CALIFORNIA. DEPT. OF WATER RESOURCES
BULLETIN.

STATE OF CALIFORNIA
The Resources Agency
Department of Water Resources

BULLETIN No. 134-69

DESALTING - STATE OF THE ART

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JUNE 1969

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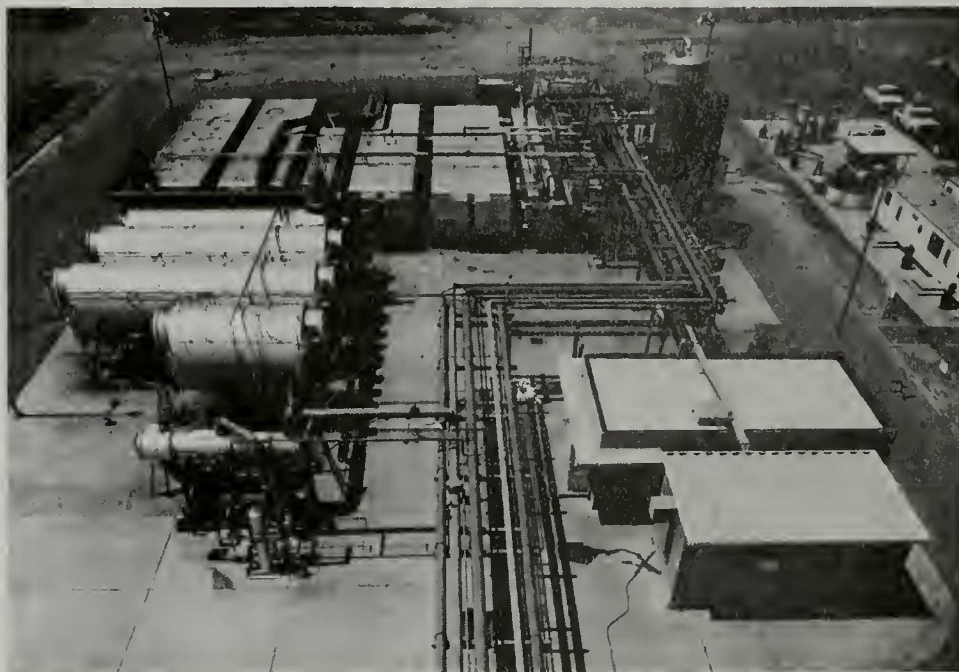
SAN DIEGO SALINE WATER TEST FACILITY, CHULA VISTA, CALIFORNIA



SENATOR CLAIR ENGLE MULTISTAGE DESALTING PLANT

MODULE OF A 50-MILLION-GALLON-PER-DAY MULTISTAGE FLASH PLANT

Courtesy of U.S. Department of Interior, Office of Saline Water

FOREWORD

Man has known for centuries that water could be obtained from the salty oceans. Only in recent times has the need stimulated commercial development of desalting processes and studies of the economics of large-capacity desalting plants utilizing the energy from the atom.

This bulletin is the first of a series concerned with the state of the art of desalting published by the Department of Water Resources for the information of the State Legislature, the California Water Commission, organizations and the public interested in the prospects of desalting for California. The Legislature authorized a departmental program in desalting in 1957. Since that time, the Department has issued two bulletins on desalting (No. 93, "Saline Water Demineralization and Nuclear Energy in the California Water Plan", December 1960; and No. 134-62, "Saline Water Conversion Activities in California", August 1963). In 1965, by the passage of the Cobey-Porter Saline Water Conversion Law (Water Code Section 12945-12949), the Legislature emphasized its intent that the Department should attempt to find economic and efficient methods of desalting saline water so that it may be made available to help meet the growing water requirements of the State.

This bulletin and succeeding issues of the series, as the state of the art and prospects of desalting warrants, will form an important part of the Department's continuing study of water sources to best meet California's water requirements. Our long-range planning will maintain its broad inquiry into the conventional reservoir and canal method of water conservation and transportation and into the possibilities of desalination, waste water reclamation, watershed management, weather modification, and every other new technology that may offer promise.

William R. Gianelli

William R. Gianelli, Director
Department of Water Resources
The Resources Agency
State of California
May 26, 1969

TABLE OF CONTENTS

APPENDIXES

FIGURES

Figure Number		Page

TABLES

ABSTRACT

The world-wide capacity of desalting plants, by the end of 1967, was about 220 million gallons per day. Construction was started on 45 plants in 1967. Most sea water desalting plants continue to employ the distillation process, while brackish water plants utilized membranes. / When large-capacity desalters are built, it is expected that the thermal distillation process, such as the multistage flash process, will be used. It is expected the large-capacity plants will use nuclear energy for steam generation. The steam will be used for the dual-purpose of power generation and water desalting. / Desalting costs are expected to be reduced substantially over the next 20 years. Such expectations are based on anticipated technological improvements in desalting processes and nuclear energy producers. / The estimated cost of desalted water from large-capacity dual-purpose facilities, based on current estimates as indicated by the Bolsa Island Project, is $120 per acre-foot at the site. This estimate includes escalation to the completion of construction of the project, assumed to be 1974-1978.

This bulletin was prepared by

Dr. Donat B. Brice
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CHAPTER I. INTRODUCTION

Desalting of sea water offers promise of becoming a supplemental source of water in certain areas of the State, and must be considered as an alternative to future water conservation projects, and as a potential source of supply to meet at least a portion of the needs of the Pacific Southwest region of the United States.

As the technology of removing dissolved solids from water is developed and the cost to carry on such processes is lowered, the financial feasibility of supplying desalted water to more areas of the State will increase. It is, therefore, incumbent on the Department to maintain an active program in the field of removal of dissolved materials from sea and brackish water, agricultural drainage water, and other water unsuitable because of chemical content or physical properties that is aimed at providing the latest information on the practicability and economic potential of desalting as an alternative source of supply. It is anticipated that developments in saline water conversion will provide new and promising means to assist in the future development of California's water resources. When one considers that almost 85 percent of the population of the State lives in the coastal zone, representing only 8 percent of the land area, it becomes apparent that desalting of sea water has the potential of benefiting many people.

The application of desalination processes could reduce the necessity for additional facilities for transporting water from distant natural sources, could improve water quality of local supplies by proper blending, and could be adopted as a measure for the treatment of highly mineralized waste waters.

Since the enactment by the U. S. Congress of the Saline Water Act in 1952, the Federal Government has been actively developing desalting technology. The Act provides for the development of practicable low-cost means of producing from sea water, or from other saline waters, water of a quality suitable for agriculture, industrial, municipal, and other beneficial consumptive uses on a scale sufficient to determine the feasibility of the development of such production and distribution on a large-scale basis for the purpose of conserving and increasing the water resources of the nation. The term "saline water" includes sea water, brackish water, and other mineralized or chemically charged water.

At about the same time the State Legislature appropriated funds for desalting research at the University of California. This research began at the University in Fiscal Year 1951-52, with the primary objective of finding and developing desalting methods for obtaining desalted water in large quantities (50 mgd or more) at low cost. "Low cost" has been interpreted to mean not more than 30 cents per thousand gallons for municipal supplies, or 12 cents per thousand gallons for irrigation waters.1/

Since 1957, the State Legislature has supported a desalting program in the Department of Water Resources. In 1965, the Legislature passed the Cobey-Porter Saline Water Conversion Law (Water Code Section 12945-12949 -- see Appendix A). The declared policy of the Legislature is set forth in Section 12946-12947, as follows:

> 12946. It is hereby declared that the people of the state have a primary interest in the development of economical saline water conversion processes which could eliminate the necessity for additional facilities to transport water over long distances, or supplement the services to be provided by such facilities, and provide a direct and easily managed water supply to assist in meeting the future water requirements of the state.
> 12947. The legislature finds and declares that a substantial portion of the future water requirements of this state may be met economically by saline water conversion facilities and that the development and utilization of such desalting facilities will contribute to the peace, health, safety, and welfare of the people of the state. It is the intention of the legislature that the department shall undertake to find economic and efficient methods of desalting saline water so that desalted water may be made available to help meet the growing water requirements of the state.

The State Legislature in 1965 also added Section 12949.5 to the Water Code for the purpose of permitting the Department of Water Resources, in cooperation with the U. S. Department of the Interior, to participate in financing the cost of site development, construction, operation, and transportation of desalted water in connection with a saline water conversion center to be located in California. This water code section also permitted the sale of desalted water by the

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1/ Howe, E. D. "Saline Water Conversion Research at the University of California" Proceedings Sea Water Conversion State of the Art Conference, June 18, 1968, Sacramento, California.

Department of Water Resources provided rates or charges would return at least all of the cost of transportation. The test center was subsequently established by the Federal Office of Saline Water as the San Diego Test Facility. The Department of Water Resources designed and constructed the San Diego Desalted Water Transportation Facility from the test center to Highland Reservoir, a distance of about 3-1/3 miles. The transportation facility cost about $400,000. It has been in operation since October 1967.

Prior to this, the Department of Water Resources has been involved in the program of the Office of Saline Water since 1958, when an agreement was signed which provided for mutual assistance in the problems of saline water conversion. When the federal demonstration plant was constructed by the Office of Saline Water on Point Loma, beginning in 1960, the Department of Water Resources provided one-half of the capital investment for the plant. The Point Loma plant was shut down in February 1964, and moved to the U. S. Naval Base at Guantanamo, Cuba, to alleviate the emergency created by the discontinuance of delivery of water from Cuba to the Base.

By written agreement, the State's interest in the Point Loma plant was transferred to a one-fourth interest in the San Diego Test Facility, not including any experimental equipment located at the facility. Three major experimental plants have been constructed by the Office of Saline Water at the San Diego Test Facility. They are the Senator Clair Engle multiple-effect multistage desalting plant, a module of a 50-million gpd multistage desalting plant, and a lime-magnesium-carbonate-feed pretreatment plant for the Clair Engle plant. A picture of the plants at the San Diego Test Facility is shown as the frontispiece.

As the unique contribution of the Department of Water Resources to the joint federal-state desalination efforts, test sections of various materials have been incorporated into the San Diego Desalted Water Transportation Facility pipeline. During fiscal year 1967-68 about 36 million gallons of desalted water were delivered through the pipeline. During the first quarter of fiscal year 1968-69 another 36 million gallons were delivered. A testing program to determine the effect of desalted water on the pipeline will be conducted. Test sections have been installed as part of the pipeline. Thus far, the pipeline has not been in service long enough to obtain data. When information is available, it will be reported in subsequent bulletins in this series.

Many nations have active programs in desalination. The largest installed capacity is in the Middle East.

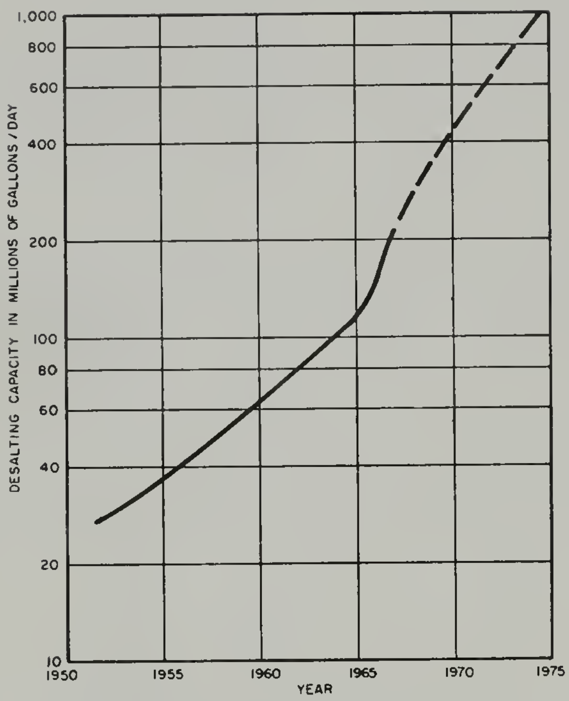


Figure 1. WORLD-WIDE DESALTING CAPACITY

A list[1/] of plant capacity by region or country is shown in Table 1. During 1967, construction was started on 45 plants in twenty countries, with an aggregate capacity of over 58 million gallons per day. Increase in capacity since the early 1950's and projections to 1975 are shown on Figure 1. Commercial plants and Federal Office of Saline Water Demonstration Plants located in the United States are shown on Figure 2. The vast majority of the 288 desalting plants located in the United States are used by powerplants, industries, and the military.

The Office of Saline Water now has a broad research and development program to advance the technology of desalting. During fiscal year 1953, OSW spent $70,000. Expenditures were modest during the early years. It was not until the mid-1960's that a large expansion was made in the program. The expenditures during the past fiscal year were about $26 million. The larger budget has permitted the OSW to substantially expand the research and development work it can support. At the beginning of 1968, the OSW had 388 active contracts and grants.[2/] For the Fiscal Year 1967-68, it awarded 316 contracts totaling $23,004,052 in connection with its program for seeking low-cost, efficient desalting processes through the research and development work sponsored at various organizations. About one-fourth of the contract amount for research and development work was awarded to California firms or for work to be done in connection with desalting activities located in California. A list of the contracts in California by company, title, and amount is given in Appendix B. The total contract amount for work in California for Fiscal Year 1967-68 was $6,671,248.

1/Desalting Plants Inventory Report No. 1, United States Department of the Interior, Office of Saline Water, January 1, 1968.

2/Hearing Before a Subcommittee of the Committee on Appropriations House of Representatives, Ninetieth Congress, Second Session, Department of Interior and Related Agency Appropriation for 1969, Office of Saline Water, March 4, 1968.

TABLE 1

DESALTING PLANT CAPACITIES - PLANNED OR UNDER CONSTRUCTION[1/]

(Producing 25,000 gallons per day or more)
As of December 31, 1967

Region or Country	No. of Plants	Total Plant Capacity (Mgd)[2/]
United States	288	39.6
United States Territories	15	7.5
North America except USA and its Territories	11	8.4
Caribbean	24	16.9
South America	20	3.7
Europe (Continental)	77	26.3
England and Ireland	62	14.1
Australia	7	1.9
Asia	18	2.1
Middle East	63	50.1
Africa	35	10.8
Union of Soviet Socialist Republic	7	40.9
TOTAL	627	222.3

1/ Desalting Plants Inventory, Report No. 1, United States Department of the Interior, Office of Saline Water, January 1, 1968.

2/ Mgd - million gallons per day

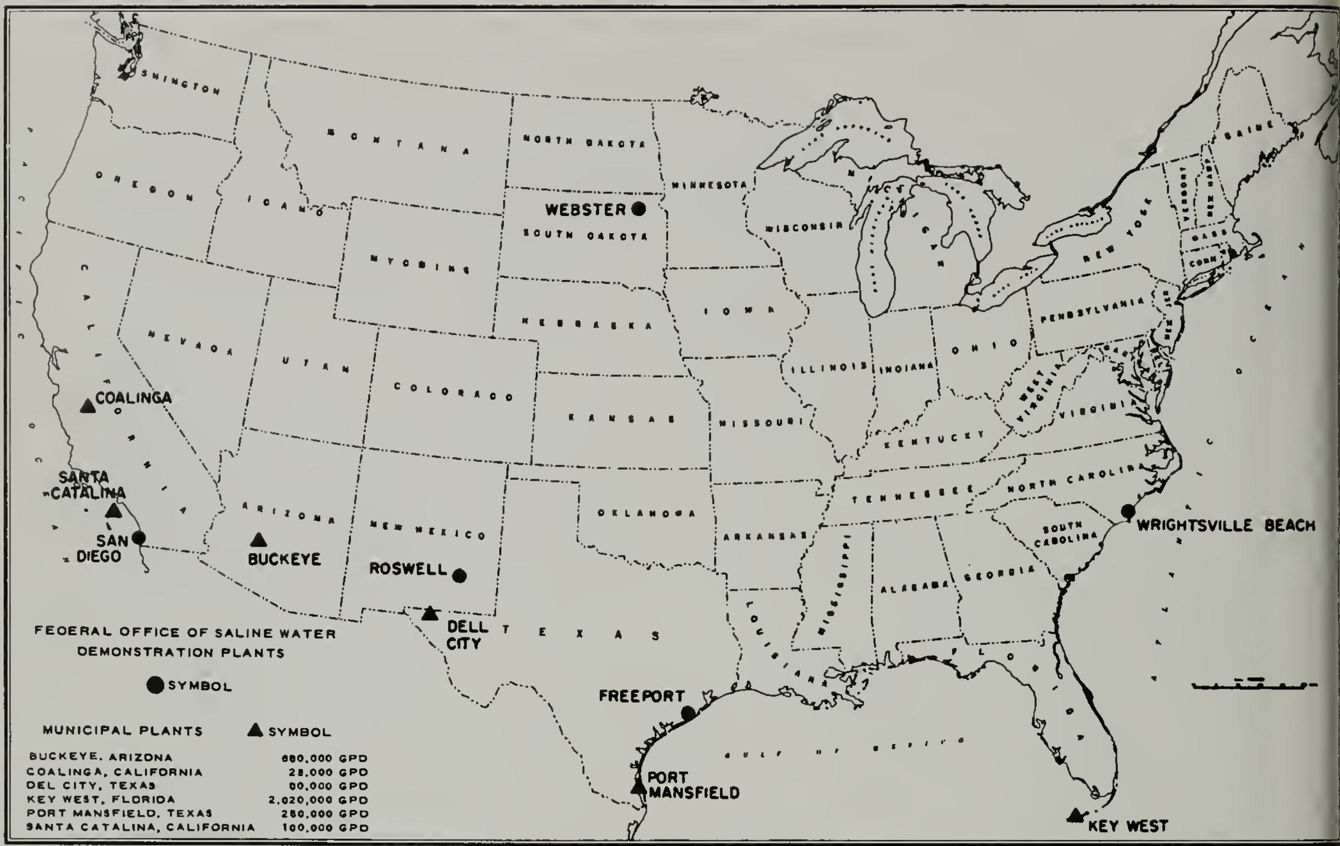


Figure 2. MUNICIPAL DESALTING PLANTS AND FEDERAL DEMONSTRATION PLANTS

CHAPTER II. DESALTING PROCESSES

Introduction

The principal conversion process employed at the present time for sea water desalting is distillation. The multistage flash distillation process is the one most widely used today. For brackish water desalting a membrane process is used. Electrodialysis and, more recently, reverse osmosis are the processes used. Other processes include freezing, humidification, and chemical. Solar evaporation is the best known example of the humidification process and ion exchange of the chemical process.

For the large-capacity sea water desalters that may be of interest in California for a supplementary water supply beyond 1990, the distillation processes now offer the most promise. The multistage flash evaporator, the vertical tube evaporator, or a combination, lend themselves to large-capacity operation, and operation in conjunction with power production where the steam supply can be used for the dual purpose of power production and desalting.

Two membrane processes -- electrodialysis and reverse osmosis -- are available for brackish water desalting. In the future, membranes may be developed for sea water applications.

Other processes that may find application include vapor compression and freezing. Solar evaporation may be used for small-capacity operations and ion exchange for pretreatment of feed to other desalting processes.

Multistage Flash Distillation

A typical process flow diagram of a multistage flash distillation plant (MSF) is shown in Figure 3. While not shown on Figure 3, sea water enters the plant through a submarine pipeline and intake pit. The water first passes through a screen and is then picked up by a sea water intake pump located behind the screen. The sea water may be introduced directly from the intake pit to the evaporator heat rejection section. Alternately, it may first be pumped to a settling tank and storage tank if such is provided.

Dissolved carbon dioxide and air must be removed from the sea water to very low levels to mitigate scaling, to retard corrosion, and to minimize the quantity of noncondensables which would impair heat transfer rate. To facilitate carbon dioxide (CO_2) removal, sulfuric acid is injected into the sea water makeup stream as shown on Figure 3. The resulting pH reduction converts bicarbonate and carbonate to CO_2 which is degassed in an atmospheric degassing tank and then steam stripped from the sea water feed.

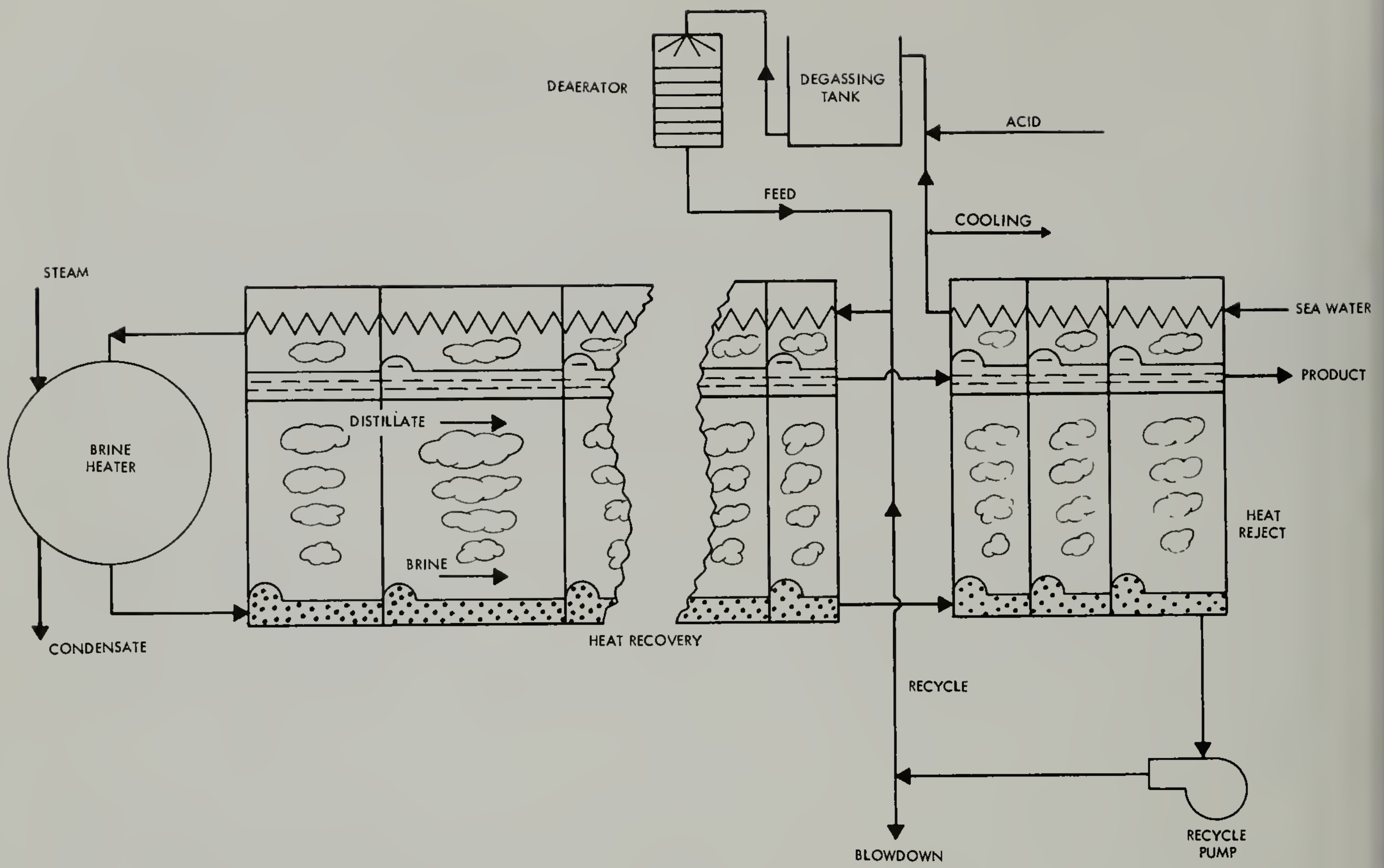


Figure 3. MULTISTAGE FLASH DISTILLATION

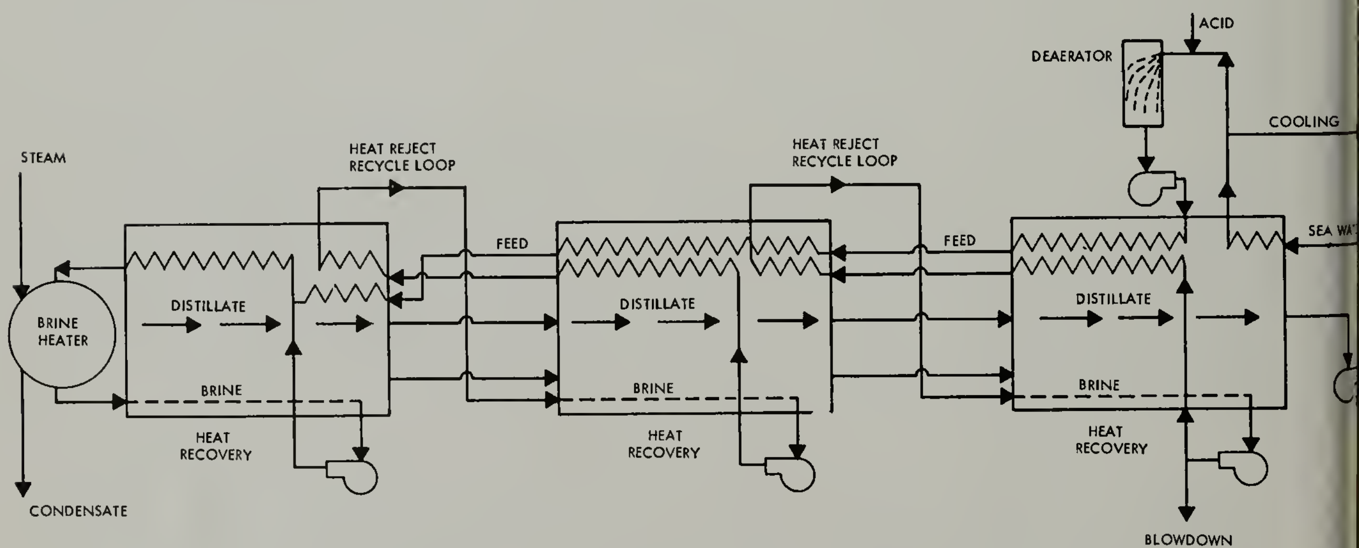


Figure 4. MULTIPLE-EFFECT MULTISTAGE FLASH DISTILLATION

Sea water in passage through the tubes of the heat rejection section is partially heated. The coolant portion of this stream is then returned to the ocean through an outfall line. Acid is proportioned into the remainder as it flows to an atmospheric degassing tank. A series of overflow and submerged weirs are provided to assure thorough mixing of the acid with sea water and to promote evolution of the CO_2 from the water.

From the degassing tank, the sea water makeup stream flows to a vacuum deaerator. This vessel is operated at the same absolute pressure as the lowest temperature flash stage. In the deaerator, the remaining dissolved CO_2 and the dissolved air are stripped from the sea water by the combined effect of the vacuum and stripping steam. A vacuum is maintained by a steam jet ejector system. The deaerated sea water serves as the makeup to the plant. It is mixed with the recycle stream. These two streams -- now combined -- are pumped through the remaining tubes of the evaporators and the brine heater before being introduced into the shell side of the highest temperature stage. The shell-side brine then cascades from stage to stage as a result of the pressure differential maintained. In each stage some of the water flashes from the brine solution. It is condensed on the tubes of the evaporator and caught in troughs positioned below the tubes. The distillate also cascades from stage to stage.

Finally, the shell-side brine and the distillate reach the lowest pressure and temperature stage. At this point, the distillate is pumped from the system as product. The brine in excess of that required for recycle is pumped from the system and discharged to the ocean as blowdown. The remainder of the brine is mixed with the makeup and recycled through the system.

Multiple-Effect Multistage Distillation

The multiple-effect multistage process (MEF), as shown in Figure 4, utilizes several simple multistage flash systems arranged in series. Each system, termed an effect, operates over a part of the total temperature range. Brine is recycled within each effect. Fresh sea water is added to the first or highest temperature effect as makeup. Each succeeding effect receives blowdown from the previous effect as its makeup. A steam-heated brine heater supplies the heat to the top temperature effect. Each succeeding effect makes use of the heat rejection stages of the previous effect as its brine heater.

Sea water makeup is heated in separate condenser bundles to the first effect blowdown temperature. At this point, it is mixed with the first effect recycle stream before entry to the first effect heat recovery section.

In other respects, the plant is similar to the MSF plant. Sea water coolant is circulated through the heat rejection stages of the last effect. Carbon dioxide, dissolved air, and other gases are removed from the sea water makeup before entry to the cycle. Noncondensables vent from each flash stage to prevent blanketing of the heat transfer surface.

In operation, the flash evaporators in this plant are identical to those in a standard multistage flash plant, except that the makeup and recycle brine flows are heated in separate condenser bundles until reaching the heat recovery stages of the top temperature effect. At this point, they are combined to a single stream.

As in a MSF, brine from the brine heater flashes into the first stage flash chamber of the top temperature effect of the MEF. This brine flashes from stage to stage in the first effect in a manner identical to a standard flash plant. In the last stage of each effect, the flashing brine is divided into two streams. One stream is recycled and the other stream is blowdown to the next effect, where it serves as makeup to that effect. This is repeated in each effect until the flashing brine reaches the last stage in the bottom temperature effect where the blowdown is rejected to the ocean.

Distillate is collected beneath the condenser bundles. It is cascaded from stage to stage and from one effect to the next. Total distillate flow from the last stage of the bottom temperature effect is pumped from the system as product.

Vertical Tube Evaporation

A forward-feed, multiple-effect, falling film, vertical tube evaporator (VTE) with a multistage flash evaporator for a feed heater as shown in Figure 5, is described on the succeeding pages. Briefly, the vertical tube effects and the flash feed heater constitute parallel streams for the flow of brine and heat. About three-fourths of the total heat supplied to the first effect is used to vaporize a portion of the sea water feed passing through the first effect. This heat is passed as latent heat from effect to effect as the vapor from each effect condenses in the succeeding effect creating an equivalent amount of vapor from the brine flowing isothermally through the tubes of that effect. In this fashion, the effects create over 80 percent of the product. The remainder of the total heat supplied to the first effect completes the heating

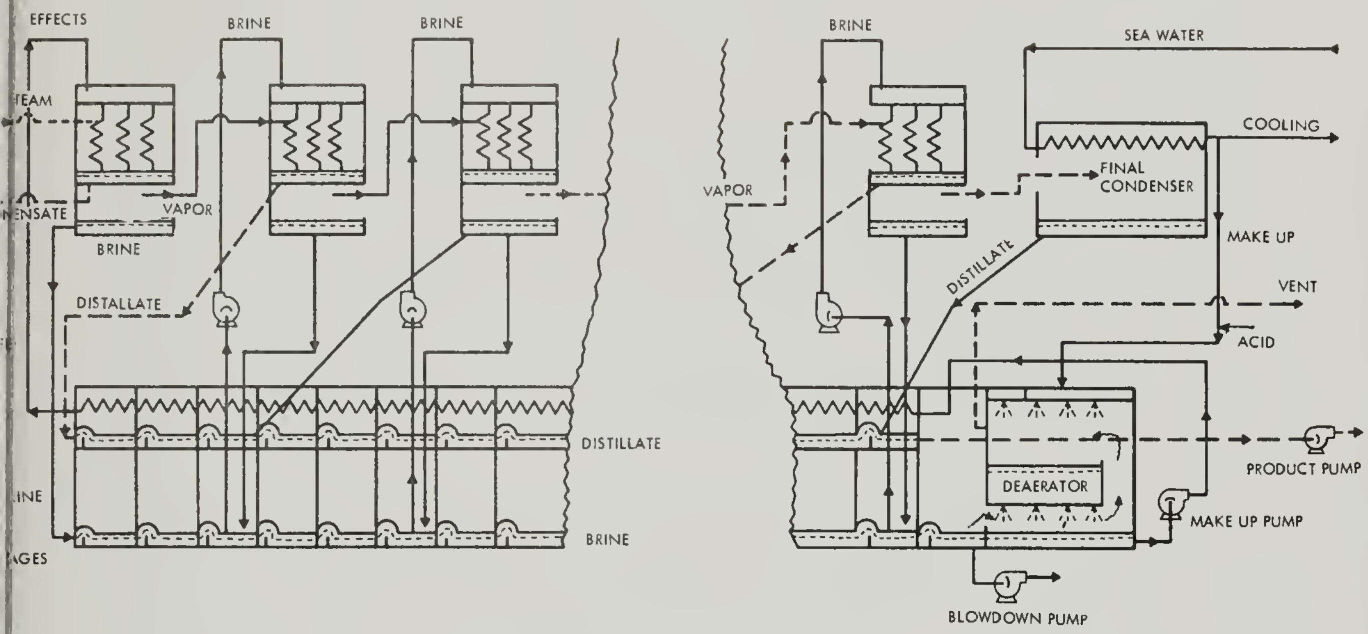


Figure 5. VERTICAL TUBE EVAPORATOR

of the sea water feed to its maximum temperature. The flash feed heater accomplishes the regenerative heating of the feed; supplies brine at the appropriate temperature to each effect; cools the cumulative distillate; and produces the remainder of the total distillate.

In a typical case, after the incoming sea water has been screened, it is pumped into the tubes of the final heat rejection condenser where it is partially heated. A substantial portion of the sea water from the final condenser is returned directly to the ocean as a heat rejection stream. The remainder of the sea water from the final condenser is acidulated and pumped to the deaerator.

The deaerated stream is then pumped into the condenser tube bundles of the multistage flash evaporator at the lowest temperature stage. The sea water feed passes through all of the stages as its temperature is increased by the heat from condensing vapor in each stage.

The entire feed stream then goes to the brine chest of the first effect, passes through individual spray nozzles, and into the vertical tubes where steam from an outside source raises the feed to its maximum temperature and vaporizes several percent of it. The brine then flows into a distribution chamber from which it passes through an orifice into the first flash evaporator stage where flashing occurs, cooling the brine to the saturation temperature of that stage. The vapor passes through the entrainment separator, condenses on the feed heater bundle, and falls into the distillate tray. The brine and distillate then flow separately through orifices into the next lower temperature and pressure stage where both streams flash down to the saturation temperature of that stage. The vapor from both streams condenses on the condenser tube bundle and falls down to join the distillate stream. This process continues through to the lowest temperature stage at which point the distillate is pumped out to the product water system. The brine, from the lowest temperature stage, is flashed back to provide the stripping steam for the deaerator before it is pumped back into the ocean.

The vapor that is generated in the first effect disengages from the brine at the tube exit, passes to the next lower temperature effect, condenses on the tubes and is collected and combined with the distillate stream in the first flashing stage. For each succeeding vertical tube effect, brine is pumped to the brine chest from a flash stage at the same temperature as the VTE effect. Vapor is generated as the brine flows down the vertical tubes and the vapor flows downward with the brine. The brine, still at the same temperature as the flash stage from which it was pumped, returns to the stage. The vapor disengages from the brine after emerging from the lower end of the vertical tube, passes through the entrainment separator, condenses in the next effect and is sent to the distillate stream in the flash stage at the same temperature. This process continues through all of the effects and in the last effect the vapor released is condensed in the final condenser, and the distillate sent to the distillate stream in the last flash stage. In this fashion, all of the heat of vaporization supplied to the first effect is passed as latent heat to the final condenser, each effect has the same heat duty, and there is virtually no gain or loss of heat between the vertical tube evaporator and the multistage feed heater.

Reverse Osmosis

Saline water is pumped under high pressure and contacts an osmotic membrane as shown schematically in Figure 6. Osmosis depends on a membrane that is selective in what can pass through it. In the case of saline water, the water can pass but the salt ions cannot. Such a selective membrane is called semipermeable. When a semipermeable membrane is used to separate fresh water from salt water, there will be a tendency to equalize the salt concentrations by a flow of water from the fresh water side into the salt water. This flow of water is called osmosis. If a pressure is gradually applied to the salt side, it will first impede the flow and finally when the pressure exceeds the osmotic pressure, it will cause the flow to reverse so that the water flows from the salt water into the fresh water, thereby accomplishing desalting of the salt water.

The amount of pressure required depends on the salt concentration, hence more pressure is required to desalt sea water than brackish water. The reverse osmosis units are used industrially and for desalting brackish water. Work is being done to improve the membranes for sea water desalting. The plate and frame[1/], tube type[2/], spiral wound[3/], and hollow fiber[4/] membrane arrangements are typical of those used in commercial reverse osmosis processes. These membrane arrangements are shown in Figure 7.

1/ Loeb, S. and Milstein, F. Design, Development and Testing of a 500 Gallon per Day Osmotic Sea Water Desalination Cell. University of California, Los Angeles, Report No. 62-52, November 1962.
2/ The Havens Reverse Osmosis System, undated brochure by Havens Industries, San Diego, California.
3/ Reverse Osmosis, undated brochure by Gulf General Atomic, San Diego, California.
4/ Robinson, W. T. "Reverse Osmosis". Proceedings Sea Water Conversion State of the Art Conference, June 18, 1968, Sacramento, California.

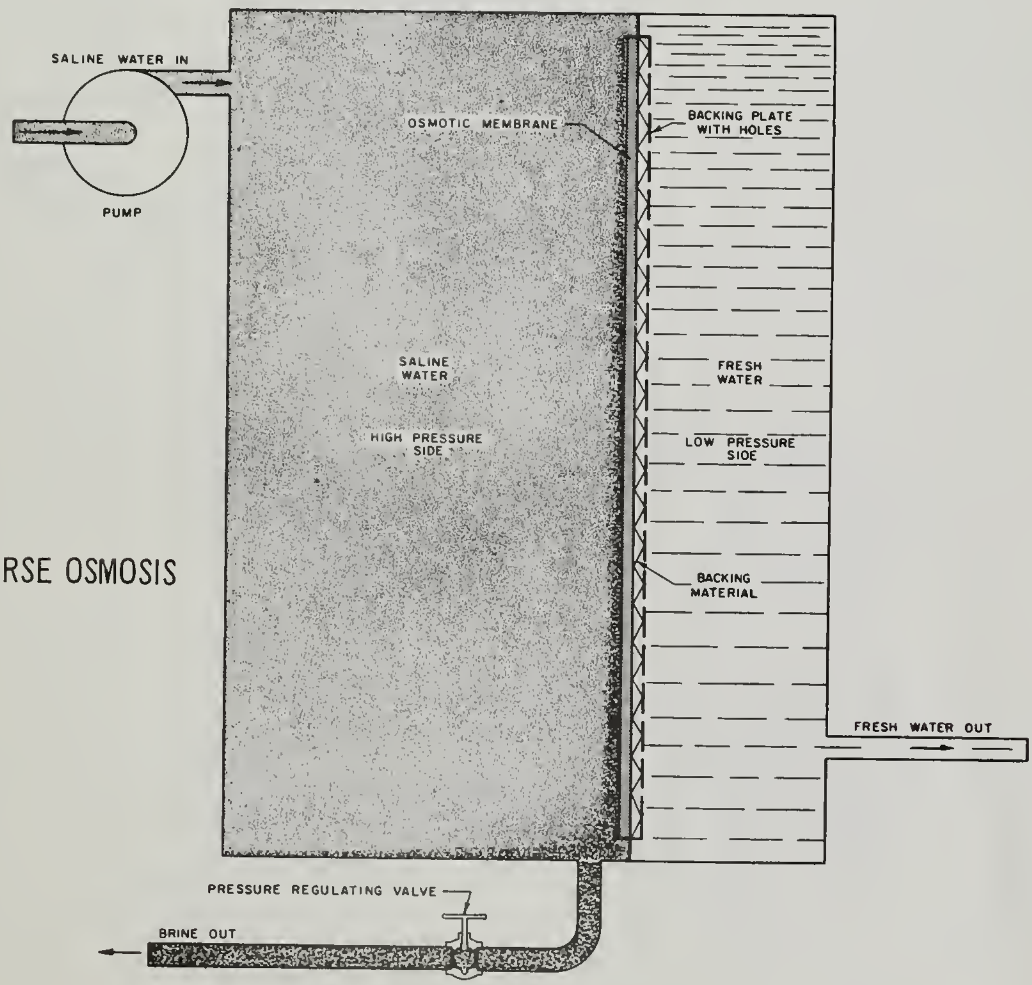


Figure 6. REVERSE OSMOSIS

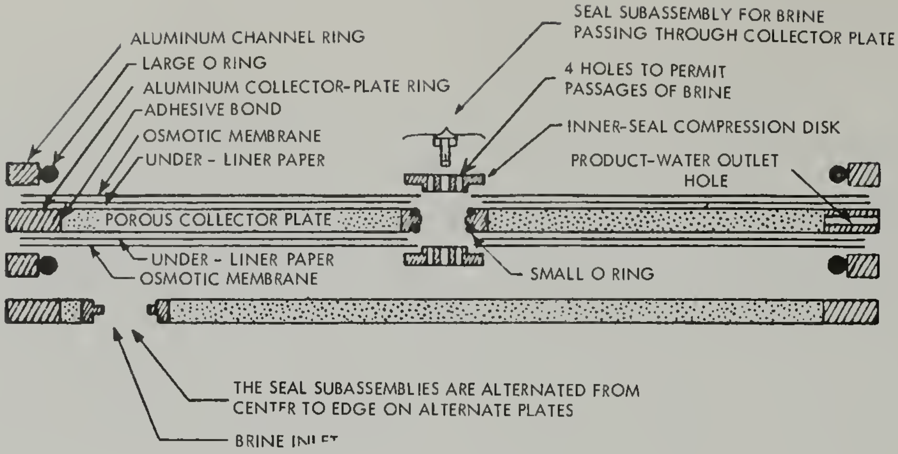
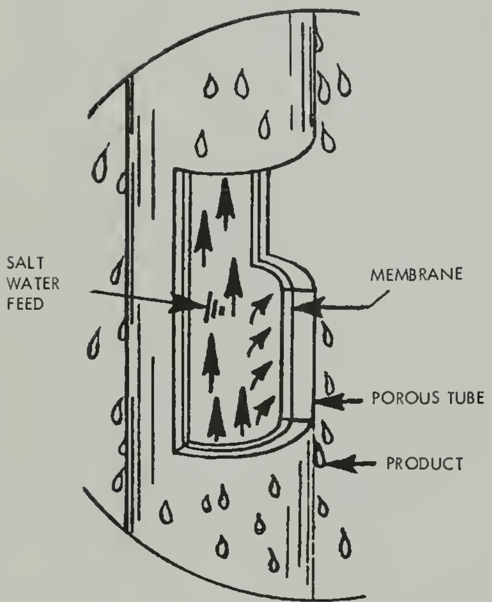
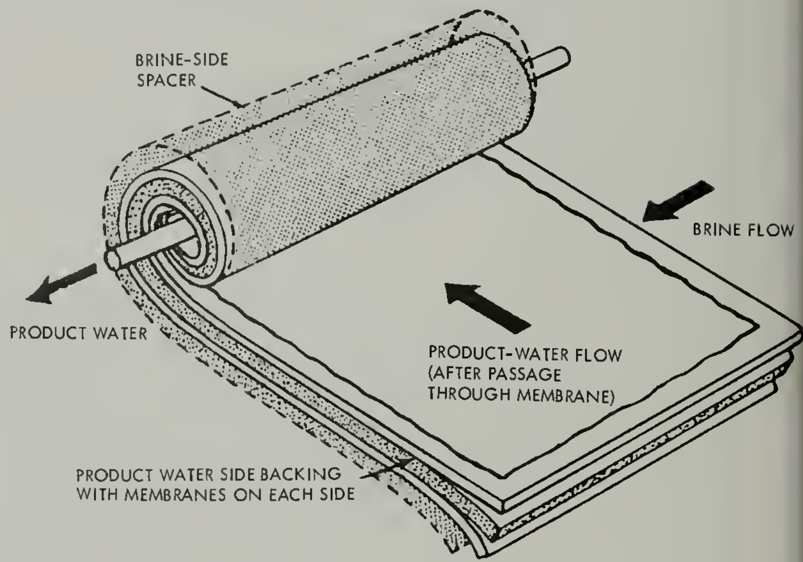


PLATE AND FRAME



TUBE TYPE



SPIRAL WOUND

HOLLOW FIBER (HIGHLY MAGNIFIED)

Figure 7. TYPICAL REVERSE OSMOSIS APPARATUS

Electrodialysis

By contrast with reverse osmosis, in electrodialysis the salt ions pass through membranes. In this process of ion transport through the membrane the driving force is an electrical field applied across the membrane as shown schematically in Figure 8. Two types of membranes are used. Cation permeable membranes permit only positive ions such as sodium, calcium, and magnesium to pass through the membrane. Anion-permeable membranes allow only negative ions such as chloride, carbonate, and sulfate to pass through the membrane. The net result is as shown in Figure 8. Alternate passages become depleted in both anions and cations, thereby becoming less salty. By proper current, flow and passages, the product salt concentration can be controlled to the desired level. The higher the salt concentration of the feed, the more electrical energy and the more passes are required to obtain a potable product. For these reasons, electrodialysis is more economical for brackish water containing no more than 5,000 parts per million of total dissolved solids than for sea water. Commercial units have found wide acceptance for desalting brackish water throughout the world. The first community in the United States to utilize this principle was Coalinga, California, which has had a unit in operation since 1959.

Vapor Compression Distillation

Another thermal process is vapor compression distillation. In this process, as shown in Figure 9, the compressor takes water vapor from the evaporator-condenser and compresses it. This compression of the vapor results in the vapor having both a higher pressure and temperature. The vapor passes through the tubes in the evaporator-condenser, giving up its heat to the salt water and, thereby, condensing into fresh water. Heat exchangers are also used to conserve heat. This process has found application for small-capacity plants. It may also be used in connection with one of the other thermal processes as shown in Figure 10.

Freeze Separation

Most of the freeze-separation processes have similar functional components. This is due to the fact that the freezing processes utilize similar mechanisms for ice formation and separation of ice from brine. An examination of the vacuum freeze-vapor compression method, as shown in Figure 11, will serve to illustrate this point. This scheme is a direct refrigeration method which utilizes the water as a refrigerant and then compresses the resulting water vapor. The incoming sea water is cooled in a heat exchanger to conserve energy. It is then sprayed into a freezing chamber maintained under

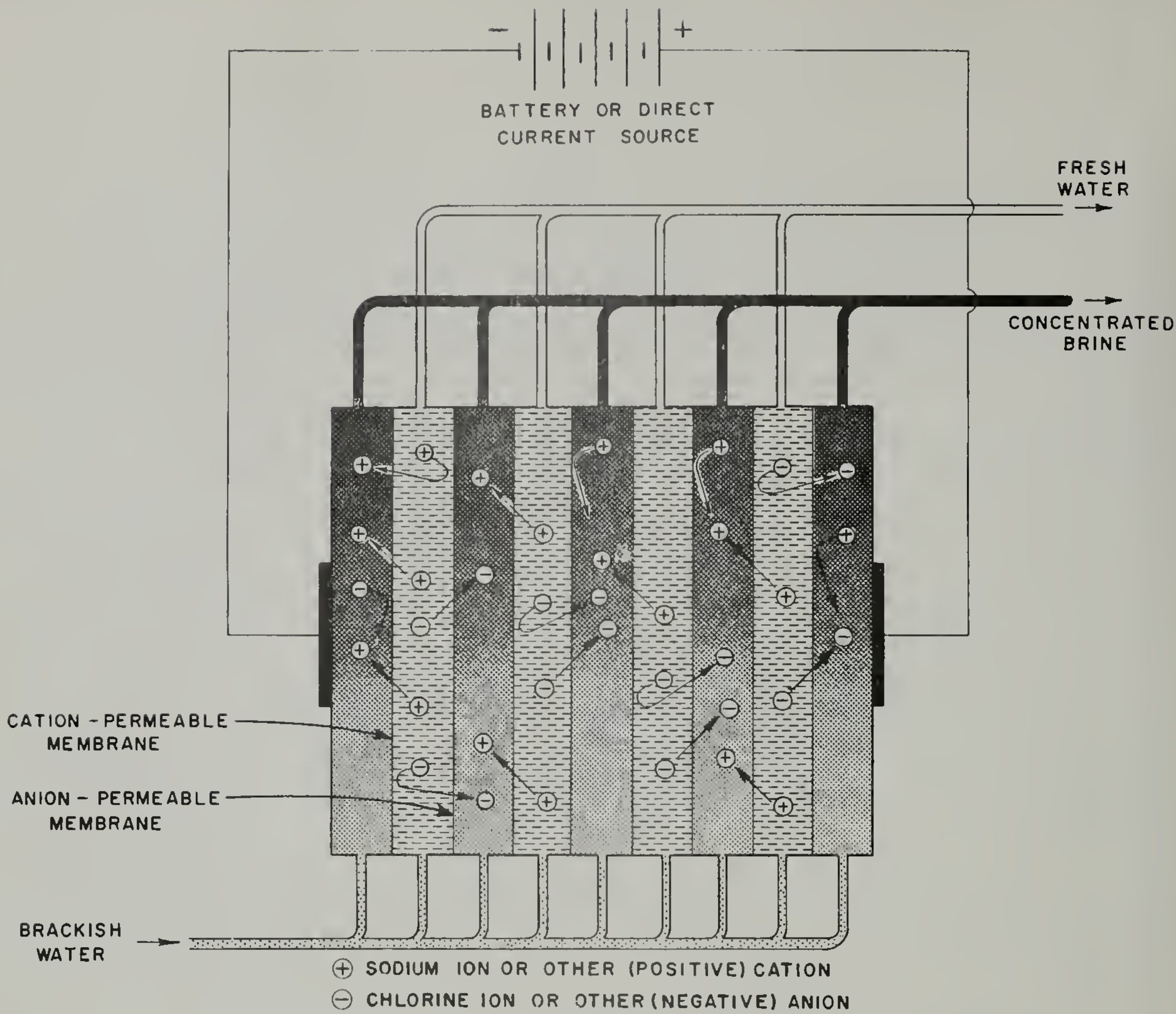


Figure 8. ELECTRODIALYSIS PROCESS

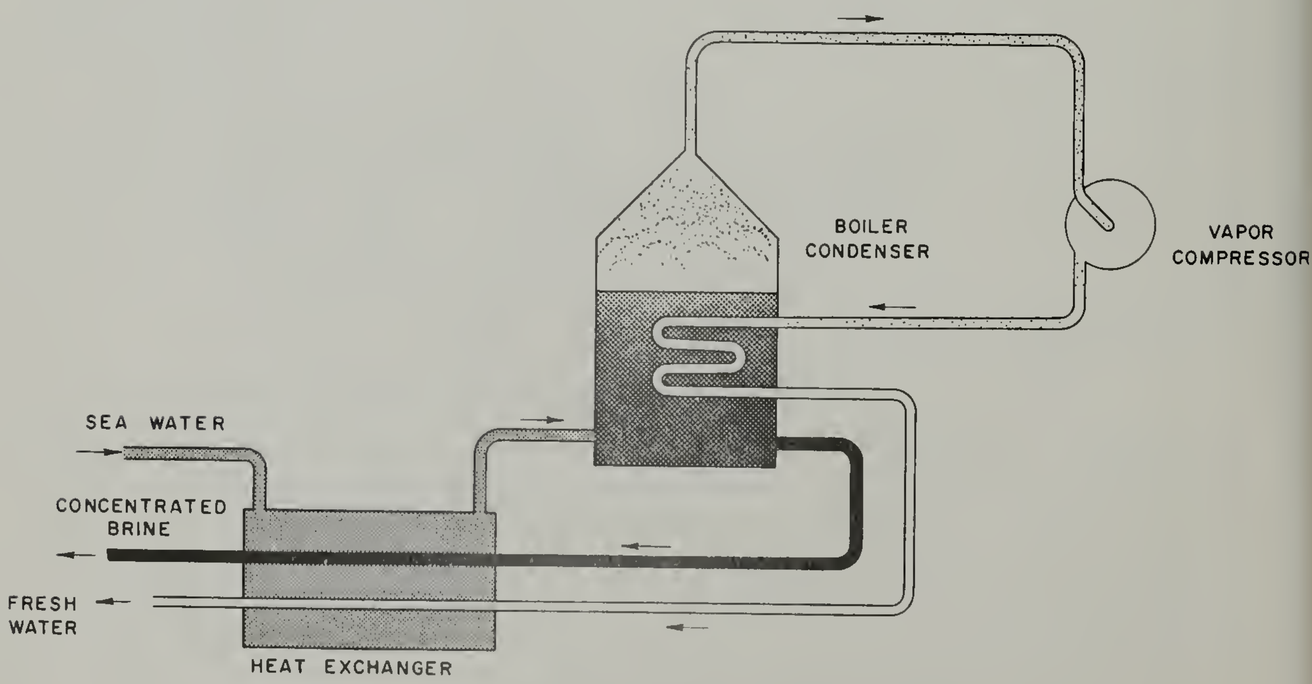


Figure 9. VAPOR COMPRESSION PROCESS

sufficient vacuum to cause ice to form. The slurry of ice and brine is led to a separator with the ice going to a melter. Cold is recovered from the melted ice before it leaves the system. The water vapor formed in the freezer is compressed and led to the melter where, through exchange of heat, the ice is melted and the vapor condensed and both become product water.

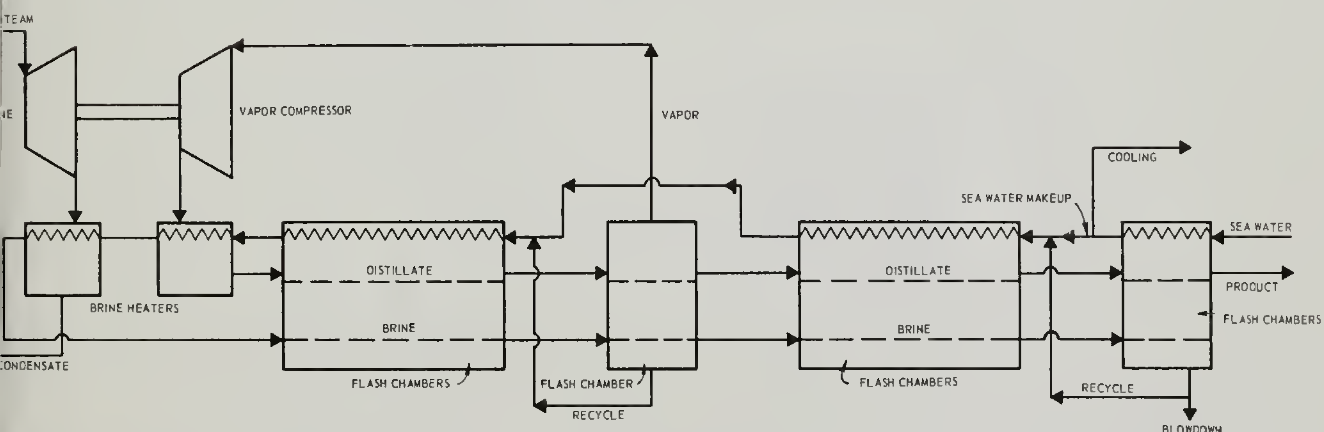


Figure 10. VAPOR COMPRESSION COMBINED WITH MULTISTAGE FLASH DISTILLATION

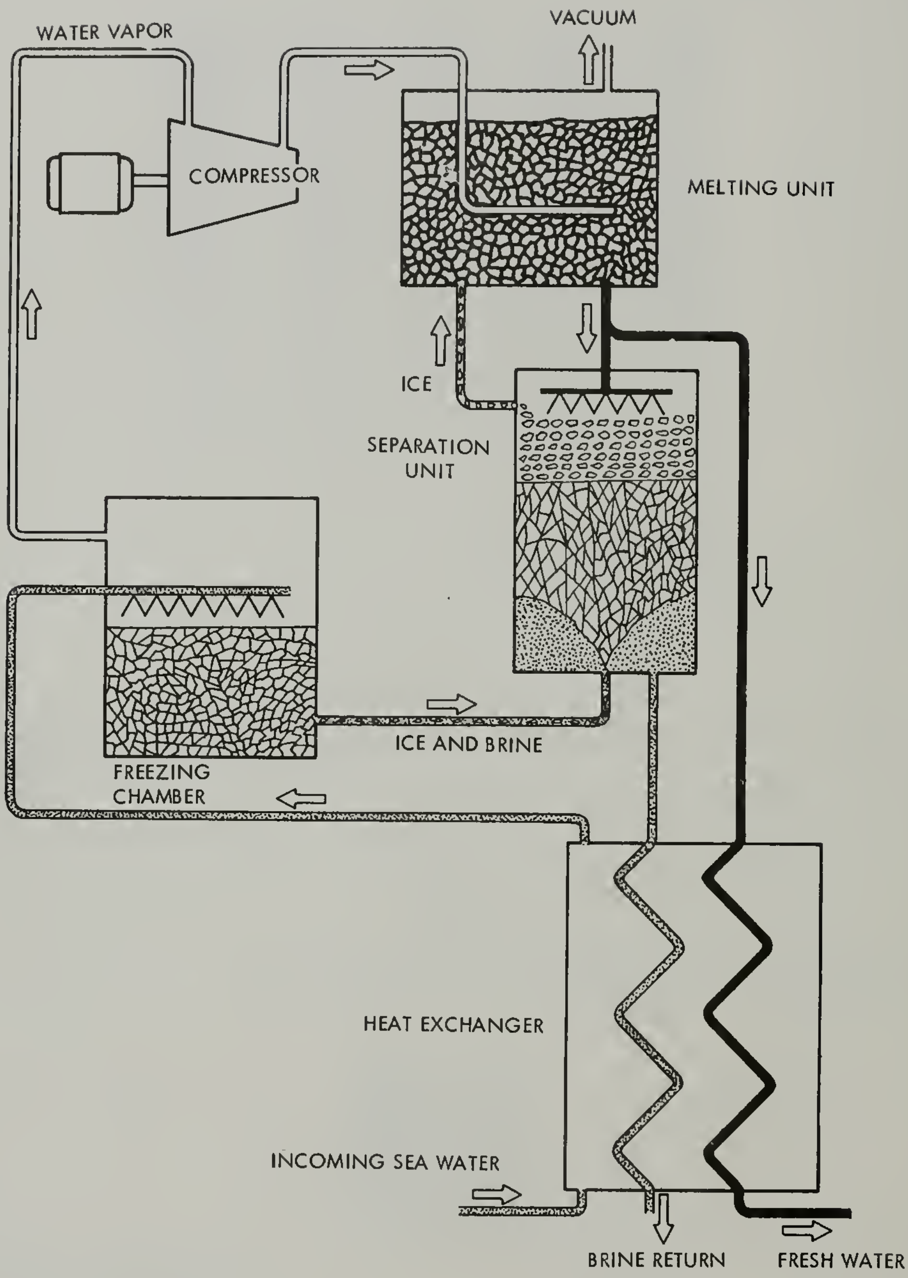


Figure 11. VACUUM FREEZE-VAPOR COMPRESSION PROCESS

CHAPTER III. DESALTING ENERGY REQUIREMENTS

All of the desalting processes require a considerable expenditure of energy to separate the water from the salt. The vapor pressure of sea water at any given temperature is less than the pressure necessary for recondensation of the vapor to the liquid. Thus, the water must not only evaporate from the sea water, but the vapor must either be cooled or compressed to effect recondensation. The compression energy is that required to separate water molecules from the ions in the sea water. This amount of energy or work of separation represents the absolute minimum for separation of water from the saline solution regardless of the desalting process used. It can be used as a yardstick to compare actual processes with the minimum energy. In any event, it is unlikely in practical cases that the actual energy required will ever be less than, say, ten times the minimum.

The minimum work of separation is the thermodynamic reversible work at zero recovery; that is, no product is produced. This work may be represented by the equation:

$$-W = \Delta F = RT \ln a$$

Where W = Minimum work of separation

ΔF = Change in free energy

R = Universal gas constant

T = Absolute temperature

a = Activity of water in salt solution

Fabuss and Korosi[1/] have calculated water activities for a standard sea water and for its concentrates based on experimental measurements of vapor pressure. At 25°C the activity of water in a standard sea water is 0.982. The minimum work of separation is, therefore:

$$W = RT \ln a$$

$$W = -(1.9872)(298.2)(\ln 0.982)$$

$$W = 10.77 \text{ cal/gram mol}$$

1/ Fabuss, B. M. and Korosi, A. "Thermophysical Properties of Saline Water Systems", U. S. Office of Saline Water Report No. 189, May 1966.

This is equivalent to about 2.63 kwhr/1000 gal (0.695 kwhr/M^3), which is in good agreement with the value of 2.67 kwhr/1000 gal (0.706 kwhr/M^3), calculated by Stoughton and Lietzke1/ from osmotic coefficients and neglecting any precipitation of calcium sulfate. To concentrate to twice sea water at isothermal conditions of 25°C. in a completely reversible manner, the minimum energy2/ is about 3.8 kwhr/1000 gal (1.0 kwhr/M^3). Figure 12 is a plot of the minimum energy of separation of water from sea water as a function of temperature, and Figure 13 is a plot as a function of the percent recovery of water.1/ The minimum energy of separation can also be calculated for selected conditions from the activity data3/ presented in Figure 14.

For practical processes which must balance energy expenditure or efficiency against the capital cost of the apparatus necessary to obtain a certain efficiency, many irreversible effects must be considered. These include fluid friction, pressure losses, temperature differences necessary in heat exchangers, heat losses, fluid mixing when there is a temperature or concentration difference and mass transfer with finite concentration gradient.

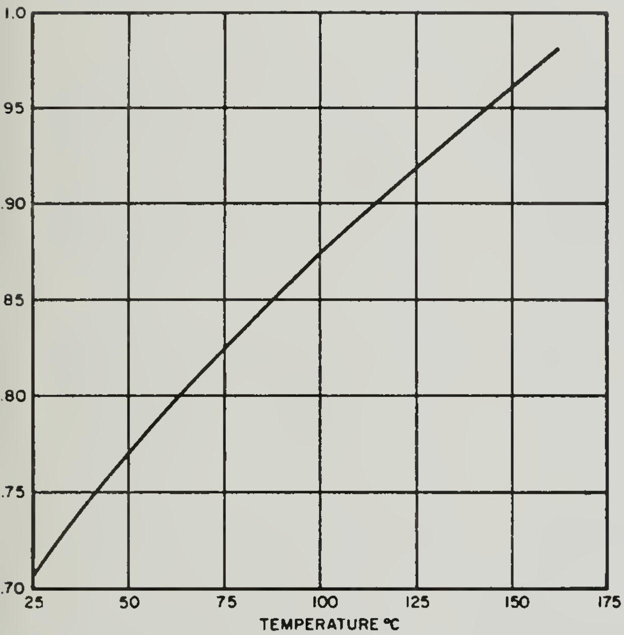
In an optimization for minimum cost, the primary consideration is the cost of energy and capital investment. The two items normally represent 80 percent or more of the total water cost. This can be illustrated as shown in Figure 15 by plotting water cost against plant efficiency for the energy and capital components. For any given energy cost as the plant efficiency is increased, less energy is required for a specified plant output. Hence, the energy cost component of the water cost per unit of output decreases with increase in plant efficiency.

In order to make the plant more efficient, for example, with the distillation processes, more heat transfer condenser surface is required. In order to accommodate more condenser surface, other items must also be increased. This results in a higher capital cost as the plant efficiency is increased. Hence, the capital cost component of the water cost per unit of output increases with increase in plant efficiency. If these two curves are added, a curve with a minimum is obtained, as shown on Figure 15.

1/ Stoughton, R. W. and Lietzke, M.H. "Calculation of Some Thermodynamic Properties of Sea Salt Solutions at Elevated Temperatures from Data on NaCl Solutions". Journal of Chemical and Engrg. Data, 10, No. 3, 254, July 1965.

2/ Principles of Desalination. Ed. K. S. Spiegler, Academic Press, 1966, New York, p. 357.

3/ See reference (1/) on preceding page.



: 12. MINIMUM ENERGY REQUIREMENTS FOR DESALTING SEA WATER AT VARIOUS TEMPERATURES

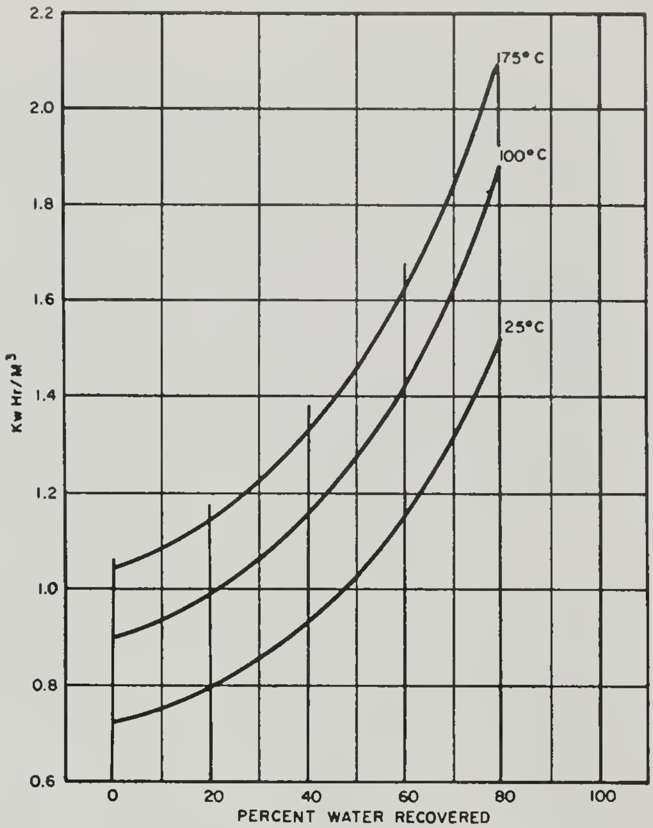


Figure 13. MINIMUM ENERGY REQUIREMENTS FOR RECOVERY FROM Na Cl SOLUTIONS AS A FUNCTION OF PERCENT RECOVERY

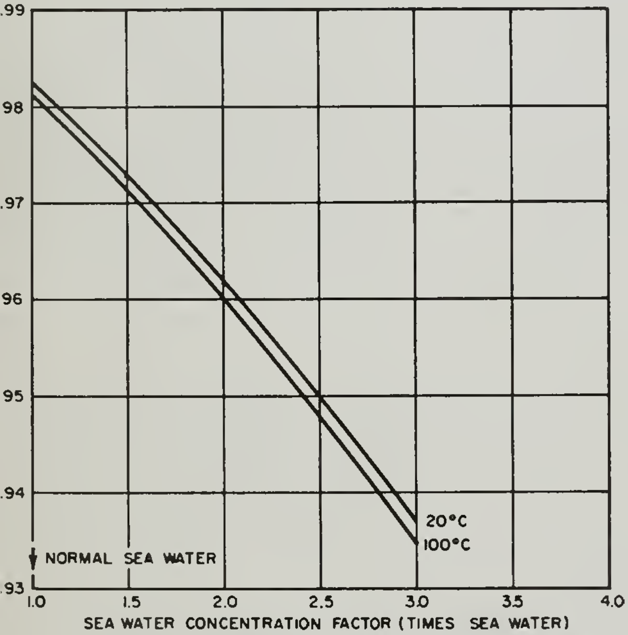


Figure 14. ACTIVITIES OF WATER IN SEA WATER AND IN SEA WATER CONCENTRATES AS A FUNCTION OF TEMPERATURE

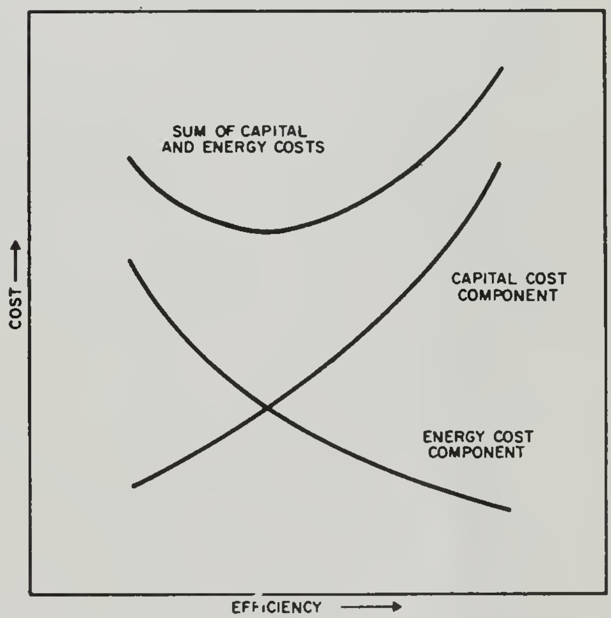


Figure 15. VARIATION OF ENERGY AND CAPITAL COST WITH PLANT EFFICIENCY

The minimum point on the curve is the least costly desalted water that can be obtained for the conditions assumed. The plant would then be built to operate at the efficiency determined from Figure 15.

For the Point Loma[1/] multistage flash demonstration plant on a typical operating day[2/] during February 1964, the thermal input to the plant was about 320,000 kwh/day. For the plant output of 1,028,000 gallons per day of desalted water, this is equivalent to about 320 kwh/1000 gal, which is more than 80 times the minimum energy of separation for a plant operating with the Point Loma conditions. Since in this plant the major pumps were steam turbine drives, most of the energy input to the desalter was in the form of steam.

By contrast, the Clair Engle Plant[3/] which utilizes the multiple-effect multistage process, is considerably more efficient.[4/] This plant uses about 145 kwh/1000 gal, which is less than 40 times the minimum energy of separation for a sea water concentration of two times normal. As previously discussed, the selection of any given efficiency, must be based on an optimization of all costs to give the lowest total cost.

In order to provide 1,000 gal/day of desalted water with an energy expenditure of 50 times the minimum work of separation in which 50 percent of the water is recovered from the sea water, would require the expenditure of about 646,000 BTU/1000 gal, or 236 million BTU annually. This amount of thermal energy consumed by an electrical generating plant operating at 33 percent efficiency is equivalent to the production of about 22,800 kwh annually. Obviously, the cost of energy is a very significant component of the water cost. A substantial reduction in the cost of desalted water could be realized if a relatively inexpensive source of energy were available. It is for this reason that nuclear energy offers considerable potential for the future of desalting.

[1/] U.S. Office of Saline Water Demonstration Plant, San Diego, California.

[2/] "Second Annual Report - Saline Water Conversion Demonstration Plant", Point Loma, California. Office of Saline Water Report No. 114, July 1964.

[3/] U.S. Office of Saline Water, San Diego Saline Water Test Facility, Chula Vista, California

[4/] Mulford, S.F., "The San Diego Test Facility and the Office of Saline Water". Western Water and Power Symposium Proceedings, April 1968.

CHAPTER IV. NUCLEAR ENERGY FOR DESALTING

Because desalting processes are energy intensive, the key to low-cost desalted water is the availability of low-cost energy. It is expected that through improved and advanced nuclear technology low-cost energy will be available from large-capacity nuclear steam supply systems.

Reactors could be built to supply energy to a desalting only plant, but it is considered more likely that power generation would be a part of any large-capacity desalting operation. In any event, the nuclear reactor types that would be utilized are likely to be the same as those utilized for power production. In the United States for the near term, this means the light water reactors.

As of September 30, 1968, the U. S. Atomic Energy Commission reported the capacity of existing, under construction, and planned nuclear powerplants1/ as follows:

		Megawatts (electric)
In operation	(14)	2,782
Under construction	(39)	28,387
Planned, reactor ordered	(36)	31,285
Planned, reactor not ordered	(11)	9,950
Total -	(100)	72,404

Practically all of this electrical capacity will be produced by light water reactors (LWR). A light water reactor derives its name from the fact that water is used as a coolant, i.e., it flows through the assembly of fuel elements, called the core, and removes heat generated by the fissioning process. It also slows down high-velocity neutrons emitted during the fissioning process, thus increasing the chance of further fission. Light water is ordinary water (H_2O) and the term is used to distinguish it from heavy water (D_2O) in which deuterium has replaced hydrogen in the water molecule. Both pressurized light water (PWR) and boiling light water (BWR) reactor types are used to generate the steam used to run the turbines.

The comparatively low energy cost of LWR is related to the large quantity of energy that can be obtained from a relatively small amount of uranium fuel. Normally, LWR's are refueled once a year. About one hundred tons of uranium fuel are required for a 1,000 Mwe reactor. Annually, no more than one-third of the fuel needs to be replaced.

1/ U. S. Atomic Energy Commission News Release L-239, October 10, 1968.

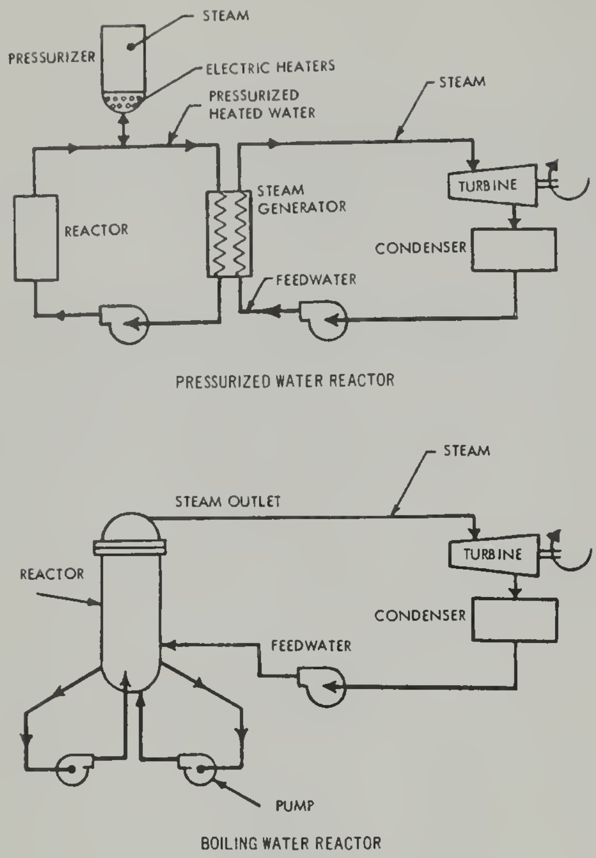


Figure 16. TYPICAL WATER REACTORS

Typical plant cycles for the PWR and BWR are shown in Figure 16. Steam is produced at pressures approaching 1000 psi in both cycles. Many of the characteristics of the design of both cycles are similar. As shown in Figure 16, the major difference is that in the PWR steam to spin the turbine is generated in a separate steam generator, whereas in the BWR steam is generated directly in the process of cooling the reactor. Sufficient pressure is maintained on the water circulated through the PWR to prevent boiling of the water in the reactor.

Pressurized light water reactors were first developed for military application. The Shippingport pressurized light water reactor was the first generation reactor for central power station application. Since the Shippingport PWR started operation in 1957, a steady improvement in design, performance, and cost has been achieved. There has also been a continuing progression to larger single-unit sizes. The maximum rating of PWR's so far planned is slightly greater than 1,100 Mwe. Design for these large PWR's is based on the experience in the fabrication, construction, and operation of the earlier units. Fuel performance has been increased. Better fuel management techniques are available and improved heat transfer has been achieved. A comparison1/ of the earlier operating PWR's with planned plants is shown in Table 2. Implicit in the increase in electrical output of a unit are the economies of scale which, for nuclear power reactors, are especially significant in reducing cost. Also, the capability of building larger unit sizes of various components has been developed.

The first commercial application of the BWR was the Dresden I reactor which was started up in 1959, with an initial rating of 180 Mwe. By comparison with the current BWR design, this first reactor was larger per unit of output and more complicated in arrangement. Various improvements in the cycle resulted

1/ Hearings before the Joint Committee on Atomic Energy Congress of the United States, Ninetieth Congress, AEC Authorization Legislation Fiscal Year 1969, Part 1, February 5, 1968, p.179.

TABLE 2

PRESSURIZED WATER,
NUCLEAR-ELECTRIC PLANT CHARACTERISTICS

	OPERATING PLANTS			NEW PLANTS	
	Yankee	San Onofre	Haddam Neck	Indian Point II	Diablo Canyon
Heat Output, Mwt	392(600)1/	1,347	1,473	2,758	3,250
Elec. Output, Net Mwe	115(175)	430	463	873	1,060
Max.Spec.Pwr., Kw/ft	6.5(9.9)	15.0	13.7	18.5	18.9
Average Pwr.Density, Kw/L	58(89)	70.7	66.0	85	98.2
Average Burnup MWd/MTU Discharge Batch	17,4002/	24,000	24,000	27,000	33,000
Average Burnup Peak Assembly	31,000				
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2
Pellet Diameter, inch	.294	.384	.384	.367	.367
Cladding, Material	SS	SS	SS	Zr	Zr
Thickness, inch	.021	.016	.016	.024	.024
Loops, Pumps	4	3	4	4	4
Pump Capacity, gpm	23,700	65,900	62,100	89,700	88,500
Pump Type	Canned rotor	Shaft seal	Shaft seal	Shaft seal	Shaft seal
Reactor Vessel					
Size, Height	31.5'	38'-6"	41.5'	42'-4"	42'-4"
I.D.	9.1'	11'-10"	12'-10"	14'-5"	14'-5"
Thickness, inches	7.875	9-3/4	10-5/8	--	--
Core Size, - Dia. inches	75	111	119	134	133.7
Length, inches	92	120	122	144	144

1/ Figures not in parentheses are initial power levels; those in parentheses are actual levels reached by operating plants.

2/ For Core V Assemblies discharged October 1966.

in a reduction in the size of the primary system and in a substantial reduction in the required containment volume. A comparison[1] of the earlier operating BWR's with planned plants is shown in Table 3.

In a recent study[2] of the feasibility of BWR with capacities up to 10,000 Mwt, it was concluded that a BWR nuclear steam supply system with a rating of 5,000 Mwt (1600 Mwe), could be available by 1970. It was further concluded that plants with a single-unit rating of 10,000 Mwt could be ordered by about 1975. The time scale for feasibility to construct large-capacity PWR's is very similar.

The LWR reactor concepts still have considerable potential for improvements in economics. Capital cost decreases[3] on the order of 10 percent in the next two decades appear to be possible through standardization, experience, reduction in component size, and increased unit capacity. Fuel cycle cost reduction on the order of 30 to 40 percent is predicted as a result of improved fuel performance and reduced unit operating costs.

Beyond this, breeder reactors* will start to find a place in the power market as more emphasis is placed on the need to obtain more energy from the available low-cost resources. A breeder reactor is a nuclear reactor in which more fissionable material is created than is consumed.

TABLE 3

BOILING WATER,
NUCLEAR-ELECTRIC PLANT CHARACTERISTICS

	OPERATING PLANTS		NEW PLANTS			
	Big Rock Point	Dresden # 1	Nine Mile Point	Oyster Creek	Dresden # 2	Brown's Perry TVA
Heat Output, MWt	240	700	1,538	1,600	2,250	3,293
Elec. Output, Net MWe	72	200	500	515(640)	715	1,064
Max. Spec. Pwr., kw/ft.	14.2	13.5	14.4	14.1	15.2	18.3
Average Pwr. Density, kw/L	45	33.2	34.1	33.6	36.7	50.8
Average Burnup MWD/MTU Batch	10,000	9,000	22,000	22,000	24,000	27,000
Average Burnup Peak Assembly	16,000	29,400				
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2
Pellet Diameter, Inch	0.345	0.496	0.488	0.488	0.488	0.488
Cladding, Material	SS	Zr	Zr	Zr	Zr	Zr
Thickness, Inch	.019	.033	.036	.036	.036	.032
Loops - Pumps	2	4	5	5	2	2
Pump Capacity, gpm	16,000	17,500	36,000	32,000	45,000	45,000
Pump Type	Shaft seal	Canned rotor	Shaft seal	Shaft seal	Shaft seal int. jet pump	Shaft seal int. jet pump
Reactor Vessel						
Size, Height	28'-8½"	40'-10½"	61'-2"	61'-2"	68'-0"	72'-8"
I.D.	8'-10"	12'-2"	17'-9"	17'-9"	20'-11"	20'-11"
Thickness, Inches	5.25	5.5	7-1/8	7-1/8	6-1/8	6-5/16
Core Size, Dia., Inches	62.5	128.9	156.1	160.2	182	187
Length, Inches	70	106	144	144	144	144

1/ Hearings before the Joint Committee on Atomic Energy Congress of the United States, Ninetieth Congress. AEC Authorization Legislation Fiscal Year 1969, Part 1, Feb. 5, 1968, p. 180.

2/ Lockhart, R. W. "Feasibility Study of Boiling Water Reactor Nuclear Steam Supply Systems with Capacities up to 10,000 Mwt", GECR 5155, February 1967.

3/ Beekman, Myron C. Incentive for Development of Fast Breeder Power Plants, NUCLEAR NEWS, Vol. 11, No. 7, July 1968, p. 34.

*Coolants may be sodium, gas, or steam.

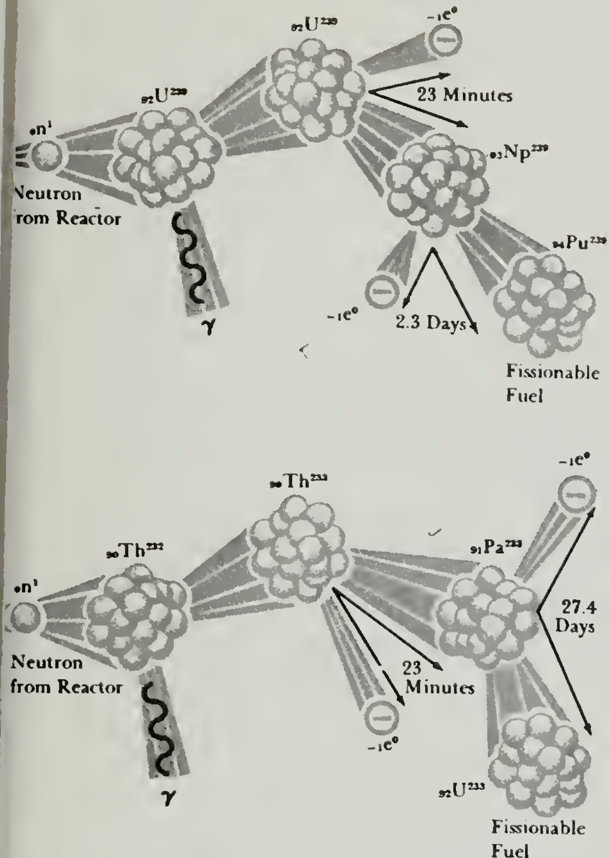


Figure 17. TYPICAL FUEL PRODUCING REACTIONS

Natural uranium has two usable isotopes for obtaining energy -- uranium -235 (U^{235}), a fissionable material which constitues about 0.7 percent and uranium -238 (U^{238}), a fertile material. Upon neutron irradiation of U^{238} during operation of the reactor a fissionable material, plutonium -239 (Pu^{239}) is formed. If more plutonium is formed than the amount of uranium -235 used to produce it, then breeding is said to take place.

Neutrons from, say, the fission of uranium -235 in a reactor are used to produce fissionable material from a fertile material. Two typical fuel-producing reactions are illustrated in Figure 17.

Development of breeder reactors should permit the utilization of substantially more than 50 percent of the uranium mined as compared with present utilization of about one percent. This will permit the use of relatively inexpensive uranium ore as shown[1] in Figure 18.

The Atomic Energy Commission has predicted that by 1970 the light water reactors will have a significant impact on the economy, and that 20 years later breeders will likewise have a significant impact on the economy, as shown in Figure 19.[2]

The estimated nuclear generating capacity[3] is compared with the total generation in Figure 20. Also included are bar

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1/ Shaw, Milton, "U.S. Fast Breeder Reactor Program" - American Power Conference, April 23, 1968, Chicago.

2/ Hearings before the Joint Committee on Atomic Energy Congress of the U.S. 90th Congress. AEC Authorization Legislation Fiscal Year 1969, Part 1, February 6, 1968, p. 272.

3/ Ibid., February 5, 1968, pages 147 and 159.

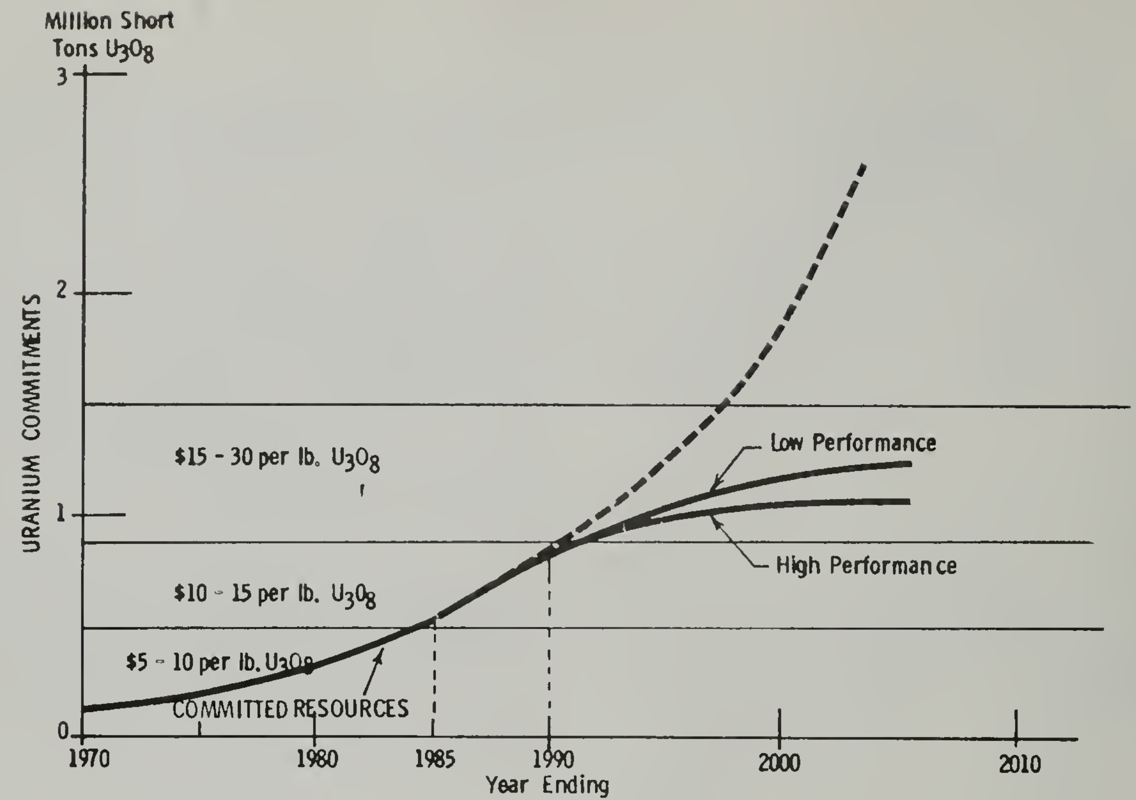

Figure 18. EFFECTS OF FAST BREEDER INTRODUCTION

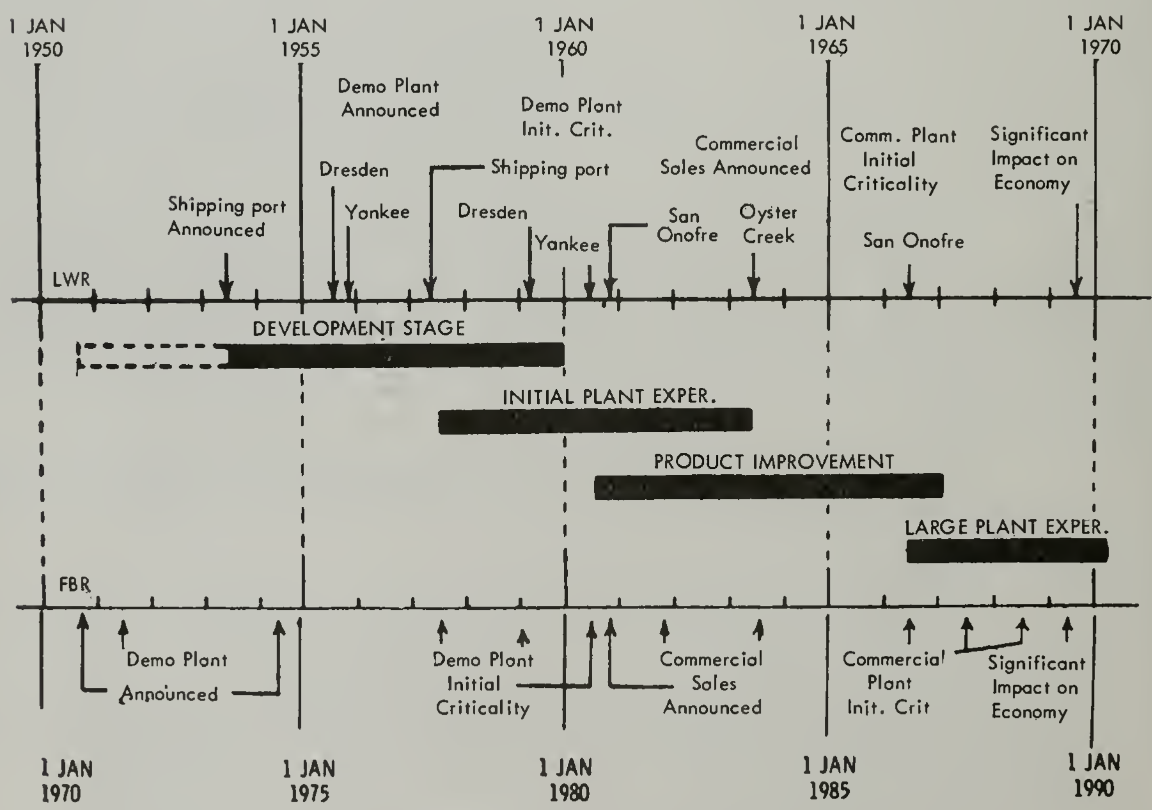

Figure 19. LWR AND FBR DEVELOPMENT TIME SCALES

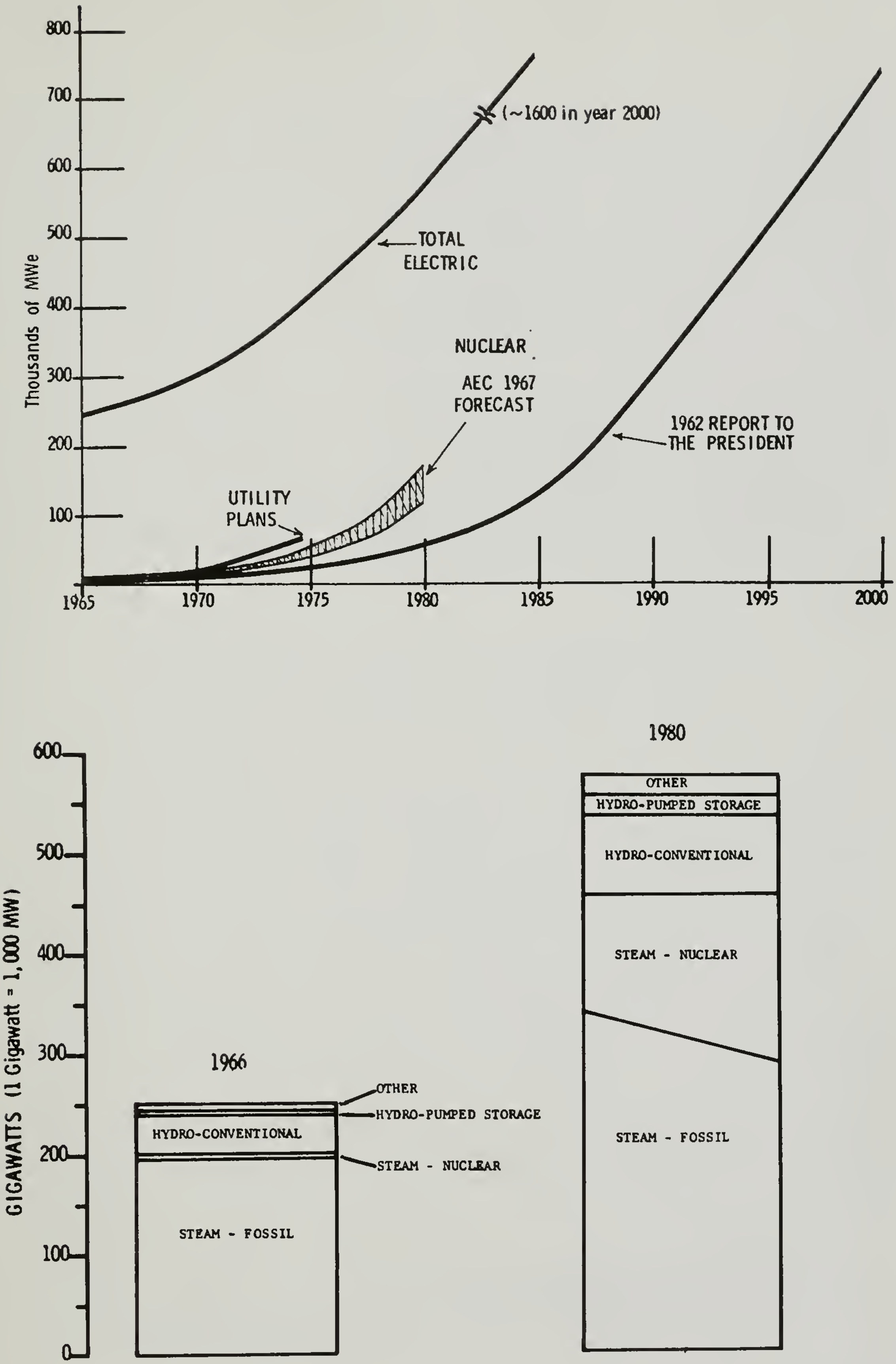

Figure 20. ESTIMATED GENERATING CAPACITY IN THE U.S. THROUGH THE YEAR 2000

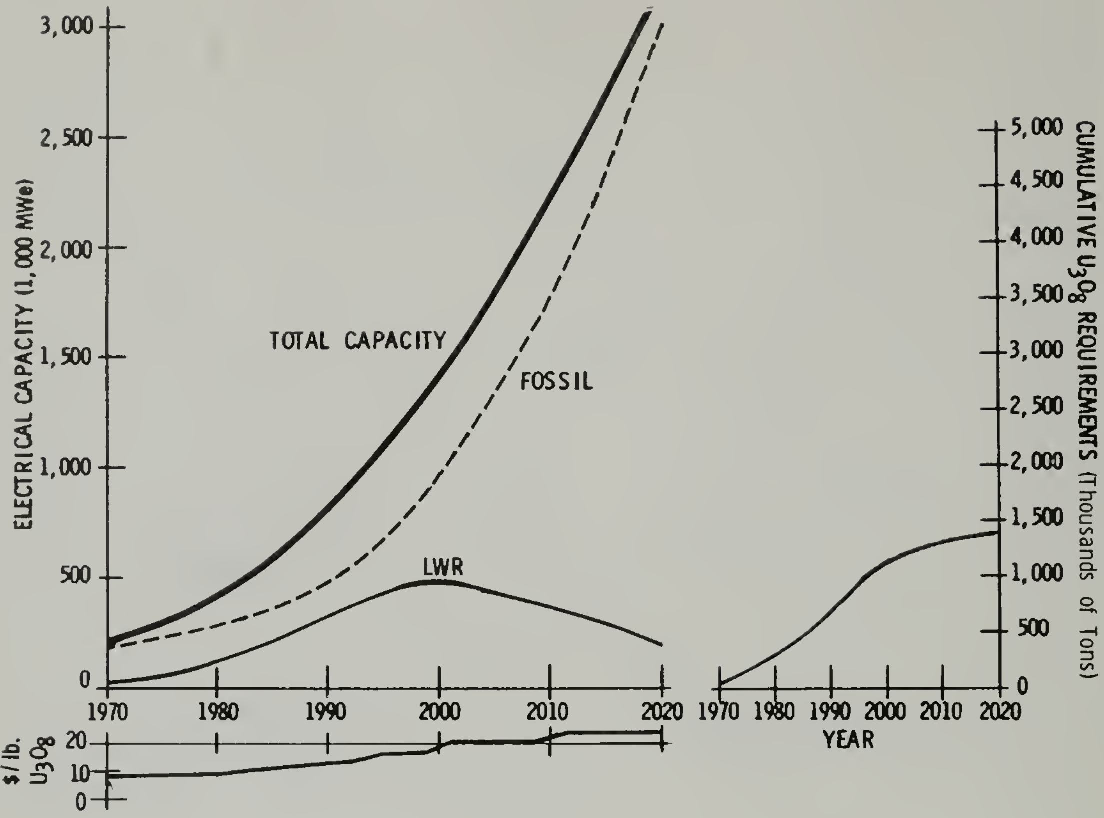

Figure 21. RELATIVE ECONOMIC POTENTIAL OF FOSSIL AND LIGHT WATER NUCLEAR POWERPLANT CONCEPTS

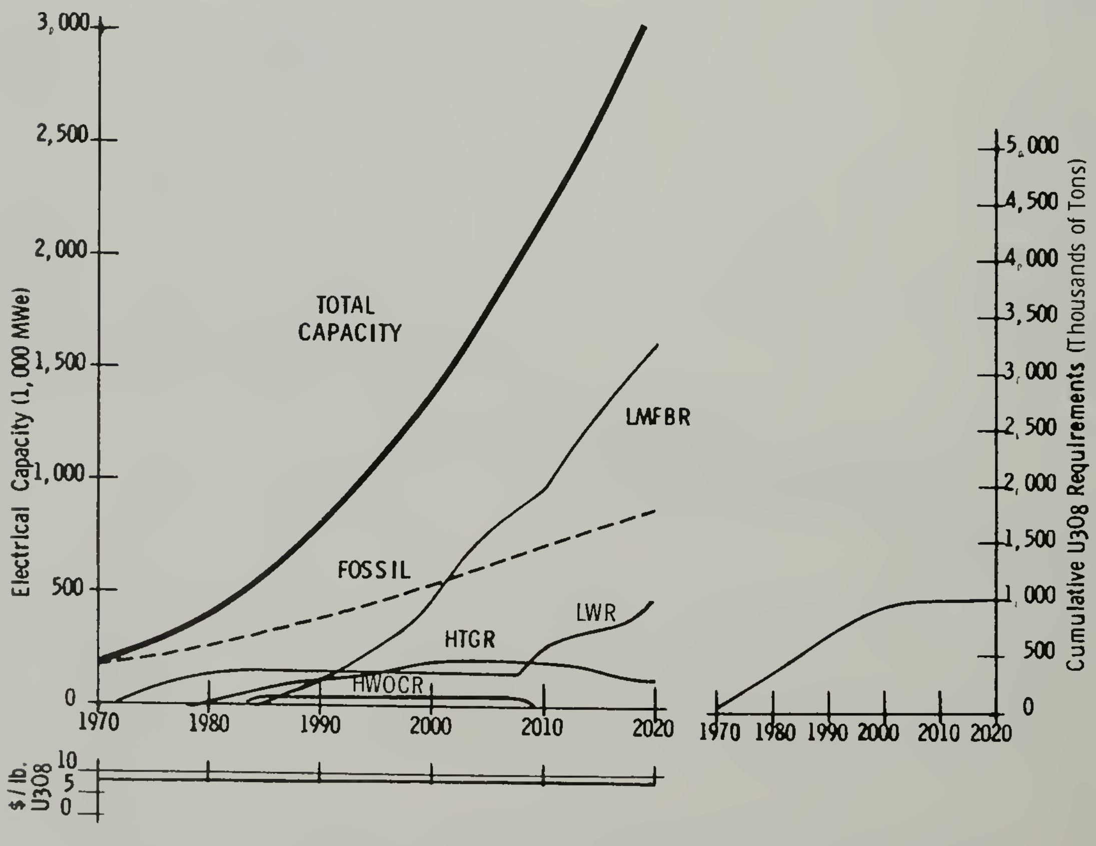

Figure 22. RELATIVE ECONOMIC POTENTIAL OF FOSSIL AND NUCLEAR POWERPLANT CONCEPTS

charts for 1966 and 1980. The slant line between fossil and nuclear for the 1980 projection represent the area of uncertainty as to the relative roles of fossil and nuclear. Based on the assumptions made, the mix of nuclear and fossil plants can vary widely. If one assumes only LWR's with uranium prices increasing as shown1/ on Figure 21, then beyond 2000 nuclear capacity decreases. However, with the successful introduction of breeders such as the liquid metal fast breeder reactor (LMFBR) beyond 2000, breeders will provide the primary source of electrical generation as shown2/ on Figure 22.

The projected capital cost3/ of a fast breeder reactor (FBR) is expected to approach that of the LWR by 2000, as shown in Figure 23. The FBR with a much lower fuel cost is, therefore, expected to produce lower cost power sometime after 1985, as shown in Figure 24. The exact time will depend on the program to build prototype and commercial plants. Part of the incentive will depend on future uranium ore prices.

1/ Hearings before the Joint Committee on Atomic Energy, op.cit., February 5, 1968, p. 206.

2/ Ibid. February 5, 1968, p. 207.

3/ Beekman, Myron C. "Incentive for Development of Fast Breeder Power Plant", NUCLEAR NEWS, Vol. 11, No. 7, July 1968, p. 34.

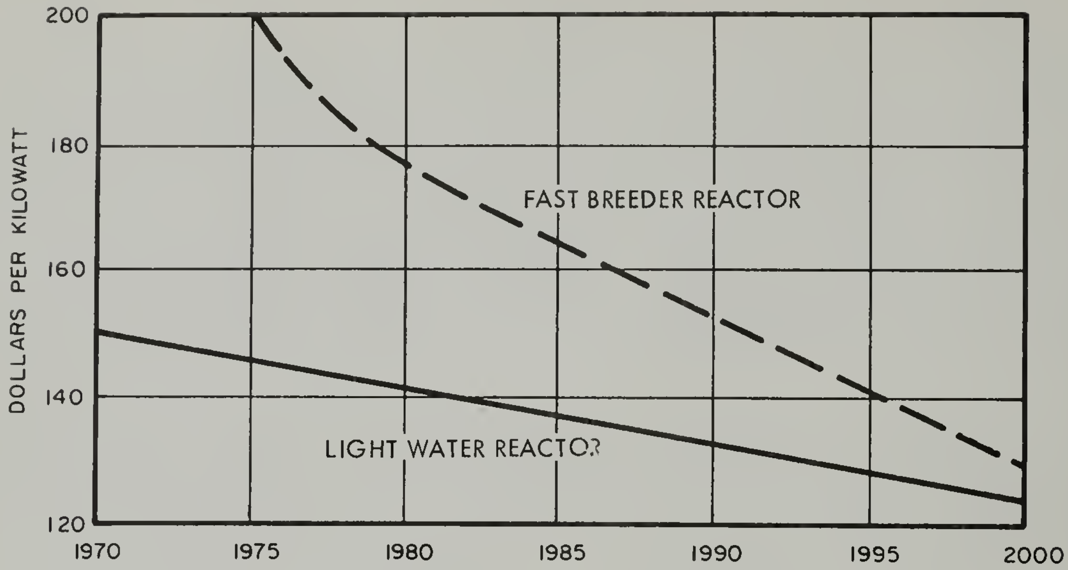

Figure 23. LIGHT-WATER AND FAST BREEDER REACTOR TOTAL INSTALLED COST

(12.5% CRF 80% CF)

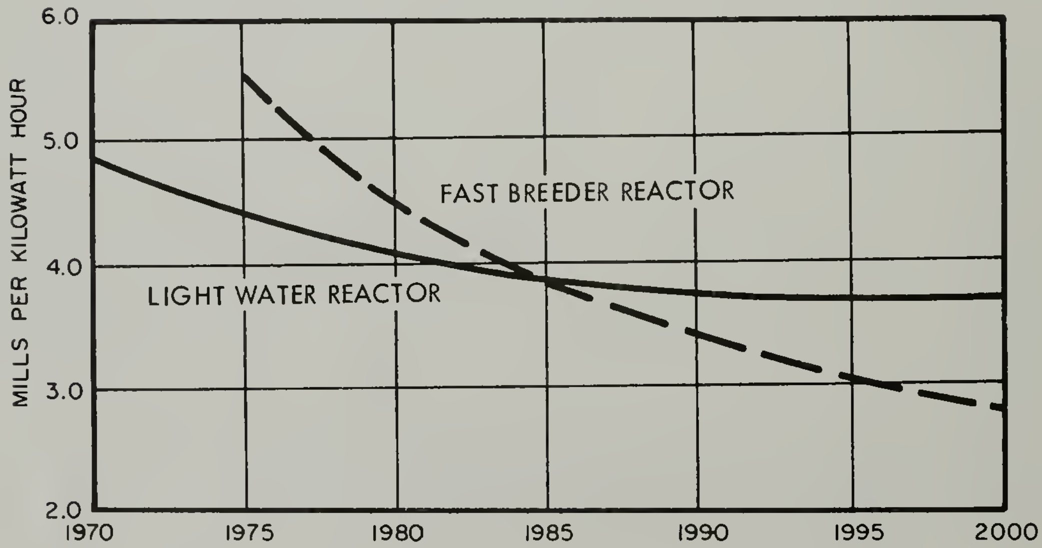

Figure 24. LIGHT-WATER AND FAST BREEDER REACTOR POWER GENERATION COST

CHAPTER V. MULTIPURPOSE APPLICATIONS

In operations where power production and water desalting can be combined into a dual-purpose facility, more efficient use can be made of the energy and, hence, the cost of power and water is lowered. This economic incentive can be very compelling. In addition, especially where nuclear reactors are involved, advantage of building a larger steam supply system can be substantial. The advantage of the dual-purpose facility was illustrated by Hammond[1/] as follows:

	Steam Supply Megawatts (thermal)	Megawatts Electric	Water Million gals/day	Waste Heat Megawatts (thermal)
Power only	1,000	300	-	700
Water only	1,200	-	180	1,200
Total:	2,200	300	180	1,900
Dual-purpose	1,500	300	180	1,200

As shown in the tabulation for the same water and power output, almost 60 percent more heat must be wasted when the plants are operated independently as two single-purpose plants rather than first using the steam to spin a turbine and then to heat brine in a desalting plant, as would be the case in a dual-purpose facility.

The ratio of power to water produced can be varied over a rather wide range without incurring much of an economic penalty. In one optimization study[2/], a 3,300 Mwt advanced converter nuclear steam supply system (800 psia and 677°F.) was used to produce 675 Mwe (gross) and 250 million gallons per day. For the longer term when breeder reactors with steam at 2,400 psia and 950°F. will be in operation, a dual-purpose plant will produce about 750 Mwe and 250 million gpd of desalted water.

At a 90 percent capacity factor, 250 million gpd is equivalent to 250,000 AF/yr. In the Federal Power Commission Electric Power Supply, Area 47 (Southern California and Central

1/ Hammond, R.P. "Prospects and Application for Large-Scale Water Supplies from the Sea", Proceedings of Sea Water Conversion State of the Art Conference, June 18, 1968, Sacramento, California.

2/ "Conceptual Design of a 250-Mgd Desalination Plant", Office of Saline Water, R&D Progress Rept. No. 214, September 1966.

Nevada), the annual base load addition is expected to reach 1,000 Mwe by 1985. This amount of power, when combined in a dual-purpose plant, could produce about 400,000 AF/yr of desalted water. Annual additions of 400,000 AF would be much more water than will be needed in Southern California. Hence, power production would impose no limitation on desalted water production. Similar quantities of water could also be produced in Northern California.

The most economical use of steam in a dual-purpose plant is first to spin a turbine with all of the high-pressure steam to produce electricity with a turbine-generator set and then to use the low-pressure exhaust steam from the turbine to heat salt water for the desalting plant. Such a dual-purpose arrangement utilizing a nuclear steam supply system would probably not be economically feasible until the capacity of the desalting plant reached about 100,000 AF/yr. The capability to build plants of this capacity could exist by the early 1980s.

CHAPTER VI. PROSPECTS FOR DESALTING

The cost of energy has a profound effect on optimization for minimum cost. Since the capital and energy cost components are likely to represent 80 percent or more of the total cost of water, generalized cost curves as shown in Figure 25 are of interest. The shape of the capital, plus energy cost curves, is typical of a plot of water cost against plant efficiency. Curve 1 is for a relatively high-energy cost. The minimum cost is more definite than the flat minimum obtained with relatively low-energy cost, as shown on Curve 2. Also, the minimum cost is found at a higher efficiency for the higher cost energy. The capital cost component does not change as rapidly as the energy cost component; hence, the two capital cost curves are relatively closer together. As the energy cost is reduced, optimization for minimum cost results in a less efficient plant, hence the result of a lower energy cost is two-fold in that both the energy cost component and the capital cost component become smaller.

It is for this reason that the projected cost of desalted water from very large nuclear desalters is considerably less than the current cost from small-capacity fossil fueled plants. Not only is there a substantial reduction, as would be expected due to scale of the plant, but also there is a substantial reduction due to the expected lower cost of nuclear energy, both directly and from reduction, in capital investment.

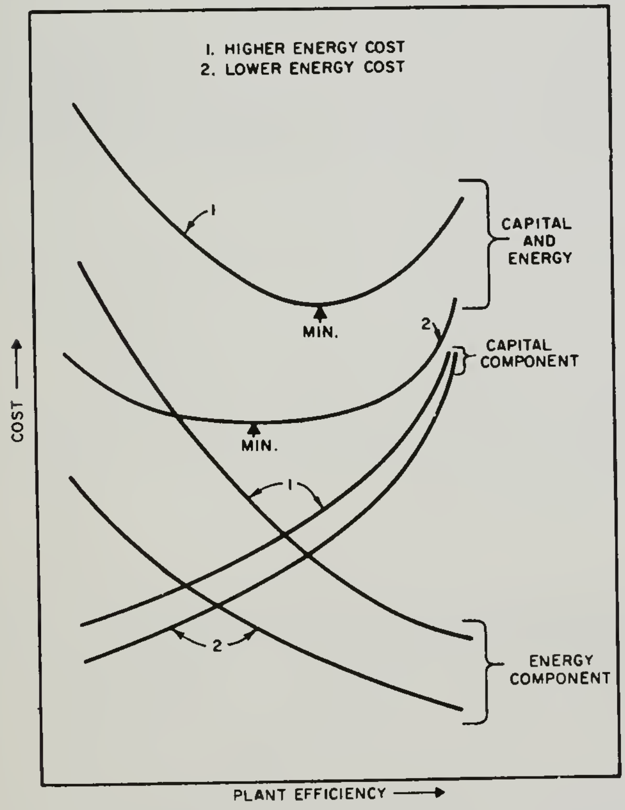

Figure 25. VARIATION OF CAPITAL AND ENERGY COST WITH DESALTING PLANT EFFICIENCY

The largest desalting plant in operation in the world is the 2,620,000 gallons-per-day single-unit multistage flash desalter at Key West, Florida. Comparable outputs at other locations are obtained by the use of two or more units. The single-purpose, or water only, Key West plant uses fossil fuel to produce steam in a boiler. The cost of desalted water from the plant[1] is about $280 per acre-foot. A photograph of the Key West plant is shown as Figure 26.

A short distance south of the California border at Rosarito Beach, Mexico, construction is nearing completion on twin unit desalters, each with a capacity of 3.75 million gallons per day for a total installed capacity of 7.5 million gallons per day. The plant is expected to start up in 1969. The estimated cost[2] of the desalted water is expected to be about $195 per acre-foot. The plant is operated in conjunction with a fossil-fueled powerplant. A photograph of the Rosarito Beach plant is shown as Figure 27.

Bids were received in September 1968, in Kuwait for two plants, each with a proposed capacity of 4.8 million gallons per day. It is expected that at least one of these plants will be placed in operation in 1970. The cost of desalted water from existing plants in Kuwait is probably the lowest in the world because of the abundant supply of low-cost natural gas and is not representative of costs that can currently be achieved in most other places.

A detailed study of a large-capacity dual-purpose electric power and desalted water facility has been made for Bolsa Island, including costs of constructing a man-made island site off the Orange County coast in Southern California. The plant was to be placed on line in 1971 and produce 150 million gallons per day of desalted water and about 1800 Mwe (gross) of electrical power. The initial economic and engineering feasibility studies made in 1965 resulted in an estimate of capital cost of $390.9 million.[3] This estimated cost included the plant investment of $357.4 million and product water conveyance facility of $33.5 million. It did not, however, include escalation to 1971, when it was assumed the plant could be in operation, nor did it include the cost of the power transmission facilities. Based on the 1965 cost estimate, the desalted water was estimated to cost about $71 per acre-foot at the Bolsa Island site. A conceptual arrangement of the plant is shown as Figure 28.

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[1] Scarbrough, B. R. Statement before Water and Power Committee, Los Angeles Area Chamber of Commerce, November 7, 1968.

[2] Loebel, F. A. "The Flash Desalting Process" - Proceedings of Sea Water Conversion State of the Art Conference, Sacramento, June 18, 1968.

[3] Engineering and Economic Feasibility Study for a Combination Nuclear Power and Desalting Plant. Summary Report No. TID-22330 (Vol.III) by Bechtel Corporation, San Francisco, December 1965.

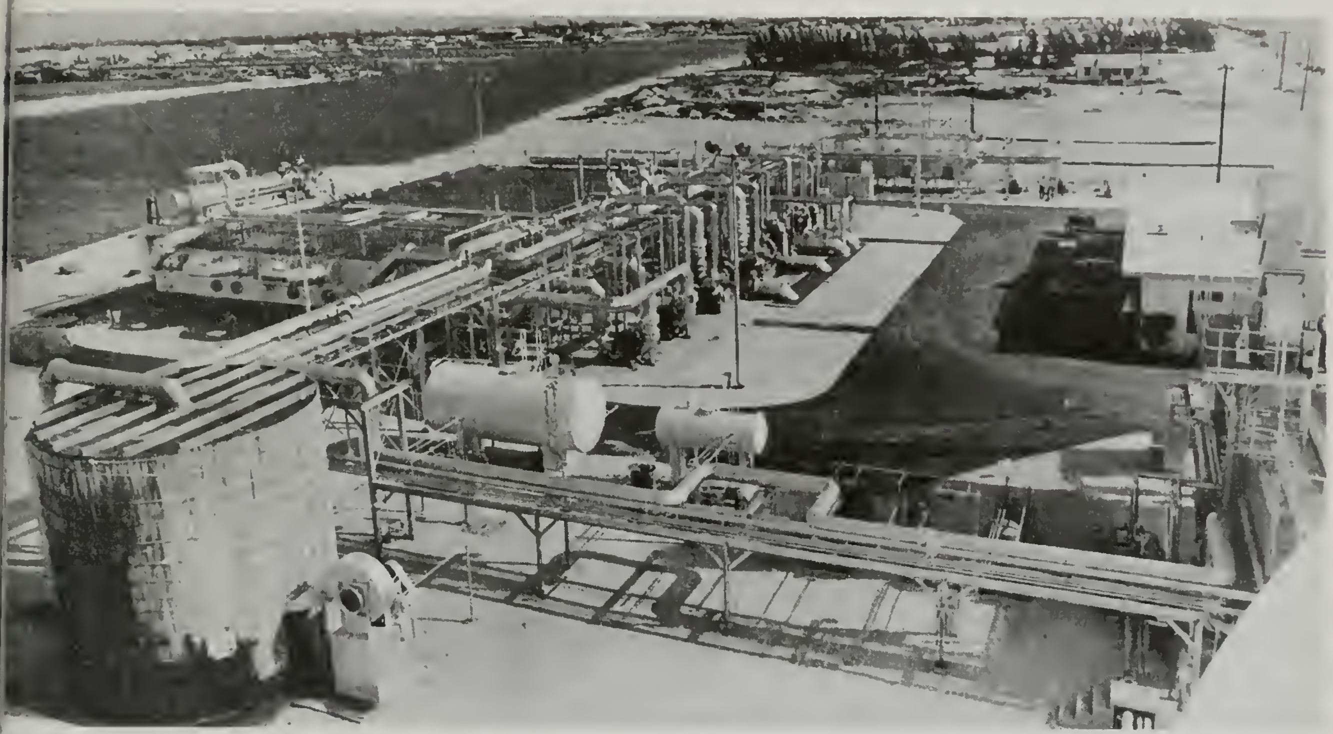

Figure 26. MULTISTAGE FLASH DESALTING PLANT, KEY WEST, FLORIDA

Courtesy of Water Province Department, Westinghouse Electric Corporation

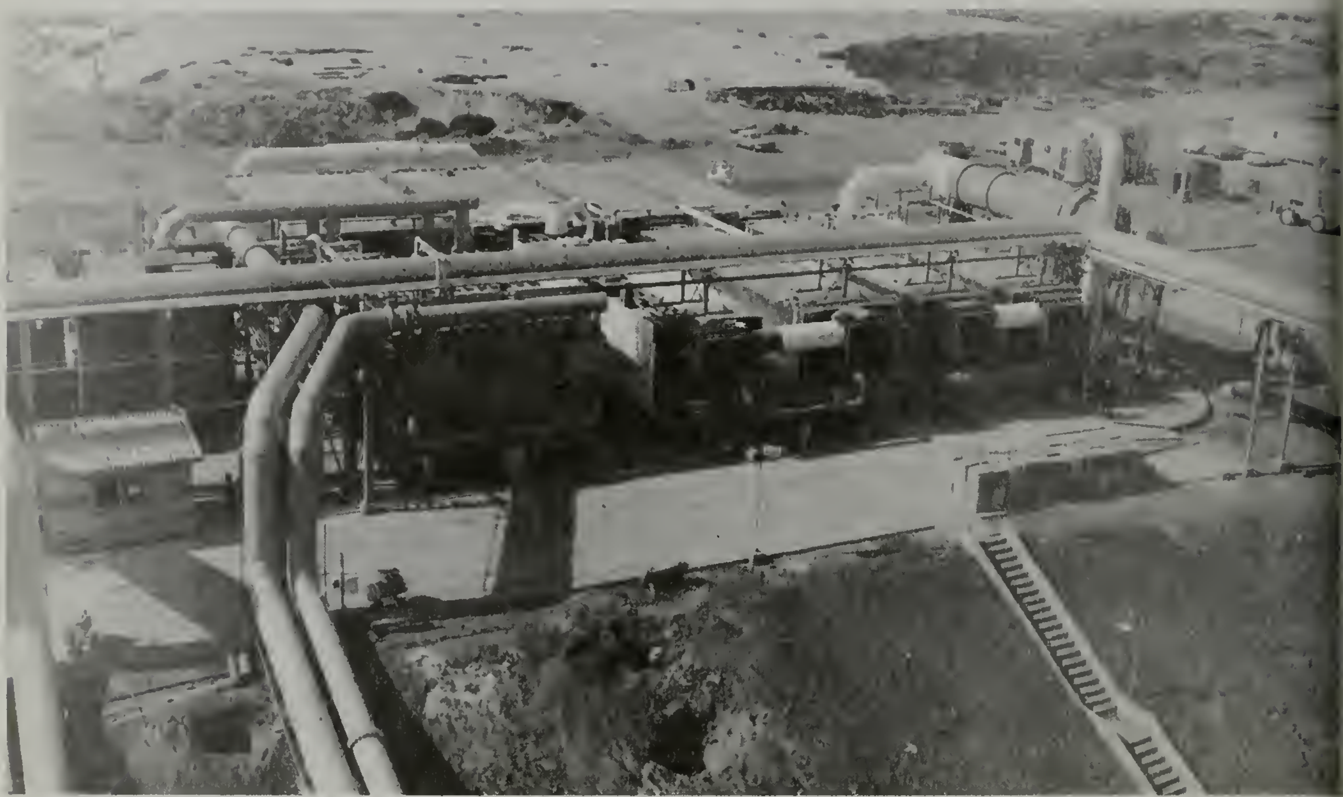

Figure 27. MULTISTAGE FLASH DESALTING PLANT, ROSARITO BEACH, MEXICO

Courtesy of Aqua-Chem, Inc.

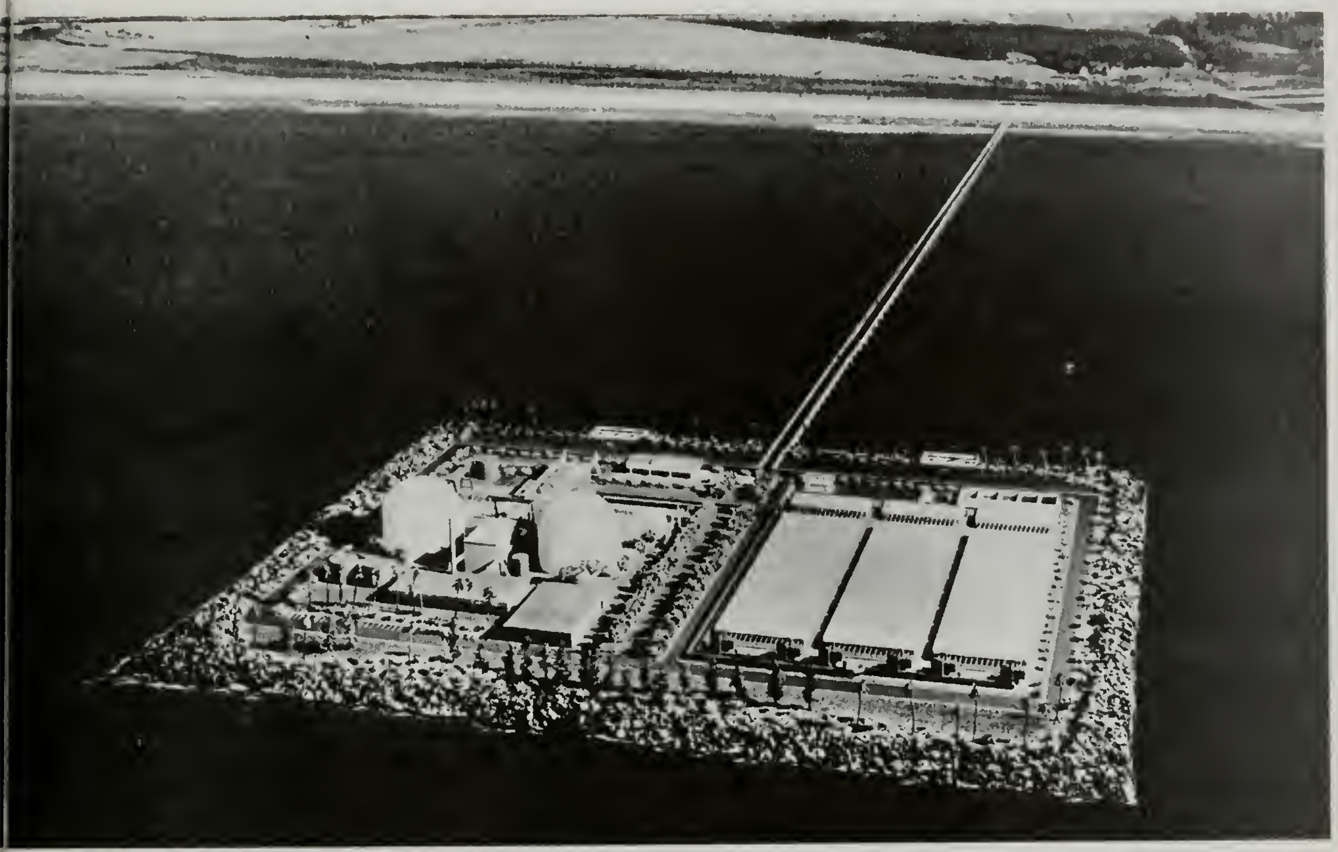

Figure 28. ARTIST'S RENDERING OF PROPOSED BOLSA ISLAND PLANT

Courtesy of Metropolitan Water District of Southern California

The Bolsa Island project cost-estimate was adjusted upward early in 1966 to allow for phased construction of the desalting facilities with a 50-million gallons-per-day unit to be operational in 1972, and a 100-million gallons-per-day unit in 1977.

Estimated costs for the phased construction were as follows:[1,2]

	1st Phase	2nd Phase
	Millions of Dollars	
Desalting plant, including inlet, outfall, evaporator	42.4	65.0
Powerplant components	22.2	-
Island and causeway	24.1	-
Water conveyance facility	32.1	1.6
Desalting Subtotal:	120.8	66.6

Desalting	187.4
Electrical Utilities	213.1
Power Transmission Costs[3]	43.5
TOTAL:	444.0

On April 5, 1968, the organizations[4] involved with the Bolsa Island project announced that the project cost had been re-estimated at $765 million. A number of items are involved in the increase from $444 million to $765 million. The largest single item is the inclusion of escalation. As previously stated, the original 1965 estimate did not include an allowance for probable escalation. The 1968 estimate included price increases from

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[1] Prototype Desalting Plant - U.S. House of Representatives. Report No. 180 on PL-90-18. April 7, 1967.

[2] Federal participation in saline water conversion hearing before the Committee on Interior and Insular Affairs, U.S. Senate on S.3823, 89th Congress, September 19, 1966, and S.270, 90th Congress, January 24, 1967.

[3] Authorizing participation in the construction of a large-scale desalting plant in the State of California. U.S. Senate Report No. 1618, 89th Congress, Second Session, September 20, 1966.

[4] Metropolitan Water District of Southern California, Southern California Edison Co., the Los Angeles Department of Water and Power, San Diego Gas and Electric Company, the U.S. Office of Saline Water, and the U.S. Atomic Energy Commission.

1965 to 1968, and escalation for the phased construction alternative, with the first desalter to go into operation in 1974 and the second in 1978. More than 12 years of escalation are, therefore, included in the 1968 estimate.

A significant increase in capital cost was made to cover anticipated licensing requirements resulting primarily from recommendations by an advisory committee[1] formed by the U. S. Department of the Interior. The committee recommended that the design of the nuclear reactor and related critical structures should allow for possibility of a sudden differential displacement of 5 to 10 inches in any direction in the sea floor, and liquefaction of the island fill as a result of seismic activities. Substantial cost increases were also made to cover changes in the off-site power transmission facilities and change in project responsibility from an assumed single engineer-manager of the 1965 estimate responsible to the owners to the concept in the 1968 estimate that each owner would assume responsibility for his portion of the project. Other increases resulted from changes in scope, higher interest rates, and state sales tax.

The total increase is accounted for as follows:[2]

Additional Costs		Millions of Dollars
Cost of escalation of island and plant facilities		152.8
Increase in licensing and safety requirements		53.4
Power transmission system		32.5
Cost due to change to divided responsibility for the various facilities		25.2
Increase in cost of borrowing		16.9
Increase in output of turbine generator plants		16.0
Product water conveyance system		7.3
Increase in California sales tax		3.0
Changes in equipment:		-0.6
Nuclear steam supply	+23.7	
Turbine	-20.1	
Tubing	- 4.2	
Additional contingencies		15.0
Subtotal:		321.5
1965-66 estimate		444.0
1968 total		765.5

1/ "Geological-Seismological Factors Pertaining to the Proposed Construction of a Nuclear-Power Desalting Plant at Bolsa Island, California". A report to the Secretary of the Interior, October 1967.

2/ From Summary Tables prepared by Bechtel Corporation for The Metropolitan Water District of Southern California, May 1968.

These increases generally fall into five categories as follows:

Escalation	45%
Change in Project Scope	27%
Licensing and Safety	16%
Phased Construction of Desalter	6%
Increase in Interest and Taxes	6%
Total:	100%

As can be seen, almost one-half of the increase is a result of including an estimate of the cost of escalation in the 1968 estimate. A substantial part of this amount would have to be added to the 1965-66 estimate if the two estimates were made on a comparable basis. The next largest change, amounting to 27% of the increase, is for changes in the project scope such as a 10% increase in the output of the turbine generator plant, over $30 million for the power transmission facilities, and about $25 million for divided responsibility for the various facilities. An extremely conservative approach to the licensing and safety requirements for the proposed man-made island, which would be located about one mile from the tectonically active Newport-Inglewood fault, accounted for about 16 percent of the increase.

A substantial increase in the estimated cost of the desalted water1/ resulted from the large increase in the estimated capital cost of the project. The desalted water cost at the plant site, based on the 1968 estimate, is summarized as follows:

	$/AF
Unphased plant (150 Mgd)	108-114
Phased plant (50 Mgd -1974) (100 Mgd -1978)	114-124

The ranges in water cost reflect variations in equipment costs as quoted by vendors. The increase in desalted

1/ From Summary Tables prepared by Bechtel Corporation for The Metropolitan Water District of Southern California, May 1968.

water cost from the 1965 estimate of about $71/AF is as follows:

	$/AF
1965 report	71
Escalation, anticipated market level at time of equipment purchase, schedule delays, changes in design, and scope	26
Decrease in power benefit	3
Increase in cost of money	10
Phased construction of desalter	10
Total	$120

Looking to the future, it is expected that the technology needed to build dual-purpose nuclear systems will exist so that single-unit large-scale sea water desalters can be built for operation in the early 1980s. It is further anticipated that light water reactor nuclear-steam supply systems will be utilized in plants built in the 1980s. Breeder reactors will begin to take over power production from water reactors in the late 1980s, and by the mid-1990s, dual-purpose plants will more likely be supplied with energy more economically from breeder reactors.

In this period of swift technological change, the practical impact of such change on the economics of desalting is somewhat difficult to envision beyond a decade. Uncertainties can be especially perplexing to policy and decision-makers when required to make a selection among alternatives that are at different levels of technological development. It is important, however, that the decision-makers' flexibility not be constrained too early by premature conclusions as to the level of future technological development. The policy-maker must retain his options to deal with future technological changes when and if they come along so as to minimize the adverse effects of underestimating or overestimating technological progress.

When we look a long way down the pipeline of invention, research, and development, we can see certain technological developments that will most likely become commercial reality. The developments that come into focus are the ones on which we must base our judgment of the prospects of desalting.

Many other possibilities are not yet clearly discernible on the technological time scale and we cannot include them in our considerations. They are indeed there and some will no doubt come down the pipeline and into the forefront before the Twenty-first Century. They will, along with serendipitous developments, serve as a reservoir of alternatives to be used at the proper time.

Experimental condenser tubing in current laboratory and pilot plant tests have been observed to provide from two to four times more heat transfer per unit area than conventional condenser tubing in commercial plants. Fluted, corrugated, and ribbed configurations in the experimental tubing reduce not only the amount of tubing required but also the size of associated equipment. As a result, the cost (in constant dollars) of heat transfer surface per unit of output in new desalting plants is expected to drop substantially within ten to twenty years. This cost reduction probably will be greater than that resulting from improvements in materials, coatings, and concrete, and in methods of fabricating, but all should help to improve the economics of future desalters.

As discussed in Chapter IV, energy from breeder reactors after 1990 is expected to be more economical than that obtained from presently available reactors. The breeder must, however, prove itself in the market place. In addition, regulation and licensing of nuclear steam supply systems will have to be improved so that the time and expense involved in compliance will not become excessive. Siting will, no doubt, undergo a revolutionary change. Already, for example, Consolidated Edison Company[1] has proposed to build at some future date an underground nuclear power station on Welfare Island in the East River in the Metropolitan New York area.

Desalters and breeder reactors are both highly capital intensive. Far-term costs of power and water will thus vary strongly with the interest rate. Also, marked advances may be made in some power-using desalting processes, most likely the membrane processes, that will improve the economics of water-only plants and increase the flexibility of plant locations.

Rapid strides are being made in controlled fusion. While we do not know today the role, if any, fusion will play in supplying energy tomorrow, its role should be clear before the Twenty-first Century arrives. The odds for the economic success of fusion by the year 2000 are often judged as about even.

Whole new vistas should be opened up to us 31 years hence, when the Twenty-first Century commences. The year 2000, in terms of technological developments, is really a long distance away. There is certainly time for some so-called far-out predictions to materialize and for new or unexpected developments to take place. The three-fourths of us living today who will still be alive then must be prepared for the vast technological, medical, and sociological changes that most surely will take place.

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[1] NEW YORK TIMES, October 7, 1968, page 1.

CHAPTER VII. SUMMARY

Desalting capacity is increasing rapidly on a worldwide basis. The majority of the plants are of modest capacity. Energy is obtained from fossil fuels. Considering plants larger than 25 AF/yr capacity, 45 plants with a combined capacity of about 58,000 AF/yr were placed under construction in 1967. On January 1, 1968, there were 627 plants in operation or under construction with a combined capacity of 222,000 AF/yr. The rate of growth in total capacity during the past few years has averaged about 22 percent per annum.

Prior to 1967, the largest single-unit desalter had the capacity of producing about 1,700 AF/yr. In 1967, a desalter was placed in operation in Key West, Florida, with a capability of producing 2,600 AF/yr in a single-unit plant. The cost of water from this plant is about $280/AF. At Rosarito Beach, Mexico, construction of a 7,500 AF/yr twin unit desalter was completed by the end of 1968, making this presently the largest single-unit desalter at 3,750 AF/yr. In November 1968, Kuwait purchased a plant with a capability of producing 4,800 AF/yr in a single unit. This plant will be on line in 1970. From 1967 to 1970, the single-unit plant capacity will have increased by 85 percent. Even so, the single-unit plant capacity remains very small, as compared with the large-capacity desalters assumed for the future.

The Bolsa Island project, under study by the Metropolitan Water District of Southern California and others,[1/] was estimated to cost $444 million and to be capable of producing desalted water at the rate of 150,000 AF/yr at a unit cost of $71/AF, all based on 1965 prices. When re-estimated in 1968, including escalation and changes in scope, the capital cost had risen to $765 million and the desalted water to $120/AF. In addition to the difficulties with escalation, problems associated with the siting of the nuclear reactors added significantly to the cost.

Desalting projects are both capital and energy intensive and, therefore, would benefit from low interest rates and inexpensive energy. A substantial reduction in the cost of desalted water is expected to result from the availability in the future of relatively low-cost energy from breeder-type nuclear reactors. The availability of such low-cost energy will also be of economic benefit to water supply projects involving inter-basin transfer of water and, possibly, in the construction of civil works for water projects.

1/ See footnote on page 40.

Significant reduction in the cost of desalted water from large-capacity plants can be achieved through the application of nuclear energy, most likely in dual-purpose plants. Nuclear desalters will encounter the same licensing and safety problems as will nuclear power-only plants. A satisfactory solution to siting on the California coast will not be easy. It has been assumed that in the future such problems will be reasonably well solved so that undue delays and unexpected increase in costs will not be encountered. Failure to achieve resolution of the siting problem may add materially to the cost of desalting and could seriously restrict the applicability of desalting as an alternative source of supply to meet future needs in California.

The distillation method of desalting, which now shows the most promise for large-capacity sea water desalting, will produce almost salt-free water. This high-quality water will have a value in blending to stretch existing supplies and, in general, in water quality management. While an absolute value cannot readily be assigned to quality, it is anticipated that on a case-by-case basis there should be a benefit in having available a supply of high-quality desalted water.

Many factors that will influence the cost of desalted water in the future cannot be determined with certainty. Expectations, however, appear to be sufficiently attractive to warrant continued consideration of desalting as an alternative for future augmentation or supplementation of water supply.

APPENDIX A

COBEY-PORTER SALINE WATER CONVERSION LAW

Since 1957, the State Legislature has supported a desalting program in the Department. In 1965, the Legislature passed the Cobey-Porter Saline Water Conversion Law (Water Code Section 12945-12949). The declared policy of the Legislature is set forth in this law, as follows:

CHAPTER 9. SALINE WATER CONVERSION

Article 1. Short Title

12945. This chapter shall be known as and may be cited as the Cobey-Porter Saline Water Conversion Law.

Article 2. Declaration of Policy

12946. It is hereby declared that the people of the state have a primary interest in the development of economical saline water conversion processes which could eliminate the necessity for additional facilities to transport water over long distances, or supplement the services to be provided by such facilities, and provide a direct and easily managed water supply to assist in meeting the future water requirements of the state.

12947. The Legislature finds and declares that a substantial portion of the future water requirements of this state may be met economically by saline water conversion facilities and that the development and utilization of such desalting facilities will contribute to the peace, health, safety, and welfare of the people of the state. It is the intention of the Legislature that the department shall undertake to find economic and efficient methods of desalting saline water so that desalted water may be made available to help meet the growing water requirements of the state.

Article 3. State Participation

12948. The department either independently or in cooperation with any county, state, federal, or public or private agency or corporation may conduct a program of investigation, study, and evaluation in the field of saline water conversion.

12949. After submission of a written report and upon specific authorization by the Legislature the department either independently or in cooperation with any county, state, federal, or public or private agency or corporation may finance, construct, and operate saline water conversion facilities. The department may sell any water made available by such saline water conversion facilities. Unless otherwise provided by the Legislature, the department shall establish rates or charges for such water so as to recover all of the costs of making such water available.

APPENDIX B

U. S. DEPARTMENT OF THE INTERIOR
OFFICE OF SALINE WATER
RESEARCH AND DEVELOPMENT
CONTRACTS TO CALIF. FIRMS OR FOR WORK TO BE DONE
IN CONNECTION WITH DESALTING ACTIVITIES LOCATED IN CALIFORNIA

Fiscal Year 1967-68

Company	Title of Contract	$ Amount
Aerojet-General Corp.		
	Desalination by reverse osmosis -- 50,000 gpd brackish water pilot plant.	$ 88,878
	Development of reverse osmosis membrane shipping and storage techniques.	308,445
	Reverse osmosis pilot plant investigation.	151,811
	Operation of a 50,000 gpd osmosis pilot plant.	106,788
	Development of new cellulose ester reverse osmosis membranes.	142,606
	Development of tubular reverse osmosis.	491,000
	Assembly press and auxiliary devices for reverse osmosis stack.	5,623
	Lease of one 10,000 gpd Aerojet reverse osmosis unit and technical services for tests on brackish waters.	32,646
	Development of new and improved cellulose ester reverse osmosis membranes.	511,931
	Fabrication and installation of a feed water blending system for reverse osmosis and electrodialysis pilot plants in Firebaugh, Calif.	22,443
	Optimization study of high-recovery reverse osmosis plants.	98,627
	Preliminary evaluation of high-retention membranes.	52,350
	Technical services of a field engineer for OSW reverse osmosis unit operation.	20,000
	Reverse osmosis membrane regeneration.	61,696
	Development of economical methods of boron removal from irrigation return waters.	46,864

Company	Title of Contract	$ Amount
Aerojet-General Corp. (Cont'd)		
	Recovery of metal salts from concentrated brine by chelation.	$ 75,800
	Aerojet-General - TOTAL:	$2,217,580
Dr. Mihran S. Agababian, Los Angeles, Calif.		
	Consultant serving on committee to study geologic and seismologic data in connection with Bolsa Island nuclear desalting plant.	2,400
Dr. Clarence R. Allen, Pasadena, Calif.		
	Consultant serving on committee to study geologic and seismologic data in connection with Bolsa Island nuclear desalting plant.	2,400
Aqua-Chem, Waukesha, Wisconsin		
	Procurement of brine heater for MSF Test Module.	700
Bechtel Corporation, San Francisco, Calif.		
	To design and construct a model of the MWD plant for the U.S. exhibit at the Water for Peace Exposition.	4,500
	Parametric economic and engineering evaluation study of the electrodialysis process.	97,300
	Bechtel Corp. - TOTAL:	$101,800
Catalytic Constr. Co., Philadelphia, Pa.		
	Maintenance and operation at Clair Engle Plant.	347,813
	Management, operation, and maintenance of the multistage flash (MSF) distillation plant (module) at the San Diego Test Facility.	313,078

Company	Title of Contract	$ Amount
Catalytic Constr. Co. (Cont'd) Philadelphia		
	Conduction of engineering development tests, evaluation progress and the maintenance and operation of the Clair Engle plant at the San Diego Test Facility.	$ 451,812
	Catalytic Constr. TOTAL:	$1,112,703
Dr. Wm. H. Diment Rochester, New York		
	Consulting services on committee to study geologic and seismologic data in connection with proposed MWD nuclear desalting plant.	2,400
Electronic Assoc., Inc. Princeton, N. J.		
	Simulation of multistage flash test module (9-stage San Diego plant).	63,950
The Fluor Corporation Los Angeles, Calif.		
	A&E for Clair Engle - Title III.	5,671
	Special design studies and piping modification and A&E.	4,541
	Technical assistance on MWD project.	107,000
	Evaluation of capabilities of the vertical tube evaporator and the multistage flash distillation desalination processes.	79,390
	The architect and engineering design of a multistage, multi-effect flash distillation saline water conversion demonstration at San Diego.	18,200
	The Fluor Corp. TOTAL:	$214,802
Foster-Wheeler Corp. Livingston, N. J.		
	Furnish and construct a MSF test module, San Diego.	3,518

Company	Title of Contract	$ Amount
Foster-Wheeler Corp. (cont'd) Livingston, N. J.		
	To provide flow tubes and piping changes for a MSF flash module.	$ 119,000
	Foster-Wheeler - TOTAL:	$ 122,518
Gulf General Atomic San Diego, Calif.		
	Operation of 10K spiral module reverse osmosis pilot plant.	26,475
	Theoretical evaluation of measurements of thermal neutron scattering.	37,438
	Study of rejection of various solutes (reverse osmosis membrane).	95,300
	Research on improved reverse osmosis membranes.	249,811
	Field testing of the 10,000 gpd spiral module reverse osmosis pilot plant.	46,716
	Further field testing of reverse osmosis test unit.	37,770
	Development and testing of large spiral-wound reverse osmosis module.	99,865
	Technical services of field engr. for reverse osmosis test unit.	6,230
	Gulf General Atomic - TOTAL:	$599,605
Havens Industries San Diego		
	One 3,000 gpd brackish water reverse osmosis test unit.	7,195
	Procurement for two reverse osmosis test units -- one brackish water unit and one sea water unit.	5,250
	Test operation of tubular reverse osmosis unit on sea water.	40,800
	Havens Industries - TOTAL:	53,245

Company	Title of Contract	$ Amount
Houston Research Inst. Houston, Texas		
	Development and procurement of instrumentation project for the San Diego improved distillation plant.	$ 20,503
	Installation of instrumentation for the one-million gpd Clair Engle test plant.	97,448
	Development and procurement of instrumentation package for the San Diego improved distillation plant.	22,785
	Installation of special instrumentation in the MSF module.	120,361
	Houston-Research Inst. Total:	$261,097
Kaiser Engineers Oakland, Calif.		
	A brackish water field test evaluation of membrane processes.	211,600
Kaiser Industries, Inc. Washington, D. C.		
	Parametric economic and engineering study of reverse osmosis process.	102,000
Dr. J. W. McCutchan Los Angeles, Calif.		
	Performance studies for OSW in connection with distillation and membrane desalting processes.	1,000
McDonnell-Douglas Corp. Newport Beach, Calif.		
	Research on porous glass membranes for reverse osmosis.	118,779
	A study of in-situ formation of regenerative cellulose acetate membranes on porous tubular supports.	32,889
	McDonnell-Douglas - TOTAL:	$151,668

Company / Title of Contract	$ Amount
North American Rockwell Corp., Canoga Park, Calif.	
Study of prescaling deposition.	$ 91,424
Study of a specific influence of ionic species on structuring in water.	97,176
Development of direct contact condensation multi-stage flash distillation process.	137,265
Studies in nucleation and growth of ice crystals.	72,941
Electrochemical and demineralization of brackish water.	160,375
Development of direct condensation multistage flash (DCC-MSF) distillation process.	34,200
North American Rockwell TOTAL:	$593,381
San Diego Gas/Elec. Co., San Diego, Calif.	
Extend culvert at San Diego facility.	6,450
Inclusion of various purchase orders issued by facility manager.	56,928
License agreement, maintenance and operation of San Diego Test Facility.	231,931
License agreement.	7,925
San Diego Gas/Elec. Co. TOTAL:	$303,234
City of San Diego	
Evaluation of materials for coating for transporting product water.	89,259
Dr. Harry Seed, Berkeley, Calif.	
Consultant services on committee to study geologic and seismologic data in connection with Bolsa Island nuclear desalting plant.	2,400

Company	Title of Contract	$ Amount
Stanford Research Inst. Menlo Park, Calif.	Revision of comparative engineering analysis of alternative processes for saline water conversion.	$26,671
Stanford University Stanford, Calif.	Transport phenomena in fused organic salt.	56,712
Stearns-Rogers Corp. Denver, Colo.	Design, construction, supervision, and startup of the lime-magnesium carbonate pretreatment system for the Clair Engle Plant.	56,016
	Design, construction, supervision, and startup of the lime-magnesium carbonate pretreatment system for the Clair Engle Plant.	32,801
	Stearns-Rogers Corp. - TOTAL:	$88,817
United Geophysical Corp. Pasadena, Calif.	Consulting services as an independent check on the interpretation of geophysical data being obtained by the Bechtel Corp. and its subcontractors, for the Bolsa Island Project.	3,315
U. S. Naval Civil Engrg. Laboratory Pt. Hueneme, Calif.	Test operation of 2,500 gpd two-stage sea water reverse osmosis pilot plant.	45,000
Universal Water Corp. Del Mar, Calif.	Evaluation of desalination properties of cellulose acetate membranes.	51,628
	Modification of the initial design of the sea water reverse unit.	7,665
	Universal Water Corp. TOTAL:	59,293

Company		$ Amount
University of		
Multicomponent ment of sali	treat-	$ 90,782
Development of		59,189
Sodium translc study.	ive	12,334
	ia TOTAL:	$162,305
Whittaker Corp San Diego, C		
Test operatior on sea water	it	16,995
Dr. Stanley Wi Seattle, Was		
Consulting ser and seismolc Island nucle	eologic olsa	2,400
	TOTAL:	$6,671,248