of the commonly used thermal processes. MSF plants usually operate at about 200° to 250° F. However, plants with capacities up to 250 MGD exist in Saudi Arabia, where thermal energy is readily available at low cost. That MSF plants have become more costly than RO plants is evidenced by a 15 MGD RO plant built about two years ago at Jeddah, Saudi Arabia, to replace part of an existing MSF plant. Due to their costs and large size, MSF desalination plants are probably not feasible in California.

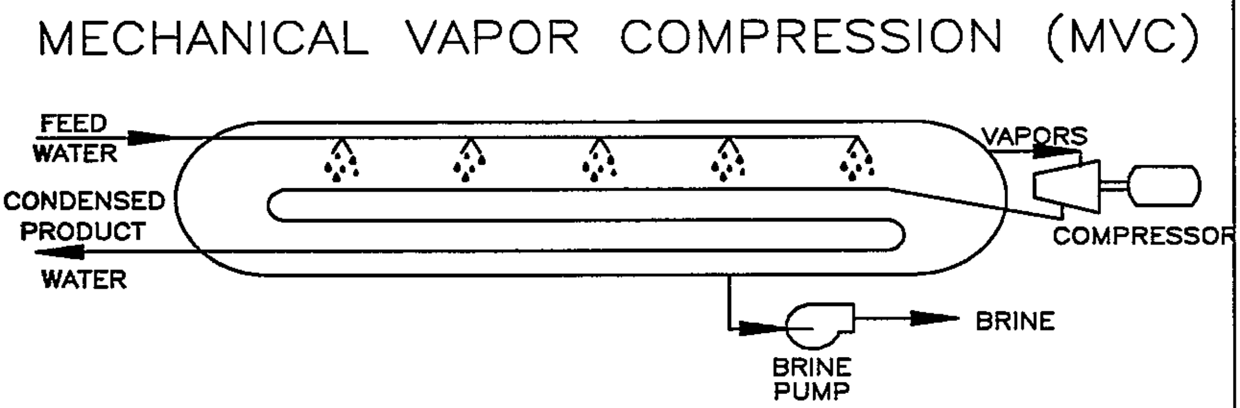
In a Multi-Effect Distillation (MED) plant, a series of evaporator-condenser vessels (called "effects") recover the heat used to boil the feed water by condensing the feed water vapor from the preceding "effect" and transferring the heat to incoming feed water to evaporate it. Each succeeding effect operates at a slightly lower temperature and pressure (vacuum) to reduce the boiling point of the feed water. The heat source for a MED plant is usually steam. By operating at a partial vacuum, low pressure steam at a temperature of about 175^{O} F. can be used. This reduces the steam cost and scaling potential since scaling in distillation plants is most prevalent at temperatures greater than 200^{O} F. A recovery rate of about 20% may be expected from a MED sea water desalination plant. Single MED desalinators as large as about 5 MGD have been built. Most MED units, however, are smaller. MED plants may be economical for California projects if a source of steam (i.e., power plant) is available.

MULTI–EFFECT DISTILLATION (MED)



TWO EFFECTS SHOWN. ACTUAL PLANTS USUALLY HAVE 10 OR MORE EFFECTS.

FIGURE 2



ONLY ONE EFFECT SHOWN. TYPICAL MVC PLANTS HAVE THREE OR MORE EFFECTS.

FIGURE 3

A Vapor Compression (VC) plant operates like a MED plant using a series of evaporator-condenser vessels ("effects"). There are two types of VC plants; thermal (TVC) and mechanical (MVC). The differences between them are how the vacuum is created in the vessel and how the feed water vapors from the evaporation chamber are compressed. TVC uses steam both to pull feed water vapor from the evaporation chamber and to vaporize the feed water.

In a MVC plant, the heat necessary to boil the feed water is provided by mechanically compressing the feed water vapor thus adding the "heat of compression" to the vapors. The heated compressed vapor flows inside tubes, over which feed water flows. The hot vapor gives up its heat to the feed water and condenses to liquid, while a portion of the feed water vaporizes. For most applications MVC operates with an internal temperature of about 150^{o} F. This relatively low operating temperature, together with scale control additives, reduces the scaling and corrosion problems associated with higher temperature processes. MVC recovery rate is about 45% for sea water desalination. Most operating MVC desalinators are fairly small; less than 0.25 MGD. Units as large as about 0.8 MGD have been proposed, but not yet constructed. MVC plants may be feasible for some California projects.

It is well known that urban water demands vary considerably from day-to-day and season-to-season. Distillation plants are able to accommodate a wide range of product water flowrates; from less than 50% to somewhat more than 100% of the rated capacity. In addition, MED and MVC distillation equipment modules are commonly small so most urban distillation plants in California would likely consist of several units.

Meeting water demands less than a distillation plant's design capacity could be accomplished in two ways:

- o Vary the product water flowrate from each desalination unit or,
- o Take out of operation (shut down) one or more desalination units for periods of time.

These two ways to reduce production could be combined, of course. The several pieces of desalination equipment could be "rotated" into and out of service by operating first one piece of equipment, then another, for a time.

It is also possible to completely shut down a distillation plant for a long period of time essentially placing the plant in "standby" until it is needed. To protect the equipment while it is idle, the following steps are required:

- o Drain the feedwater from all the equipment, including pumps, and connecting piping;
- o Remove any sludge and scale that may have accumulated in the equipment;
- o Flush the equipment and piping with product water;
- o Drain and dry out the equipment.

Membrane Processes

There are two types of membrane processes in use: those using pressure and those using electrical charge. Pressure-driven processes include membrane softening reverse osmosis (MSRO), brackish water RO (BWRO), and sea water RO (SWRO). The electrical charge-driven process is electrodialysis reversal (EDR). Reverse osmosis will be discussed first.

Water tends to equalize the concentration of dissolved materials throughout its volume. If a dissolvable substance, such as salt, is introduced into a tank of water, before long that substance will be distributed evenly throughout the water. If a semi-permeable membrane, which permits water to pass but restricts the passage of dissolved salts, separates the saline water from the fresh water, water will tend to flow from the fresh side to the salty side in order to equalize the salt concentrations. This process is called osmosis. The tendency for water to pass through the membrane depends on the difference in TDS concentrations between the two sides. It is expressed as pressure (pounds per square inch), and is called "osmotic pressure". Applying a pressure greater than the osmotic pressure to the more saline side of the membrane "reverses" the osmosis process and forces water backwards through the membrane from the more saline to the less saline side thus producing "desalted" water. (See Figure 4.) Thus, while "thermal" energy is required for distillation processes, "pressure" energy is required for RO.

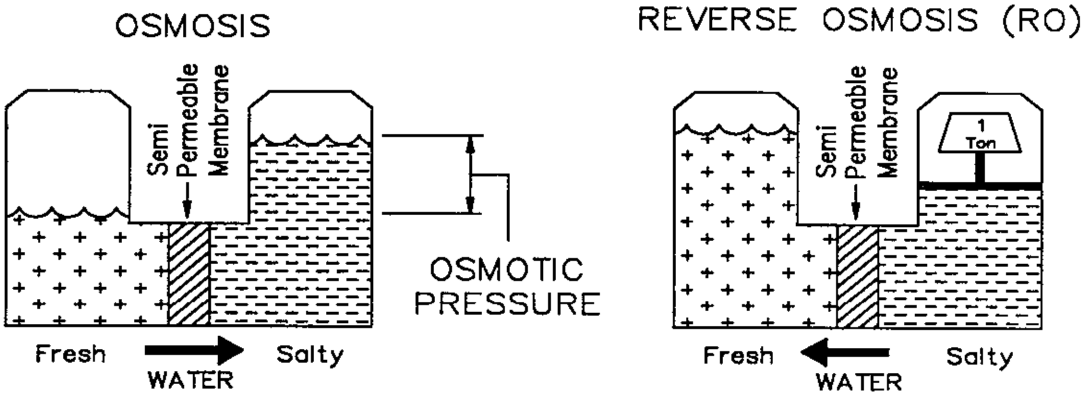


FIGURE 4

The primary energy requirement for a RO plant is for pumping (pressurization). A SWRO system requires pressure in the range of 800 to 1200 pounds per square inch (psi). MSRO systems usually require pressure less than 150 psi. BWRO pressures range up to 600 psi. For any RO plant, the pressure required depends on the membrane type, the TDS and temperature of the source water, and other factors. (See Figure 5.)

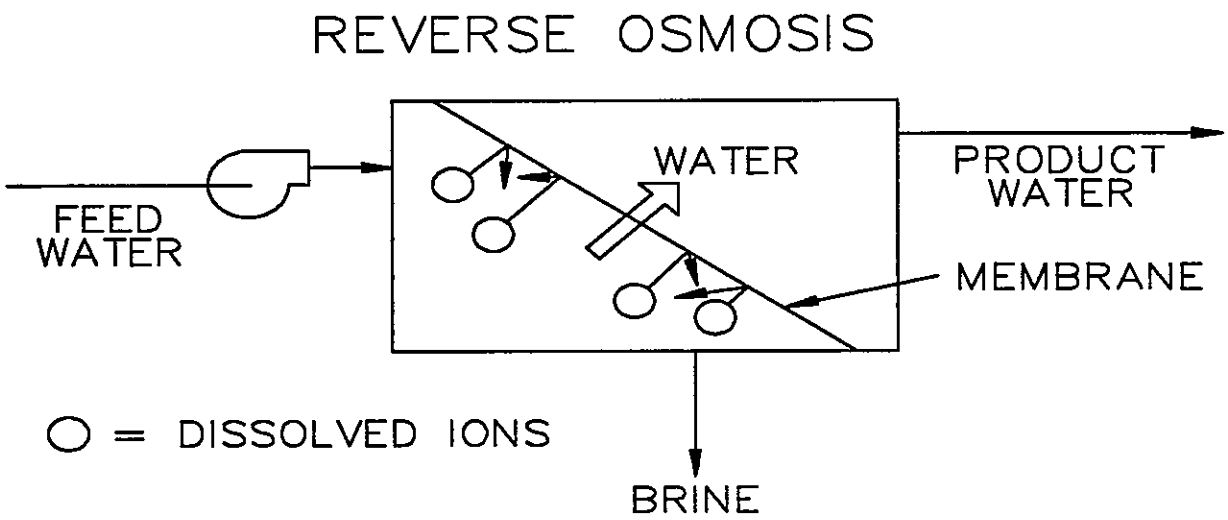


FIGURE 5

RO membranes come in several configurations, the two most common types being spiral wound and hollow fine fiber. Membranes are typically made of plastic materials such as cellulose acetate and polyamide.

RO removes a number of other contaminants from the feed water including trihalomethane (THM) precursors (but not THM's), viruses, bacteria, giardia cysts, and organics such as pesticides.

Recovery rates up to 45% are common for sea water reverse osmosis. For hard and brackish waters, recoveries up to 90% are possible, depending on water chemistry. RO plants can be constructed to satisfy any desired product water capacity by varying the number of membranes. The world's largest brackish water RO plant (72 MGD) is at

Yuma, Arizona, and was built to desalt drainage water from the Welton Mohawk Project before it enters the Colorado River. Sea water RO plants from a few gallons per day to 15 MGD have been successfully constructed and operated.

A "single pass" sea water RO plant can produce water with a TDS of less than 500 mg/L, most of which is sodium and chloride making the water corrosive. This quality may be acceptable, especially if a source of blending water is available.

For some sea water applications, however, a "two pass" RO system may be required, especially where water qualities better than 500 mg/L are desired. In a two pass RO system, the product water from the first RO pass is further desalted in a second RO pass. TDS of the second pass water can be less than 200 mg/L.

RO membranes are subject to fouling from suspended materials, biological growths, and certain minerals in the feed water. If a clean source water supply is not available, the source water must be treated to remove virtually all suspended materials prior to RO treatment.

Biological growth problems may be overcome by use of a non-toxic, biodegradable biocide or disinfection prior to the RO process. However, disinfection with chlorine or ozone, for example, must be used with care as these chemicals may attack the membranes. Disinfection prior to RO will also convert THM precursors to THM's and THM's are not removed by RO as are THM precursors. Scale formation potential may be reduced by use of scale inhibitors and reducing recovery rates to lessen mineral concentrations in the brine.

RO plants may be operated over a wide range of product water flowrates as they are typically constructed in several "modules" so that the total product water flow from all modules equals the design flowrate. Modules may be taken out of production for short periods of several hours or more with no adverse results. Accordingly, a RO plant consisting of, say, five modules can easily be operated to deliver 20% of the design product water flowrate by operating only one module at a time for several hours, then taking it out of operation and using another module, and so on.

It is also possible to reduce the product water flowrate from a single RO module, within limits, by reducing the flux (gallons per day of product water per square foot of membrane area) and the brine discharge pressure. This also reduces the operating pressure and, therefore, the energy required for pumping.

If a RO plant is to be shut down, the following procedure should be followed:

- o Equipment flushed with product water;
- o The membranes cleaned by a solution of product water and a non-toxic cleaning agent such as caustic soda or citric acid;and
- o The system filled with product water containing a biodegradable biocide such as sodium bisulfite;

o about once a week or so, a fresh product water/sodium bisulfite solution should be pumped through the membranes.

Electrodialysis (ED), the predecessor of EDR, uses an electrical potential (voltage) to move dissolved solids through a membrane, leaving fresh water behind as product water. Dissolved solids are of two kinds, cations and anions, which contain opposing electrical charges. "Cations" are the positively charged portions and "anions" are the negatively charged portions of the dissolved solids. ED membranes are made of ion exchange resins which allow either cations or anions, but not both, to pass through. Thus, two types of membranes are used in ED to produce desalted water. (See Figure 6.)

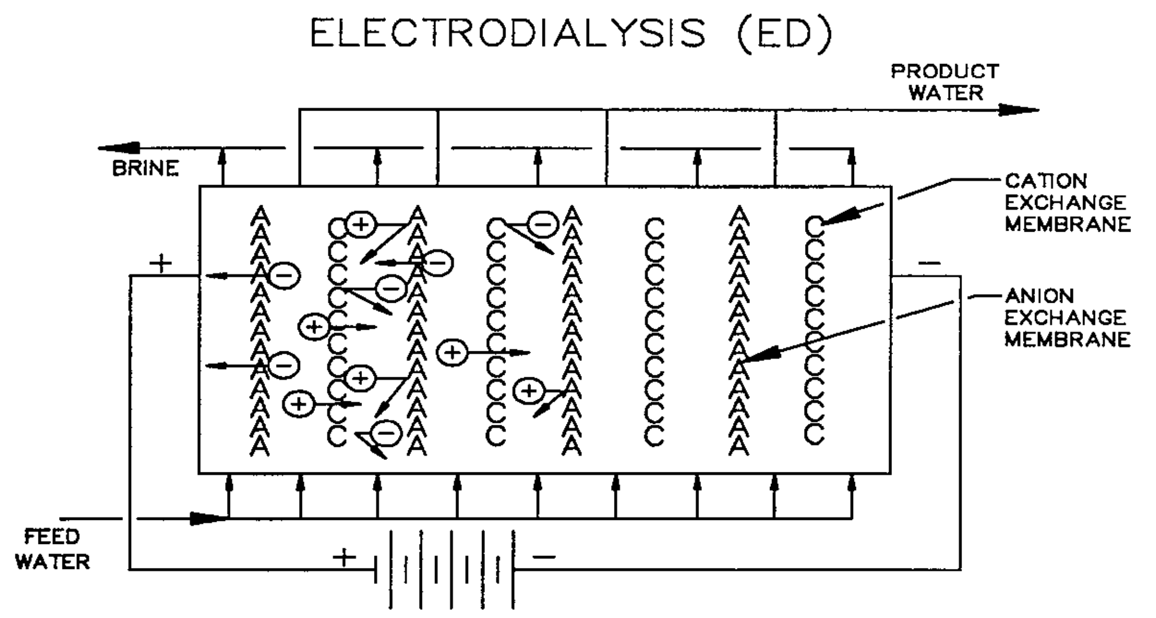


FIGURE 6

Cations (such as calcium and sodium) and anions (such as chloride, sulfate, and bicarbonate) are present in water such that positive charges equal negative charges, effectively neutralizing their individual electrical charges. When electrodes connected to a source of direct current are placed in a container of saline water, electrical current is carried through the solution by ions migrating to the electrode with the opposite electrical charge. Membranes that will allow either cations or anions, but not both, to pass are placed between a pair of electrodes. Anion-selective membranes are arranged alternately with cation-selective membranes. A spacer sheet that permits water to flow along the face of the membrane is placed between each pair of membranes.

Concentrated (high TDS brine) and diluted (low TDS product water) solutions are created in the spaces between alternating membranes. These spaces, bounded by two membranes, are called "cells". Groups of cells are enclosed in a "stack". Feed water passes simultaneously in parallel paths through all of the cells and desalted product water and brine emerge from the stack in two separate streams.

The raw feed water must be pre-treated to prevent materials that could harm the membranes or clog the narrow channels in the cells from entering the membrane stack. ED is more tolerant of suspended solids in the source water than RO as the solids may be carried into the product water. However, ED does require cleaner water than needed for distillation processes.

In the early 1970's, an American company commercially introduced electrodialysis reversal (EDR). An EDR unit operates on the same general principle as a standard electrodialysis plant. At predetermined intervals, the polarity of the electrodes is reversed (the positive electrode is made negative and the negative electrode is made positive), and the flows are switched simultaneously so that the brine channel becomes the product water channel, and the product water channel becomes the brine channel.

The result is that the ions are attracted in the opposite direction across the membrane stack. Immediately after polarity and flow are reversed, product water is wasted until the cells are flushed out, and the desired product water quality is restored. The flush takes about 30 seconds and occurs every 20-25 minutes. The reversal process helps break up and flush out scales, slimes, and other deposits in the cells before they can build up and create a problem. Reversal allows the unit to achieve higher recoveries with fewer pretreatment chemicals and minimizes membrane fouling potential resulting from suspended solids, biological growths, and scaling.

Unlike RO, ED (or EDR) does not remove THM precursors, viruses, bacteria, giardia, cysts, silica, nor organics from the feed water.

EDR is used to desalinate brackish water with TDS's up to several thousand mg/L. A 12 MGD EDR brackish water plant, the world's largest, is under construction in Florida. Recoveries up to about 95% have been reported for brackish water desalination. Energy requirements make it economically uncompetitive compared to RO for sea water desalination.

EDR plants, similarly to RO plants, are built in "modules" (stacks). As with RO plants, some variation in the flow through a stack can be obtained to vary the product water output. Stacks can also be taken out of service for a short time (several hours at least) to reduce product water output. Stacks can be "rotated" every few hours to maintain product water flows substantially less than the design flow for long periods of time.

If an entire EDR plant is to be taken out of service for a short time (several months, for example), it is only necessary to turn on the feed water pumps about once a week to "change" the water in the stacks. To restart the plant, a "shock treatment" with chlorine may be used to destroy growths that may have built up inside the stacks.

For a long term shutdown, the stacks may be flushed and filled with product water containing a biocide such as sodium bisulfite and wrapped with a plastic material to avoid evaporation of water from the stacks. To restart the plant, the plastic is removed and the stacks flushed with feed water and chlorine to "shock treat" the equipment. Normal operation may then resume.

DESALINATION PROCESS ENERGY REQUIREMENTS

All desalination processes require energy to separate the dissolved solids (salts) from the water. Table 2 compares the energy requirements of the several desalination processes discussed. In order to fairly compare the energy needs, thermal (steam) and electrical power demands have been converted to "Equivalent Barrels of Oil". The conversions for each process were based on the following assumptions:

- o One barrel of oil is equivalent to 6 million British Thermal Units (MMBTU - a commonly used heat unit).
- o Power plant efficiency of 35% (one barrel of oil produces the equivalent of 2.1 MMBTU of electrical energy).
- o Boiler efficiency of 80% (one barrel of oil produces the equivalent of 4.8 MMBTU of thermal energy [steam]).

Table 2 also compares the energy needed to desalt water to the energy needed to deliver water from Northern California to Southern California via the State Water Project (SWP). Depending on the final delivery point of SWP water (Perris Reservoir on the East Branch or Castaic Lake on the West Branch of the California Aqueduct), about 4000 to 4500 kilowatt hours (KWH) of electrical energy are needed to deliver one acre-foot (AF) to Southern California. In addition, energy is needed to treat the water; about 200 KWH per AF. As shown in Table 2, a figure of 4500 KWH per AF was assumed which is equivalent to about 7.3 barrels of oil based on the assumptions used.

TABLE 2

COMPARISON OF DESALINATION PROCESS ENERGY REQUIREMENTS

PROCESS	APPROX. RECOVERY	ENERGY REQUIRED THERMAL(1)	ENERGY REQUIRED ELECTRIC(2)	EQUIVALENT BARRELS OF OIL/AF(3)	% OF ENERGY USED FOR SWP	% OF ENERGY USED FOR AVG.HOME
Softening						
RO	90%	--	400	0.7	10	3
Brackish						
RO	80%	--	1,600	2.6	36	12
EDR	85%	--	2,000			
3.3	45	15				
Sea Water						
MSF	15%	270	4,000	62.8	860	289
MED	20%	230	3,000	52.8	723	243
MVC	45%	--	10,000	16.3	223	75
RO	45%	--	6,000	9.8	134	45
SWP Water	--	--	4,500 (4)	7.3	--	34
Average Home	--	67(5)	6,500 (5)	21.7	297	--

NOTES:

1) Thermal energy in millions of BTU's (MMBTU's) per AF of product water.
2) Electrical energy in KWH's per AF of product water.
3) Based on: 6 MMBTU's per barrel of oil
   Electric power plant efficiency of 35%
   Oil to steam (boiler) efficiency of 80%.
4) SWP (State Water Project) energy required to deliver and treat one AF of water to Southern California. This water serves the average annual needs of two homes.
5) Based on PG&E (1989) average home demand of 67,000 cubic feet of gas and 6,500 KWH per year.

Another comparison is also made in Table 2; desalination energy requirements are compared to the average California home energy consumption. To make this comparison, the average single family home electric power and natural gas demands in Pacific Gas & Electric's (PG&E) service area for 1989 were used. In that year, the average single family home used 6500 KWH of power and 67,000 cubic feet of gas. The "thermal energy" demand of 67 MMBTU's was based on 1000 BTU's per cubic foot of natural gas, or 11.2 "Equivalent Barrels of Oil". The 6500 KWH's of electric power demand represented 10.6 "Equivalent Barrels of Oil". Total energy consumption was equal to 21.8 "Equivalent Barrels of Oil".

As indicated in Table 2, there are dramatic differences between the various desalination processes in the energy required to desalt water. In terms of "Equivalent Barrels of Oil", sea water desalination using MSF requires six times as much energy as RO; MED five times as much. However, both MSF and MED are substantially more efficient than simply boiling water at atmospheric pressure and condensing the steam which would require about 560 "Equivalent Barrels of Oil" based on 80% efficiency in converting oil to heat. It is interesting to note softening or desalting a brackish water, if available locally, would take less than one-half of the energy needed to deliver SWP water to Southern California.

It is also interesting to note that desalinating sea water using RO requires only one-third more energy than delivering SWP water to Southern California. In Southern California, one AF of water will supply two families for one year. Based on SWP water, each family's water supply requires at least 3.7 barrels of oil. Sea water RO would require 4.9 barrels; a difference of 1.2 barrels per year per family or only 6% of the average single family home's annual energy demand.

DUAL PURPOSE PLANTS

Since desalination processes require large amounts of energy and because the early desalination plants used distillation and relied on heat energy, they were often built in conjunction with power plants. Steam to drive the distillation process was extracted from the turbine driving the electrical generator. Most, if not all, of the very large plants in the Middle East were constructed as part of a power plant project. A facility which produces both electricity and water is called a "dual purpose" plant.

The efficiency of modern power plants has largely removed the advantages of dual purpose plants today. There is, however, no "waste heat" in a modern power plant. Since a modern steam turbine exhausts steam at less than atmospheric pressure (vacuum), the temperature of the spent steam is about 120^{o} F.; less than the 212^{o} F. boiling point of water at sea level. All of the distillation processes operate at temperatures exceeding 120^{o} F. The amount of power generated by a steam turbine depends on the steam exhaust temperature. Steam extracted from a turbine at a high enough temperature for distillation reduces the amount of electrical power produced by the generator thereby reducing the power plant's ability to produce water.

Dual purpose plants can be economical, however, when power demand is lower than the steam generating capacity of the power plant. At such times, steam could be extracted from the turbine to desalt water. Or, if electrically powered, the desalination plant could be operated during periods when the electrical power demand by consumers is less than the plant's power generating capacity. Steam driven pumps for distillation or membrane desalination plants may also be less expensive to operate than electrically driven pumps. Dual purpose plants can also share seawater intakes and outfalls. The power plant's cooling water system can provide the water supply to and carry the water brine away from the desalination plant.

"Hybrid" facilities, a combination of distillation and RO desalination plants, have been built at power plants. The differing product water qualities produced by distillation and RO plants can be used to advantage in a hybrid plant. Distillation processes produce water with a TDS of less than 25 mg/L; while single pass RO produces a TDS of perhaps 500 to 1000 mg/L. A 50-50 blend of the two waters would result in a product water TDS of about 250-500 mg/L which is a suitable quality for municipal water supplies. The TDS would be essentially all sodium chloride (common salt) and the water would need post-treatment as described later in this paper.

PRETREATMENT OF SOURCE WATER

Physical feed water quality requirements vary significantly between membrane and distillation desalination processes. Distillation equipment can accept relatively high levels of suspended solids, such as soil particles or algae, (as much as 100 mg/L), particularly if these solids are not abrasive. Membranes require very low suspended solids in their feed water. Normal practice for membrane systems requires feed waters to have a silt density index (SDI) less than 4. Silt density index is a measure of particles larger than 0.45 microns (0.000018 inches) suspended in water. It is not directly related to turbidity or any other commonly measured water quality characteristic.

If the feed water contains suspended solids in excess of that acceptable for the particular desalination process used, pretreatment is needed. Pretreatment may consist of filtration and/or chemical addition to inhibit fouling and scaling. Other cost factors being equal, a water source requiring minimal pretreatment should be selected. For example, it is usually more cost effective to obtain sea water from beach wells, where possible, than from open intakes, since beach sand provides "pre-filtration". In a similar fashion, brackish water wells usually require minimal pretreatment. On the other hand, surface waters, where beach wells are not possible, require high levels of pretreatment.

Several filtration methods can be used as pretreatment for membrane processes. The most common is two-stage filtration, where the source water passes through two separate filter beds, often following conventional clarification systems. Single-stage filtration, while usually acceptable for distillation processes, generally cannot provide sufficiently low solids content for membrane desalination plants.

Newer filtration technologies are capable of producing very low solids content feed water. Ultra-filtration can produce extremely low solids content and provide extended run times for membrane desalination systems. Various microfiltration systems also have been proposed for pretreatment. These newer processes add capital and O&M costs but provide higher quality feed water to the desalination equipment. The additional costs for such pretreatment must be balanced against the cost savings provided by better performance of the desalination equipment.

Some minerals in water can form scale inside the desalination equipment. The scaling tendencies of source waters can be dealt with in several ways. The first is to reduce recoveries in the desalination process. This reduces the concentration of scaling substances in the brine, thus reducing the tendency to scale. It also increases the amount of source water required for a given amount of product water recovery as well as the amount of brine. Another method is to add scale inhibiting chemicals to the process prior to desalination. These chemicals delay scaling until the brine has exited the process equipment. Scale inhibitors are generally required for distillation systems and may be required for membrane processes depending upon source water quality.

POST-TREATMENT OF DESALTED WATER

Desalted sea water may range from a TDS of about 25 mg/L for a MED or MVC plant to about 500 mg/L for a single pass RO plant most of which is sodium chloride (salt). The product water is corrosive, especially the lower TDS product water from a distillation plant. Water from a sea water desalting plant is usually post-treated to add some hardness and alkalinity. This makes the water less corrosive and gives it a better taste.

Limestone (calcium oxide) can increase the hardness and alkalinity of a desalted sea water. The limestone is loaded into beds resembling gravity sand filters, and the carbon dioxide (resulting from pH adjustment of the feed water caused by acid addition or injection of carbon dioxide gas) in the desalted water reacts with the limestone, resulting in both calcium and bicarbonate (alkalinity) concentration increases in the product water.

Generally, desalted brackish or hard waters require less post-treatment than desalted sea water. In many instances, only a portion of the source water is treated and blended with untreated source water to meet the water quality objectives.

The State Department of Health Services developed a protocol for desalination treatment plants in April, 1991. The protocol addresses filtration and disinfection requirements for desalination plants.

ENVIRONMENTAL AND SITING CONSIDERATIONS

To select the least costly, most environmentally acceptable site for a desalination plant, several factors should be considered including:

- o Source water quality
- o Pretreatment needs
- o Desalination process
- o Post-treatment needs
- o Waste disposal
- o Delivery of product water to the distribution system
- o Energy availability
- o Size
- o Environmental impacts
- o Access
- o Geotechnical.

Variations in source water salinity affect RO and EDR more than the distillation processes. The thermal energy required for distillation is unaffected by salinity. However, the higher the salinity, the higher the energy required to operate a RO or EDR desalting plant.

Source water temperature affects both membrane and distillation processes. With RO, the lower the source water temperature, the lower the "flux" (gallons per day of product water per square foot of membrane area) and the greater the operating pressure needed to produce a given flowrate of product water. Moderate changes in temperature have less effect on distillation plants because most of the heat energy required is for the actual vaporization of the feed water.

The presence of chemical/organic constituents in the source water can affect the treatment process design. Certain minerals can affect the efficiency of both membrane and distillation plants. RO can remove some types of contaminants that distillation and EDR cannot.

The quantity of source water needed, which affects intake, pretreatment, and disposal system sizes and costs, depends on the desalination process used. With sea water, RO and MVC can realize recoveries as high as 45 percent. MED may only recover about 20 percent. For example, a RO or MVC plant producing 5 MGD requires as little as 11 MGD of feed water; 6 MGD will be returned to the water source. For a 5 MGD MED plant, 25 MGD or more may be needed; 20 MGD will be returned to the water source.

Two types of waste may be generated by a desalination plant liquid and solid. The quantity of liquid waste (brine) varies with the type of desalination process because of the differing recovery rates. In all cases the brine will be saltier than the source water. The brine may have some minor amounts of treatment chemicals. For a RO plant with a 45% recovery, the TDS in the brine is approximately twice that in the source water. For a MSF plant with 15% recovery, the TDS in the brine is only about 18% greater than in the source water.

Solid waste in the form of "sludge" may be generated, especially if pretreatment is needed to remove solids from the source water. Returning the solids back to the water source with the brine is the most economical means of disposal if environmentally sound and allowable. If not, disposal to a landfill would be required. For a RO plant, the elements from cartridge filters (used ahead of the RO membranes to guard against accidental occurrences of excessive solids in the RO feed water) and used membranes constitute another solid waste source. Membranes may be expected to last 3 years in a sea water RO plant and 7 years in a brackish water RO plant, although longer lives have been observed.

Delivering the product water to consumers can be a major cost affecting the site selection. In a recent California project, for example, 20 percent of the estimated desalination project construction cost is for water transmission facilities to deliver the product water to the distribution system.

The size of a site must be carefully considered. In general, MVC equipment needs about three times as much surface area as RO. However, the area that may be needed for pretreatment for RO, depending on the source water quality, can offset the size advantage of RO equipment. Potential future expansion of the plant should also be considered.

Site access for power and water facilities is as important as access for construction. The largest pieces of equipment to be brought to the site need to be considered. This is especially true for MED and MVC equipment.

Geotechnical conditions at a site can have a substantial impact on the cost of a desalination plant. Variations in foundation loads required by different types of desalination equipment must be considered.

Environmental impacts for each site, such as aesthetics, noise, air pollution, and other factors need to be considered, which affect the plant cost. In general, RO plants have less aesthetic impact than distillation plants because they are smaller and can be easily housed in a building with any desired architectural features. And, since RO plants may be entirely electrically generated, air pollution problems at the RO plant site are negligible.

Permitting can be a major task in a desalination plant project, especially with sea water desalination projects because of the sensitive environment of coastal areas. An NPDES permit will probably be required for brine disposal. In addition, permits from many other agencies such as the Coastal Commission, State Lands Commission, Corps of Engineers, State Department of Health Services, State Department of Fish and Game, and others will probably be needed.

Since all of California's major urban areas are not in compliance with air quality standards, major new distillation projects will be difficult, if not impossible, to permit in these areas. The exceptions would be projects associated with repowering of existing power plants where net air quality benefits can be achieved.

COST OF DESALINATION

The total cost of any treatment process consists of two components: the cost of constructing the facility (capital cost) and the cost of operating the facility (operation and maintenance costs - O&M). Both of these cost components are extremely sensitive to site specific considerations.

<u>Capital Costs:</u> Questions that arise relative to capital costs are as follows: The source of the water to be treated affects the capital costs. What is its quality -- physical and chemical? TDS is a major consideration. Will low pressure RO or EDR suffice (for softening or brackish water) or will high pressure RO or a distillation process be needed (for sea water)? What form of pretreatment will be needed, if any? Will wells or an open intake be used? Is energy (power or heat) available or will it need to be brought to the site? How will waste be disposed of? Are facilities needed to pump, store, or convey the product water to the consumers? How will the project be financed and what is the interest rate? These are only some of the major issues that affect the capital cost of a desalination plant.

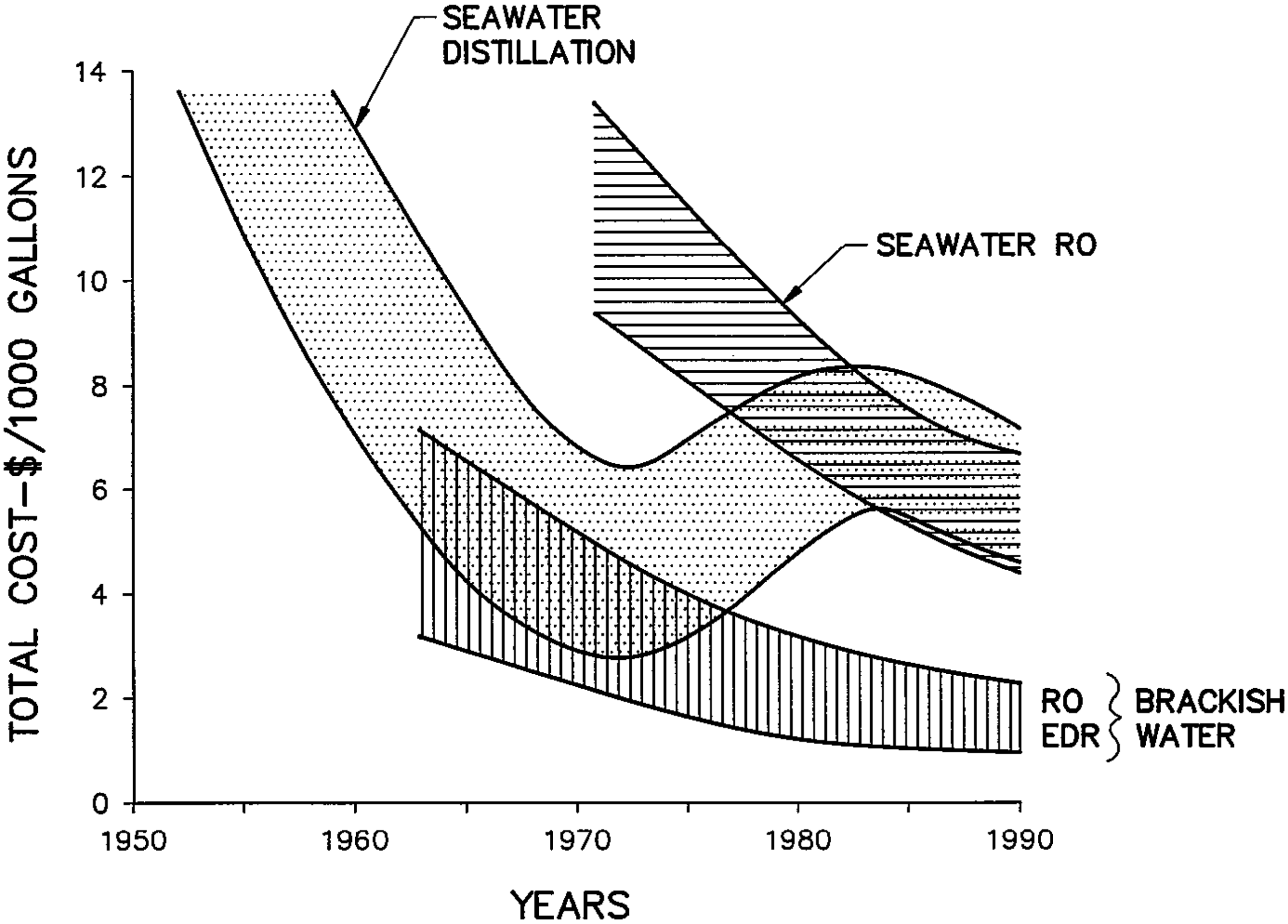
<u>O&M Costs</u>: What is the cost of labor to operate the plant? What will the energy costs be, now and in the future? What chemicals will be required? What limitations will be placed on chemical usage in the future?

A graphical representation of the range of total costs for desalination plants, prepared almost 30 years ago, has been updated and reproduced many times in the literature. Figure 7 is based on costs updated to 1990. The figure shows costs in $/1000 gallons, which is the total annual cost (annual capital cost plus annual O&M costs) divided by the annual plant production in 1000's of gallons It is important to note that the water costs indicated are for full time plant operation. As discussed further on, part-time operation can substantially increase the cost of water. Based on reports presented at a membrane conference in early 1991, the costs represented in the figure are still reasonably accurate.

Figure 7 shows several interesting trends. Forty years ago, desalted sea water cost about \$14/1000 gallons or about \$4600 per acre-foot (AF). Sea water distillation costs were reduced to about \$5/1000 gallons (\$1600 per AF) by the early 1970's, then increased as energy and financing costs increased. The cost of sea water distillation is now about \$6/1000 gallons (\$2000 per AF).

Desalination of sea water by reverse osmosis began in the early 1970's. As a result of improvements in membrane technology, the cost has decreased from about \$12/1000 gallons (\$3900 per AF) to about \$6/1000 gallons (\$2000 per AF).

The figure also shows the cost history of brackish water desalination using reverse osmosis and electrodialysis (reversal). The cost has declined from about \$5/1000 gallons (\$1900 per AF) in the early 1960's to about \$2/1000 gallons (\$700 per AF).



SOURCE:
"RO AND NF SYSTEM COST" BY WILLIAM J. CONLON
PRESENTED AT AMERICAN WATER WORKS ASSOCIATION
MEMBRANE PROCESSES CONFERENCE, MARCH 10–13, 1990
AT ORLANDO, FLORIDA.

APPROXIMATE DESALINATION COSTS

(TOTAL WATER COST INCLUDING AMORTIZATION OF
CAPITAL COST AND O&M BASED ON FULL TIME PLANT
OPERATION IN 1990 DOLLARS.)

FIGURE 7

L1506-2

The figure does not illustrate the cost of membrane (RO) softening as this process is relatively new, the first such plants having been installed in Florida in the 1980's. Cost figures published in the literature indicate that membrane softening plants are slightly less expensive to construct and operate than brackish water RO plants. Total cost (capital and O&M) for a membrane softening plant is less than $2/1000 gallons ($600 per AF).

Two conclusions may be reasonably drawn from the cost curves. First, RO or EDR are definitely less expensive than distillation for desalting brackish waters. RO and distillation processes (MED and MVC in particular) should be considered for desalting sea water. Based on recent studies in California for desalination projects, RO will probably be less expensive than MED or MVC, at least for "single purpose" (water production only) plants.

As noted, many site specific factors affect the costs of desalination plants. The figures given here are intended to give only a general estimate of the costs of desalination. For a specific situation, a relatively inexpensive "reconnaissance level" feasibility study should be prepared to identify the major factors impacting cost to determine if desalination should be considered further.

EFFECTS OF PART TIME OPERATION ON WATER COST

As noted previously, water demands in an urban area vary from day to day and season to season. The cost of desalted water is, in most cases, more expensive than other water supply sources. These two factors give cause for considering operating a desalination plant at less than design capacity and/or shutting down the plant for several hours a day, several days a week, or for a month or longer. As also discussed previously, shutting down a desalination plant and restarting it after even an extended period of time can be done, although it is not a common practice.

It is important to realize that although a desalination plant shutdown will reduce O&M costs, amortization of the capital cost and "fixed" O&M costs continue even if production is zero. The total water cost (annual capital plus O&M costs divided by the annual production) for a plant operated at design capacity is about 50% capital and 50% O&M.

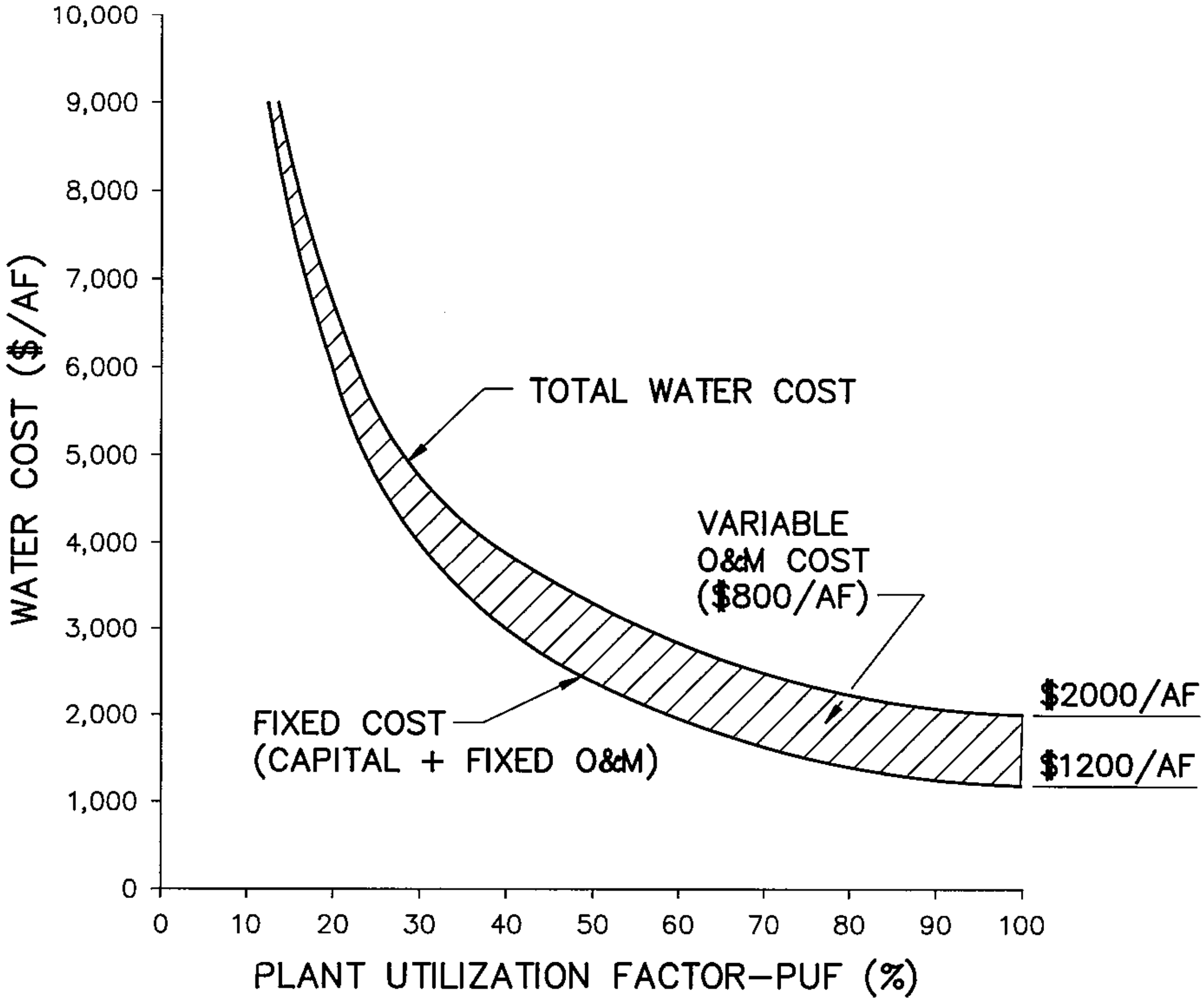
To illustrate the effects of operating a plant at less than the design capacity, Figure 8 was prepared. Figure 8 shows the increase in the cost for one AF of product water for a sea water RO plant as the "plant utilization factor" (PUF) decreases. The curves were calculated based on the following assumptions:

- o Total water cost (capital and O&M) when the plant is operated at design capacity is $2,000/AF.

- o Capital cost, when operated at design capacity, is $1000/AF.

- o O&M costs, totaling $1000/AF when the plant is operated at design capacity, consist of:

    - o Fixed O&M costs equivalent to $200/AF based on full production, and are incurred whether the plant is operated or not,



WATER COST VS. PLANT UTILIZATION FACTOR SEAWATER RO PLANT

FIGURE 8

L1506-1

- Variable O&M costs are $800/AF and are incurred only when the plant is operated.

As shown, the "total water cost" per AF produced increases rapidly when PUF falls to less than 50%. The "variable O&M cost" component of the "total water cost" remains constant at $800 per AF. The "variable O&M cost" might also be termed the "avoidable water cost" because it is incurred only when the plant is operated. The "fixed cost" might be termed the "unavoidable water cost" because it is incurred even if the plant is not operated.

This example is intended to show the impact of less than design capacity production on the water cost per AF from a single source considered independent of other water sources. In those instances where a desalination plant is only one of two or more water sources, as will be the case in most situations in California probably, a desalination plant would be operated only if:

- The other water sources are not sufficient to meet demands;

- Operating the desalination plant will achieve the lowest total water cost.

In the first case, the desalination plant would be operated up to its capacity to meet demands. Cost would be a secondary consideration as the only "extra cost" would be the "variable O&M"; the decision to incur the "fixed" costs (capital and O&M) already having been made.

In the second case, the desalination plant would only be operated if the incremental cost of operating the desalination plant (the $800/AF "variable O&M cost" on Figure 8) was less than the incremental cost of additional water from another source.

In addition to the capital costs to be paid even though a desalination plant is shut down, there are other costs. While examples are very few, there is a 3 MGD sea water RO plant at Key West, Florida, that is maintained as a backup facility in case the normal supply via a pipeline along the Florida Keys is disrupted. Feed water for the plant is from wells. The total annual cost to maintain the plant in operable condition is about $500,000 per year with no production. A 3 MGD plant can produce about 3000 acre-feet per year (AFY). The $500,000 annual maintenance cost is equivalent to about $165 per AF which is comparable to the "fixed O&M" cost of $200 per AF used in the example in Figure 8.

Another possibility, considering the relatively high energy consumption of desalination plants, is to operate a plant during periods of lower energy costs. This is particularly applicable to plants, such as RO, EDR, or MVC, using electricity, as their primary, if not only, energy source. Pacific Gas and Electric's (PG&E) power rate schedule E20 applies to facilities with power demands greater than 1000 KW. Schedule E20 would apply to desalination plants with a capacity greater than about 1 MGD. Schedule E20 offers two basic classes of service; "firm" and "non-firm" and three rate structures; "peak", "partial peak", and "off peak" also referred to as "time of day" rates. Non-firm service means that

PG&E can cut off service for not more than about 100 hours per year at their convenience. Peak power rates are charged during periods of the greatest power demands -- summer afternoons for example. Partial peak rates apply when power demands are less than peak demands and off peak rates during those periods when power demands are the lowest.

What is the impact on cost of selecting a firm or non-firm power service? What is the effect of operating a desalination plant only during partial peak and/or off peak periods? Consider a 1 MGD sea water RO plant. Table 3 below lists the annual production and power costs for the two classes of service and the three rate structures described above.

TABLE 3

POWER COSTS FOR

1 MGD SEA WATER RO PLANT

	Firm	Non-Firm
o Full Time Operation		
Annual Production	1120 AF	1120 AF
Annual Power Cost	$450,000	$430,000
o Partial Peak and Off Peak Operation		
Annual Production	979 AF	979 AF
Annual Power Cost	$340,000	$325,000
o Off Peak Operation		
Annual Production	514 AF	514 AF
Annual Power Cost	$160,000	$150,000

NOTE: Based on PG&E rate schedule E20 (1991)

The figures in the table indicate that substantial power cost savings can be realized; the off peak, non-firm power cost per AF is only 73% of the firm, continuous power cost. However, to achieve a production of 1120 AFY operating only during off peak hours would require a desalination plant with a capacity of 2.2 MGD, more than twice the capacity needed if the plant were run continuously. The cost of just the RO equipment, not considering pretreatment, post-treatment, and other design features, will be at least $3,000,000 more for the larger plant. Based on a production of 1000 AFY, the maximum realizable power cost savings would be $110,000 per year. It would take 27 years to recover the extra capital cost of just the RO equipment.

These economic factors of part-time operation are true of any project, but are noted here because of the likelihood that a plant constructed to provide supplemental water is not always going to be operated at full capacity. The impact on water cost must be considered.

COST COMPARISON - DESALINATION vs. OTHER OPTIONS

In some instances, the costs for desalinated water may be comparable to or even less than the costs for water from more "conventional" sources. For example, desalination is being considered by the Marin Municipal Water District which even in years of normal rainfall has a water shortage. In addition to a desalination plant, importing water from rivers to the north is being considered. Preliminary estimates of the total cost of imported water range from $1400 to $1600 per AF.

Monterey Peninsula Water Management District is considering desalination and construction of new dams and surface water treatment plants to meet water needs. The recently completed sea water desalination feasibility study indicates the total cost (capital and O&M) for sea water desalination will probably be less than $2000 per AF. The dam alternatives are expected to cost more than $2000 per AF and are not "drought proof".

In Southern California, Metropolitan Water District and San Diego County Water Authority are considering desalination of sea water as a possible long term solution to a growing need for water in an area with limited water sources. Desalting of brackish groundwaters using RO and EDR at costs up to more than $900 per AF are being considered to supplement imported water supplies in the near future.

These examples are intended to indicate that while desalination may appear expensive, there are cases where desalination may be less costly than other water supply options.

When considering the cost of desalination, it is appropriate to consider the impact that water shortage would have on the economy. A report prepared for the California Urban Water Agencies in April, 1991, addresses this issue. The study indicates a one-year 30% water shortage would cause a direct economic loss of $8 billion and 56,000 jobs statewide. It is important to note, however, that the firms included in the survey upon which these figures are based constituted only 53% of all of the manufacturing industries in the state employing only about 18% of the workforce. Potential "ripple" effects could multiply the economic and job losses substantially.

It is also important to note that many of the firms included in the survey reportedly were considering relocating or expanding outside of California because of the potential water supply problem. Specific types and percentages of industries considering expanding or relocating outside of California include:

- Computer and office equipment - 50%;
- Food industries - 49%;
- Aircraft/Aerospace - 41%;
- Communications and computer - 30%.

One final consideration when comparing desalination to other water supply options is reliability. Most, if not all, other water supply options are dependent on the weather in

California. Sea water desalination is not. And, at least for coastal areas, sea water desalination plants could be in or near the areas where the water is used. There is less chance the supply will be interrupted than with an imported water supply.

POTENTIAL TECHNOLOGY IMPROVEMENTS

With the cost of desalinating water high, as compared to "conventional" supplies, improvements in the technology are desirable to decrease the costs. The question arises: can improvements be made to reduce capital and/or operating costs? Are any such improvements likely to occur from "breakthroughs" resulting in substantial cost reductions or will improvements be made in small increments? The following discussion demonstrates that, although there will undoubtedly be some improvements, the only "breakthrough" that is likely to result in major cost reductions would be the development of a cheap power source.

The total cost of water from a desalination plant is the sum of two components: the amortized capital cost and the O&M cost. Table 4 shows the breakdown of these two cost components by the individual items making up the costs. The source of the figures was the Preliminary Design Report for Marin Municipal Water District's proposed sea water RO plant which was prepared in 1991. The costs are based on a two pass RO design (the first pass product water would be subjected to a second pass) to achieve the desired product water quality goals. (TDS = 170 mg/L, hardness 70 mg/L [as calcium carbonate], alkalinity 75 mg/L [as calcium carbonate]). Pretreatment would be needed because water from San Francisco Bay is the proposed water source. Post-treatment, using limestone as described earlier, is also included to meet water quality goals.

TABLE 4
COST BREAKDOWN
5 MGD SEA WATER RO DESALINATION PLANT[1]

Capital Cost	Const.[2] Cost	Annual[2] Cost	Water Cost/AF	% of Total Cost
Construction				
Intake	$5.5	$0.56	$112	5.9
Pretreatment	9.1	0.93	186	9.8
RO Desalination	17.6	1.79	358	18.9
Post-Treatment	2.6	0.26	52	2.8
Waste Disposal	1.2	0.13	26	1.4
Site Improvements	7.5	0.76	152	8.0
Delivery to Distribution	11.5	1.17	234	12.4
Total Construction	$55.0[3]	$5.60	$1,120	59.2
O&M Cost				
Chemicals		$0.29	$58	3.1
Power		1.46	292	15.5
Labor		0.45	90	4.8
Waste Disposal		0.13	26	1.4
Membrane Replacement		1.31	262	13.8
Miscellaneous		0.21	42	2.2
Total O&M		$3.85	$770	40.8
TOTALS	$55.0	$9.45	$1,890	100.0

NOTES:

(1) Plant is designed to produce 5 MGD and a total of 5000 AFY.

(2) Costs in $Millions.

(3) Includes incidental expenses and contingencies.

Table 4 shows the estimated "Construction Cost" for the facilities making up the entire project. The "Construction Cost" for each project component includes allowances for incidentals and contingencies. The "Annual Cost" is the "Construction Cost" amortized at 8% interest over 20 years. "Water Cost" is the "Annual Cost" divided by the 5000 AFY anticipated plant yield.

O&M "Water Cost" figures were calculated by dividing the estimated O&M "Annual Costs" by 5000 AFY. There are, of course, no "Construction Cost" figures included in O&M costs.

How the "Water Costs" are distributed is interesting to note: 59% for capital and 41% for O&M. In the construction cost category, only 16% of the "Water Cost" is for the RO equipment. Even a substantial reduction in RO equipment cost would not have much impact on the total "Water Cost". And, no such "breakthroughs" are expected, as discussed below.

A large factor in the "Water Cost" is the "cost of money". For example, amortizing the construction costs $2.85 million per year, assuming an 8% interest rate and 20 year payback. If the interest rate were only 6%, the annual "financing" cost would be $2.05 million, a reduction of $160 per AF, or more than 8% of the total "Water Cost" based on a yield of 5000 AFY.

In the O&M cost category, two relatively large cost items stand out: power at almost 16% of the "Water Cost", and membrane replacement at about 14%. Power costs were based on $0.06/KWH. Membrane replacement costs were based on a 3 year life for the first pass RO membranes and 7 years for the second pass membranes.

With RO, the energy required is directly related to the TDS. The osmotic pressure of sea water is about 370 psi. Yet, sea water RO plants operate at pressures ranging from 800-1200 psi. It appears, offhand, that substantial reductions in operating pressures should be achievable. However, there are several reasons this is not true. The percentage of feed water recovered impacts the pressure needed. The system needs to operate at sufficient pressure to overcome the highest osmotic pressure in the desalination equipment. At 50% recovery, the TDS in the brine is approximately twice that in the source water as the total pounds of dissolved solids introduced into the system are concentrated in one-half of the water (brine) at the last membrane in the RO system. The osmotic pressure at the last membrane of the RO system is, therefore, almost 800 psi. Lower recoveries result in less concentrated brine and subsequently, lower osmotic pressures. While lower recovery means lower pressure, it also means more membranes, more source water to be pumped and pretreated, and more brine to be disposed of. An economic analysis must be made for each project to determine the least costly desalination process design.

Temperature of the source water has a significant impact on the operating pressure of a RO plant. The lower the temperature, the higher the operating pressure to obtain the same recovery. And, since there are limitations on the pressure, more membranes may be required for cold source waters. For example, for a 1 MGD (product water) sea water RO plant with a source water temperature of 68^{o}F and a recovery of 45%, 60 pressure vessels containing 420 membranes (7 per vessel) costing about $800,000 are needed. If the sea water temperature is only 50^{o}F, as observed for California sea water, 80 pressure vessels with 560 membranes costing about $1,100,000 would be required; an increase of $300,000 per 1 MGD of capacity for the colder water.

Therefore, significant reductions in the cost of energy for a RO plant can probably only be achieved by developing less expensive energy sources. It is unlikely that "significant" reductions in required feed pressures will occur.

Another area which may reduce RO costs is improving the fouling resistance of membranes. This may include modification of membrane surface electrical charge and use of new materials. If less "foulable" membranes are developed, the replacement cost for membranes may be reduced as their "service life" would be extended. Since membrane replacement may be about 13% of a sea water RO plant's total water cost, extending membrane service life would result in a reduction in water cost. However, even a significant increase in membrane life would not have much effect on water cost and, no membrane "breakthroughs" are anticipated.

While the above discussion used a sea water RO plant as an example, the same conclusions would be reached for a distillation plant. Distillation processes have approached the limit as far as efficient use of energy. As noted in the discussion of "Desalination Process Energy Requirements", the equivalent of about 560 barrels of oil are needed to boil one AF of water at atmospheric pressure. MSF and MED processes require only about one-tenth as much; MVC only about one fortieth as much. Therefore, energy cost reductions for distillation processes will probably not be realized unless cheaper energy sources are developed.

Improvements in distillation technologies will most likely result from improvements in materials used in fabricating the equipment to reduce scaling and corrosion and increase heat transfer. There are a number of materials used in distillation equipment including aluminum, carbon steel, stainless steel, copper-nickel alloys, and titanium. The more expensive materials, such as titanium, last longer but do not transfer heat as readily as the less expensive materials, such as aluminum. The designers of distillation equipment already have, therefore, the means to affect capital and O&M costs by using more expensive, longer lasting materials, thereby increasing capital costs but reducing O&M costs, and vice versa.

With respect to scaling, improved scale inhibitors (chemicals) could increase recoveries. A limitation on distillation process recoveries is the increase in TDS in the unevaporated feed water (brine) as water vapors are extracted and condensed, especially at temperatures over about 200^{o} F. Better scale inhibiting chemicals could allow for greater TDS concentrations in the brine thus allowing more product water to be recovered. This could reduce capital and O&M costs because less source water would be pumped and heated to recover a given quantity of product water.

With the above discussion in mind, the answer to the first question is that improvements will undoubtedly be made. However, in answer to the second question, there will probably be no substantial cost reductions resulting from a "breakthrough". Desalination technologies are "mature". "Wonder" technologies have come and gone. Improvements will most likely occur as a result of efforts by individual desalination equipment designers in response to a growing demand for such equipment. Large sums of money spent in an accelerated research program will most likely not produce significant cost reductions. Money, if available, would be better spent on building desalination plants to gain more experience in how to better design and operate such facilities.

SUMMARY

Water demands in California are expected to continue to increase into the foreseeable future. Meeting these increases in demand with "conventional" water sources is becoming increasingly difficult and expensive. Desalting high TDS water, such as brackish groundwater and sea water, is being considered by more and more water suppliers. Desalting has been practiced for over 2000 years. But, only in the last few decades has desalting become a significant contributor to the world's water supply. It is expected that desalting will play an increasing role in meeting California's water needs.

There are three basic desalination process types, ion exchange, distillation, and membrane. Ion exchange is not economically feasible for desalting water with TDS levels of more than about 1000 mg/L. Electrodialysis reversal (EDR) should be considered for desalting water with TDS concentration of less than 4000 mg/L. Reverse osmosis (RO), another membrane process, can be used to soften hard water and desalt brackish waters and sea water. Distillation processes, such as Multi-stage Flash (MSF), Multiple-Effect Distillation (MED), or Vapor Compression (VC), can be used to desalt sea water. The pretreatment needs for these different processes vary. The product water qualities also vary and post-treatment may be required, especially for sea water desalting applications.

Siting a desalting plant, especially a sea water desalination plant, requires consideration of a number of factors: These include:

- Source water quality
- Process - Pretreatment, desalination, post-treatment
- Waste disposal
- Delivery of product water
- Energy availability
- Environmental

Desalination processes do require energy; the saltier the water, the more energy is required. Softening a hard water or desalting a brackish water, however, use relatively low amounts of energy. Desalting a brackish water, for example, would probably use about one-half of the energy needed to deliver water from Northern to Southern California via the State Water Project. For sea water desalination, distillation processes require more energy than reverse osmosis.

The total costs (amortization of capital plus O&M) for desalting water are approximately:

- Brackish water desalting — $700 per AF
- Sea water desalting — $2000 per AF

These are generalized cost estimates; site specific conditions can cause costs to vary widely from these figures.

Future technological discoveries may reduce the cost of desalination. However, the cost of the desalination equipment is usually only a small part of the total project cost, so even a large reduction in desalination equipment cost would have only a small impact on total water production cost. Power cost represents a substantial portion of the O&M cost, but overall, is only a small portion of the total water cost. Development of less expensive power sources would reduce costs.

While no technological breakthroughs are foreseen in the currently used desalination technologies, other processes not now used may be developed, and could result in a reduction of the cost of desalination.

GLOSSARY

To assist the reader's understanding, the following definitions are offered:

Acre-Foot (AF) - the quantity of water covering one acre one foot deep; about 326,000 gallons. One million gallons = 3.07 acre-feet.

Brine - the wastewater containing the salts removed from the source water.

Desalination (formerly Desalinization), Desalting - the reduction of Total Dissolved Solids in a source water. The process of removing salt from brine to get fresh water.

Distillation (Thermal) Processes - desalination processes requiring energy in the form of heat to evaporate feed water. The vapors are then condensed to obtain product water.

Fouling - phenomena that inhibit the passage of water through membranes including scale, biological growths, and accumulations of solids (dirt).

Feed Water - the water fed to the desalination equipment. This can be source water with or without pretreatment.

Membrane Processes - desalination processes that rely on pressure or electrical voltages and membranes to obtain product water by concentrating the dissolved solids (salts) in the feed water in the brine.

Plant Utilization Factor (PUF) - the percentage of time that a desalination plant is operated. For example, the PUF for a plant operated six months per year would be 50%.

Product Water - the desalted water delivered to the water distribution system.

Recovery - the percentage of feed water "recovered" as product water. For example, a desalination process producing 50 gallons of product water from 100 gallons of feed water has a "recovery" of 50%.

Scale - mineral deposits.

Source Water - the water as taken, particularly with respect to quality, from its source, be it ground water, surface water, or sea water.

Total Dissolved Solids (TDS) - the concentration of dissolved minerals, such as calcium, magnesium, sodium, sulfate, and chloride, in water. TDS is usually expressed as milligrams per liter (mg/L) or sometimes as parts per million (ppm).

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