Desalting the Pacific

A progress report on how we are tackling the problem of getting fresh water from the oecan

by Jack E. McKee

From the earliest days of recorded history, man has dreamed of using the vast quantities of ocean water for drinking or for irrigation. Of all of the water on the surface of this planet, over 99.99 percent occurs in the ocean. If it were piled on the land, it would stand over 2 miles deep. In comparison, the total yearly rainfall over the entire land surface is only about 24 inches, and all of the moisture in the atmosphere is equivalent to only about 2 inches. Yet, the great bulk of water has been locked away from us because it is too saline for our use, and we haven't discovered how to convert it at reasonable cost.

Certainly, the desalting of sea water is one of the most challenging and fascinating problems ever faced by scientists and engineers. Until recently, its solution was not too urgent; but with increasing pressure from population growth throughout the world, and with larger and larger per capita use of fresh water as our civilization becomes more industralized, the problem has been brought into sharp focus.

In military activities, where expense is not a consideration, the desalting of sea water is a practical and accomplished fact. Special kits are available on life rafts, employing the ion-exchange process, which produce fresh water from the ocean at a cost of about $5.00 per pint. On Iwo Jima, during World War II, the entire supply of drinking and cooking water for more than 30,000 Army, Navy, and Marine personnel was produced by various types of distillation units. This method of producing fresh water is also used aboard many ships. It is certainly cheaper to haul one gallon of fuel oil than the 100 gallons of potable water that can be produced from the heat of such oil.

Distillation units are already employed for municipal water supply where no other sources are available. At Curacao in the Dutch West Indies, a population of 45,000 is supplied with fresh water by a 6-stage evaporator having a capacity of 770,000 gallons per day (gpd). At Kuwait on the Persian Gulf, and at Aruba, near Venezuela, similar distillation units are employed to supply these oil-producing communities. Even in California, the Pacific Gas and Electric Company distills 144,000 gpd of fresh water from the ocean. The cost of such water, however, is approximately $2.15 per thousand gallons or $700 per acre foot.

At this point it might be wise to pause and consider the standardization of price quotations. You may read one promoter's claim that his scheme for getting fresh water from the ocean costs only 15 cents per ton of fresh water, which sounds ridiculously cheap. More frequently, you will see a figure such as 60 cents per thousand gallons, which still appears to be quite inexpensive. The same price, when expressed as $600 per million gallons sounds prohibitive. Here in the West, we are accustomed to the term "acre foot" (AF). Any rancher or waterworks operator knows how much he can afford to pay for an acre foot of water; therefore, I shall confine all price quotations here to dollars per acre foot. If you are accustomed to other yardsticks you might remember that water priced at $10/AF is equivalent to:

	$30.70 per million gallons
or	3.07 cents per 1000 gallons
or	2.30 cents per 100 cubic feet
or	¾ cents per ton

Thus, the quotations of 15 cents per ton or 60 cents per thousand gallons, as mentioned before, are both equivalent to about $200/AF.

It is also important to standardize methods of computing costs to take into account maintenance, deprecia-

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tion, and interest on the capital investment, as well as power or heat costs. Often you will see a ridiculously low price quoted for desalting sea water. If you can pin down the source you will probably discover that the cost is for power only, and then probably at an impossible rate.

To minimize rash statements that may lead to false hopes, the Department of the Interior's Office of Saline Water has established a realistic standardized cost-estimating procedure. It includes amortization based on a 20-year plant life and 4 percent interest. Power is rated at ½ cent per kwh, heat at 25 cents per million Btu, and steam at 55 cents per 1000 lbs. Land costs are figured at $3 per gpd capacity and storage is provided for 10 days production of water. Most of the cost figures in this report comply with this standardized procedure.

The three large categories of water uses in the United States are irrigated agriculture, domestic use, and industrial requirements. Let us take a look at the prices that these three groups are accustomed to paying.

TYPICAL RATES FOR WATER

	Approximate Water Rates per acre foot		
Beneficial Use	*Lowest*	*Common*	*Highest*
1. Irrigation water			
a. Bureau of Reclamation	$1-2	$ 2-6	$ 27
b. Independent districts	2-5	5-10	40
c. Individual wells	2	10	20
2. *Municipal Water*			
a. Raw water cost to city	2	10	50
b. Owens Aqueduct (Los Angeles)*	—	19	—
c. Pasadena, MWD water* (1956)	—	44	—
d. Retail Cost to consumers	5-10	50-80	200
3. Industrial water	2	50-100	1000

*Total costs, including amortization of bonded indebtedness and treatment.

Irrigators are accustomed to cheap water. Most sales by the Bureau of Reclamation are at rates $2-6/AF, and the highest at $27/AF. To pump water from underground basins generally costs $4-5/AF per 100 foot lift. Many ranchers pump 150 to 400 feet, at a cost of $6-20/AF.

When considering municipal water, one must recognize the difference between the cost of raw water to the city, and the cost to the consumer of the treated and distributed water at the tap. Most raw water costs are comparable to those of irrigation water. From a study of water rates around the country, it is apparent that the retail consumer pays a price considerably higher than the raw water cost, with most householders paying about $50-80/AF. Note that the cost to the consumer at the tap is two or three times the cost of the raw water. In other words, it costs more to distribute the water than to obtain it initially.

Insofar as industry is concerned, the value of water depends entirely upon the nature of the industry. Paper, textile, tannery, and steel mills must have abundant and cheap water, probably as cheap as irrigation water. Most industries can afford delivered city water, that is at $50-80/AF or even more. Some highly specialized industries need small quantities of fine-quality water, and they can afford to pay a premium price for it. Or, they may treat the water by expensive means, at costs up to $1000/AF or more. To industry, water is a raw material. For this reason, many industries tend to locate where water is abundant, cheap, and of good quality.

At the beginning of the Saline Water Conversion Program of the Department of Interior in 1952, two arbitrary cost goals were set, one for municipal water and one for irrigation water. The goal for municipal water was set at $125/AF and that for irrigation water at $40/AF. As the table (left) indicates, however, these goals are still at the upper end of the scale for the typical rates now being paid for municipal and irrigation water. If these rates can be obtained by practical sea-water conversion units, such water will begin to become competitive with alternate existing supplies in a few localities.

The salinity of ocean waters is fairly uniform at about 3.5 percent solids, or, in the concentration term most commonly used, 35,000 milligrams per liter (mgpl). In the Persian Gulf, however, it is nearly 40,000 mgpl, and probably almost as high in the Gulf of California. In Chesapeake Bay it is about 15,000 mgpl and in the Baltic Sea only 7,000 mgpl. When considering the Pacific Ocean, 35,000 mgpl is a suitable figure. It may be broken down into the most common constituents as shown in the table below.

MAJOR SALTS IN SEA WATER

		Concentration Expressed as	
Substance		*mg/liter*	*lbs/1000 gallons*
Cations:	Sodium	10,722	89.5
	Magnesium	1,297	10.8
	Calcium	417	3.5
	Potassium	382	3.2
	Strontium	14	0.12
Anions:	Chlorides	19,337	161.2
	Sulfates	2,705	22.6
	Bicarbonates & Carbonates	104	0.9
	Bromides	66	0.5
	Borates	18	0.2
Trace ions		17	0.2
	Totals	35,079	292.7

When the sea water is desalted, how pure must the fresh water be? The drinking water standards of the U.S. Public Health Service specify that the total dissolved solids should not exceed 1000 mgpl. The USPHS also specifies that the magnesium should be less than 125, the chlorides less than 250 and the sulfates less than 250 mgpl.

For irrigation water, it is desirable to keep the total dissolved solids less than 650 mgpl, and certainly less than 1200 mgpl except for the hardiest crops under the most favorable irrigating conditions. In addition, chlorides should be less than 200 mgpl and boron less than 0.5 mgpl. Sodium is particularly detrimental in irrigation water, especially when the ratio of sodium ions to total cations on an equivalence basis exceeds 60 percent. The table below shows a summary of these water quality criteria for domestic and irrigation waters.

SOME APPROXIMATE LIMITS OF WATER QUALITY

	Concentrations in mg/liter	
Substance	*Domestic*	*Use Irrigation*
Total dissolved solids	1000	650-1200
Chlorides	250	200
Sulfates	250	500
Magnesium	125	—
Boron	—	0.5
Sodium ratio (Na/Ca+Mg+Na)	—	60%

Based on total solids, these criteria show that over 97 percent of the salts must be removed from the water; but this would still leave the sodium concentration at 320 mgpl and the sodium ratio far greater than 60 percent. For domestic use and irrigation, such high sodium concentrations would be prohibitive. It appears, therefore, that almost 100 percent of the salts must be removed from sea water.

For industrial water, the requirements for purity vary tremendously with the characteristics of the industry and the use to which the water is put. For example, high-pressure boiler feedwater must be close to distilled water in quality. On the other hand, sea water itself can be used for once-through cooling water. For most industries, water that meets the domestic criteria will be suitable as a source of raw water, although the industries may have to modify this water somewhat for special purposes.

Until a few years ago, research in the desalting of sea water was sporadic and uncoordinated. In 1952, however, the Congress of the United States recognized the importance of this problem and passed Public Law 448. This act authorized the Secretary of the Interior to develop practical low-cost means of producing from sea water, or from other saline waters, fresh water of a quality suitable for agriculture and for industrial, municipal, and other beneficial consumptive uses. The initial appropriation was $2,000,000 for a five-year period, extending to June, 1957. The last Congress extended the program for an additional five years, and has increased the money value of the research to a total of $10,000,000 or $2,000,000 per year. To assist the Secretary of the Interior in broad policy matters, an advisory group was named consisting of nine qualified persons in various fields related to the program. One of this advisory group is Caltech's President Lee A. DuBridge.

Within the Department of the Interior, an Office of Saline Water was established. This office administers the program by research and development contracts with many private agencies.

Various methods have been investigated for the desalting of sea water. Utilizing principles of thermodynamics and physical chemistry, it is possible to calculate the absolute minimum free energy required to separate salt from water, regardless of the method used. This is a theoretical energy requirement which is a property of the molecular forces holding the salt in solution. At 25°C this minimum free energy is 2.89 kwh per 1000 gallons, or 940 kwh/AF.

This is the work required when operating an *ideal* process, infinitely slow, with an infinitesimal fraction of fresh water from a huge volume of sea water, with no heat losses and no inefficiencies. To recover one gallon of fresh water from every two gallons of sea water, the minimum free energy is about 1200 kwh/AF. The best overall efficiency we can hope for is 33 to 50 percent, making this energy requirement 2400 to 3600 kwh/AF. Costs for amortization and maintenance of the plant must be added.

According to a recent OSW report the actual minimum energy requirements have been calculated for two methods of desalinization, taking into account the rate phenomena, plant costs, and several other factors, but still excluding many losses in energy conversion devices and the water transport requirements. This report computes theoretically that the minimum energy requirement will be about 3500 to 4000 kwh/AF, or about four times the theoretical ideal minimum. On this basis, with power at 0.5 cents per kwh, the minimum cost would be about $18/AF. To allow for energy losses and other inefficiencies, this figure would probably be doubled to about $35/AF.

Desalting processes

All processes for desalting sea water can be divided into two categories; those that extract the water from the saline solution and those that remove the salts from the solution. The costs of processes that extract water will be relatively independent of the salt concentration except for problems of scaling. For processes involving the removal of salts, the cost will be approximately proportional to the concentration of salt.

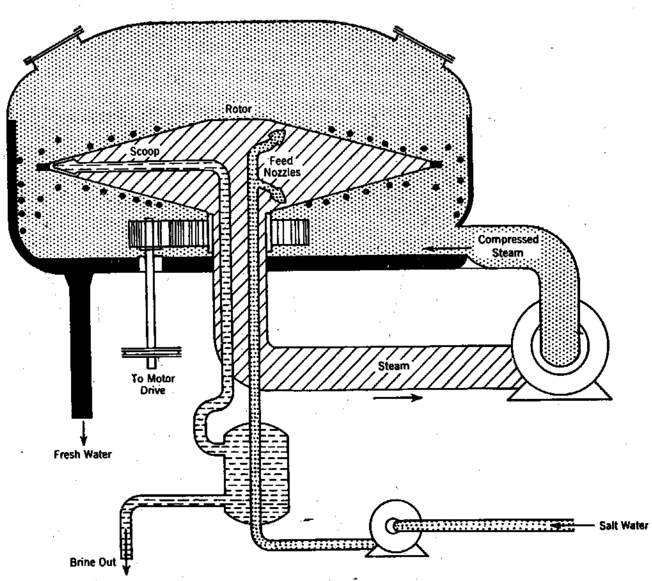
Methods of desalinization have been divided also into physical, chemical and electrical processes. Among the most prominent of the physical processes are the various distillation methods, solar radiation, temperature-difference processes, nuclear-energy adaptions, freezing, ultrasonics, and osmosis. Chemical processes include precipitation of salts and ion exchange. Electrodialysis constitutes the most significant electrical process.

Simple distillation operates like a conventional laboratory still, but it is not nearly as useful for salt-water conversion. The heat required is equivalent to about 900,000 kwh/AF or about 1000 times the minimum free energy. Needless to say, the cost is prohibitive.

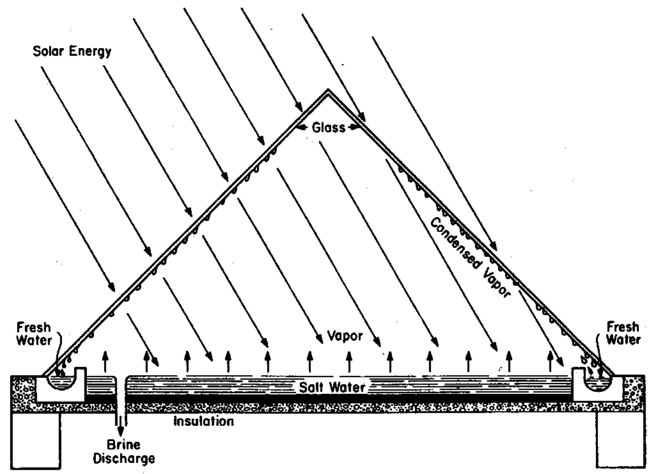
Engineers discovered long ago that the efficiency of distillation could be improved by several stills in series. Multiple-effect distillation utilizes the vapor from each still to heat the next still at a lower pressure, which is maintained by vacuum pumps. Heat requirements have been cut to about 200 times the theoretical minimum, but costs are still in excess of $700/AF. W. L. Badger of Ann Arbor, Michigan, has proposed a multiple-stage long-tube vertical evaporator of the type used by the salt industry. The cycle requires completely scale-free operation. If this can be achieved without the use of acid or non-ferrous metals, Badger feels that fresh water conceivably *might* be produced at $130/AF. Before this optimistic estimate can be accepted, the process must be tested adequately.

If the vapor from a still is compressed it will condense at higher temperature and can be used to heat the sea water. This process is known as vapor-compression distillation. With the aid of heat exchangers, the heat input can be greatly reduced, but expensive electric power is required. During the war, water from such equipment cost about $400/AF, but with technological improvements this cost might be cut appreciably. One such improvement is the Hickman rotary still (below). Here the feed water is spread by centrifugal force in a thin film over the surface of a conical rotator. This action increases the rate of heat transfer from 500 up to 3500 Btu per hour per square foot per degree F. Inasmuch as salt water at temperatures as low as 125° F can be sprayed on the inside surface of the rotating drum, the probability of scale formation is minimized. A pilot plant designed to produce 25,000 gpd is under construction and there is promise that the cost *might* be reduced to $115/AF, but this remains to be demonstrated.

As far back as 1930, a Frenchman named Claude proposed that the difference in temperature between cold deep ocean waters and warm surface waters could be used to produce power and fresh water. When warm sea water is taken in under reduced pressure, some of it evaporates. This vapor can be used to drive turbines and generate power to help operate the pumps. Then the vapor is condensed by cold sea water. Where deep ocean canyons are close to shore, this process may prove to be feasible. At present, such a plant is being planned by French engineers at Abidjan in West Africa to produce 150,000 gpd of fresh water, The French engineers estimate costs of about $150/AF now and possibly as low as $100/AF in the future.



The Hickman rotary still combines vapor-compression with evaporation from a thin sea-water film maintained by centrifugal action.



In a solar still, vapor formed by evaporation condenses on the underside of the glass and flows into the trough.

Why not copy nature and use solar heat for vaporization? Solar stills of the type shown above will produce fresh water at the rate of one pint per day per square foot of exposed surface in sunny climates. Expressed otherwise, one acre of stills will yield 6 acre feet of fresh water per year. At this rate, one acre of stills would be needed for every 2 or 3 acres of irrigated land or residential area!

In the Southwest, the energy received on a horizontal surface is about 2000 Btu per square foot per year. A solar still will collect about half of this energy, but its efficiency in vaporizing water is less than 1 percent. Furthermore, the cell operates only 6 to 8 hours a day. By using the ground as a storage bank for the sun's heat, or by combining solar stills with multiple-effect or vapor-compression distillation, it is hoped that some of these disadvantages can be overcome. Other proposals include a 10-stage sandwich-like arrangement of alternating absorbing and condensing layers on a sloping surface, which shows promise of a five-fold increase in the production rate. Former costs were about $900/AF but present estimates with improved stills range from $325 down to $165/AF.

Another way to copy nature is to freeze water, inasmuch as the concentration of salt in ice frozen from sea water is considerably less than in the original water. Slow freezing combined with centrifugal action can be used to produce water relatively free of salt, and by successive cycles in this fashion, water of acceptable quality can be produced. Inasmuch as the heat removed in the freezing of water is only one-seventh of that required to boil water, one might anticipate that freezing would be considerably less costly than distillation. A further advantage lies in the reduction of scale and corrosion.

Unfortunately, however, low-temperature refrigerating machinery is inherently more expensive than high-temperature heat-exchange equipment. The University of Washington has made a careful economic study of all

continued on page 28

existing and potential equipment for freezing sea water. An ideal arrangement of such units could provide fresh water at a cost of approximately $750/AF.

The Carrier Corporation is conducting research to determine the economic feasibility of a method to combine freezing and evaporation. Another new approach, known as "zone freezing," is being evaluated by the Battelle Institute. There have been been reports of pilot-plant studies on the freeze-evaporation system developed by Zarchin in Israel, and the process was studied analytically by the University of California, but the university could not reconcile its cost estimates with the enthusiastic ones of the inventor.

Miscellaneous physical processes

As any student of high school physics knows, water molecules will pass through a permeable membrane from a zone of fresh water into a zone of salt water by a process known as osmosis. If sea water and fresh water are placed on opposite sides of a permeable membrane, the water surface on the sea-water side will be about 850 feet higher than on the fresh-water side. In other words, the osmotic pressure of the sea water is about 350-400 lbs/sq. in. This phenomenon can be reversed, and water made to flow from the salty side to the fresh side by superimposing a tremendous pressure. With cellulose acetate membranes, 90 to 95 percent of the salt can be removed from the water in one operation. To get drinking water, two or more passes would be required. From an engineering point of view, there are many practical disadvantages to such an operation, especially when large pressures and membrane clogging are involved. Cost estimates for this process are not available, but they are known to be prohibitive.

It has been suggested that saline water conversion can be combined with nuclear power generation to reduce the energy cost. At present, however, the cost of power or heat from nuclear energy is not competitive with that from fossil fuels such as coal and oil. Nuclear energy is not likely to become cheaper than conventional sources of energy until the latter are nearing depletion. It is possible, however, that there may be ways of using nuclear reactors primarily to produce low-temperature steam or by utilizing the power during the off-peak periods. The Fluor Corporation has just undertaken a study of the applicability of combining nuclear energy processes with saline water conversion.

Up until now, we have considered methods by which the water is removed from the saline solution. Would it be cheaper to take the salt from the sea water?

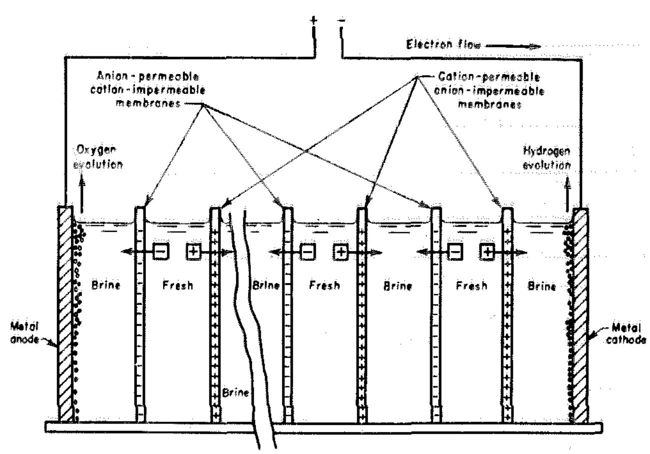
It is possible to remove salts from solution by chemical precipitation; for example, chloride ions can be removed by precipitation with silver. Chemical treatment of sea water requires the use of many different salts, some of which are quite expensive. The cost of the salts alone would amount to over $10,000/AF. Obviously, this method is beyond any further consideration for large-scale desalting processes, although it was used on life-rafts during the war.

The principle of softening by ion-exchange resins can be extended to the removal of all salts from sea water. What is more, these resins can be regenerated and re-used. Unfortunately, this regeneration requires large quantities of chemicals. The cost of these chemicals alone has been estimated at $6,000 to $8,000/AF of fresh water produced. Thus, it appears unlikely that any known chemical method for desalting sea water will be economically practicable.

When electrodes are placed in a saline solution and subjected to an electrical potential, cations in the solution will migrate to one electrode and anions to the other. If the container is divided into three compartments by means of two porous diaphragms, the center compartment will soon become free of ions that have migrated in either direction. To accomplish this purification, a high proportion of the ions must be neutralized at the anode or cathode, with a large expenditure of electrical energy. Minimum cost has been estimated at over $500/AF.

A new type of membrane, consisting of sulfonated polystyrene divinyl benzene or similar resins, was developed a few years ago. These membranes can be negatively charged so as to permit the passage of cations but not anions, or they can be positively charged so as to permit the passage of anions only. They provide a means whereby the costly neutralization of the ions at both electrodes can be minimized by the use of multiple channels (below). Any ion can pass through one membrane but not through two in succession; consequently, every other channel becomes fresh, while the alternate ones get twice as brackish.

continued on page 32



Costly neutralization of ions at both electrodes is minimized because no ion can pass through two charged membranes. Alternate channels then become free of ions.

The announcement of this process a few years ago was greeted by enthusiastic "armchair" estimates as low as $100/AF. Recent figures, based on pilot-plant experiments, are far less encouraging. Because the electric power requirements are proportional to the concentration of salt, the process does not look promising for concentrated sea water, but it appears to offer some good prospects for brackish waters. For a flow of 1.0 mgd, the cost of changing the salt concentration from 4,000 mgpl to 500 mgpl has been estimated at $260/AF. For desalting sea water, this method now appears to be completely uneconomical.

Other potential methods of desalinization are being studied, but the experimental work has not progressed to the state where reliable cost estimates can be made. For the methods just described, the table below shows a summary of the estimated costs based on large-scale installations. You will note that present costs are considerably in excess of the two goals described previously—$125 for municipal water and $40 for irrigation water. It is possible, however, that refinements in these processes will eventually bring down the costs to the neighborhood of $125-150/AF.

ESTIMATED PRODUCTION COSTS

Estimated Production Costs for Large-scale Sea Water Conversion Processes (in dollars per acre foot)

Process	*Present*	*Possible Future*
Multiple-effect distillation	$700	$130
Vapor-compression distillation	400	115
Temperature-difference vaporization (French)	150	100
Solar distillation, with combinations	325	165
Freezing, with combinations	750	?
Chemical precipitation	10,000	10,000
Ion exchange	8,000	6,000
Electrolytic action	500	500
Ion-permeable membranes (for brackish water only)	260	260

The major cost factor in the water supplies of our large cities, such as Boston, New York, San Francisco, and Los Angeles is attributable to the transportation of the water; that is, to the amortization of the large aqueducts. Fortunately for most of these cities, the water has its source in mountains, and flows to the city by gravity. When fresh water is produced from the ocean, however, it will have to be pumped to a municipality or irrigation district. The cost of such pumping, and the amortization of the necessary pipelines, will cost 30 cents to 70 cents/AF/mile. To pump water from the Gulf of California to Phoenix, for example, will cost $50-$100/AF, depending on power rates, amortization, and type of aqueduct. Transportation costs such as this must be included in the total cost of fresh water from the ocean delivered to a city or irrigation district.

This question is often asked: In addition to fresh water, can't we also recover magnesium and other valuable chemicals from sea water? The answer is yes, but let us examine the practicability and the economic feasibility. Already there are plants in the United States where sodium chloride, magnesium salts, calcium sulfate, and bromine are obtained from sea water. In addition, most of our domestic iodine is recovered from oil-field brines which are more saline than sea water. None of these processes involve the simultaneous production of fresh water.

The evaporation processes described previously do not remove *all* of the water from the saline solution. In fact, care must be taken not to remove too much because of scale formation and corrosion problems. To evaporate the sea water to dryness, or to a very concentrated brine from which chemicals might be recovered, would add greatly to the cost. Furthermore, there would be a high cost for separating the mixed salts and purifying them for marketing. Finally, the average water demand corresponds to over 5 *tons* of by-product salts per year per person.

In his book, *Fresh Water from the Ocean*, Cecil B. Ellis has analyzed other economic facets of this problem and has reached the conclusion that the profits from recovery of by-product chemicals would lie between zero and $6/AF of fresh water produced, provided only that no more than one plant of 1000-mgd capacity were built. Further plants would flood the market with chemicals.

Conclusions

By technological improvements, it is remotely conceivable that desalinization of sea water can be accomplished for $125-150/AF in the next five or ten years. Such water might find a market in certain industries or isolated communities located at sea level. For inland communities, the cost of transportation must be added.

Based on the theoretical considerations of thermodynamics and physical chemistry, it should be possible to produce fresh water from the ocean at costs of about $35/AF at sea level. This is an ideal figure, however, and to date no known process gives promise of approaching it, barring a major "breakthrough" of science and technology. In essence, we haven't the fundamental knowledge at present, we haven't studied enough, and we haven't researched enough. On the other hand, we haven't proved that it can't be done either.

Waterworks officials, ranchers, industries, and everyone interested in abundant supplies of fresh water at reasonable cost must recognize that *cheap water from the ocean is not around the corner*. On the other hand, by encouraging an accelerated program of basic research we are justified in adopting an attitude of conservative optimism.