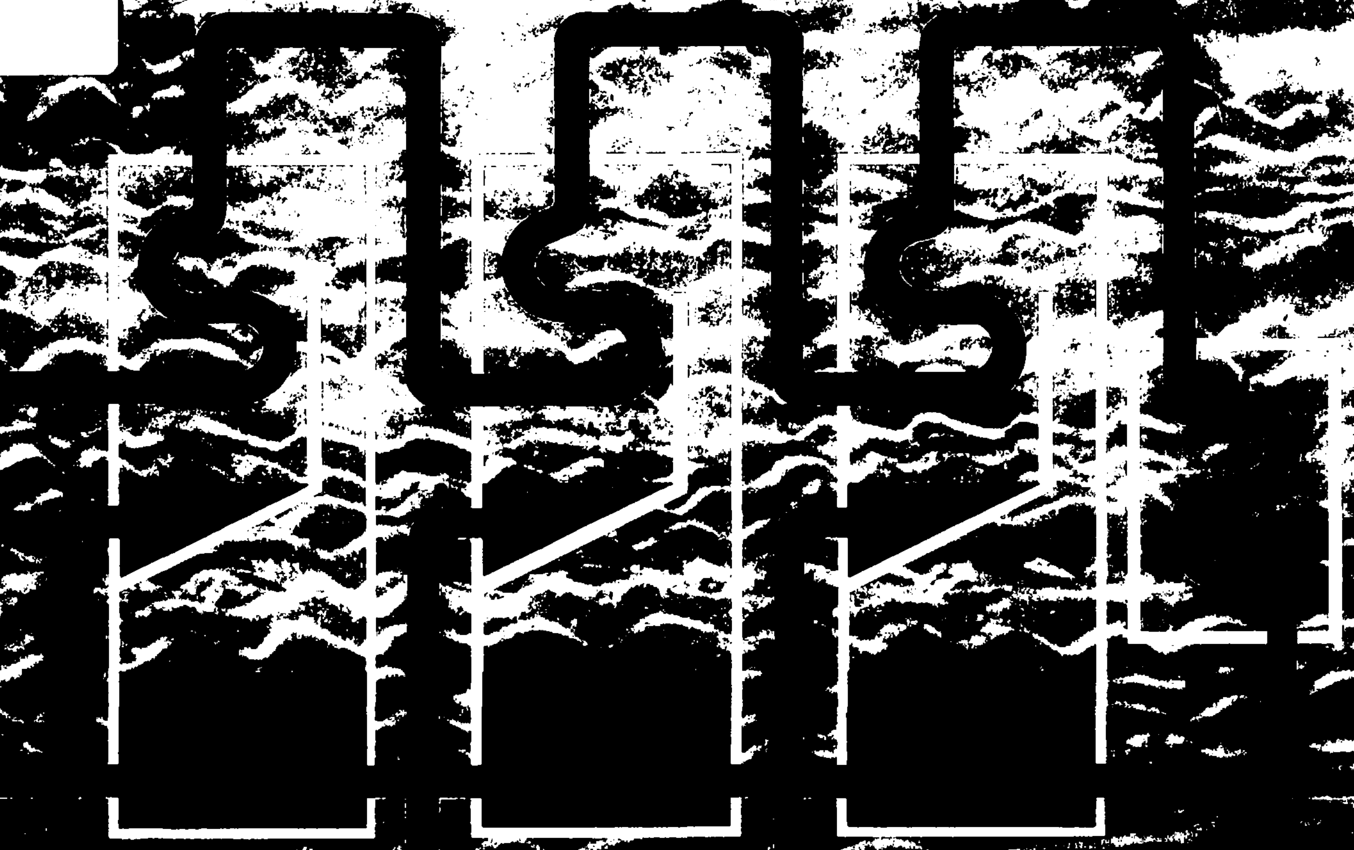
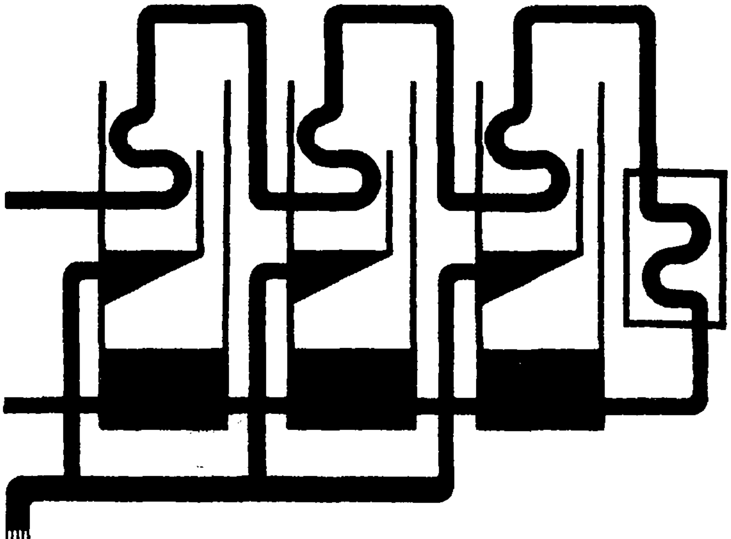


Proceedings of the Interregional Seminar on the Economic Application of WATER DESALINATION

New York, 22 September—2 October 1965

UNITED NATIONS

Department of Economic and Social Affairs



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NOTE

Symbols of United Nations documents are composed of capital letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

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INTRODUCTION

1. The Economic and Social Council in its resolution 1033 A (XXXVII) dealing with water desalination recommended that the Secretary-General, in consultation with United Nations agencies, should "continue and intensify" activities in the field of desalination. The Council took up this topic again in July 1965 and, in resolution 1069 (XXXIX), after referring to desalination as a "means of facilitating the process of economic development in water-short areas", requested the Secretary-General *inter alia* to "intensify the role of the Secretariat as a clearing-house for the exchange of information and as a focal point for co-operation in the broad field of desalination, while recognizing the specialized role of other organizations".

2. The Interregional Seminar on the Economic Application of Water Desalination was held at United Nations Headquarters from 22 September to 2 October 1965. It was convened in implementation of Economic and Social Council resolutions 1033 A (XXXVII) and 1069 (XXXIX) and pursuant to the aims set for the United Nations Development Decade and the priorities recommended by the Advisory Committee on the Application of Science and Technology to Development.

3. The principal purpose of the seminar was to review in a systematic manner the conditions under which desalination plants might fulfil a role as a source of water supply within the framework of water resources development plans. Consequently, the seminar dealt first with all possible alternatives to desalination, namely water from conventional sources (ground water and conveyance over long distances) and second with the technical and economic factors influencing decisions as to whether or not the establishment of a desalination plant is economically justified. Thus, the major objective of the seminar was to provide guidelines for the economic application of desalinated water based on the most recent developments in desalination technology and the actual experience gained thus far from the operation of desalination plants in several parts of the world. Special attention was given to the factors influencing the selection of the appropriate size and type of desalination plants required in water-short areas.

4. The seminar was organized by the Department of Economic and Social Affairs, through its Resources and Transport Division. The project was made possible through close co-operation between the Division and the Bureau of Technical Assistance Operations, which provided financial and administrative support.

5. Preparatory work for the seminar was based largely on the experience presented in the two United Nations documents dealing with specific problems of water desalination in developing countries. These documents are: *Water Desalination in Developing Countries*, published in 1964, [1] and *Water Desalination: proposals for a costing procedure and related technical and economic considerations*, published in 1965. [2]

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[1] United Nations publication, Sales No.: 64.II.B.5.

[2] United Nations publication, Sales No.: 65.II.B.5.

6. Some fifty countries among those eligible to receive United Nations technical assistance and believed to have possibilities for application of desalinated water now or in the near future, were invited to indicate their interest in the forthcoming seminar and to submit up to three candidatures for possible award of a United Nations Fellowship to participate in the seminar. In the light of the replies received, and a review of the candidatures submitted, forty-two participants were approved from thirty-four countries in Africa, Asia, Latin America and Eastern Europe. In view of the interest in the subject matter, a number of countries sponsored a second participant at government expense, in addition to the candidate attending under United Nations auspices. A list of particpants and countries is presented in annex I.

7. Several meetings were devoted to the presentation of reports by participants reviewing water resource problems in their respective countries. In the course of daily question periods, participants and lecturers were given the opportunity for a broad exchange of views.

8. A particularly significant feature of the programme was the round-table discussion reviewing the actual performance of a number of desalination plants currently in operation. This was the first time that the difficulties encountered in plant operation and the remedies applied in each case were openly and objectively discussed at an international gathering; the personal experience of the plant managers who presented their views in the course of this discussion proved to be one of the most valuable contributions to the work of the seminar.

9. At the opening session, statements were made by the Under-Secretary for Economic and Social Affairs, Philippe de Seynes and the Director of the Resources and Transport Division, Roberto Arce. Paul Hoffman, Managing Director of the United Nations Special Fund, and William R. Leonard, Deputy Commissioner for Technical Assistance, addressed the participants at the closing meeting of the seminar.

10. The seminar was timed so as to precede the First International Symposium on Water Desalination, held in Washington, D.C., from 3 to 9 October 1965. All participants in the United Nations seminar were invited to attend the Symposium as guests of the United States Government and also visited desalination installations at Wrightsville Beach, North Carolina.

11. This report is divided into three parts. Part One covers the highlights of the seminar and its recommendations, and summarizes the principal points brought out in the lectures and discussion periods. Part Two contains the texts of the nineteen lectures (three in two parts), five of which were presented by staff of the Resources and Transport Division of the United Nations Secretariat. Part Three contains three reports prepared for the round-table discussion on the operational experience of desalination plants.

PART ONE

HIGHLIGHTS OF THE SEMINAR AND RECOMMENDATIONS

HIGHLIGHTS OF THE SEMINAR AND RECOMMENDATIONS

Great pressure is being exerted on the water resources of many developing countries, particularly those located in arid or semi-arid regions. Acute water shortage exists in many areas of the world and is likely to become more severe in future years. In some areas further economic growth will not be possible until adequate additional water supplies become available. In other areas failure to increase the water supply may well result in standards of living being reduced below present levels. Water shortage is one of the most important problems facing administrators and policy-makers in many developing countries.

Water shortage is not always the result of lack of water resources; not infrequently it is rather the result of lack of water resources development. Few areas of the world have been explored adequately enough to provide full knowledge of present and potential surface or ground water resources. Many desert and arid regions are the least explored in so far as ground water resources are concerned.

It is therefore important that efforts should always be made to determine any region's present and potential water resources before giving serious consideration to desalination. All alternative ways of obtaining fresh water should be investigated in order to determine the most feasible and economic water supply scheme. These alternatives are the development of ground water, conveyance of water by pipeline or other means, and desalination of brackish or sea water.

The economic application of desalination therefore depends on the results obtained from the above comparative technical and economic investigation. Desalination can provide a supplementary, major or sole source of water supply, particularly in water-short areas which have economic growth potential (in tourism, mining, or industry) and where water from all other alternative sources of supply is brackish, inadequate, lacking or more costly. Thus desalination is an important tool for the economic development of water-short areas wherever the economic and resource conditions are favourable to its application.

When a decision is taken to construct a desalination plant, the most suitable desalination process must be selected. Desalination processes include flash distillation, multiple-effect boiling (falling film and submerged tube), vapour compression, freezing, electrodialysis, ion exchange and reverse osmosis. However, of the processes which have been tested and put into operation for many years, multi-stage flash evaporation for desalting sea water and electrodialysis for treating brackish water are considered to have the best immediate and potential economic advantage. Thus, depending on the feed water source, either of these two processes should be evaluated in the majority of cases where a need for desalination is considered.

Dual-purpose plants (capable of supplying both desalinated water and electric power) have, in certain instances, advantages over water-only desalination plants. It is therefore recommended that in water-short areas, particularly those where there is a need for additional power, a comparative study of single and dual-purpose desalination plants should be undertaken in order to determine the most economic type of plant required.

The application, however, of large-scale dual-purpose plants in developing countries seems to be limited. This is mainly due to the non-existence of an electricity and water grid system and to the fact that the additional water and power requirements are small in most of the water-short areas in developing countries. Shortage of capital, particularly the foreign exchange component, is another limiting factor.

In studying the problems of possible application, it is necessary to distinguish between two basic situations: locations where desalinated water might be a major or sole source of supply, and those where desalination is integrated within a system which is partly dependent on desalination. In the first case, reliability in supply is an overriding consideration and additional investment will probably be required to ensure this.

The most appropriate relationship between storage capacity and load factor of the plant is an important consideration, requiring complex and detailed calculations in order to establish the most economic combination of plant output and storage capacity. During the planning stage, therefore, the proper relationship between desalination and water storage capacity should be given careful attention.

One of the ways by which desalinated water costs may be reduced in the future (apart from advances in desalination technology) is the further development of the art of application. This involves either the blending of high-cost desalinated water with low-cost brackish water to obtain an economically attractive product, or the production of desalinated water in combination with other products. This refers, in addition to the production of water and power within one operating complex (dual-purpose plant), to the extraction of minerals from the residual brine (multi-purpose plant). In Kuwait, for example, the production of desalinated water is associated with the production of power and also of caustic soda, salt, chlorine and hydrochloric acid from the brine. The application of multi-purpose desalination plants in other areas is expected to increase in the future.

Specifications for desalination plants should be well prepared, preferably by engineers with operational experience. Carefully prepared specifications will contribute to the formulation of standardized bids and this in turn will help to reduce the time required to evaluate the bids and hence to construct a desalination plant.

Prototype tests in the laboratory or on the site and the proper choice of materials, chemicals, and coating are important considerations and can lead to savings in capital, operation, and maintenance costs.

Advances in technology are expected to result in further reduction in the cost of desalination. Research in the field of desalination may be divided into two major fields. The first aims at improving known processes through the use of less and cheaper material per unit of capacity and by developing better designs. The second aims at developing new processes or known processes which have not yet been produced commercially (such as reverse osmosis which appears to have encouraging prospects for early application).

The round-table discussion on the experience and operation of desalination plants highlighted the importance of operational experience to efficient management and operation of the plant. Thus, during the planning stage, it will be necessary to give serious thought to staffing plants with competent and well-trained personnel.

Costing, pricing and allocation techniques remain among the most challenging questions still to be settled. The establishment of the most appropriate depreciation rates will require additional time to test the durability of equipment currently available. Approaches to pricing and allocation will, in most cases, depend to a large extent on social and political considerations. It is important, however, that the authorities responsible for the planning and administration of water supply should take fully into account the implications of costing and pricing procedures, with a view to establishing appropriate subsidization policies, when and where they may be needed. Further studies on water rates applicable to desalinated water are required.

To sum up, the availability of adequate water supply is the key to the economic development of water-short areas which have economic growth potential. Existing desalination technology is satisfactory for application in many such areas where the need for water is primarily for tourism, mining operations and industry. Desalinated water for domestic use appears to be feasible in areas where the cost of water from existing and potential conventional sources is very high. In other areas, the use of desalinated water for domestic purposes may have to be subsidized, depending on the purchasing power of the population and government policy. Desalinated water, even when blended with brackish water, remains too expensive for irrigation save for special purposes such as the supplementary irrigation of high value crops.

The following recommendations are among the most important submitted by the participants:

(a) That the United Nations should intensify its advisory activities in the field of technical assistance and in the preparation and execution of pre-investment surveys leading up to the possible establishment of desalination plants, when and where warranted.

(b) That the United Nations should prepare a basic questionnaire to be sent once a year to authorities charged with the responsibility of operating desalination plants, in order to assemble and maintain up-to-date operational data on desalination plants, which should be published and distributed periodically. Such a publication could be a very useful source of information in the field of desalination, particularly for those developing countries which are interested in the application of water desalination.

PART TWO

LECTURES DELIVERED AT THE SEMINAR

I. WATER DESALINATION: PRESENT APPLICATION AND OUTLOOK FOR THE FUTURE

by the United Nations Secretariat

I shall first briefly review the history and present application of desalination. I shall then discuss the rapid increase in water needs, followed by the outlook for conventional water and the extent to which and in what areas technological improvements and further development of conventional water may satisfy increasing water needs. Finally, against this background, I shall review the outlook for desalination.

A. Present application

The first operational desalination units came into being with the development of steamships. Until then, a large part of the carrying capacity of ships had to be utilized for the carrying of water. With desalination units on board, therefore, water could be produced from the sea and a large part of the carrying capacity of the ships, formerly used for water, could be devoted to the transporting of passengers or goods.

From the use of desalination units on steamships followed the application of desalination in stationary units on land. Although the first land-based stationary commercial units were built more than forty years ago, it was only after the Second World War that desalination came to be considered as a possible solution to acute and extreme water problems in areas where water was needed at any cost. Over the last fifteen years, research, development and application have moved ahead quite rapidly, and the United Nations world-wide survey found that in 1962 there were about eighty land-based desalination plants operating, with a combined output of approximately 56 million gallons per day. More recent data based on a similarly detailed survey for later years are not available at this time. However, we estimate that in 1965, there are about 120 desalination plants operating or under construction with an output of about 120 million gallons per day. 1/

Most of the commercial desalination plants now in operation are found in three areas: namely, around the Mediterranean, the Persian Gulf and the Caribbean. There is no commercial plant yet in the Far East, but Hong Kong will have one soon. 2/ The first desalination plant in the Soviet Union is now reported to be in operation and four commercial plants are reported to be in operation in Europe.

Desalination has now reached a stage of development and momentum at which it is visualized that wherever water needs are critical, where high-cost water is economically acceptable, and where there are saline water bodies nearby,

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1/ These estimates do not include electrodialysis plants, movable units, units operated by military forces, pilot plants and demonstration plants, and units operating on ships.

2/ A small desalination plant has recently been installed in a Hong Kong hotel.

desalination can provide a solution to the shortage of water. The survey which you have before you describes the application of desalination in the development of natural resources, and its use in tourist industries as a source of potable supply. Thus, I do not need to describe the present use of desalinated water in detail. It should be noted that about 90 per cent of desalination plants are located in developing countries and that so far very few are found in industrial countries, and that the majority of these plants are operating in areas in which there is no other source of water.

B. The rapidly rising demand for water

Although water statistics are still in their infancy, it is obvious that there is a persistent increase in the demand for water for two reasons, namely:

(a) The growth in population and the rise in the standard of living, and

(b) The growth in commodity production and in service industries.

World population is rising at present at an average rate of about 2 per cent per annum, which means that, other factors being equal, world water demand will double about every thirty-five years. This demand, however, is further raised by the rise in the standard of living, leading to greater requirements for water for human consumption. This is brought about by the movement of population from primitive to modern housing, with water supply and bathrooms; by the rapid urbanization evident in all countries; and by numerous other factors.

Practically every increase in the production of goods - from rise to electricity and chemicals - requires increased quantities of water. 3/ The same applies to service industries, from commercial laundries to hotels. The increased demand for water resulting from the growth in the production of goods and the expansion in service industries is difficult to estimate because much will depend on the type of commodities to be produced and the type of service industries to be established. It should be noted, however, that the increased demand for water for the production of goods and services is independent of the increased demand for water for the population and is therefore additional to the latter.

The rapid increase in the demand for water, considered on a world-wide basis, is too abstract to be fully meaningful, however, because there are still a number of areas which have very large unused water resources. In such areas, a rapidly rising demand for water would create no problem. It is essential, therefore, not only to look at the rising demand for water but also to try to pinpoint where such demand takes place. If the growth in population and production were restricted to water-rich or water-surplus countries, much of the significance in the increase in demand for water would be lost; thus, we might argue that a very sharp increase in the population of the Amazon Valley or of a similar water surplus area would be meaningless from the point of view of water as a supply problem. It is noteworthy,

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3/ In industry especially, improvements in technology may sometimes lead to a reduction in water requirements per unit of output. However, this is by no means general and furthermore the increase in the total volume of production usually leads to an increased water demand even in commodities for which improved technology for the unit requirements of water have been reduced.

however, that both population and production seem generally to grow more rapidly in areas where there is a shortage of water than in areas where too much water is available, such as the Amazon Valley. Since the last World War, there has been a rapid development of desert areas. A large part of the world production of petroleum comes from desert territories and the same applies to copper, phosphates and a number of other minerals. For these reasons, the geographic location of the rapid rise in the demand for water must be noted.

C. The outlook for conventional water

Conventional water supplies are the backbone and the basis of all human activities and 99 per cent of all water needs are supplied by conventional water. On a world-wide basis, the total amount of fresh water available from conventional sources is very large indeed, although there are no reliable estimates as yet. It is also obvious that such a world-wide approach is fruitless and that the availability of water has to be studied on an area basis, as will be described in some of the other papers.

It is also important to note that not every lack of water is the result of a lack of water resources. In many areas where detailed studies have been carried out by the United Nations, we have found that there is frequently a neglect of water resources development and not a lack of water in the physical or economic sense, meaning that conventional water is either not available or too expensive to develop. For a long time to come, conventional water will continue to supply the bulk of all water needs.

Water can usefully be evaluated only in a given area within which water can be physically and economically conveyed. Within such an area conventional water could be considered as a given stock of water which, in the few cases in which it is fully utilized, cannot be increased unless additional fresh water is obtained through desalination, if applicable.

The stock of conventional fresh water is in itself a concept undergoing changes over time - with changing technology and changes in the use and re-use of water and the economic effect of water utilization - so that this stock of conventional fresh water may acquire a new meaning. Some of these questions are discussed in the following:

1. The cost of conventional water resources development

It may be stated that usually a country will develop the lowest-cost water sources, which are usually those closest to the points of need. Gradually, as the population moves away from the rivers, more distant water resources have to be developed, ground water has to be pumped from greater depths, etc., and, on a long-term basis, as the country and the population develop, additional conventional water development becomes more expensive. This reflects a secular trend, but each set of circumstances has to be examined on its own, particularly in the light of any changes in the technology of conventional water resource utilization. It is essential, therefore, to take a look at conventional water resources technology.

2. Technology applicable to conventional water

In river basin development as well as in many other aspects of conventional resources development, technology has until recently moved comparatively slowly. It is true that there has been development in large-scale earth-moving equipment on river constructions, that there has been some improvement in drilling equipment and so on, but it is hoped that more important technical improvements in conventional water resources exploration, development, use and conservation will occur. Among such possible developments, most of them still in the research stage, the following may be mentioned:

(a) Evaporation control. A successful method of achieving evaporation control at low cost from open reservoirs would not only prevent heavy losses of water, and in this way substantially increase the supply of surface water, but would also lower the cost of such water.

(b) Rain-making and weather modification. The significance of such possible developments are so obvious that they need not be discussed here in detail.

(c) Recharge of ground water. This is a new method of water management which is now beginning to be applied. Where this method is applicable, and this depends on geological and other factors, surplus water during the rainy season can be stored underground and pumped up during the dry period.

(d) The development of geophysical methods for the exploration of ground water by air and on the ground. Equipment for these purposes is now being developed and may allow the discovery of fresh ground water in areas where such water is not yet known to exist.

Other possible technological developments relate, for example, to the reprocessing of sewage water and of acid mine water, and the lowering of the cost of water conveyance through such devices as dracones and plastic pipelines.

Practically all the possible new technological improvements described above will lead to increased water supplies and to the lowering of water costs.

Our long-term view, expressed earlier, that countries move from the development of their low-cost resources to that of their high-cost resources remains true particularly on a project-by-project cost comparison basis. Technological improvements, however, may lead to a lowering of conventional water costs in future projects and even in existing projects, if such new improvements can be incorporated. In this respect, water resources follow the same pattern as that experienced in mineral resources, as for instance with copper. The improvement in technology has been so rapid that the decline in the quality of the ore - from a 10 per cent ore exploited one hundred years ago to 1/2 per cent today - has not raised the cost of copper on a long-term basis. It is doubtful whether technology in the case of conventional water will move as rapidly and as effectively as it has moved in respect of many minerals; but that this technology will move must be expected and must be taken into account by the water specialist who studies water projects for the future.

3. The utilization of water

The cost of water may in future be reduced by improvements not only in the exploration and development of conventional water resources but also in the utilization and protection of conventional water. This includes a further group of factors which may have a significant long-term effect on the demand and supply of water. Three factors have to be noted in this respect, namely:

(a) The price charged for water;

(b) The re-use of water; and

(c) Pollution control.

The use of water for purposes other than potable water supply for human consumption is basically a matter of economics. It follows that in a given water-short area a re-allocation of water through higher prices may substantially diminish the demand for water, and, in this way also increase the available supply of water for the remaining consumers. In other words, under particular conditions, an increase in the price of water may eliminate all water demand for which the new water price is too high, with the result that existing supplies will be sufficient. A policy of overcoming water shortages by eliminating water customers through increases in the price of water is a policy which may have many side effects and will need, in every given case, a very detailed study of its possible effects and side effects. It is not a policy which can be applied rashly and indiscriminately.

The re-use of water, already applied in some water-short areas, induces industries to recycle water and may lead to the reprocessing of water after use from sewage or industrial waste. Such re-use will obviously have its economic limits, but where applicable it will diminish the demand for water as compared to the once-through use of water.

Pollution control involves the protection of rivers, lakes and underground water against spoilage by the indiscriminate disposal of waste products into water bodies. Where water bodies can be protected, large water resources will remain uncontaminated and will be available as water supply sources. This pollution control, which is not yet an important problem in most developing countries, is, however, significant in countries with considerable industries and to some extent for countries using large quantities of fertilizers in their agriculture. In such countries, early pollution control will maintain the capacity of conventional water resources to serve as water supply sources.

The possible technological improvements in conventional water resources development and the possible improvements in water utilization and application must be given full consideration in viewing the future applicability of desalinated water in various parts of the world.

D. The outlook for desalination

The outlook for desalination will depend basically on two important groups of factors, namely, the demand for desalinated water and the cost of desalinated water.

The demand for desalinated water on a world-wide basis is almost as difficult to estimate as is the total demand for fresh water on a world-wide basis. One lecture - to be given later - will deal specifically with the question of how to estimate the demand for desalinated water, and in this short statement I do not wish to touch on the methods. However, in looking at the future role of desalination, it is essential to visualize its possible application in the light of three aspects which I would like to stress:

(a) the demand by geographic location;

(b) the demand by economic sectors; and

(c) the demand by size.

(a) The demand by geographic location

As our survey has shown, desalination is needed and applied today in the following four types of areas: (i) arid areas; (ii) semi-arid areas; (iii) islands; and (iv) areas of concentrated water demand. The first three categories are more or less obvious and need not be discussed here in detail, as an arid or semi-arid area is, by definition, as area characterized by its lack of water. Islands are areas which have no hinterland for water supply, the only source of water being that which is on the island. For this reason, it is found that today many islands are short of water. But there is a fourth category which is now beginning to be considered as a possible area for desalinated water supply - namely, areas of concentrated water demand. These areas are not arid or semi-arid, and often have a water supply which is largely developed. Whether such areas will turn to desalination will depend largely on the technology of conventional water utilization, on the cost of desalinated water, and on the art of application of desalination, which will be discussed later.

(b) The demand by economic sectors

Where a desalinated water supply exists, desalination is already used by all sectors except irrigation, and it is unlikely that the situation will change in the near future. Desalinated water will remain, as it now appears, far too expensive under most conditions for irrigation of staple crops and vegetables, although it may become cheap enough for a drinking-water supply for cattle. For supplementary irrigation of high-value crops, desalination may in exceptional cases be economically justified.

(c) The demand by size

There are two typical situations which are met almost everywhere - either a small demand based on an individual water supply or a large demand based on a water supply system. Desalinated water in areas where there exists only a small water supply will very often be cheaper than the alternative of long-distance water conveyance or similar alternative solutions, although each case will have to be tested separately.

Where a large-scale water demand already exists, there are usually also - except on islands and in arid areas - alternatives, and in such a situation large-scale desalination units will have to compete with large-scale conventional water resources development projects. In this case, a desalination plant will probably have to operate on a base load, and this will require a full cost comparison. In such a situation not only the alternative conventional water resources but also energy supplies and costs and a number of other related considerations will be decisive factors. Even in locations of large water demand the quantities needed are not as massive as are required for irrigation, and therefore the giant combined desalination plants, so much talked about, will often have to wait until water-grid systems exist in developing countries and such water grids will probably develop only over the next twenty years.

1. The cost outlook for desalinated water

The cost outlook for desalinated water is by no means a straight technology question. I should prefer to regard the cost outlook as determined basically by three groups of factors:

(a) the technology;

(b) the unit size and energy requirements; and

(c) the art of application.

(a) The technology

The technology of desalination is still progressing and will continue to advance for a considerable period of time. New processes will come into being but it will be a number of years until we have a number of tested desalination technologies. Improvements might be expected in the near future in corrosion and scale control and in better and cheaper materials. Great caution is necessary, however, in envisaging a technological break-through in the immediate future that will radically lower the cost of desalination. We also know that whatever technology is developed, desalination will need much equipment and machinery and a great amount of energy. It must be expected, therefore, that technology alone will not lead to greatly reduced costs of desalinated water if full costing is applied, as it should be. We should, therefore, realistically assume that over the next twenty years desalination costs will show no spectacular decline, and that 50 cents per thousand gallons is probably a realistic estimate for the cost of desalination for single purpose desalination plants, based on full costing.

As a corollary to these assumptions concerning possible improvements in desalination technology, rapid obsolescence of existing desalination plants should not be expected. It follows that it is not sound to postpone the construction of desalination plants in the hope that a technological break-through in the near future will lower costs considerably. The technology available today is fully satisfactory for a reliable supply of water. Where water is urgently needed and there is an economic justification for the use of such desalinated water, nothing can be gained economically by not using present technology and postponing development projects which depend on the use of such desalinated water.

(b) The unit size and energy requirements

There is much speculation at present regarding the impact which might be expected from upscaling the size of desalination units from about 1 to 2 million gallons per day to 50, 100 or 200 million gallons per day. I think we should be aware that the size of a unit depends first of all on the size of a water supply system. A small market cannot utilize large units and, therefore, for most of the locations where desalinated water is needed today, the large-scale units will be ruled out by market conditions. I also feel that the possibility of lowering costs of desalination by going to bigger units is over-stated because the energy requirements are proportionate to output and do not decline noticeably with the increase in unit size. One authority on this subject has intimated that, for relatively small units, technological factors may effect savings of 10 to 15 per cent by going to very large units, while relatively large units would gain savings considerably less in magnitude. An unpublished study appears to indicate that over a certain size, lying between 50 to 100 million gallons per day, unit costs would actually rise again. The question of unit size will, I expect, be discussed in more detail during the seminar.

Energy costs are another important factor and it is obvious that where the real energy costs can be very low this will contribute to lowering desalination costs. This applies especially to areas where surplus natural gas can be used; it applies to low-cost fuel oil, etc. A noticeable saving of energy cost can also be obtained through the combined production of water and power in a dual-purpose plant. However, this involves a series of other problems which will be discussed separately during the seminar. Among the unconventional sources of energy which may become significant for desalination, geothermal energy must be noted. The United Nations is already working in a number of countries on the development of geothermal energy and its utilization for desalination can be expected in the near future. The tantalizing promise of using so-called free energy, namely solar energy, for desalination has remained largely a promise. However, during the last few years real progress has been made and where energy costs are otherwise very high the use of solar energy may be economically justified for small units. It is noteworthy that the first working solar desalination plant has recently been installed in Greece.

By and large, conventional sources of energy will have to provide the necessary energy for desalination and if desalination should develop rapidly it may well become one of the most important consumers of energy. One of our colleagues has calculated that desalination in future will require so much energy that the conventional sources of energy will be insufficient to satisfy this need and that nuclear power is needed for this purpose. I do not foresee such a large-scale increase in desalination and in energy requirements for desalination. It should be remembered, however, that the long-term cost of energy is a separate problem and has nothing to do with the technology of, or need for, desalination. If, on a long-term basis, energy costs should rise, it will affect desalination.

(c) The art of application

Under the art of application I include various methods involving either the mixing of desalinated water with brackish water or other degraded water, or the production of desalinated water in combination with other products. The art of mixing and grading of water, the possible combined production of water with power, with minerals through utilization of the brine, etc., open many new ways of reducing the ultimate cost of the water or the water-mix for the consumer. This art of application is something we should now develop and cultivate. It often involves an interdisciplinary approach, and may often take unexpected forms. For example, take the case where a body of fresh ground water is adjacent to brackish ground water. When the fresh ground water is pumped, brackish water is drawn into the fresh water zone. The intrusion of the brackish water into the fresh water zone can be prevented by pumping of brackish water, which in our case is done in order to provide the raw material for an electrodialysis plant. By applying electrodialysis to this type of brackish water, not only is fresh water obtained through the desalination plant but the output of the fresh water aquifers are increased. I do not wish to spend much time on what I term "the art of application" except to quote one other case which was developed through a United Nations expert mission in Southern Tunisia. Here a United Nations team found that the best solution was to use surplus steam from a fertilizer plant for distilling fresh water from sea water and then to take the distilled water and mix it with brackish water in order to obtain a product-mix acceptable for the purposes for which the water was needed. In this way, by avoiding energy costs and by mixing with brackish water, the cost of the product-mix was reduced to below $US0.40 per 1,000 gallons, a cost unobtainable through straight desalination only, or in any other way.

Some of the research now going on, such as in the use of algae for desalination in such a way that the end products would consist of fresh water and algae as chicken feed, might provide further tools for the art of application of desalination. Some of the necessary tools already exist. There are plants in the world which extract certain minerals from sea water as a single-purpose operation, such as plants for the extraction of magnesium or bromine. It is obvious that if such plants are situated on sea coasts where fresh water is needed, the art of application would combine such mineral extraction with desalination, probably reducing the cost for all the products involved.

All these examples indicate that the art of application is creating the need for a new interdisciplinary approach for the skilful use of local conditions and of natural resources in order that the end product, the final water-mix, may be reduced in cost. The desalination technology already existing is, in my opinion, sufficient to begin to apply this art of application and to improve it. This approach presents wide possibilities and may in a given locality contribute more to the reduction of the cost of desalinated water or of the water-mix than straight improvements of desalination technology alone.

2. The economic significance and future of desalination

Desalination as a new method of providing urgently needed water is also a new instrument for economic development. With the help of desalination we now can utilize natural (including locational) resources which because of a lack of water could not be developed, provided that such resources are located within a relatively short distance of saline water bodies. Desalination will also be applied in the future as an instrument of insurance for areas with unreliable conventional water supplies or for areas where heavy water demand will in the near future lead to the full utilization of existing conventional water supplies.

In view of these tasks which desalination can and will fulfil, the world-wide application of desalination will depend to some extent on the tempo of economic development in arid and semi-arid areas and in the other areas discussed above. Given the fact that frequently, but not always, the only important obstacle to the development of arid areas is the lack of water, it appears that the rapid growth of mineral development in such areas noted over the last ten years, as well as the settlement in such areas for industrial and other purposes noted, for instance, in the United States, the United Arab Republic and Israel, will spread to other arid areas. The settlement of a desert, once a water supply is provided, involves fewer difficulties as regards infra-structure than the development of jungle areas, mountainous areas, marshy areas and other categories of land. As arid areas are very often also dry areas and therefore healthy areas, resort facilities are developing in such areas too (as for example in Arizona in the United States and the Western Desert of the United Arab Republic), and it appears that over the next twenty years a large-scale demand for water, often met by desalination, will occur wherever a water supply at reasonable cost in such areas can be introduced.

Desalination used in this way as an instrument for making livable and productive areas so far excluded from permanent human settlement, will not only facilitate economic development but may also make a modest contribution to a better distribution of population and to a wider utilization of natural resources.

The improvement in the technology of desalination and its skilful application will gradually lead to lower cost and, if and where this is coupled with rising national income and rapid economic development, it is likely that desalination will be increasingly important in water-short areas. In areas where low-cost conventional water resources are no longer available, desalination will have to be considered as an alternative to expensive conventional water resource development projects. In this way desalination will acquire its permanent place among the potential sources of water, a place which is minor today but which will grow in importance in the future.

II. EVALUATION AND SELECTION OF WATER SOURCES: SURFACE WATER

by H. MacDougall

Man is essentially an aquatic animal. Physiologically, he could be considered as a group of organs living in an aqueous medium surrounded by a permeable membrane. The whole organism to sustain life requires a minimum water supply to replace that continually being lost through the membrane. The amount depends on the habitat, but the order of magnitude is one gallon per day. Man, however, being a social animal, lives in a society which has many supplementary water requirements and it could be said that these are requirements of the society rather than of the individual. When planning a water supply it is therefore necessary to consider it in relation to the social structure it must support. Water requirements for so-called domestic purposes may range from as low as 5 gallons (US) to as high as 150 gallons (US) per capita per day, depending on the social mores, complexity and wealth of the community. In addition, there may be commercial and industrial demands to be satisfied. The water supply engineer must analyse and forecast the total demand, examine all available sources of supply, select the most economical source or sources, and design the treatment plant and the conveyance facilities required to deliver the water to the consumers. This paper will consider the problems involved in the evaluation and selection of surface water sources.

However, because this seminar is considering supply of water by desalination, further discussion in this paper will be orientated towards those areas of the world in which there would appear to be insufficient natural fresh water to supply even the minimum requirements of the community. The term "appear to be" is used because, unfortunately, only a few of the geographical areas of the world have been explored thoroughly enough to provide a full knowledge of all potential fresh water resources, either on the surface of below ground.

Nothing in this paper will be new, and no startling revelations in the field of water supply will be presented, but it may perhaps serve as a refresher on conventional water supply techniques. One of its objectives is to emphasize that desalination should always be considered in conjunction with all other possible ways of supplying fresh water. Desalination is a process for making use of a saline water resource. Just as most fresh surface water must undergo extensive treatment before its quality is satisfactory for the intended use, a saline water must also receive treatment. The chief differences are the method and cost of treatment and the locale where its use is economically justified. In this connexion it is worth while to make a distinction between "water-short" and "water-scarce" areas. Until quite recently, desalination was only considered feasible in areas where there is a deficiency of water due to low precipitation or unbalanced and erratic precipitation - actually "water-scarce" areas. Now we find that desalination is proposed for New York City which lies in an area of tremendous water riches but is temporarily "water-short". The situation vividly underlines the necessity for examining desalination as one solution among many to a water supply problem. It is difficult to justify the treatment of salt water by desalination for New York City when Hudson River water could be treated at much lower cost.

A. Surveys of water resources

It is obvious that one must have a reasonably firm estimate of the immediate and future water demand and when looking for water supplies, this estimate must be kept in mind. Whether or not there are available water resources from lakes or streams is usually apparent, but other sources may be overlooked. Occasionally they may have been pre-empted for other purposes which are believed to have higher priority; for example, water which has been used for generations for irrigation where the farmers' claim has an almost sacrosanct position. In such circumstances, the problem should be studied economically to determine which usage would result in the greater economic benefit and, if politically feasible, to decide the issue on the basis of the usage of greatest value to the community.

There is also the problem, when looking for water, of deciding how far from consumer centres one should go to examine the possible sources. This again is a matter of economics, since it hinges on an assessment of total cost of water, including conveyance, from all possible sources, including ground water and desalination. In this connexion a warning is pertinent. Sometimes the cost of production of desalinated water is compared with cost of delivered water from other sources. This obviously gives a false picture. The cost of conveyance may be an important factor in the total cost of water and a comparison of total costs must be made for water delivered to the consumer.

It is important to remember that water is not used in the sense that it is destroyed or disintegrated. It can be employed over and over again and its usefulness is limited chiefly by other materials it carries in solution, or by its temperature. Water has a remarkable ability to dissolve other compounds and to carry heat, and these qualities account in large part for its great usefulness. Our ability to re-use or recycle water depends on the techniques for removing the unwanted substances which it may contain, or for reducing its temperature. The only limits to the re-use of water are economic and psychological, not technical. Therefore, any survey of water resources must consider the possibility of conditioning used water and in water-deficient areas the economics of reconditioning and recycling water must be closely examined.

The intentional re-use of polluted water such as sewage for domestic purposes often meets with a prejudiced resistance. What many people do not realize is that as water moves down a river system in heavily populated areas such as the Rhine Valley, it may be extracted a number of times for domestic use and returned as sewage which may or may not have received any treatment. No water-deficient area should overlook the possibility of reclaiming sewage for further use. The degree of treatment required depends on the intended use. Partial treatment such as the removal of suspended solids may be sufficient for sewage farming or the recharge of ground-water aquifers. Complete treatment making sewage acceptable for human consumption is possible. It is, however, not cheap. Research now being conducted by the Robert A. Taft Sanitary Engineering Centre indicates that $0.54 per 1,000 gallons is required for processing in a 10 million gallon per day plant. As a basis for comparison, the national average cost of conventionally supplied water in the United States is $0.30 per 1,000 gallons and this figure includes all costs of water delivered to the consumer including treatment. However, there is one advantage for reclaimed sewage worth noting. A considerable portion of the cost of water may be the cost of conveyance, whereas sewage is produced at the point of possible re-use.

What is true of domestic sewage is also true of industrial waste water. Techniques have been developed capable of removing almost any form of industrial pollutant. One exception is radio-active pollution, and considerable research is being devoted to this problem. In water-short areas, in fact in any area, it should be the policy of the Government to insist that new industries should build into their industrial processes the facilities to prevent pollution of public water supplies and where water is scarce, to recycle and reclaim water wherever possible.

When surveying the water resources of an area and the conservation of existing supplies, such as the reclamation of sewage, a careful study may reveal other possibilities. For example, the present water shortage in New York has brought to the fore the fact that only 25 per cent of New York's water is metered. The balance is distributed at flat rates which provide no incentive for economy, and in fact encourage waste. A comparison of water consumption in eleven major American cities shows that in four cities with partial metering (maximum 32 per cent) the <u>per capita</u> consumption ranges from 154 to 232 gallons with an average of 200 gallons, while in the seven cities with almost complete metering the range is between 120 and 164 gallons with an average of 146 gallons. Metering is thus a useful tool for restricting consumption. First, it discourages waste and secondly, by setting up a progressive rate structure, it could penalize excessive use.

Other conservation possibilities may be found. Where brackish water is available, it may be substituted for purposes which do not require fresh water. This, however, has a disadvantage in that it may require a dual distribution system. Also the dilution of brackish water by fresh water, while retaining the salinity at an acceptable standard, could be considered.

In general, then, a survey of surface water resources should encompass much more than the conventionally used sources from lakes and rivers. It may also reveal possibilities for reclaiming water and the conservation of already developed supplies. Also, where desalination is envisaged, it may discover sources of raw brackish water for desalination.

B. Evaluation of water sources

When evaluating a water resource, four important factors must be considered. These are: (a) quality; (b) quantity; (c) dependability; (d) availability.

(a) Quality. This first factor must be related to the intended use and the standards acceptable to the community. The chemical content of a raw water source must be known and also the temperature range during the year, in order to determine whether the water is suitable without treatment or, if not, to determine the treatment required to make it acceptable. Standardized tests for important characteristics, such as hardness, alkalinity, salinity and turbidity, are easily performed, and treatment practices based on these determinations are also fairly well standardized as far as treatment of municipal supplies is concerned. This usually involves sedimentation, filtration and chlorination. The objectives are to reduce turbidity, and sometimes hardness, to eliminate harmful bacteria and possibly to adjust the pH and dissolved oxygen content.

Not long ago, a reduction in hardness was often considered economical because the value of the soap saved by a community exceeded the cost of softening, but since the use of detergents has become so prevalent, hardness is no longer such a serious disadvantage in a water supply.

The definition of an acceptable quality standard should be made with reference to the local situation. Standards such as those advocated by the United States Public Health Service need not be universally accepted, in all circumstances. For instance, the maximum salinity acceptable according to the Public Health Service is 500 ppm. Where water is scarce, this amount could be doubled without serious consequences to health. Indeed, during the war in the Western Desert in Africa, water with a salinity below 2,000 ppm was considered good. Modification of other standards such as iron content or alkalinity may be advisable in areas of water scarcity.

The cost of conventional treatment of surface water for municipal use is of interest to this seminar which is concerned with a specialized form of treatment - desalination. The following tabulation gives average costs of treatment of 1,000 gallons in the United States and also the investment costs of plants of various sizes.

	Plant capacities mgd		
	1.0	10.0	100.0
Operation and maintenance (including chemicals)	$0.084	$0.050	$0.039
Capital amortization (at 4 per cent over 30 years)	0.035	0.018	0.010
Totals[a/]	$0.119	$0.068	$0.049
Plant cost	$220,000	$1,150,000	$6,550,000

Source: Data derived from the Office of Saline Water publication, Standardized procedures for estimating costs of conventional water supplies.

[a/] Operating at 100 per cent load factor.

(b) Quantity. With regard to the quantity of water available from a surface water source, no problem arises if the amount required is obviously smaller than the amount readily available from a lake or river. But in water-scarce areas where desalination is contemplated, all available surface water resources must be most carefully evaluated and conserved. Most rivers have large variations in discharge throughout the year and also in total annual discharge from year to year. Streams in arid regions are particularly erratic and often may not have perennial discharges. Methods for estimating the total annual discharge and probable variation of this quantity from year to year are well known and need not be discussed here. However, there is one important factor to be considered in the development of a surface water supply in a water-scare area and that is the high value of the water. If the only alternative to the development of a surface water supply is desalination, and assuming there is a market for such water, one can afford to spend much more on its development than would otherwise be considered economically feasible. Storage must usually be provided in order to make the total annual runoff of a stream available on a continuous and uniform basis throughout the year. This could be done by storing water in an impounding reservoir created by damming the valley of the stream, if topographic and geological conditions permit, or alternatively by building lined basins with pumping stations for transferring the water. The former method is commonly employed, but the latter, for economic reasons, is hardly ever used to provide a perennial supply. A hypothetical example will illustrate the point. Assume that an intermittent stream whose total annual runoff is capable of producing a net daily yield of 10 million gallons after evaporation losses, is being developed. The inflow occurs during only one quarter of the year and consequently a reservoir of about 5 1/3 billion gallons is required, the evaporation losses being nearly equal in an arid tropical climate to the net yield of the reservoir. If an impounding site were available, such a reservoir might cost, using average American cost figures, about $0.05 per 1,000 gallons. However, storage basins would cost about $0.40 per 1,000 gallons which would be economically prohibitive, except in an area where the only alternative is desalination.

When estimating the productivity of a surface water source, evaporation losses must be considered as they often account for a large share of the total runoff. Reservoirs should be located or designed so that their surface areas are as small as possible. Although considerable research has been carried out into the reduction of evaporation losses by covering water surfaces with films of oil or other materials, it has had only limited success under special conditions. The storage of water below ground as ground water to be recovered later from wells may be feasible, if subsurface conditions are favourable. Although some loss is expected, the method deserves consideration since it eliminates evaporation and may be less expensive than the construction of surface storage.

(c) Dependability. By dependability is meant the reliability of an estimate of water quantity with regard to time. The dependability of a surface water source involves a study of the probable frequency of the recurrence of periods of low precipitation on the watershed. The basic assumption is that weather has a cyclic behaviour, and any particular precipitation record may be repeated at a certain frequency. There is always a possibility that the minimum record may be reduced. As the length of time over which records are accumulated increases, the probability of having at least the minimum recorded precipitation approaches 100 per cent. It may be unreasonable to design on the basis of 100 per cent dependability which is the theoretical minimum available 100 per cent of the time. Particularly in water-short areas, people should be prepared to accept deficiencies and make sacrifices occasionally because so many water uses in modern society contribute only fringe benefits. Many communities do not have continuous water services and have become adjusted to the situation. This has its danger because there may be pollution of the pipelines when pressures are reduced, but the idea that a continuous high-pressure service must be maintained under all circumstances may be a luxury which some locations cannot afford.

At the moment, the people of New York are being asked to reduce water use and certain curtailments are enforced, but no real deprivations have resulted as yet. In this connexion, the dependability of the New York supply is of interest. The estimated dependable supply was based on three consecutive dry years, 1929, 1930 and 1931, during which the annual precipitation on the watersheds supplying the city was 10 per cent below normal. Unfortunately for the planners and the city, from 1961 through 1964 the precipitation was 20 per cent below normal and the drought is continuing. The question naturally arises whether the planners were sufficiently cautious in their estimates. In any particular situation it is obvious that the dependable quantity of water should be equivalent to the minimum demand that must be satisfied without undue hardship. In planning, someone must ultimately take the responsibility for a decision as to the dependability of the evaluated supply.

(d) Availability. Water availability, as here considered, is intended to distinguish between water which can be delivered by gravity, and water which must be pumped to reach its destination. Where there is a choice of water sources there are two factors which favour the selection of the gravity source. One is the saving in power cost, and the second the reliability of a supply which cannot be interrupted by a power failure.

C. Selection of water sources

Although there are many places in the world where the only available water is saline and desalination alone can provide a fresh water supply, other water-short areas have limited supplies of fresh water, both above and below ground, and possibly brackish waters of various degrees of salinity. In such circumstances, the planner, having inventoried and evaluated all water sources, must select the source or combination of sources including desalination which best satisfies the demand. The most economical solution is usually but not inevitably the acceptable solution. The reliability of a supply could influence the decision and it is possible that desalination, although probably the most expensive source, could be the only completely reliable source. Another important factor may be the amount of foreign exchange required for a source development, and it is also possible that a saving in total capital investment is more critical than the price of delivered water.

Multi-purpose possibilities must also be considered. On occasion water supply can be combined with power generation and the construction of a reservoir primarily for water supply may perhaps also provide recreational opportunities or make possible the development of a fishing industry.

The combination of waters from different sources may also provide advantages. If brackish water is available, the mixing of desalinated water with brackish water giving an acceptable product of low salinity could reduce the cost of the delivered product. Also a desalinated supply might be used in conjunction with an inadequate fresh water supply whereby the desalinated supply might provide the base water load and the fresh water be used to satisfy daily or seasonal peaks. Ground water supplies are particularly adapted to this type of combined operations. There may also be possibilities for combining the usage of surface water and ground water, using surface water when available and supplementing it with ground water when the former supply is exhausted. In some circumstances, the use of water from three sources - desalination, ground water, and surface water - may have economic advantages. In principle then, when a number of water sources are available, an exploration of various combinations of water from all sources may provide the best solution to a water supply problem.

Whatever the source, conservation in the use of water in water-short areas may result in savings more important than any savings possible in providing the water. Where water is scarce or costly, the greatest care must be taken to ensure that it is used efficiently and waste eliminated. The only sure way of making people careful in their habits of water use is to make them pay for it. Therefore, the most effective control over waste by the consumer is metering and a rate structure which imposes penalties for extravagance. But even metering may not be sufficiently restrictive where water must be carefully used, because the largest consumers are usually capable of paying high prices, and the cost of water is not an important part of their total living expenses. In such circumstances, other control measures must be taken, such as restricting the size of service pipes, or reducing system pressures.

In many developing countries, large segments of the population obtain water without charge from public hydrants. The fact that such water must be carried by hand, very often in the ubiquitous five-gallon can, automatically restricts wastage because of the considerable human effort involved in transporting it. Although the quantities of water used by the poorest classes, particularly in water-short areas, are minimal, it often happens that unit prices paid by such people are very high because water is purchased from private vendors in very small quantities and indeed unit prices may be much higher than those paid for water by the wealthier classes. The total cost of the supply to the latter is, of course, very much greater because of the relatively larger volumes sold. However, it would not be correct to base any market prediction, supposing more water to be available, on a much greater use by the poorer segments of the population without first considering the fact that it is not always the cost of water itself which prohibits greater use of water by the poor, but rather the expense of installing the water utilities and sanitary fixtures required to use the water.

Because water is absolutely essential to life, it is impossible to state a top limit to the price people are willing to pay for it. Nor is it possible to place a value on water for human consumption as, for example, might be done for water used for irrigated agriculture. In essence, man pays for water whatever he has to. However, it should be remembered that water is very cheap, even if desalinated, in comparison with other beverages which some people might think were indispensable, as for example coffee. The cup of coffee you had for breakfast this morning cost you at the rate of $3,000 per 1,000 gallons. The water, if you drank any, perhaps no more than 30 cents per 1,000 gallons.

II. EVALUATION AND SELECTION OF WATER SCURCES: GROUND WATER

by J. Geraghty

It probably seems self-evident that serious consideration should never be given to building a desalination plant in any particular locality unless natural sources of fresh water are known to be either absent or totally inadequate to satisfy the demand. At present, desalination is quite expensive when compared with most traditional methods for obtaining fresh water, which leads to the conclusion that construction of a desalination plant should be a last resort, after all other attempts at developing water have failed.

As already stated by the previous speaker, few geographical areas of the world have been explored thoroughly enough to provide a full knowledge of all potential fresh-water resources. It is the purpose of this paper to take a closer look at the one potential water source which is commonly the least understood or appreciated - ground water. The ground water referred to throughout this paper is fresh water. In the previous talk, we heard about some of the ways of evaluating the dependability of surface waters in rivers, lakes, and reservoirs. Many of these concepts are also applicable to ground water, but since the latter is a hidden resource, concealed from view beneath the land surface, it is usually much more difficult to arrive at answers regarding its availability. For that reason, ground water is often overlooked entirely when governmental agencies or other planning bodies are studying ways of increasing water supplies. This can be a serious oversight, for if ground water can be located and developed at or near a point of water demand, it very often constitutes the cheapest way of all for solving a water-supply problem.

The basic question, therefore, is how to make a reasonable evaluation of the availability of ground water before going ahead with alternative schemes such as desalination. There are, of course, ways of arriving at such an answer, but before discussing them, it may be well to spend a few moments reviewing the basic principles of ground-water occurrence, since subsurface conditions are quite variable all over the earth, and the local environment is usually the major consideration controlling availability of ground water.

In most parts of the world, ground water originates through downward seepage of moisture falling on the land surface as rain, snow and ice. Some of the water from precipitation runs off over the ground in streams or is returned to the atmosphere by evaporation and transpiration; the remainder filters slowly into the earth to a level below which all openings in the geological formations are saturated with water.

In semi-arid and arid regions, the water contained in underground geological formations may have accumulated slowly over decades or even centuries, or perhaps have moved into the region through lateral migration from distant places where rainfall is heavier. Regardless of climatic conditions, however, it is rather unusual to find no ground water at all in the rocks underlying the land surface - even in some of the driest regions where rainfall is negligible. Thus, ground water has been discovered in relative abundance in certain of the world's deserts, and with each passing year, new discoveries are made of large ground-water reserves in regions previously considered as totally deficient in water.

Ground water is generally in motion under the influence of gravity or other pressure differentials toward points of discharge such as springs, streams, pumped wells, or the ocean. This movement is comparatively slow, owing to friction between the water and the earth materials, and generally is on the order of a few feet per day.

When man begins to withdraw water artificially from the earth through wells, the underground water level in the area starts to fall. If there is little or no replenishment of ground water from rainfall, the decline may continue indefinitely as more and more water is taken from storage in the rocks. Commonly, however, the volume of water contained in the geological units may be so vast that the decline can go on slowly for years, decades, and in some instances centuries, depending on the pumping rate, without exhausting the supply. In places where some replenishment is available from rain, seepage of water into the soil will retard the decline of ground-water levels, and if the pumpage does not exceed the natural rate of replenishment in the region affected by the wells, a balance between inflow and outflow may take place, so that the ground-water level stabilizes and ceases to fall.

The top of the saturated zone beneath the land surface is called the "water table". It is a more or less continuous surface in most localities, and its configuration in humid areas roughly conforms to the surface topography, with the highest water elevations under the uplands and the lowest elevations in valleys. Where the water table intersects the land surface in low-lying places, ground water discharges by seepage into perennial streams, lakes, swamps or the oceans.

Because the water table naturally slopes downwards towards perennial surface-water bodies, it is always a reasonable assumption that the water table is at a higher elevation than the surfaces of those bodies, and that the farther one moves away from the lowland discharge areas, the higher the altitude of the water table will be. In semi-arid or arid regions where the streams contain water only during storms, however, the water table is generally below the valley floors, and estimates of its depth can only be made by referring to water levels in wells.

The flows of perennial streams often furnish evidence of relative abundance of ground water, because much of the water in the streams is derived from discharge of underground waters. If stream records show very high flood flows during periods of precipitation and very low flows at other times, it may indicate that the outflow of ground water is not very great. On the other hand, if the stream discharge shows only slight increases or decreases following storms, ground water may be present in large quantities in the underlying and adjacent aquifers.

Ground water is said to be "artesian" where the water-bearing unit is overlain by beds of low permeability, and where natural pressure causes the water in a well to rise about the top of the water-bearing bed. Where sufficient pressures are encountered in an artesian system, the water in a well may rise above the land surface, causing the well to flow. In other cases, the water level rises part way up the hole but does not reach the surface. Any well drilled into a formation containing water under pressure is said to be artesian.

Although water is present in all openings below the water table, the rates at which it can be pumped from wells vary considerably. Successful wells can be constructed only where the geological formations transmit water easily. The capacity of rocks to absorb, store, and yield water depends on the type, size, and number of pore spaces or fractures. Some earth materials, such as sand and gravel, have hydraulic characteristics that make them particularly prolific from a water-yielding standpoint. Other materials, such as clay and shale, may contain as much water per unit volume as sand and gravel, but their low permeabilities may retard the movement of water to such a degree that they will not yield more than a trickle to a well. The rock units which yield water freely to wells are called "aquifers"; the rock units which retard the flow of water are referred to as "confining beds".

The safe yield of an aquifer, which is the rate of pumping that can be maintained indefinitely without eventually depleting the supply, depends on two factors: the first of these is the capacity of the aquifer to transmit water, a characteristic usually referred to as "transmissibility". The second, which may be called "intake opportunity", means the combination of circumstances that provide water for recharging the aquifer at a time when there is unsaturated storage space within it. As noted previously, the water already contained in a natural underground reservoir may have accumulated over many decades, and thus constitutes a sort of reserve water supply in the bank, which can often be tapped for very long periods of time, even if no new water is added to balance the supply.

In general, the problem of developing ground water in a particular area can best be understood by examining the types and hydraulic properties of the different rock formations or aquifers in which water occurs. In some places, no ground water whatsoever will be found and all drilled holes will be dry, although this is an uncommon condition. In other areas, well yields can differ radically between sites as little as a few hundred feet apart, owing to the local complexity of the geology.

Broadly speaking, geological formations can be divided into four major types of aquifers, each of which has rather distinct characteristics and properties from the viewpoint of ground-water development. They are:

(1) Loose uncemented materials such as sand and gravel. In many regions, the shallow geological formations fall into this category, and if ground water is present in these layers, it is not at all unusual to be able to develop a million gallons or more of water daily from a single well.

(2) Cemented layered rocks, such as shale and sandstone. These formations were originally laid down as beds of mud or sand, which have slowly become consolidated over long periods of geological time. The cementing material tends to close off some of the openings in the beds, but many of these layered rocks are capable of yielding up to several hundred gallons per minute to single wells, and in a few instances, as much as 1 million gallons daily or more.

(3) Limestones or karstic formations. These geological units, being soluble in water, are sometimes honeycombed with open channels and conduits that can deliver incredibly large amounts of water to individual wells. In other places, however, they may be dense and relatively non-porous, so that well yields are on the order of only a few gallons per minute.

(4) Crystalline bedrock such as granite, schist, and gneiss. Formations in this category make up the deep basement or bed-rock in many parts of the world, and are usually poor aquifers for supplying ground water in large amounts. Yield of wells penetrating crystalline formations seldom exceed a few gallons per minute.

Extracting water from the earth basically involves construction of some type of hold or excavation deep enough to reach into the saturated zone below the water table. The usual method of developing water from the ground is to sink a vertical hold or well into a water-bearing bed, and then to install a pump or other lifting device in the well to bring the water to the land surface.

The equipment used for drilling wells ranges from simple, manually-operated drilling tools to extremely expensive well rigs such as those used in petroleum exploration. Each variety of equipment has its specific uses and functions, and the choice of drilling rig is usually based on local geological and ground-water conditions. If the water well must be quite deep in order to penetrate the best water-bearing aquifer, simple drilling machines will not serve the purpose, and it may be necessary to bring in heavy construction equipment capable of completing a deep hole. In very shallow deposits, however, and particularly where speed and efficiency are not prime requirements, it is often possible to construct a perfectly serviceable water well with either manual labour or with the simplest auxiliary power.

Generally speaking, knowledge of ground-water resources tends to be scantiest in the undeveloped regions where water historically has been in short supply. Thus, deserts and arid localities, since they can rarely support a large population or a high level of economic activity, are commonly the least explored as far as ground-water resources are concerned.

Recent large-scale surveys, especially those being made by agencies of the United Nations, have begun to show that many of the so-called "dry" regions of the world may actually be underlain by rather large ground-water reserves. Drilling and testing operations, carried out with modern scientific methods, can prove or disprove these possibilities, and it would seem axiomatic that efforts should always be made to determine any region's ground-water potential before resorting to expensive alternative methods of importing water or of desalting sea water.

A hydro-geological investigation of an area is the all-important preliminary to the development and exploitation of ground water. It requires that certain basic surveys should be made, or, if such surveys have already been carried out - by a government or by oil or mining companies, for example - that their results should be made available. The surveys may be of one of the following types or of any combination of these: aerial photographic, topographical, hydrological, geological, geochemical, geothermal, or geophysical.

A knowledge of the geology of an area is of fundamental importance in the study of ground waters, because the occurrence, distribution, movement, and quality of the waters are dependent on geological factors, particularly permeability, fissuring, and area of outcrop. Following the geological mapping of the surface distribution of the rocks, the most favourable zones for the occurrence of the ground water can be delimited. The next stage may call for a geophysical survey which, when correlated with surface geological observations, can indicate features of the subsurface geology and topography. By such means, the limits of an aquifer may be revealed and the more favourable areas for test drilling selected.

Hydrological investigations of a ground-water system enable estimates to be made on such matters as total storage, movement, and volume of recharge and discharge. Much attention is given to information and statistics on precipitation - the source of water recharging a ground-water system. Surface waters are studied in their relationships to ground water. Records of changes of water levels are collated, particularly the fluctuations of the ground-water surface.

In the course of a hydrological investigation, valuable and often essential information should be obtained from wells and bore-holes. These provide useful data on the nature of the rocks and their water-yielding capacity, and the depth to and the movement of the ground-water surface.

Test bore-holes are usually put down to obtain information for the purposes of a hydrological survey, or frequently as a preliminary to a ground-water development programme. They record movements of the ground-water surface and measure the direction and rate of flow of the ground water itself; they provide useful information on the hydraulic properties of the aquifers, which constitute the basis for the correct design and construction of production wells and pumping equipment. Test bore-holes are also of value in geophysical investigations, both for logging purposes and for calibrating or checking the results of surface geophysical surveys. However, notwithstanding the usefulness of the preliminary surveys and the greater assurance which they afford, only the drill will give ultimate proof of the presence of subsurface water, and the drill is therefore the final arbiter on most ground-water problems.

The economic principles which provide a guide to ground-water development are the same as those applicable to the evaluation of any other type of resource development. One of the first economic tests is to determine whether the proposed ground-water development will promote the general economy in relation to the required investment better than any other development. A second principle is that the proposed ground-water development should be more economically advantageous than all alternative methods of supplying water. This point deserves special emphasis wherever desalination has been proposed, because salt-water conversion processes are quite expensive and the costs of exploring and developing ground water would normally be far less. Now once this determination has been made, the next and crucial test is whether the over-all benefits will be greater than the over-all cost.

In under-developed regions, the cost of investigation and planning may be high. The total of these exploration costs should, however, not be included in calculations of economic feasibility, since they relate only to initial undertakings. Governments must be prepared to use general revenues to meet a large part of the cost of preliminary investigations in such cases. Preliminary investigation costs, in addition to geophysical surveys, may include drilling and pumping of a number of test wells. Dependable cost estimates covering the drilling of wells can usually be established without too much difficulty. This is especially true where sufficient test wells have been drilled to provide basic data on the kind, size, and depth of wells. Well-drilling contractors and suppliers can furnish reliable cost estimates on the well equipment.

Where ground water is available in adequate amounts, it almost always constitutes a much cheaper source of supply than a desalination plant. In most places, ground water can be produced for less than 10¢ per 1,000 gallons, whereas desalinated water from existing conversion plants costs many times more, and in some instances as much as several dollars per 1,000 gallons. Moreover, ground water can be developed in stages, as the demand increases, simply by drilling additional wells. Desalination plants, on the other hand, must be designed for a specific output of water, and must be operated at or close to full capacity at all times in order to keep production costs per unit of water as low as possible.

Thus, any proposal for building a new desalination plant must take into account the possibility of locating and developing ground water as a cheaper alternative source. If some knowledge of local ground-water resources already exists, this should be studied most carefully to determine the feasibility of developing additional supplies. If nothing whatsoever is known about ground-water availability, then it would be most desirable to undertake at least a preliminary survey to define the likelihood of locating new ground-water resources. Such a survey, carried out by specialists experienced in making regional assessments of ground water, is relatively inexpensive - and if it points the way to development of cheap and abundant water supplies, represents the soundest of investments from the viewpoint of water management.

III. ANALYSIS OF WATER DEMAND

by the United Nations Secretariat

Demand for fresh water may be defined as the quantity of fresh water which is required for use by various user categories at a particular time. In strictly economic terms, it may be defined as the various quantities of water that will be bought at current price levels at a particular time.

It is necessary to distinguish between demand for water and water need, since the latter may overstate or understate demand to the extent that value-judgement and subjective (or objective as would be the case for water duties in irrigation) considerations are brought to bear on this matter.

Water requirements for hydroelectric energy, navigation, recreation and fish and wildlife will not be considered in this presentation: in the case of hydroelectric power, it is demand for energy rather than for water which would be involved, while the other three categories are not of specific interest to this seminar.

Analyses of water demand are usually a necessary premise to decisions concerning the present or future availability of water resources in an area or region. In order to assess present and future demand on a regional or area basis as a yardstick against which new projects can be drafted and meaningful cost comparisons made, all pertinent and available statistical data must be collected and analysed.

Thus, the usefulness of such analyses will be determined by the extent to which an accurate assessment can be made of the quantity of water required in the light of population needs and of the levels of present and projected economic activity.

Subordinated to this issue but also of great importance are the geographical distribution of demand and its daily, monthly and seasonal fluctuations. Requirements over, say five-, ten- and twenty-year period will also have to be assessed. Closely related and equally relevant are considerations regarding quality requirements by various consumer categories.

The degree to which such data can be obtained and pieced together into a meaningful composite picture will determine the reliability which the planner can attribute to water demand analyses.

A. Assessments of water demand

Water demand, as defined in this paper, refers to one or more of six principal consumer categories: households and municipal use, industry, tourism, commerce, mining and agriculture.

It is customary to express demand for non-agricultural uses on a per capita basis; however, it would be erroneous to think that the use of water in a community is strictly speaking a function of population, since water requirements of other consumer categories could be increasing more rapidly than total population, particularly in developing areas. It is a fact, however, that the point of departure for any analysis of demand is a projection of population needs and that numerous statistical methods have been developed for assessing these. [1] The extent to which any one method may be considered satisfactory will largely depend on local conditions, for reasons which will be discussed at greater length below.

Rates of demand are likely to vary widely in different environments. Among the most important factors affecting such variations are: climate (particularly rainfall distribution), location and size of the community, the standard of living, the existence and ramification of the distribution system, the pressure maintained in the distribution system, the quality of water supplied, the price of water, [2] the degree to which metering is undertaken, and the degree to which a sewerage system may be developed. [3]

If demand is considered over a one-year period, such variations in demand will exhibit seasonal (or monthly), daily and hourly fluctuations. It is thus customary to speak of average demand by month in relation to the annual mean, average demand per day in relation to the monthly mean, and average demand per hour in relation to the daily mean. These relationships make it possible to establish (i) the month with the highest average demand; (ii) the day with the highest average demand, usually found to be in the month with the highest average demand; (iii) the hour of mazimum demand, generally encountered in the course of the day of maximum demand.

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[1] See United Nations, Methods of Estimating Total Population for Current Dates (United Nations publication, Sales No.: 52.XIII.5); United Nations, Methods of Appraisal of Quality of Basic Data for Population Estimates (United Nations publication, Sales No.: 56.XIII.2); United Nations, Methods for Population Projections by Sex and Age (United Nations publication, Sales No.: 56.XIII.3).

[2] Price of water, discussed at length in lecture 18, deserves particular consideration as a factor affecting the level of demand. Its unique characteristics in the field of water resources, in which price is often socially established, bearing little or no relation to the cost of the commodity, will have to be borne in mind when making water demand analyses. If, in particular, high-cost desalinated water may have to be envisaged as a potential source of supply, the related price elasticity of demand may become relevant when estimating future levels of per capita demand.

[3] It is interesting to note that even in relatively water-short areas, great variations are found to exist in daily per capita utilization of fresh water. The following figures derived from United Nations, Water Desalination in Developing Countries (United Nations publication, Sales No.: 64.II.B.5) are indicative of the differences encountered in various areas surveyed: Zarzis (Tunisia), 5 litres (in addition to quantities of brackish water); Manta (Ecuador), 15 litres; Bandar Abbas (Iran), 22.5 litres; Mogadiscio (Somalia), 25 litres; Nouakchott (Mauritania), 71 litres; various villages in Cyprus, 91-114 litres; Athens (Greece), 100 litres; Port Sudan (Sudan), 105 litres; Tacna (Peru), 235 litres.

While it is usually possible to take into account hourly variations in demand by means of balancing reservoirs in the distribution system (gearing distribution-system capacity to the daily maximum average demand) average annual demand and seasonal (or monthly) fluctuations will to a large extent condition the characteristics of the supply system.

B. Projecting the size of water demand

The uncertainties which necessarily arise when making predictions of water demand based on population growth and on future levels of per capita demand apply not only and more particularly to developing areas, but also to industrialized environments where conditions would seem to favour the application of refined statistical and analytical techniques. 4/

As far as developing countries are concerned, there are a number of conditions which tend to diminish the effectiveness of such projections, particularly if they refer to an extended period of time:

- historical records of population growth may be spotty or incomplete and, in any case, not geared to present trends of urbanization or to current rates of net population growth;

- rising levels of living are likely to lead to continuous modifications of per capita levels of demand;

- changes in standards of living may also lead to increased demands for better quality water than heretofore;

- population growth in areas subject to rapid development may bear no relation to historical trends owing to large-scale migration into the area from the surrounding countryside or from other regions.

These considerations may make it extremely difficult to base projections on twenty-year periods (as is usually done when planning for large reservoirs, canals or pipelines); this may to some extent explain the cautious approach followed in a number of developing areas visited in connexion with the desalination survey, where the expansion of supply systems was geared to shorter terms, following the trend of demand as it develops.

This raises the general question of whether the approach to be followed when making an analysis of demand should be the same regardless of time period. The decision as to the most appropriate time period to select will obviously depend on many factors such as the population and economic growth trends envisaged, capital

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4/ In the multi-volume publication Water Resources Activities in the United States, prepared for the United States Senate's Select Committee on National Water Resources pursuant to Senate Resolution 48 of the 86th Congress (issued in 1960), the reader is repeatedly cautioned with regard to the reliability and interpretation of projections of demand for the years 1980 and 2000 appearing in various volumes (Nos. 5, 7, 8, 12 and 32), dealing with this topic.

availability, social aspects and established regional priorities, etc. In this connexion, it is likely that the time period over which demand is assessed will have an important bearing on the degree of refinement required for the analysis. In general, the shorter the period envisaged for analysis, the more specific will the analysis have to be as regards the geographical break-downs of demand (by township, hamlet, village, valley, watershed, etc.), since an analysis over the short term presupposes the desire to meet immediate needs at the local level. Longer-term analyses (ten to twenty years), on the other hand, are more likely to encompass regional patterns of demand, presumably to be met at a later date by relatively large-scale supply schemes. However, the degree of detail required in the analysis will also depend to a large extent on the topography of the area surveyed. If the area is very hilly, individual villages or hamlets will probably have to be supplied from relatively short distances, given that conveyance costs (particularly pumping costs) are likely to be relatively high. 5/ This type of situation will obviously require a very detailed analysis which can take the needs of the single communities into account. If the topographical relief is very flat, on the other hand, distribution will not give rise to particular problems and a demand analysis may not require the same degree of refinement.

Thus, as opposed to electricity where distribution does not give rise to similar problems, the degree of detail required for analyses of water demand can be strongly influenced by the topographical conditions of the area to be surveyed. As a necessary precautionary step, regardless of time period selected and of degree of break-down of information, it would in any case appear advisable to base projections on, say, three possible demand levels: low, intermediate and high, so that a more realistic range of requirements can at all times be taken into account when considering possible ways of meeting future demand.

Assessing size of demand by industry is usually feasible to the extent that an industrial census or industry statistics exist or that water use by industries is regulated, or envisaged within the framework of, say, a five-year development plan.

The inherent difficulties in this case are due to the fact that if, as has not infrequently been found to be the case in developing countries, there is no industrial census and industries are self-supplied from their own wells or by private pipeline, it is practically impossible (from the viewpoint of a demand analysis) to make an accurate assessment of their demand for water. The desirable situation would be to find all industrial demand in an area registered automatically through metering; this would apply to cases where water is made available by an external supplier (regardless of whether it is governmental or private) and purchased on a unit consumption basis. However, such situations are rather rare.

Furthermore, when it comes to making projections of future demand, not only would it be necessary to know in each case the type of industry and its location but also the particular technology involved (which might be more or less

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5/ Ground-water costs in particular are very much affected by conveyance costs.

water-intensive. 6/ It is quite apparent therefore that if no industrial census exists, this is one sector where an accurate assessment of future demand is made difficult, with the possible exception of a highly centralized economy where all development is planned in advance in great detail.

The difficulty is compounded, as already stated, by the fact that size of demand is largely dependent on the technology involved. When industries are self-supplied with well water, little thought is usually given to gearing the process to a water-saving approach since fresh water is usually available in sufficient quantities from the industry standpoint and at low cost. When water is purchased from outside sources on the other hand, and additional supplies have to be made available at prices which the industries may feel to be relatively high, industries may be stimulated to meet this challenge through a major re-orientation in technology or through the installation of recycling equipment. Alternatively, it may be found more economic to use sea or brackish water directly for cooling.

On the other hand, the availability of good quality water (or of better quality than heretofore) may represent an incentive for the establishment or expansion of particular industries whose activities might have been handicapped by a lack of fresh water, and for which a relatively higher price might not be a strong deterrent.

Projections of demand will of course be geared to the requirements of specific industries if these are likely to be major projects within an area. 7/

In the case of water requirements for tourism, an estimate of size of demand can be particularly hazardous unless accurate monthly statistics are maintained of tourist flow, 8/ taking into account the approximate duration of stay within the confines of the area under investigation. Furthermore, per capita demand for water

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6/ To illustrate the great variations in industrial water requirements per unit of product, a few representative figures are given, taken from the United Nations publication Water for Industrial Use (Sales No.: 58.II.B.1):

Product and country	Unit of product	Water required per unit (litres)
Aluminium, USA	ton	1,340,000
Acetic acid, USA	ton of HAc	417,000-1,000,000
Fine paper, Sweden	ton	900,000-1,000,000
Blast furnace, Belgium	ton of iron	50,000
Stearine, soap and washing agents, Sweden	ton of fat	70,000- 200,000
Sulphuric acid, Belgium	ton	20,000- 25,000
Sulphuric acid (chamber process), USA	ton of 100% H_2SO_4	10,400
Gasoline, USA	litre	7- 10

7/ Gabes and Sfax in Southern Tunisia are a case in point where a water-supply project involving a 6000 m^3 per day desalination plant has been proposed to meet the needs of a chemical fertilizer complex and of the population in the area. See United Nations publication Alimentation du Sud Tunisien en eaux naturelles améliorées par dessalement, (TAO/TUN/4, 1965).

8/ In some of the water-short Caribbean islands such as Nassau (Bahamas), St. Thomas (Virgin Islands of the United States) or Curaçao (Netherlands Antilles), government tourist bureaux keep records of tourist traffic throughout the year.

by tourists must be clearly differentiated from demand by local residents since, regardless of water availability or water price in the area, tourists are habitually large and rather wasteful consumers of fresh water. 9/

One of the characteristics of water demand by the mining sector is that size of demand covers a very broad range, from the tens or hundreds of litres per day required by small prospecting groups or mining camps to the thousands of cubic metres required by large-scale mining and refining operations on an industrial basis. In this sector, the time factor is of vital importance since, whether it be for exploration or exploitation, mining groups do not wish to be put in the position of having to interrupt or delay operations for lack of water.

Characteristically, water is almost always self-supplied in this sector. In a number of water-short areas (particularly for oil exploration and exploitation) desalination plants (sometimes mobile as in Libya) are frequently found producing fresh water at high cost. The advantage in this case is that no time need be lost in looking for a reliable fresh-water supply, provided that ample brackish ground water is available or that operations are undertaken relatively close to the seashore. In any case, the bearing of water costs on over-all operation costs is negligible in these instances, even though the cost per unit of product water is sometimes extremely high. 10/

9/ A few illustrations of water demand by tourists in areas surveyed in the United Nations Desalination Survey follow below:

Location	Category of consumer	(litres) Daily water demand
Nassau (Bahamas)	Tourists	690 (estimate)
Nassau (Bahamas)	Local population	114 (estimate)
Curaçao (Netherlands Antilles)	Tourists	197 a/ (estimate)
Cuarçao (Netherlands Antilles)	Local population	55 a/
Djerba (Tunisia)	Tourists	100 a/
Malta	Tourists	227
Malta	Local population	136

a/ Desalinated water.

10/ Numerous examples may be provided of self-supplied desalinated water for mining purposes, among them: distillation plants at the oil field and refinery at Ancon and at La Libertad in the Saint Elena Peninsula (Ecuador); the many small electrodialysis (some mobile) installations for the oil groups in Libya and the Umm Gheig lead and zinc mine in the United Arab Republic. Chañaral (Chile) offers an example of a port town which has commissioned a desalination plant to meet the urgent and growing demand for fresh water by the 5,200 miners who live there and work in the neighbouring copper-mining district of Potrerillos. A 250 kilometre-70 litre per second high-pressure pipeline from the Cordillera was not found to be competitive with the desalination plant, given the relatively limited size of demand for fresh water in the area and the urgency of meeting the need.

Finally, irrigation water demand can be estimated with some degree of accuracy over time, provided all technical factors (such as cropping patterns, rates of evaporation and transpiration, etc.) have been predetermined.

The principal difficulty lies in making accurate assessments of minimum irrigation requirements, to ensure that the most efficient use of available water resources can be made for the economy of the area or region as a whole. Thus, when an analysis of demand indicates that there is a shortage of water for one or more consumer categories, a first step is to see the extent to which water resources are tied up in agriculture and whether possibilities exist for a modification of cropping patterns to less water-intensive or higher value crops; for the establishment of accurate minimum water duties; and for evaporation and transpiration control. 11/

One of the studies made for the United States Select Committee on National Water Resources 12/ goes precisely into an assessment of the expected water requirements in the agricultural sector for the years 1980 and 2000, bearing in mind population growth, probable dietary trends, water requirements per irrigated acre on the basis of stipulated trends in water use, and possible improvements in technology, leading to higher outputs and to a re-orientation of land surface under cultivation. Needless to say, the study has many limiting qualifications, but it is a very interesting attempt to project demand for water on a sector-wide basis, taking into account a considerable number of both independent and dependent variables.

C. Seasonality of water demand

Water requirements by different consumer categories obviously have seasonal and daily trends which may be in or out of phase with one another. This will have an important bearing on the possible ways by which demand can be adequately met in the most economic manner. In particular, monthly or seasonal fluctuations in average and peak demand may affect, quite considerably, the degree to which desalination could be envisaged as a possible source of supply.

Water demand for domestic, industrial and mining uses generally tends to exhibit a smaller degree of seasonal fluctuation than do demands by tourism and irrigation.

Residential areas usually show more variation than industrial areas, with the same aggregate consumption. In general, summer peaks reflect increased urban demand for bathing, showering, garden sprinkling and, where applicable, air conditioning. Of course, industrial demand could be discontinuous and exhibit a specific pattern if the principal activity is seasonal (such as food processing), with summer or autumn peaks. Moreover, it should be borne in mind that industries may work at

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11/ A recent United Nations mission to Madras (India) investigated prospects for the application of desalinated water in the city and surrounding countryside. The most economic solution in this case was found to be the reduction of rice paddy so as to make more ground water available to the city for industrial and domestic use rather than the installation of a costly desalination plant. In Israel, where the expansion of water resources will be by large-scale desalination, planners are realistically assessing prospects for the reduction of areas sown with water-intensive low-value crops.

12/ Water Resources Activities in the United States, prepared for the United States Senate's Select Committee on National Water Resources (Committee Print No. 12, 1960).

varying levels of output during the year, thus affecting the monthly and seasonal nature of demand. In most cases, water demand by the mining sector shows considerable uniformity throughout the year.

Tourism, particularly when this represents the most important economic activity in an area (as in the case of some of the Caribbean islands), can lead to very erratic seasonal demand patterns, with pronounced peaks in the high season, falling off very sharply in the low season (unless the area is fortunate enough to have more than one tourist season throughout the year). This reduction in demand will be even more noticeable when the low and the rainy seasons coincide, leading to a probable decrease in average per capita demand, not only by tourists but also by the resident population. 13/

Irrigation demand, in terms of volume required, (exclusive of water naturally supplied from rainfall), is probably the one which exhibits the greatest degree of seasonality. Environmental conditions (latitude and continentality, or the degree to which marine or land mass influences determine the thermal characteristics of a climate), coupled with soil and crop types, affect the duration of the irrigation period and the intensity of demand per hectare or acre. Regardless of the time period involved (which may go from a few days in humid climates to many months per year in the more arid regions), the periodicity of irrigation requirements is of great importance within the framework of annual water demand variations within the area. One additional aspect related to agricultural demand is that livestock naturally require drinking water throughout the year, and that demand for fresh water, particularly in the case of milk cows, is likely to increase in the hotter months of the year.

D. Qualitative characteristics of water demand

An assessment of the qualitative characteristics of demand is just as important as a determination of quantitative requirements. 14/ This is due to the fact that if an area is short of fresh water but endowed with a number of water sources with varying salt content, it may be possible to meet the demand of various user categories (with different qualitative requirements) by an appropriate distribution of available supplies or by blending.

13/ On the supply side, this type of demand pattern can create serious difficulties for water resource planners who are faced with the problem of how best to design systems and provide additional storage capacity in such a way that both average and peak demands can safely be met. Additions to the system may have to be geared to peak demand, thus having an enlarged system which (initially) will operate on a relatively low average load factor. The large difference between base load and peak load demand may be a significant consideration when desalination plants are involved, even though such plants will probably be run on base load with peak requirements provided by cheaper conventional sources.

14/ See World Health Organization publications: European Standards for Drinking Water (Geneva, 1961); International Standards for Drinking Water (Geneva, revised 1963 ed.).

What constitutes an acceptable quality of water for domestic use varies from country to country and, not infrequently, from area to area. In temperate climates, for instance, accepted upper limits for salt content of potable water are frequently of the order of 500 ppm; in arid and semi-arid environments, on the other hand, salt concentrations are usually found to be much higher (frequently between 800 and 1,000 ppm), and, in fact, physiologically required at these levels in many cases.

In the course of data collection for the United Nations Desalination Survey, 15/ a number of areas were brought to light in the Middle East where waters with salt contents well in excess of 2,000 ppm. are in current use.

A qualitative distribution of supplies for domestic use was found to exist in one or two cases (islands in the Caribbean and North Africa), where double piping systems were installed in homes and hotels with brackish water used for washing and flushing, and fresh water used only for drinking and cooking. The qualitative characteristics of water are very relevant in tourist areas, since this category of consumer generally requires that relatively abundant quantities of fresh water be made available for drinking, washing, showering, etc. This consideration is of importance in areas where the local population may be accustomed to using waters of inferior quality which would not be acceptable to visitors. 16/

Quality aspects of water demand for industrial purposes will obviously largely depend on the uses for which water is required. If it is primarily for cooling, quality of water is of little importance since, if necessary, even sea or brackish waters could be used for this purpose (provided pipes are adequately lined against corrosion). On the other hand, the availability of high quality water may be the necessary condition which will attract new industries to a particular area. For instance, pharmaceutical, bottling, 17/ food processing, 18/ and electrolytic plating 19/ are types of industry, which, given the nature of their demand, might favour the establishment of a distillation plant in addition to, or in place of, water from other sources (given that such users would probably be willing to pay a relatively high price for very good quality water). Moreover, the demand for very pure make-up water required for boiler feed in power stations may necessitate the installation of desalination plants for this purpose alone.

15/ Op cit., note 3.

16/ The island of Djerba (Tunisia) may be given as an example. On the island, brackish water with a salt content of 2,000 ppm. is currently used by the local inhabitants for domestic use. Tourists drink mineral water costing approximately $0.20 a glass, while sea and brackish water are used for washing, bathing, etc. Desalination of brackish water appears to be the only way by which fresh water could be provided to new hotels which will give a strong impetus to the development of the tourist industry on the island. (See TAO/TUN/4.)

17/ Distilled water is used for the production of soft drinks in Manama (Bahrein) and blended water for the same purpose at Doha (Qatar). The use of highly mineralized waters for such purposes would alter the taste of the product.

18/ Desalinated water is used at Lüderitz and Walvis Bay (South West Africa) for the fish canning industry and in Peru in numerous fish-meal factories along the coast.

19/ In Venado Tuerto (Argentina), distilled water is imported regularly for use in a local electro-plating industry.

In agriculture, the application of brackish waters to salt-tolerant crops is an accepted procedure, the composition of the saline content being relevant in these cases (in view of different resistance levels to the various radicals). Interesting experiments are under way in Israel to improve the quality of brackish irrigation water through dilution with water desalinated by electrodialysis.

These experiments would seem to indicate that this can be economically done for the irrigation of citrus and that water requirements per hectare are inferior to those formerly needed when brackish water only was used. 20/

From the viewpoint of supply, it is clear that the qualitative aspects of demand can be significant for desalination as a way of meeting or raising qualitative standards with desalinated water.

In this connexion it should be noted that the choice of desalination process may hinge on the required purity of product water. Distillation processes usually produce water with a salt content below 50 ppm, 21/ while it is not found economically convenient to reduce salt content of water obtained by electrodialysis below 400-500 ppm.

According to the latest information on the Zarchin freezing process (see lecture 9), 250 ppm product water is currently produced at Eilat and a 100 ppm product can be reliably produced with only a 1-2 per cent drop in output.

E. Matching supply with demand

The ultimate purpose of any water-demand analysis is to arrive at the most economic means of matching supply with demand. Probably the most important points to be considered in this connexion are to what extent: (i) demand and supply are suitably located with respect to each other from a geographical viewpoint; (ii) competing demands for water by various consumer categories create annual, seasonal or daily shortages.

The geographical location and concentration of demand are primarily the result of (i) governmental and private development and investment policy; (ii) the location of natural resources (cultivable land, forests, minerals, etc.) which is fixed and of economic activities, which depend on such factors as the location of markets and the existence of appropriate infra-structures; (iii) the concentration, size and growth characteristics of population; (iv) the space characteristics of the land, which depend on the combination of resources peculiar to each region, the human resources either locally available or attracted into the area, and the physical dimensions of the territory. 22/

20/ See lecture 8 for further details on this item.

21/ Since the degree of purity normally reached with distillation plants is very high, such high-quality water may be considered an unnecessary luxury if the output is primarily for household use. This is borne out by the fact that often distilled water has to be remineralized at some cost to remove flatness.

22/ See Ackerman and Lef, Technology in American Water Development (Johns Hopkins University Press, 1959).

The location of supply is of course dependent both on nature and on the ways in which man can adapt natural conditions to his own ends (for instance, through the construction of storage reservoirs or the installation of desalination plants).

With respect to the existence of competing demands for water, these can occur in a number of different ways and are largely dependent on whether demands (particularly of a seasonal nature) by various consumer categories are complementary to or competitive with one another.

Competition, for instance, could occur when daily or seasonal peak demands (say, for irrigation or tourist use) conflict with demand patterns which are constant throughout the year (for domestic or industrial use); alternatively, when peaks occur concurrently for different consumer categories. Conflicts may also arise when demand in one season may conflict with demand by other consumers at a later date, for instance, when water availability for other purposes is reduced following the evaporation of water stored primarily for irrigation.

The extent to which competition can be reduced or be replaced by complementarity will in part be dependent on the degree to which there is appropriate management of water resources.

F. Analysis of water demand: procedural steps

To conclude the foregoing brief presentation, the procedural steps to be undertaken when making an analysis of water demand will be set out below.

1. Preliminary appraisal phase

(a) Define purposes for which analysis is required and time period(s) which the analysis will have to cover.

(b) Define area(s) to be surveyed.

(c) Establish degree of required detail for analysis (break-down of demand by region, watershed, valley, township, village, etc.).

(d) Review all available information: population and industrial census, pre-existing analyses of demand, current demand patterns for water, current price levels for water, etc.

2. Economic base projections

Assessment of the growth of population and of the economy in the area over the selected time period: if possible make projections for three rates of growth (low, intermediate and high).

3. Seasonal and monthly water requirements

For each assumed rate of growth and on the basis of: (i) population growth and activities envisaged under 2; (ii) probable standards for daily *per capita* demand

and for daily demand by the various sectors of the economy (bearing in mind probable price levels and other relevant factors);

- establish monthly patterns of demand for each user category;
- analyse seasonal and monthly demand fluctuations;
- assess the occurrence, size and frequency of peaks to be compared to average levels of demand.

4. Annual water requirements

On the basis of monthly demand by user category, compute annual water requirements for the area surveyed.

5. Conclusions

On the basis of the foregoing presentation, and for each assumed level of growth, reach conclusions as to the size of demand and qualitative aspects of demand for the time periods envisaged. Underline seasonal fluctuations in demand, particularly with respect to peaks.

IV. ECONOMICS OF CONVEYANCE OF WATER

by the United Nations Secretariat

This seminar is concerned with economic applications of water desalination, or essentially with factors to be taken into account when considering the practicability of converting sea or brackish water to meet present and prospective needs for fresh or better water.

Since the emphasis is on finding the most economic solution, careful consideration must in most cases be given to conveyance of water as one of those factors. 1/

Conveyance of water - over a shorter or longer distance - to where it is needed, is always a technical possibility. Whether it is more economic than desalination or another alternative such as deeper drilling for ground water, is a matter of relative cost.

The technology of conveyance is certainly highly developed, and improving all the time; improved technology may be expected to reduce costs, although the rate of reduction may become faster in the field of desalination proper - at least if major "breakthroughs", such as are hoped for by many, are achieved - and thus give desalination a relative advantage. Conveyance technology has of course a long history, going back to the engineering marvels of the Roman aqueducts and earlier canals, but it is being continuously improved through better techniques and materials; water conveyance is the beneficiary of developments devoted essentially to moving other, more expensive, bulk commodities such as petroleum and chemicals as well as the beneficiary of the general development of transport techniques and systems.

The costs of conveying alternative fresh water may be said to set the economic boundary for desalination. Where that "boundary" will be drawn will vary from case to case, and must be determined by filling in the proper local costs in each case. The break-even point between desalination and conveyance will be determined by a number of factors, among them principally the method of conveyance; the distance of conveyance; the quantity (capacity and conveyance rate); cost, if any, of raw water; cost of quality improvement (treatment) of conveyed water; storage at intake and/or delivery end; and of course the cost of desalinated water. 2/ The cost elements

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1/ The term "conveyance" is preferred to "transport" for the sake of clarity. In the English language "water transport" may mean either "transport of water" or "transport by water". The terms "dollars" and "gallons" in this paper refer to United States dollars and United States gallons.

2/ The cost of an acceptable mix containing desalinated water and water from conventional sources (possibly brackish) should also be borne in mind in this context.

for desalination as such and their orders of magnitude are dealt with elsewhere and and will not be taken up here, except to note that in the ultimate analysis a comparison is made between conveyance, desalination and possibly other alternatives in terms of cost per cubic metre or per 1,000 gallons delivered to the distribution system. The distribution costs are excluded from the comparison, and indeed generally from the topics of this seminar, since they are basically independent of the source of water from which the distribution system is fed. It may be noted, however, that in conventional water-supply systems, the distribution costs predominate; in the United States, for example, the distribution system investment represents on the average some 70 per cent of the total value, leaving some 30 per cent for intake, storage, conveyance and treatment. 3/

Ideally, then, the comparison is brought down to the cost per cubic metre or 1,000 gallons of water (of comparable quality) delivered to the distribution system. The ultimate policy decision in favour of one solution or another may however be influenced by further factors, notably the capital intensity or requirement of one versus the other, the foreign exchange intensity or share of the investment and of the unit water cost, and reliability. The latter consideration may be particularly relevant in the case of long-distance conveyance solutions where water would have to be brought in from another province or country. Some of these aspects will be referred to below.

There are many alternative means of conveyance, and again the choice is a matter of economics, governed primarily by the quantity and distance involved. In view of the limited time and space available, we can only touch on the variables - by highlighting factors and characteristics - so as to give some guides for narrowing down alternatives in the particular case, for which the details have to be calculated in each instance on the basis of local costs.

Each means of water conveyance has its physical cost and characteristics, advantages and disadvantages. These aspects are discussed briefly below, as the main part of the paper, with regard to pipelines, canals, rail tank cars, highway tank trucks, towed barges, tanker vessels and towed dracones. This whole field is extremely vast and complex, and indeed the economics of conveyance of water forms the subject of a separate research project 4/ in the Resources and Transport Division, being carried on alongside and complementing the work on desalination proper. The presentation here is aimed mainly at providing some perspective, so that conveyance of water may be given full consideration as an alternative to desalination when appropriate. Some aspects are relevant also to the conveyance of raw water to, or product water from, desalination plants, but these generally are minor parts of the unit cost of desalted water delivered in bulk to the distribution system or to big water users.

3/ Louis Koenig, "Economic boundaries of saline water conversion", Journal of the American Water Works Association, Vol. 51, No. 7 (July, 1959), pp. 845-862.

4/ The present paper obviously draws on work already done for that project, including a background paper prepared by Dr. Louis Koenig as consultant to the Division. Most of the material and statistics pertain to United States experience, which therefore predominates in the illustrations.

Characteristics of means of conveyance

Many factors enter into consideration in selecting conveyance of water instead of desalination or indeed in selecting one means of conveyance instead of another to meet a certain demand for water. The characteristics of the demand itself also have to be given important consideration, notably with regard to seasonal and shorter-term fluctuations and to growth rates which may seriously affect the choice. If the maximum monthly demand is double the average and four times the minimum monthly demand, as is typically the case in the United States, this will obviously affect the degree of utilization, or load factor, of the conveyance system, and if the design is based on the maximum monthly demand it will result in a 50 per cent utilization of capacity with consequent effect on average cost. A 50 per cent load has been adopted in the calculations given in this paper. It should however be noted that this load factor can be considerably increased by modifications in storage or system capacity.

The carrying capacity of the different means varies enormously, from motor tank trucks of up to 7,000 gallons to canals able to convey many hundreds of millions of gallons per day (mgd). The total investment also varies enormously, not only with capacity but also with type of conveyance.

Some means, notably pipelines and canals, have considerable economy of scale, i.e. the investment per unit of capacity (mgd) and the unit cost of conveyance ($/1,000 gallons/mile) fall significantly with increase of capacity. This may be an incentive for "pre-building" or initial over-dimensioning, but the fixed costs (interest and depreciation) which predominate in this case then have to be borne by a relatively small quantity, and serious under-utilization of capacity can lead to high unit conveyance cost. The other types of conveyance, which may be called collectively the "containerized" means, possess some but not comparable advantages of economy of scale; they have to be multiplied in number for significant increase in capacity, in addition to such capacity increase as may be achieved through higher and more economic speed in moving the "containers" and through their more efficient utilization.

A system depending on containers, such as tank cars, barges, or dracones, can have its capacity expanded gradually, by the addition of more units as peak demand grows. Their radius of operation can also be extended to more distant sources of water supply, in contrast to pipelines and canals which have practically fixed capacity (as modified by pumping) and location, but the extension of the distance travelled will of course require more time and reduce delivery capacity correspondingly.

The effective time of water conveyance is limited in the case of the container types by the fact that the "containers" have to be returned, usually empty, to the source of supply, i.e. the "load factor" is practically cut in half as compared with pipelines and canals which can convey water continuously and up to capacity depending upon demand. The timing of the arrival of water and the return of empty containers can be regulated to a limited extent to meet short-term fluctuations in demand. The inherent discontinuity in the container system calls for at least some storage at the receiving end. In exceptional cases, the container vessels might find employment during seasons of low demand for purposes other than carrying water. It might be possible in some cases to achieve better economy by finding another liquid as a return load for the containers, in shuttle traffic, but this is likely to be offset by cleaning and other costs, and health hazards from contamination of the water would have to be watched. The most interesting case would appear to be that of carrying fresh water back in large oil tankers, but in this case oil would be the prime commodity, bearing most of the total cost.

The closed containers and pipelines are all capable of conveying water without effect on its quality, in contrast to open canals, so that the water can be treated as necessary at the source and fed directly into the distribution system at the delivery end. Adequate quality safeguards will however be necessary, especially when the water is destined for drinking purposes, and for a fair comparison with desalination as an alternative (or as a supplementary source of supply) differences in quality should be taken into account.

The relative importance of the cost components making up total annual cost varies with the means of conveyance, as discussed further below. Fixed costs, deriving from investment in the form of interest and depreciation, account for the bulk of the total in the case of pipelines and canals. Variable or operating costs are relatively much more important for the container types, because of wages and fuel costs for running the vehicles or vessels moving the containers and the handling of them. Overland conveyance in containers presupposes the existence of adequate highways (for motor tank trucks) or railways (for rail tank cars), which could not normally be built economically for the specific and principal purpose of conveying water, although the latter might make feasible otherwise marginal projects. Similarly, overwater conveyance (by barges, tankers, or dracones) of course presupposes reasonable access to shipping, as is often the case on water-short islands.

Sometimes it will be advantageous to combine different means of conveyance, so that the total annual cost and average unit cost in the system is minimized. These combinations may employ different means of conveyance over the distances to be covered between supply sources and users, such as pipelines for the main stem and trucking in bulk to outlying districts until demand grows sufficiently to justify a pipeline, or the employment of means with relatively high variable costs as a standby to meet peak demand. A careful analysis in the specific case will of course serve as a guide to the decision not only as to whether desalination should be adopted but also as to whether the time has come to shift from one means of conveyance, say tank trucks, to another, such as pipelines.

1. Pipelines

There is a tendency to think of conveyance of water mainly in terms of pipelines. They have indeed been most important in freeing man from the necessity of being close to rivers and other bodies of water, and they do account for the conveyance of tremendous quantities of water, supplementing and rerouting the water conveyed by nature in rivers and underground. Pipelines may not compare in quantity-terms with open canals, which however mainly serve irrigation (as a water use which is largely economically beyond the application of desalination in the foreseeable future), but they will grow rapidly in importance as we have to go further for water and, incidentally, get used to paying higher costs for water.

Space does not permit us to dwell on the fascinating history of pipeline development, but to provide perspective a few facts may be noted. The oldest known closed pipe system, in Crete, goes back to about the year 2000 B.C. About 1000 B.C., King Solomon built a pipe system to Jerusalem, while the oldest known pressure pipe system, twenty miles long and located at Pergamon, Greece, dates back to 200 B.C. Then the Romans perfected pipeline conveyance; by 100 A.D., Rome had over 240 miles of long-distance lines, of which about 200 miles was underground, and by 270 A.D. this system was so developed that Rome's 1,200,000 inhabitants had available 450 gallons (1,700 litres) *per capita* per day. The largest line was 150 miles long, of which 60 miles was underground, and had a capacity of 4 cubic metres per second or 91 million gallons per day. The Romans built significant long-distance conveyance systems in all their realms, including for example a line to Carthage 75 miles long. With the collapse of the Roman Empire, the construction of large, long-distance lines came practically to a standstill and was not revived again until towards the middle of the nineteenth century, when the growth of big cities and industry made it necessary to bring in larger quantities over longer and longer distances. [5]

Water demand and modern techniques have combined to bring about giant systems, based on pipelines and supplying up to some 1,000 million gallons per day (mgd). The median capacity in the United States, according to a survey for 1955, was 4.7 mgd and conveyance distance ranged up to about 400 miles for the Colorado River supply to Southern California, which now will also bring in water from the Feather River 600 miles away. There is a clear connexion between size of supply and distance conveyed, as illustrated by table 1 below.

Table 1

Average conveyance distance for various capacity groups in the United States

Capacity group million gallons per day	Number of supply systems	Conveyance distance miles
0- 3	142	5.1
3- 10	129	9.5
10- 30	59	16.5
30-100	40	31.7
100-300	9	81.6
300 or more	7	151.3

Source: F.P. Linaweaver, Jr. and C. Scott Clark, "Costs of water transmission", *Journal of the American Water Works Association*, Vol. 56, No. 12 (December, 1964), pp. 1549-1560.

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[5] Wilhelm Gandenberg, *Über die wirtschaftliche und betriebssichere Gestaltung von Fernwasserleitungen* (Munich, R. Oldenbourg Verlag, 1957).

Pipelines can be geared, in the design stage, to practically any desired capacity, whether it be 10,000 or 100 million or more gallons per day. This is a matter of choice of pipe diameter. Pipes in service range up to 150 or more inches in diameter.

The choice of diameter involves many economic factors, among them current demand, its rate of growth, storage at both ends, utilization factor, life of pipe, etc. Once laid, the maximum capacity is inflexible except for such boosting as can be achieved through pumping pressure. But there are limits to the latter, set by the strength of the pipe and the increase of friction losses in the pipe. Pumping may be needed to overcome friction as well as elevation difference, thereby adding pumping stations to investment, and energy and other costs to operation.

In most circumstances, the major component of the cost of conveyance by pipeline is the cost of the pipeline itself, and of this the major component is the cost of the pipe. The latter may vary with the type of material (although this is not the case in the United States), which may be steel, concrete, cast iron or asbestos-cement, or for smaller pipes of shorter life, plastic or wood. Modern pipes may have a useful life of 100 or more years; this implies a low depreciation rate but also careful planning in fixing capital in a major investment. Choices of types and sizes will be influenced, at least in part, by the availability of locally made material, so as to conserve foreign currency expenditures on equipment and freight.

The design and construction of pipelines is a highly specialized engineering field. For example, the pipe must be strong enough to withstand the pressures and stresses involved. This may sound simple enough, but there have been some painful experiences, as in the case of a large, long gravity line laid to carry a huge quantity of water down from the mountains in a developing country; when the valves were turned on amid great ceremony on opening day, the water rushed down and immediately burst the pipe, the ruins of which lie as a reminder of a great dream.

The designer also has to consider whether the pipeline should be on the surface or be buried, protection against corrosion, the material the pipeline passes through, the routing of the line and other factors having a bearing on the cost. Pipelines normally follow as straight a line as possible, but sometimes it may be economic to go around rather than over an obstruction, to reduce the need for pumping stations and energy: conversely, it may be advantageous to tunnel through the obstruction.

Distance is a vital factor. In the case of pipelines, the conveyance cost is directly proportional to the distance for a given quantity; for example, the cost of conveying one million gallons per day over 100 miles will be ten times that for ten miles. This proportionality is due to the overwhelming importance of the pipe in the investment and of depreciation and interest on it in the annual cost; by contrast, the cost of conveyance by container types such as highway truck or tankers increases less than in proportion to the distance. Thus, for small quantities, such as 10,000 gallons per day, it is cheaper to use highway tank trucks than a pipeline beyond a certain distance (16 miles under average United States conditions).

The major factor in cost, then, is the capacity or pipe diameter, while the cost per mile may be multiplied by the distance for horizontal pipelines. As an illustration, the following table from the background study by Dr. Louis Koenig referred to in foot-note 4 draws together the key figures from average United States conditions based on extensive statistical analysis.

Table 2

Conveyance in horizontal pipelines in the United States

Average conveyance rate million gallons per day	Optimum pipe diameter inside inches	Unit conveyance cost $/1000 gallons/mile	Unit investment $/gallon per day/mile
0.01	2.5	0.209	0.505
0.1	6.0	0.0342	0.0878
1	12.75	0.0082	0.0218
10	34	0.00325	0.0081
100	96	0.0013	0.0032
1,000	270	0.0005	0.0013

Note: The calculation is based on a load factor of 50 per cent, i.e. the design (or maximum) capability is double the "average conveyance rate". The computation of the "unit conveyance cost" employs a depreciation period of fifty years and an interest rate of 6 per cent on investment. The "unit investment" refers to "capability", i.e. a 100-mile pipe to carry an average of 10 million gallons a day would cost $16.2 million.

The preponderant role of fixed costs in pipeline conveyance is illustrated by the fact that interest (at 6 per cent) and depreciation (fifty years) on the pipeline alone account for about 80 per cent of the unit conveyance cost in table 2 above, irrespective of capacity for horizontal lines. The remainder is accounted for by interest and depreciation on pumping stations, operation, maintenance and repair on them and on the pipeline, and energy for pumping, which takes up a growing proportion of the "remainder" as the quantity increases. To amplify the example from the table of the average conveyance of 10 million gallons per day over a distance of 100 miles, it may be noted that the total investment would be $16.2 million and the total conveyance cost $0.32 per 1,000 gallons, of which interest and depreciation on pipeline and pump stations account for $0.28; if the interest rate were 0, the total would be reduced to $0.14. The remaining $0.04 includes $0.02 for energy (at $0.015/kilowatt-hour) and $0.02 for operation, maintenance and repair. As regards investment, the average in the United States for a 32-inch line is $152,500 per mile, including $78,000 for pipe alone, $37,000 for installation and $14,000 for other materials. The above figures are given purely for illustration and would be found to vary from place to place - even within the United States (owing to physical differences such as difficulty of access or excavation); they do, however, indicate orders of magnitude which can be adjusted according to differences in costs of pipes, material, labour, energy, interest rates, etc., as a first approximation to the specific, local case and they can narrow down the focus for detailed engineering feasibility studies.

Before concluding this section on pipelines, which have been discussed at great length and in detail because pipelines will presumably be the most common alternative to desalination among the means of conveyance, it should be noted that the above figures apply to horizontal pipelines and that pipeline conveyance costs are significantly affected, particularly by energy costs, when water has to be pumped uphill. This is especially so for very large capacity lines. On the other hand, when pipelines run downhill and enjoy gravity flow, pump stations and energy become unnecessary, and in that case interest and depreciation on the pipeline alone account for almost the whole conveyance cost.

As a companion to table 2 above, the following table is reproduced (also from Dr. Koenig's background paper) to illustrate the effect of hydraulic gradient (measures in feet per mile) on pipeline conveyance costs.

Table 3

Effect of hydraulic gradient on pipeline conveyance costs

$/1000 gallons/mile, United States conditions

Gradient ft/mile	50	20	0	-20	-50
Average conveyance rate million gallons per day					
0.01	.291	.242	.209	.180	.162
0.1	.046	.039	.0342	.030	.026
1	.014	.011	.0082	.0071	.0059
10	.0078	.0051	.00325	.0023	.0018
100	.0057	.0030	.0013	.00064	.00059
1,000	.0048	.0022	.00051	.00024	.00019

The column under 0, i.e. for a horizontal line, in table 3 is the same as column 3 in table 2 and both tables are based on the same conditions or assumptions, including an energy price of $0.015 (15 mills) per kilowatt-hour. From table 3 it will be observed, for example, that if water has to be pumped up a gradient of fifty feet per mile and the quantity is 10 million gallons per day, the conveyance cost per mile amounts to $.0078 per 1,000 gallons, as compared with $.0032 for a horizontal line, i.e. the conveyance cost is more than doubled because of the energy cost. For larger quantities, the relative differences for uphill pumping costs and advantages from downhill flow are even more pronounced.

If energy costs are higher than the 15 mills per kilowatt-hour used in the illustration, the effect of energy costs on pipeline conveyance costs will of course become correspondingly more pronounced. They may, in fact, turn the balance in favour of desalination in exceptional cases, although desalination itself is energy-intensive and is usually at lower (sea) level. Put another way, uphill pumping would considerably reduce the distance that a given quantity of water could be conveyed for a given limiting cost, which might be the cost of an alternative such as desalination. If that limit were $0.50 per 1,000 gallons and the given quantity (average conveyance rate) 10 million gallons per day, the water could be conveyed for 154 miles by horizontal pipeline and a longer distance in case of gravity (downhill) flow, under the conditions applicable to tables 2 and 3.

2. Canals

Canals and pipelines have some characteristics in common, but they also have significant differences. Both can be designed to carry large quantities, but there is a more marked economy of scale for canals. Fixed costs predominate in total annual costs for canals, especially lined canals. The design is also complicated in that the range of possible variations in design of canals has a great influence on the cost, more so than in the case of pipelines. Both canals and pipelines essentially have their capacity fixed at the design stage, although unlined canals especially can be cut deeper and wider to increase capacity; such later expansion can be provided for in the design stage, and lined canals lined only in a lower section in the first stage. Alterations may however require stoppages of the water flow with sufficient storage at the receiving end to carry over these periods.

The main difference between a pipeline and a canal is that the former is closed and may be operated under pressure whereas a canal is open and flows free by gravity. As such, the latter has more design restrictions and also has quality control problems. The canal is subject to pollution, theft of water, and evaporation losses; it may be exposed to sandstorms and, especially in the case of unlined canals, heavy seepage losses and problems of vegetation control. Extra treatment will probably be required at the receiving end to remove pollution from transit to achieve a water quality comparable with that produced by other means of conveyance, and will have to be allowed for in the cost comparison. In addition, canals require fencing to prevent them from being physical hazards for people and animals, and usually entail the construction of road crossings, falls, etc. In contrast to buried pipelines, they also take up land which might be put to other use.

As already stated, canals can only flow downhill whereas pipelines can be taken both up and down steep hills. There is, however, a limitation on the slope down which a canal can be taken, even with the construction of several costly canal falls, imposed by the limits for the velocity of water in open channels. The water must then be taken over a more circuitous route, i.e. the conveyance distance may become considerably longer and, not to mention the extra losses involved, outweigh any advantage in cost per mile.

A major question in canal design is that of lined versus unlined. A large number of technical aspects - such as velocity, channel shape, scour, sedimentation and losses - enter into this question. This has been dealt with extensively, notably in literature on irrigation, which is by far the major user of water conveyed in canals. Lining is expensive, both in material and labour, and the investment required for a lined canal may be several times that for an unlined canal; yet, reductions in seepage losses, utilization of greater slopes and velocities with the corresponding reduction in channel sections, and other factors, including the value of the water itself, may be such that the cost of conveyance may be lower in the lined canal. Depreciation and interest normally account for a much larger share of the total annual conveyance cost in lined canals than in unlined canals. However unlined canals may have to be shut down for maintenance and where vegetation is a problem, this could be for as much as one month in the year. Such shutdowns may not interfere with irrigation, but could not be accepted in most other uses without compensation through storage or other means.

Canals do have the advantage, particularly for developing countries short of foreign exchange and of equipment and fuels required for alternative solutions, of not being foreign-exchange intensive; local labour is the main item and imported items are not so significant in the total cost.

The total canal investment will be made up of expenditures chiefly for excavation; compacting of embankments; lining, where applied; structures such as regulators, falls, bridges and fencing; and right-of-way. The exact proportions of these items will vary with the size of the canal, the techniques and materials used, the type of material found in the excavation, wage rates, etc.

The range of absolute costs will show wide variations. From the computation (by Dr. Koenig) under "average" United States conditions, it may be noted however that for a canal lined with three inches of unreinforced concrete and capable of carrying 200 million gallons a day, the investment would be $120,000 per mile, including $58,000 for the lining. With an average conveyance rate of 100 million gallons a day (50 per cent load factor) and based on 50-year depreciation and 6 per cent interest (as is the case of pipelines), the total conveyance cost in this case is $0.000257 per 1,000 gallons per mile or $0.0257 for 100 miles (the comparable figure for pipelines is $0.129, or about five times more). The conveyance cost for 10 million gallons a day is also worked out for 100 miles, as follows:

Average Conveyance Rate, mgd		10	100
Canal (lined)	$	0.145	0.0257
Pipeline	$	0.325	0.129

It will therefore be seen that under these conditions canals are a cheaper means of conveyance than pipelines. If the average quantity were 10 million gallons a day, the canal could carry the water 345 miles for $0.50, as compared with the 154 miles mentioned earlier for a horizontal pipeline.

3. Container-type conveyance over land

Under certain circumstances, rail tank cars or highway tank trucks may provide the most economic solution. We leave out of consideration here other types such as water carts or containers pulled by horses or donkeys and human water carriers, which are still important in developing countries but belong to the distribution rather than bulk conveyance category; the same applies to bottled water, the most expensive of all.

Conveyance by rail tank car or highway tank truck may be economic when the quantity needed is relatively small, such as less than 100,000 gallons per day or more likely in the 10,000 gallon range, and the water source is located say at least 15-20 miles away. For shorter distances or larger quantities, pipelines would be more economic. The container types may well be forerunners for pipelines or desalination plants until demand becomes sufficiently large to justify the latter, and when that stage is reached, the tank cars may become bulk distributors for them, fanning out to areas served most economically in that way. The tank cars can of course be switched to other areas or sold when they are made superfluous by pipelines or desalination plants, and by the same token it may be possible for several localities, in case they have time differences in demand, to form a tank car pool so that the total capacity is minimized and effectively utilized.

The conveyance system using rail tank cars requires, of course, a railway line between the points of supply and use, the tank cars themselves and storage at the delivery end to hold water for use between tank car arrivals and as a safeguard for possible breakdowns and delays. Spur lines may have to be built from the main rail line to the water source and to a suitable place for the distribution system to receive the delivery. Multiple use of the tank cars may be uneconomic in shuttle traffic but might be possible on a seasonal basis. Modern techniques of plastic bags or liners is a possibility for carrying water back say from ports to mining areas.

Rail tank cars are available in various sizes, up to a capacity of 20,000 and 30,000 gallons; a common size in the United States is 8,000 gallons, costing about $11,000 in steel and about 50 per cent more for aluminium cars. The investment required depends on the quantity needed, the capacity of the cars, the distance, the speed or round-trip time, and other factors. Considerable time may be lost in waiting for freight train schedules and in switching.

The rail tank cars may have to be purchased by the water agency, thus requiring significant investment and, in most developing countries, expenditure in foreign exchange. The main part of the conveyance cost, however, will consist of the freight cost, i.e. the freight rate set by or negotiated with the railroad. If the freight charge is on a straight dollar per ton-mile basis, irrespective of quantity, there is also practically no economy of scale.

To illustrate orders of magnitude, the following may be noted from a computation under typical United States conditions for an average conveyance of 10,000 gallons per day for a distance of 100 miles: the total conveyance cost would be about $15 per 1,000 gallons, assuming a freight rate of $0.0275 per ton-mile (or $11.50 of total) and interest of 6 per cent and depreciation over 15 years on investment ($100,000) mainly in the tank cars, with the latter contributing $3.20 to the total; if one uses 30 years and 0 per cent interest, the total would drop to $13.20, whereas a reduction in freight rate to $0.01 per ton-mile would cut the total to $7.50. On the same computation, the total would be $8.68 for 10 miles and $65.50 for 1,000 miles, so there is relative economy with distance for rail cars, a reason for their advantage over pipelines beyond a certain distance at small quantities.

Conveyance by highway tank truck is more flexible, both in time scheduling and geographically, provided adequate highways are available. As it happens, under average United States conditions, the cost for conveyance by highway tank truck is on the same order of magnitude as that by rail tank car and either one is economic over conveyance by pipeline only at low quantities and relatively long distances. There are however significant differences in the cost characteristics of the two container types, which may result in large differences in relative advantages between the two as between different countries, depending for example on drivers' wage rates, overhaul and repair costs and fuel costs; these make up the bulk of the total cost of conveyance by truck, but depreciation is also significant since the truck may last only ten years or less. The system also will be foreign-exchange intensive if both trucks and fuel have to be imported.

Tank trucks are available in various sizes, with the tank mounted on the truck in sizes up to 1,500 gallons and in the form of trailers up to 7,000 gallons. A 1,000-gallon tank truck would cost about $9,000 in the United States and a 3,000-gallon tractor trailer about $20,000. Much of the economy lies in the speed, which may be greatly to the advantage of trucks over rail tank cars thus requiring much higher unit investment (per gallon per day of capability); if, for example, a tractor trailer travels 45 miles per hour and the rail tank car 150 miles a day, the tractor trailer could do the work of six tank cars each of equal capacity.

Cost of conveyance by highway truck increases less than in proportion to distance and there is some economy of scale. In view of the relatively high proportion of variable costs (fuel, wages of drivers and others to the extent they can be alternatively employed, etc.), the economy of truck conveyance is also less dependent on utilization or load factor, i.e. trucking is less sensitive to seasonal variations and may be used in peak periods to supplement inadequate pipeline or desalination capacity to some extent.

4. Container-type conveyance over water

Fresh water is conveyed over salt water in barges, tankers and dracones, all of which may grow in importance as water demand increases in islands and coastal areas readily accessible to such means of conveyance. They may present significant alternatives to desalination in the areas concerned, even though these areas have of course ready access to raw water for desalination plants and even if the system involves dependence on a source in another area or country. Occasionally, where the intervening body of salt or brackish water is shallow, the conveyance may also be undertaken through submarine pipelines; the investment and cost of conveyance in the latter are of the order of two to three times those for comparable overland pipelines.

Barges are used in several cases, notably for conveyance of water to and between islands. The system requires, beside the barges, tugs for propulsion, docks, loading and unloading facilities at each end and storage at least at the unloading end. The nature of the water demand, its seasonal characteristics, the prospective quantity and length of dependence on barging will have a bearing on whether an investment should be made in all or part of the barge and/or tugboat capacity or whether they should be hired, where available. At least the tugs can find other employment part of the time and might be more economically hired. Barges are available in various sizes, such as between 1,000 and 4,000 tons capacity (about 300,000 to 900,000 gallons); in the United States a 2,000-ton barge (480,000 gallons) will cost about $300,000.

The cost of tug hire or purchase will be a major component of conveyance cost, while most of the remainder is accounted for by depreciation, interest, maintenance and insurance on the barge. The price of water at the loading end will be important in considering alternatives, whether they be desalination or different sources of supply. Conveyance costs increase much less than in proportion to distance so it may be economic to go to another source further away, and there is economy of scale. Calculations based on United States experience indicate, for a 10-mile haulage, a conveyance cost of about $1.30 to $2.60 per 1,000 gallons for conveyance rates ranging from 10 million to 100,000 gallons per day, and much more for smaller quantities; a ten-fold increase in distance would less than double the cost. For larger quantities and longer distances it will be cheaper to use tankers. As with other containers, the barges have to return, perhaps empty, and provision has to be made to safeguard supply at the receiving end in case not only of delay but also of interruption from total loss of the vessel, especially when only one or a few vessels are used in the system.

Over-ocean conveyance of water can be accomplished with self-propelled tanker vessels, for large quantities and distances, in respect of both of which there is considerable economy of scale. Tankers range in capacity up to 25 million gallons. The use of tankers for water conveyance alone would be exceptional, other than in emergencies, for several reasons, among them the probability that for the quantity involved desalination would be cheaper, the high investment and foreign exchange component, and dependence on imported water.

An interesting case, studied in some detail by the Resources and Transport Division, is however presented by the possibility of conveying water on the return trips of oil tankers, particularly from Western Europe and Japan to the water-short oil exporting countries along the Persian Gulf and in North Africa. This might be accomplished either by carrying water in the separate ballast tanks; or in the hold itself, after cleaning of the tanks; or by providing for the holds of the tankers plastic liners which could be collapsed and returned on deck on the outgoing voyage. The simplest method would be to convey the fresh water in the separate ballast tanks which are normally filled with sea water on the return journey. Rough estimates in the study indicated a conveyance cost of about $0.15 per 1,000 gallons for the separate ballast tank method and about $0.25 by the plastic container or liner method, for conveyance to the Persian Gulf and at an average conveyance rate of 25 million gallons per day. The cost of a similar operation in ships in a system devoted entirely to water conveyance would be of the order of $3 per 1,000 gallons. To these figures must of course be added the price of water in the exporting port, ranging from perhaps $0.20 to $0.50 or more per 1,000 gallons. Present desalination costs in the Persian Gulf area are considerably higher than the indicated cost based on return trips of oil tankers.

The most recent conveyance type is the dracone, a term applied to sausage-shaped flexible containers made of reinforced plastic, which are used as containers for water and towed by vessels over the sea, such as between islands in the Greek archipelago. Dracones have certain advantages, compared with barges, in that there is no need to tow them back; instead they are folded up and shipped back on deck to the supply point, and the towing and return shipping may be handled by freighters plying between the two ports. Moreover, the investment per gallon of capacity in dracones 4/ is only about one fourth that in barges, but the service life is probably very considerably shorter. The full comparison also has to consider relative speed, need for harbour and handling, and ability to stand rough seas, all of which may be to the disadvantage of dracones. All factors considered, however, and where physically applicable, conveyance by dracones may be expected to be cheaper than by comparable barges, and may turn out to be a more favourable alternative than desalination in the particular case.

4/ Characteristics of large-sized dracones are as follows: capacity 278,000 gallons, length 314 feet, diameter 13 feet, empty weight 5.6 tons, draft 12 feet, cost f.o.b. United Kingdom port $60,000; about 100 horsepower are required to tow such a dracone at 5 knots.

V. INTRODUCTION TO DESALINATION PROCESSES: A GENERAL REVIEW OF THE UNITED STATES DESALTING PROGRAMME

by J.W. O'Meara

As a part of his quest for water, man has been trying for a long time to brew a drink of fresh water from the sea, probably a lot longer than most people realize. For centuries people generally have known how to turn the trick: just distill it. Aristotle, almost 350 years before Christ, taught his students that vapour formed from sea water, when condensed, is no longer salt.

Although the distillation phenomenon had long been known, the first practical conversion units did not come into being until the advent of the steamship with its requirement of fresh water for boilers. For many years, desalination equipment was of major interest only to the maritime industry and navies. There were two principal criteria for equipment for this use: reliability of operation and the space requirement of the desalting machinery. The cost of conversion was a minor consideration. Not until a decade or two of the twentieth century had elapsed did man try to build land-based conversion plants to supply fresh water and these were built in very arid regions where little or no natural fresh water was available.

A new dimension was added to the conversion of sea water to fresh water when the Congress of the United States approved the Saline Water Act of 1952. Rising concern over the acute shortage of water in the arid areas of the nation and the excessive use of underground waters throughout the nation, impelled the Congress to provide for the development of practicable low-cost means of producing from sea water, or other saline waters, water of a quality suitable for agriculture, industrial, municipal, and other beneficial consumer uses.

To carry out the directive of the Congress, the Secretary of the Interior established the Office of Saline Water to conduct a research programme for the development of large land-based plants capable of supplying a city or an industry with fresh water from sea or brackish water sources.

The entire thrust of the Federal desalting programme is aimed at a single objective - low cost. That was the target when the programme was established in 1952; it is the same today. While the goal has remained the same, the scope and thrust of the programme have changed considerably. Just how much the present programme differs from the initial programme can best be described by a brief review of the legislative history of the operation.

Legislation providing for saline water conversion research was introduced in the Congress as early as 1948, but it was not until four years later that the first legislation was approved. The 1952 Act provided $2 million for a 5-year programme "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".

It quickly became evident that this amount of money and a 5-year time period were wholly inadequate. While it is relatively simple to produce fresh water from ocean water, to do it at low cost is extraordinarily difficult. The legislation was amended in 1955 by extending the life of the programme over an 11-year period and increasing the authorization funds to $10 million.

In 1958, the Congress provided an additional $10 million for the construction of not less than five plants to demonstrate the reliability, engineering, operating, and economic potentials of the most promising of the presently-known processes, with each plant to utilize a different process.

A major increase in the activities of the Office of Saline Water was provided in 1961 when the Congress extended the programme for an additional six years and authorized research and development funds in the amount of $75 million, and an even greater expansion occurred just last month when the Congress authorized an additional $15 million for research and development activities in the fiscal year 1967, plus such additional sums as the Congress may hereafter authorize and appropriate, not exceeding $185 million, to carry out the purposes of the Saline Water Act during the fiscal years 1962-1972 inclusive. Thus we are now poised for a substantial expansion of our desalting programme, with increasing emphasis to be placed on engineering development through module and prototype plant construction.

When President Johnson signed this legislation into law he said: "Over the past several weeks, Congress has sent to my desk for signature an unprecedented procession of legislative measures which can only be described as truly historic.

"It is my own studied and considered judgement that this bill may well be the most historic of all: not for what it provides but for what it promises, not for what it accomplishes but for what it symbolizes.

"I have faith that we will succeed - and I have a vision that such success will be one of history's most vital contributions to the cause of peace among nations".

The programme recognizes four distinct areas of need which exist both in our own nation and in the world community, as follows:

(1) Rapidly growing, major population centres which will need additional water to supplement existing sources;

(2) Developing areas in arid or semi-arid zones;

(3) Inland and coastal areas where the mining of ground water has resulted in brackish or sea water intrusion; and

(4) Areas where the present water supply is adequate but of substandard quality.

The increase in the use of water in the United States has been phenomenal. At the turn of the century, we used about 40 billion gallons of water per day. By 1920 the figure had doubled. It doubled again by 1944, and again by 1965. The current use of water in this country is now estimated to be 360 billion gallons per day and use is increasing at the rate of 25,000 gallons per minute!

Even with this great daily demand, some areas of our nation have ample supplies for present needs and for many years to come, but in the more arid areas and in some areas where population density continues to rise and industrial operations continue to expand, the ability of readily available natural fresh water to meet the unrelenting requirement for more and more water is being sorely taxed. To meet today's demand for fresh water and the ever-increasing demand in the years ahead, scientists and engineers are working to develop a variety of methods to conserve and supplement our inventory of fresh water. One potential incremental source of new water may come through desalination. How soon this may come about, in a large measure depends on the ability of the scientists and engineers who are working on desalination problems to drive down the cost through the development of new or improved conversion processes.

When the Office of Saline Water was established, the cost of producing 1,000 gallons of fresh water from sea water ranged upwards from $4. The cost of conversion is calculated by a procedure developed by the Office of Saline Water to compare the economic feasibility of the various processes. In most instances, it does not provide a basis for comparing the cost of desalted sea or brackish water with the rate charged for natural fresh water delivered to the consumer. Briefly, the costing method endeavours to include all costs at today's prices. It begins with the cost of land required for the plant, to which is added the total capital investment for the necessary equipment, operating costs including fuel and personnel, maintenance, taxes, interest, and insurance. This formula provides the cost of water at the plant but does not include the cost of distribution.

The work of the Office of Saline Water is programmed to reach short, intermediate and long-range goals. The short-range goal is to provide processes and plant designs with the lowest possible desalting costs at the earliest possible time. To accomplish this, an engineering effort is under way to analyse the significant amount of research and development technology acquired in this programme to date, and to choose that which is best for intermediate incorporation into the conceptual design of a desalting plant sized in the range of 50-million gallons per day. Construction and testing of modules and prototype equipment will be undertaken at a West Coast Test Station to acquire the engineering data which is still needed to provide a reliable basis for the design of a 50-million gallons per day plant. The largest desalting plants built in the United States to date have design capacities of 1-million gallons per day.

The intermediate range goal is aimed at the development and pilot plant demonstration of hardware components having their greatest technological potential for utilization in the 50-million gallons per day plants while concurrently developing and pilot testing hardware components applicable to new processes now emerging from laboratory and bench-scale operations. Modifications and improvements of existing processes will be conducted at the pilot-plant level to provide the data necessary to determine the technical merit and economic potential of new approaches. Much of this work will be conducted at the Office of Saline Water Research and Development Test Station at Wrightsville Beach, North Carolina.

The long-range goal, and a very important function of the over-all programme, is basic research. The primary goal of the research programme is the generation of new concepts, new ideas, and new scientific knowledge generally applicable to any process of saline water conversion. No immediate benefit is anticipated from this phase of the programme, but the information produced from these studies will advance today's technology and produce tangible results in the years ahead.

The programme of the Office of Saline Water is conducted through the award of grants or contracts to other United States agencies and with universities, private research organizations and industrial firms. Proposals submitted to the Office are evaluated to determine their scientific merit and economic potential. Proposals which receive a favourable evaluation, within the limits of appropriate funds, may receive financial support.

Processes under development by the Office of Saline Water can be conveniently divided into five principal categories, with a number of different approaches under study in each group. These are: (1) distillation, using either nuclear or fossil fuels; (2) membranes; (3) crystallization; (4) humidification; and (5) chemical.

Early pilot-plant activities of the Office of Saline Water to develop new or improved processes were conducted on dock space made available for our use by the International Nickel Company at Wrightsville Beach, North Carolina. Community interest in Office of Saline Water activities eventually resulted in the establishment of a Research and Development Test Station at Wrightsville Beach on twenty-five acres of seashore property donated to the Department of the Interior for this purpose by the State of North Carolina.

The Test Station consists of a series of reinforced concrete slab foundations for pilot plants, a skimmer pond, aeration basin, impounding basin, office building and laboratory, corrosion test building, maintenance shop, garage, utility building, and fuel storage facilities. The station is equipped to supply our pilot plant contractors with raw sea water, fresh water, high and low-pressure steam, compressed air, propane gas and electricity. A structural steel framework extends over each pilot-plant plot to support overhead travelling cranes which are used to facilitate the erection and maintenance of experimental equipment. With this facility we are able to test and develop new or improved conversion processes under standard conditions. Nine pilot plants are currently operating at the Test Station together with corrosion test studies on ferrous metals.

Long-tube vertical evaporators have been used for many years in the chemical industry for the concentrating of liquors, such as waste sulphite in the pulp industry. Experimental work on the development of the long-tube vertical multiple-effect distillation process (LTV) to adapt it for use as a sea-water conversion method was carried out in a 2,000 gallons per day pilot plant at Wrightsville Beach, N.C. The test work resulted in the design of a process which was selected for the first demonstration plant. The 1-million gpd LTV plant was built at Freeport, Texas, in 1960-61, at an initial cost of $1,255,712. Experience gained from the construction and operation of the plant has resulted in a number of plant modifications and improvements. Although the average cost of water produced by the plant has been about $1.35 per 1,000 gallons, during one recent test run the plant produced 1.1 million gallons of water per day while using only two thirds of its evaporator capacity, indicating a process potential of producing 1,000 gallons of fresh water for less than $1 in the 1-million gallons per day size range.

The plant at Freeport is composed of a series of 12 large evaporators, or effects, with approximately 500 tubes, 2 inches in diameter and about 40 feet long. These tubes, arranged vertically in the evaporators give the process its name. Steam is admitted into the first evaporator and fills the space around the outside of the tubes within the evaporator shell. Sea water, preheated through a series of heat exchangers is introduced in the top of the first evaporator and falls through the tubes. Steam around the outside of the tubes and within the evaporator shell causes part of the sea water to boil as it falls through the tubes. Emerging at the bottom of the evaporator is a mixture of vapour and hot brine. The residual hot brine is pumped to the top of the second evaporator where under slightly reduced pressure it again falls through the inside of the tubes. The vapour produced in the first effect flows to the outside of the tube bundle in the second effect. Here the vapour is condensed to fresh water by giving up its latent heat of vaporization to the sea water falling through the tubes which again causes part of the water in the tubes to boil.

This same process is repeated through all 12 effects of the plant. The condensed vapour, which is fresh water, is pumped from each effect through heat exchangers to recover as much heat as possible and then into a common line leading to the storage tank.

A second 1-million gallons per day sea-water conversion demonstration plant utilizing a multi-stage flash distillation process was built on Point Loma near San Diego, California, at a cost of $1.6 million. Through improved operating techniques, the operating temperature of the plant was increased from 190°F to 250°F. At the higher temperature the plant produced 1.4 million gallons of water per day. This 400,000-gallon bonus was achieved with virtually no increase in capital investment and only a slight increase in operating costs. The cost of fresh water produced by the plant ranged from $1 to $1.25 per 1,000 gallons. On 26 February 1964, after operating for slightly less than two years, the plant was transferred to the Navy, dismantled, and shipped to Cuba, where it was re-erected on the Guantanamo Naval base.

In a flash distillation plant the sea water is progressively heated and then introduced into a large chamber where a pressure just below the boiling point of the hot brine is maintained. When the brine enters this chamber the reduced pressure causes part of the liquid to immediately boil - or flash - into steam. The remaining brine is passed through a series of similar chambers (multi-stages) at successively higher vacuum where the flash process is repeated at progressively lower temperatures. The San Diego demonstration plant utilized 36 such flashing stages.

The progressive heating is accomplished by piping the incoming sea water through the flash chambers, starting at the low temperature end. In each chamber the flashed vapour condenses as it gives up its heat to the cooler sea water in the condenser. Final heating of the sea water before flashing takes place in a salt water heater. By this arrangement about 90 per cent of the heat required for boiling is re-circulated, and only 10 per cent is supplied by the salt water heater, which for the San Diego plant was a steam boiler utilizing fuel oil.

A third 1-million gallons per day plant, using a forced-circulation vapour compression process, was completed in 1963 near Roswell, New Mexico, at a cost of $1.7 million. A number of process and equipment problems have plagued the operation of this plant, but the difficulties are being gradually resolved and the process gives promise of potential commercial utilization in areas of high fuel costs.

Forced-circulation evaporators have been used successfully in a number of industrial applications. Combining a vapour compressor with two forced-circulation evaporators is a new approach to the problem of obtaining fresh water from saline water. The saline feed water is introduced into an ion exchange unit for removal of hardness and then is heated to about 144°F. At this point the feed water is treated with acid and then introduced into a vacuum de-aerator for the removal of dissolved gases. Upon leaving the de-aerator, the feed is further heated to about 224°F and then pumped into the first effect evaporator. The water in the first effect is circulated through the tubes under pressure to prevent boiling, at the rate of 90,000 gallons per minute. As the water emerges into the lower pressure vapour dome, part of the water immediately vaporizes into steam, concentrating the water to 1.6 times its original salinity. The water that did not vaporize in the first effect is fed to the second evaporator where further heating concentrates it to a factor of 4.0 as it vaporizes in the second vapour dome.

The concentrated brine is then drawn off and sent through a series of heat exchangers to give up its heat to the incoming feed water. This is the operation that heats the incoming feed water to 224°F, as noted above.

The steam generated in the first effect is collected in the vapour dome and pumped to the outside of the tubes in the second evaporator where it gives up its latent heat of vaporization by increasing the temperature of the water in the tubes and thereby is condensed to fresh water. Steam generated in the second evaporator is compressed by the vapour compressor - thus raising its temperature, and is re-cycled to the first effect to boil more water and to be condensed to fresh water.

The condensed steam in the first and second effects is collected and sent through a series of heat exchangers to give up the heat it still contains to the incoming feed water. This is the operation described earlier that elevates the temperature of the feed water to 144°F.

A $482,200 construction contract was awarded in 1960, for the construction of a 250,000 gallons per day electrodialysis process demonstration plant to demineralize the brackish well water of Webster, South Dakota. An electrodialysis cell, as utilized in this process, consists of a sandwich of alternating cation and anion permeable membranes. Upon the application of an electric current the positively charged ions (such as sodium), pass through the cation permeable membranes and the negatively charged ions (such as chloride), move in the opposite direction and pass through the anion permeable membranes. The water in the centre chamber of each membrane cell is thus depleted of salt while the water passing through the intervening pairs is enriched. The cost of conversion using an electrodialysis process is directly tied to the salinity of the raw feed water. Electrodialysis is presently considered to be the most economical process available for mildly brackish water, but it is not competitive with other processes for the conversion of sea water.

A distillation process requires a double phase change: from a liquid to vapour and back to liquid. A crystallization process also requires a double phase change: from a liquid to a solid and back to a liquid. An ice crystal is pure water, thus a freeze-demineralization process involves freezing part of the sea water to form a slush or a slurry of ice crystals, removing the ice from the brine, washing it free of occluded salt and melting it to fresh water. We are working on the development of this promising system in several pilot plants at the Wrightsville Beach, N.C., Test Station. There are definite theoretical advantages inherent in the freezing process, but as yet a number of mechanical problems remain to be solved.

One of the most promising of the new processes under development is known as reverse osmosis. For some time, scientists have known of the salt-rejection properties of cellulose acetate. Specially cast membranes of this material have made possible initial development of an inherently simple desalting process. In this process, the application of hydrostatic pressure to saline water produces a flow of fresh water through the membranes. Less than 10 years ago the best membranes available for this purpose permitted a flow of .2 gallons of fresh water per square foot of membrane. Membranes are now available with a water flux of 23 gallons of fresh water per square foot of membrane. The process has good economic potential because it avoids the costly phase change required by both distillation and crystallization processes. We are now operating a 1,000 gpd pilot plant and plan to construct a 50,000 gpd plant soon.

Studies conducted by the Office of Saline Water indicate that substantial cost savings will accrue as today's technology is incorporated in multimillion gallon per day plants. Preliminary information produced by a study currently under way, which is jointly sponsored by the Office of Saline Water, the Atomic Energy Commission, and the Metropolitan Water District of Southern California, indicates that a large nuclear-fueled combination power and water plant could produce 150 million gallons of fresh water in the cost range of 22 to 30 cents a thousand gallons.

This study provides the most optimistic cost data yet developed and it clearly indicates the fresh water may be produced from the salty sea in large quantities and at a price that is economically feasible for municipal and industrial uses, but this attractive cost estimate is possible only because of the size of this specific project as regards both water and power production. With today's technology, it is not attainable in small plants.

From a survey conducted by the United Nations Department of Economic and Social Affairs, through its Resources and Transport Division, of the water needs of 43 developing countries, it is clear that the most immediate need for desalting plants is in the size range of 10 million gallons per day or less. The report of this study 1/ is the most comprehensive compilation of its kind available, but it wisely points out that it is still necessary to conduct extensive feasibility studies upon which economic appraisals of available and realistic alternatives may be considered. Desalination is not a panacea for all water ills, but there are locations where today it can represent the cheapest and most reliable source of supply. As new technology is developed, and I am confident that it will be, desalted water will play an ever greater role in meeting the increasing world-wide thirst for this most common yet most vital product.

A second United Nations publication in this field 2/ provides an excellent formula which policy-makers and administrators may gainfully utilize to determine realistic costs of desalted water from both existing and planned installations.

1/ United Nations, Water Desalination in Developing Countries (United Nations publication, Sales No.: 64.II.B.5).

2/ United Nations, Water Desalination: proposals for a costing procedure and related technical and economic considerations (United Nations publication, Sales No.: 65.II.B.5).

Technical data gained through the Office of Saline Water programme is not for the exclusive use of the United States. At the direction of President Johnson, our desalting technology is being shared with other nations. This is one reason why we are sponsoring the First International Symposium on Water Desalination; it is the reason you have been invited to attend the Symposium; it is why we are sharing the sponsorship of a feasibility study of a large desalting and power plant for Israel; it is why our scientists and engineers have visited the United Arab Republic and Saudi Arabia, Tunisia, Spain, Italy, the United Kingdom, the Federal Republic of Germany, Greece, the Soviet Union, France, Mexico and Japan; it is why we are here today.

In the President's own words: "It would be difficult to exaggerate the power for good, the palliative effect on age-old animosities and problems, that would result from providing an abundance of water in lands which for countless generations have only known shortage".

VI. CORROSION CONTROL AND MATERIALS IMPROVEMENT

by M.N. Fokin

The selection of economic structural materials for modernizing sea water desalination plants in line with the latest advances confronts the corrosion specialist with the problem of setting scientific and technical durability standards for individual units that must operate at high temperatures with chloride-laden media.

Current research is directed toward effective employment of various heat-exchange devices aimed at decreasing energy losses and lowering desalination costs in the thermal processing of sea water. Prevention of internal pipe scaling is being closely studied for the purposes of extending the duration of periods of uninterrupted service. In addition to research on intensified heat exchanges specifically aimed at achieving a considerable reduction of the surface-heat exchange without affecting output rates, practical means are being sought for raising corrosion resistance in the major units.

The corrosion of materials, as it occurs in sea water distillation, is due chiefly to the aggressive effects of sea water aeration and brine deaeration. There are many reasons why oxygen, the basic depolarizing agent in metal corrosion in neutral media, should be removed at a point located as close as possible to the water intake. In this connexion, an ejector-type vacuum deaerator offers a preferred solution in countercurrent multi-stage heat-exchange facilities. The optimal location for the deaerator is usually at the point in the water-intake chain where the temperature rises to 35-40°C, bearing in mind the degree of deoxidation due to heating.

In the water intake unit, the standard procedure is to clear the sea water of suspended matter and then chlorinate it, in order to prevent the growth of bacteria.

At present, theoretical and laboratory investigation, oceanographic studies, [1] and tests with evaporators and heat exchangers performed on sea-going vessels, and at seaside electrical plants and oil refineries, have yielded much useful information which has been carefully analysed and synthesized. However, without a detailed study of various corrosion problems, this does not give a definitive answer to many questions encountered in practice.

During the last few years, a specific list of structural materials suitable for various units has been compiled, to include those tested and proved to be serviceable for 15 to 20 years when properly used. The list mentions: carbon steel and cast iron, chromium-nickel (18-8) and more frequently chromium-nickel-molybdenum (17-13-3) stainless steels, aluminium brass (76-22-2) and bronze, copper-nickel alloys (90-10 and 95-5), and titanium. There are differences of opinion regarding the advisability of making wide use of aluminium alloys in sea water at high temperatures.

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[1] G.V. Akimov, ed., Problemy morskoï korrosii (isdatelstvo AN, USSR, 1951).

The tested and approved materials, other than metals, include, besides concrete, asbestos cement, plastic glass, polyvinyl chloride (for water pipes), rubber lining (for sealing devices) and some other linings.

Theoretically low rates of corrosion often prove to be much higher in actual operation, owing to many factors that may have been overlooked. Research is intended to remove the causes of the high corrosion rates of structural materials, as revealed by the observation and analysis of worn out experimental and full-scale equipment.

The author, realizing the impossibility of justifying the validity of all attempts to eliminate corrosion in contemporary sea water desalination plants, will merely describe and codify in this paper, in so far as this is possible, the broad aspects of the corrosion problem. For purposes of classification, the following scientific technical problems that were and are being worked upon by specialists seeking effective means of protection against corrosion may be listed.

A. Corrosion by contact

A steel heat-exchanger casing, when joined with stainless steel or copper-base alloy tube plates, will actually behave as a galvanic couple at the contact of sea water. As the record shows 2/, desalination installations using heat exchangers of this type produced 3,780 m^3 of water a day for 2 months after starting up (Freeport, Texas, United States). In seven heat exchangers it was necessary to replace 1,700 steel guide blades that were in contact with copper alloys. From the corrosion standpoint, this unit was unsatisfactory for according to laboratory determinations the average corrosive penetration of carbon steel forming a galvanic couple with an equal area consisting of copper alloys is about 18 mm/yr in an aerated sea-water flow of 1 m/sec at 70°C.

The steel barrel of heat exchangers before deaeration (temperature below 40°C), can be satisfactorily protected from corrosion by means of shields (made, as a rule, of zinc or magnesium) at the points of dangerous contact with various metals. Sometimes false tube plates made of black sheet are used for this purpose.

Aluminium alloys are rejected in practice as structural materials for desalination plants, because of the risk inherent in their contact with nobler materials. Only in one instance, namely in the careful planning of field equipment for distillation of water for the army (water output 10 m^3/24 hr) from which copper alloys were excluded, did aluminium heat exchangers show satisfactory endurance after 2,000 hours of operational testing 3/.

2/ Corrosion, Vol. 17, No. 9 (1961), p. 37.

3/ R.J. Gainey, Corrosion, Vol. 17, No. 11 (1961), p. 98.

B. Corrosion of carbon steel by drinking water and distillates

With regard to corrosion, the permanent and temporary hardness ratio of the water must be allowed for, in other words, its bicarbonate content, in the form of magnesium and calcium compounds for a drinking water containing about 1 Gm/l of salt in the presence of not more than 150 mg/l of chlorine ions, must be known. Any excess of carbon dioxide in the water prevents the formation of an almost insoluble protective film on the steel by lowering the pH and making the water chemically more active. Neutral water (pH=7) can neither be called aggressive nor non-aggressive until the extent of its temporary hardness is known. In very soft water, bicarbonate may separate from the calcium and magnesium, so that their protective action on the steel tends to shift into the alkaline range. In waters where Langelier's corrosion index is positive, independent of the dissolved oxygen content, adequate safety is maintained for the hot and cold water supply. In distillates and waters containing less than 35 mg/l of calcium carbonate, the metal is left practically without any protective film, and the rate of corrosion is consequently accelerated. Mixing the distillate with other fluids and filtering it through a magma of marble chips supplies the necessary salts and hardness, and practically solves the problem of protecting carbon steel water piping from corrosion.

C. Pitting and/or blistering of carbon steel in brackish waters and graphitization of cast iron

In waters containing more than 150 mg/l of chlorine ions, steel may become pitted and/or blistered, which breaks up the continuous bicarbonate film. Local corrosion of steel may then cover considerable areas in aerated water.

Thus, for example, the formation of air holes in underwater steel pipelines in the fairly brackish Lake Maracaibo (Venezuela) goes with a mean local corrosion rate of 1.65 mm/yr, while the maximal penetration corrosion due to blistering sometimes reaches the astronomical figure of 34 mm/yr. [4]

Pitting and/or blistering of steel water piping is also very noticeable in insufficiently deaerated brackish waters, especially at high temperatures. Cast iron pipes, though suffering a somewhat higher corrosion rate than carbon steel, show a more regular pattern of disintegration. Asbestos cement, and glass fibre pipes, as well as various linings, are being tested in attempts to find more dependable and economic materials.

The cast iron bodies of pumps used for the conveyance of brackish and sea waters undergo relatively uniform corrosion. However, deep disintegration of the metal occurs while the surface retains its porous graphite matrix, which can be scraped out with a knife. There are recorded cases, in which the graphitization of cast iron reached a depth of 11 mm/yr. Graphitization can be reduced by adding a small amount of nickel to the cast iron. The use of Ni-resist austenitic cast iron containing 15 to 20 per cent of nickel as a material for sea water pipes is fully justified and confirmed by the high resistance they show under operating conditions.

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[4] F.G. Baptista and H.F. Finley, Corrosion prevention and control, Vol. 10, No. 9 (1963), p. 31.

D. Corrosion of carbon steel in deaerated brine at high temperatures

The consequences of the corrosive action of brine on ferrous metals in evaporators proved to be less serious than had been expected. Excess chlorides in brine counteract the tendency to the local corrosion of carbon steel, which usually occurs in insufficiently deaerated brackish waters. At the present time, without resorting to any additional measures, it is considered permissible to use carbon steel for operation in brine up to 60°C, provided its oxygen content remains at a level of 0.01 mg/l and water velocity does not exceed 1.5 m/sec.

In boiling (naturally deaerated) sodium chloride solutions simulating sea water, the corrosive penetration of carbon steel reaches about 0.5 mm/yr. There are attractive possibilities regarding the raising of the temperature limits applicable to brines in contact with carbon steel. Research has defined the units of deaeration required and evaluated the effects of hydrogen depolarization on the process of steel corrosion at various temperatures.

E. Crevice and pitting corrosion of stainless steels

Chrome nickel stainless steel, thanks to its high resistance to corrosion in flowing aerated sea water, is widely utilized as a structural material in desalination plants. In zones of stagnant sea water, with overgrowing marine life, under strata in grottoes and clearings, stainless steel exhibits localized forms of disintegration, thought to be the result of partial breaks in the inert film formed on the metal surface. The results of many years of marine research under natural conditions (i.e. at temperatures up to 30°C) gave, for the maximal blister penetration of XI8H9T and XI7HIZMT steels, calculated values of 0.45 and 0.2 mm/yr, while this type of steel has never been known to reveal any corrosion when used in running sea water.

Laboratory investigations show that molybdenum stainless steel exhibits high resistance to corrosion in sea water flowing at a rate of 0.5 m/sec and up to boiling point, in the absence of a "hot wall".

By simulating such conditions as those indicated above for a heating pipe unit in a recirculating condenser model, it can be shown that, at 100°C, localized corrosive penetration of XI8H9T steel may reach 30-40 mm/yr, while molybdenum stainless steel remains practically corrosion-proof under the same conditions.

Pitting occurs on the inner surface of heating pipes near the aerated sea water inlet. A detailed analysis shows that when chlorine ions are present in water the oxidizing properties of the water are sufficient to cause local breaks in the inert film formed on stainless steel. The maximal pitting penetration of stainless steel in pipes made of "18-8", during a two-year period of experimental desalination, was estimated at 0.6 mm/yr. However after three months of operational observations it was shown to be 1.8-2.0 mm/yr.

The trend of these investigations is described more fully in a report presented before the First International Symposium on Desalination.

F. Stress corrosion of stainless steel

In the presence of thermal and mechanical stresses, the appearance of corrosive fissuring and splitting of austenitic stainless steel was observed in many instances during the operation of heat exchangers cooled mainly with river water. 5/

Some specialists markedly overemphasize the danger of stainless steel corrosion under the action of sea water, on the grounds of the observed catastrophic rate of steel disintegration under stress in the presence of boiling concentrated magnesium chloride solutions, 6/ and under conditions of periodic condensation and evaporation of water on metal surfaces in a steam-and-water ambient containing a small amount of chlorides. 7/

A series of laboratory tests confirmed that austenitic chromium-nickel steel shows relatively little tendency to cracking or bursting in contact with sodium chloride solutions as compared, for example, with manganese stainless steel (the latter is more resistant in magnesium chloride). 8/

Meanwhile, any evaluation of the danger of corrosive bursting of stainless steel in sea water and particularly in the heating tube assembly evaporating equipment, requires convincing corroboration based on objective standards.

Clad tube plates (made of stainless and carbon steels) may carry a considerable load in evaporators and can be protected to a great extent against the dangerous consequences of bursting.

G. Selective corrosion of copper base alloys

A characteristic instance of selective corrosion is the process of zinc disintegration in brass. To a large degree, brass dezincification ceased to be a matter of concern on seagoing vessels since the wide adoption of arsenical aluminium brass 76-22-2 as a material for condenser tubes. On the other hand, heat exchangers in coastal oil refineries operating on hard waters, during the cooling process of oil products, using an inlet temperature of 230-250°C, showed serious corrosive damage caused by the "stripping" of nickel from Monel metal and copper-nickel. 9/ Serious selective corrosion on copper alloy heat exchangers can develop as early as the first year or two of operation in stagnant waters, owing to slime sedimentation (underslime corrosion) and accumulation of carbon dust (graphite), particularly at the pipe bends, where zones of overheating also appear. Tube descaling often will offer a more radical means of protection than a change to another type of copper alloys. The corrosion rate of brass after the loss of zinc as scales reaches

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5/ H. Ternes, Werkstoffe und Korrosion, Vol. 14, No. 9 (1963), p. 729.

6/ K.C. Thomas et al., Corrosion, Vol. 20, No. 3 (1963), p. 89.

7/ J.L. English and J.C. Griess, Materials Protection, Vol. 2, No. 11 (1963) p. 18.

8/ H. Kohl, Werkstoffe und Korrosion, Vol. 14, No. 10 (1963), p. 831;
E.H. Phelps and R.B. Mears, Proceedings of the First International Congress on Metallic Corrosion (London, Butterworth, 1962), p. 319.

9/ W.S. Janssen, Materials Protection, Vol. 1, No. 10 (1962), p. 43.

0.02-0.06 mm/yr, while, after porous dezincification, it reaches 4.5 mm/yr. Increase in the copper content of the alloys (Tombac L-95 and pure copper) raises brass resistance to dezincification but lowers the resistance to flow or scouring corrosion when the sea water flow exceeds 0.9 m/sec. Reduction in nickel content of copper-nickel alloys, especially with a small admixture (1 to 2 per cent) of iron or manganese, also increases resistance to selective corrosion, while maintaining resistance to flow corrosion in water flowing at relatively high speed.

Copper-nickel alloys of the 90-10 and 95-5 types are also considered reliable materials for heat exchange piping in desalination plants because, unlike brass, they are practically never subject to ammonia attack while under mechanical stress.

For example, in order to secure maximal operational reliability for a thermal distilling plant producing 90 m^3/24 hr of fresh water, and despite the extremely high initial cost this entailed, a five-stage plant was installed on a tanker, and the material selected was made up, for 80 per cent of the total weight, of copper-nickel alloy (90-10). 10/

Aluminium brass and admiralty brass compete with the 90-10 and 95-5 alloys as materials for heat exchange piping in desalination facilities.

H. Flow corrosion: scouring

In connexion with the tendency toward acceleration of the intake stream in evaporation processes, the problem is to select a material of great resistance to impact-flow corrosion. Local turbulence of the water flowing in separate units of the installation requires substantial adjustments in the corrosion index, allowing for the mean velocity of the water flow. Abrasive admixtures, air leaks, high water salinity, all markedly aggravate flow corrosion, so that the final decision regarding the choice of suitable structural materials for reliable operational units must depend on the results of tests conducted under normal operating conditions.

Flow corrosion is not absolutely linked with the durability of the material, but dependent, in a great measure, on the protective properties of the oxide film covering the metals. Aluminium bronze, copper-nickel alloys and titanium were the first to be selected for thorough testing, and an assessment of their applicability from the costing viewpoint will soon be forthcoming. No less significant is a study of the allowable wall thinness in copper-nickel alloy and titanium pipes operating in flash-evaporation type sea-water desalination plants. 11/

This review of structural materials for several of the units found in desalination facilities, as well as of the means used for their protection from corrosion, is indicative of a common approach to the corrosion problem, which is being solved independently and concurrently in several countries.

10/ E. Ruppersberg, Nickel-Berichte, Vol. 20, No. 11 (1962), p. 335.

11/ R.A. White, Materials Protection, Vol. 4, No. 3 (1965), p. 48.

VII. DISTILLATION: PRESENT TECHNOLOGY AND RELATED PROBLEMS

by R.S. Silver

It is a privilege to take part in this seminar organized by the United Nations. Amidst all contention these discussions of the ultimate problems of human welfare shine through as examples of international co-operation. No problem is more ultimate than that of food supply - which is inseparable from the problem of water supply. The uneven distribution of rainfall over the world has in the past led to the use of desalinated water from sea water in special areas. We must prepare for a time when advancement of living standards all over the world will require an increasing dependence on the sea as a direct source of fresh water, economically produced.

The report "Water Desalination in Developing Countries" by the United Nations Department of Economic and Social Affairs 1/ has done valuable work in recording what has already been achieved and in pin-pointing the world's immediate and future needs. In my remarks I shall assume that you are all familiar with that document. I shall also try to avoid repeating material from earlier papers or anticipating in detail what may be said at the Washington Symposium in two weeks' time. However, it does seem worthwhile to give a review, as suggested by your organizers. They have asked me to limit myself to the distillation process and to comment on its various forms and of course to give particular emphasis to the economic circumstances.

Before proceeding to do this, I think it is wise to set the scene, by briefly stating what I take to be the general scientific background of desalination.

A. The general scientific background of desalination

Sea water contains 35,000 parts per million of dissolved salts by weight. Human beings cannot tolerate a consumption of more than 500 ppm and remain in good health, and neither can food crops nor food animals be reared on water of much greater salinity. Hence nearly all of our present-day life depends, and in our history and pre-history as a developed species must have entirely depended, on naturally occurring water supplies of less than 500 ppm. Such supplies have been possible only because of the low level of solubility of most minerals in water, so that in the giant distillation cycle operated by the sun, the pick-up of minerals is such as to give only 35,000 ppm in the sea and usually much less than 500 ppm in the reflux streams which we call rivers and the hold-up areas which we call lakes.

The heat of solution of the salts in sea water is about 0.67 kcal/kg of water, i.e., this is the free energy change when .035 kg of salt are dissolved in 1 kg of water. Hence, for basic thermodynamic reasons, we know that no process could possibly obtain fresh water from the sea with an energy consumption of less

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1/ United Nations, Water Desalination in Developing Countries (United Nations publication, Sales No.: 64.II.B.5).

than 0.67 kcal/kg. This represents an absolute minimum energy consumption. In the United Kingdom at the present day thermal energy from fuel costs about 2.2 x 10^{-4} pence per kcal.

The current price of fresh water supplies varies very much throughout the world, but in the United Kingdom is probably an average of about 5 x 10^{-3} pence per kg. For new developments in the United Kingdom, domestic fresh water supply today is expected to cost about 10^{-2} pence per kg. In some parts of the world it is already costing 3 or 4 x 10^{-2} pence per kg. But agricultural or irrigation water at present has to be not more than about 4 x 10^{-3} pence per kg to be economic.

At current fuel prices, the basic thermodynamic energy of 0.67 kcal/kg would cost only 1.5 x 10^{-4} pence/kg. If we had a process which could do this, without any other cost, it would obviously add negligibly to our existing water costs and we should certainly have been desalinating the sea extensively, long before now. But of course, we have no such process.

The most elementary and obvious process would be to boil the water and condense the vapour, i.e., distillation. If this is done we require to use at least 540 kcal/kg which would therefore give us water costing 1.2 x 10^{-1} pence/kg in energy alone, before even considering the repayment of interest on the capital cost of the plant. The distillation process can be developed into sophisticated forms so that we use the heat given out by condensation to do effectively some of our other evaporation. By such means we have in recent years managed to reduce the energy consumption of distillation to about one twelfth of the latent heat, i.e. to reach a figure of 45 kcal/kg. The prime energy cost of this water is, therefore, about 10^{-2} pence/kg. But by using as input thermal energy to the distillation plant thermal energy rejected from a plant producing useful power for sale, we can get it much more cheaply. With present temperatures of major steam turbines, about 830°K at the boiler and 310°K at the condenser, the Carnot rejection ratio is about 0.36. With supply to the distillation plant at 400°K, the Carnot rejection ratio is about 0.48.

By the laws of thermodynamics, we must reject at least 0.36 kcal of each input kcal and hence, when we choose to raise our rejection temperature to 400°K to permit distillation and reject 0.48 kcal per input kcal, we have gained 0.48 kcal of usable thermal input at the cost of a loss of only 0.12 kcal of useful generated power. Now on the new base of 400°K we obtain 0.52 kcal of power for each kcal of heat input. Hence, to replace the lost 0.12 kcal of power we require an extra 0.23 kcal of thermal input. Thus, the gain of 0.48 kcal of usable thermal input for distillation requires only an input of 0.23 kcal, i.e., the effective energy cost of the thermal input is only 23/48 = 0.47 of the primary energy cost.

Hence, by combining power and water supply by distillation we can now get energy costs for distilled water as low as 4.7 x 10^{-3} pence/kg.

The capital cost of the equipment which we need to do this is at present about 18 pence per kg/day capacity. Now to pay interest and repayment of that capital over a reasonable period of about 10 to 20 years life of the equipment, we have to charge about one-tenth of the capital cost per year as part of the water cost, i.e. the capital charge rate is $\frac{1}{3650}$ per day. Thus the capital costs are $\frac{18}{3650}$ pence/kg = 5 x 10^{-3} pence/kg. Thus the total cost of the water is 9.7 x 10^{-3} pence/kg, say 10^{-2} pence/kg.

Thus we see that this process has already a substantial claim to consideration for domestic water supply in many parts of the world. But we also see that we have to reduce costs still further if we are going to satisfy the needs of irrigation. Moreover, since there may not always be appropriately matched demands for power and water, we should like to have a process where the reduction of energy cost was not so dependent on the joint production of power as it is in the above calculation. Finally, since at 45 kcal/kg we are still far above the ultimate theoretical limit, there is a natural expectancy that we can yet develop new processes consuming much less energy. However, it is important to note that not only must they consume less energy, but they must do so at less capital cost. It would be perfectly easy to make the distillation process still more regenerative so as to make the energy consumption less, but at an increasing capital cost. In effect, if E is the energy consumption per kg, we have the situation that the capital cost is almost inversely proportional to E and the energy cost is proportional to E. Hence the product water cost is of the form

$$K = aE + \frac{b}{E} + C \;\ldots\ldots\ldots\ldots\; (1)$$

Clearly this has a minimum value when $E_o = \sqrt{\frac{b}{a}}$, and $K_{min} = 2\sqrt{ab} + C$

Hence a plant should not be designed for the lowest E which is technically possible, but for the optimum $E = E_o$ which will give the lowest costs.

The object of research and development is therefore really that of finding ways to reduce the value of the co-efficients a and b and c. The former a can only be reduced by engineering the fuel supply system as in the combination with power or in schemes using waste heat. The others, b and c, are dependent on the designer's ingenuity, and on his knowledge of all the phenomena which take place in the plant, so that he may build in a manner which will permit all the necessary phenomena to occur to the correct extent and yet be as cheap as possible. It is here, therefore, that research and development is vital.

It is this situation which has led us to begin to consider processes other than distillation. When sea water is frozen, the salt separates from the ice crystals. If the salt can be washed from the interstices of the ice crystals before the latter are remelted, we have a method of obtaining fresh water. The latent heat involved here is down to about 80 kcal/kg instead of 540, and if it also can be made a regenerative process, we have a reasonable chance of getting down to energy consumptions of the order of 10 kcal/kg.

At present all forms of freezing process which seem to be able to accomplish this order of result require such high capital costs that the total water cost is greater than is now possible with distillation. But the situation may be transformed in the future. Distillation is advanced and well developed. Freezing is in its infancy as a desalination process.

Even newer is reverse osmosis which is also at present uneconomical and only in the laboratory stage. But again, it could be transformed by research and development.

Electrodialysis is already more economic than distillation for brackish water up to about 8,000 ppm. For waters of greater salinity, and certainly therefore for sea water, it does not appear that electrodialysis can reach the economy obtainable by distillation.

It must be recalled that any process, such as electrodialysis, or reverse osmosis, which necessarily takes its input energy in the form of power as distinct from heat, suffers from a penalty in energy compared with distillation - because of the limitations to energy conversion determined thermodynamically. Thus, for example, in the case of freezing, where we have already noted that we might reach an input energy consumption of 10 kcal/kg, the thermal input to a power-generating device to produce 10 kcal of power must be of the order 20 to 30 kcal. Hence the actual prime energy costs may not be so much less than for distillation. It may be that development of an absorption freezing process can assist in this respect.

Having surveyed the general background possibilities, I shall now review the current practical status, concentrating mainly on the distillation process.

B. The effects of capacity

When sea water distillation first began, in marine practice, the unit capacity was of the order 200 gallons per day. The largest existing unit capacity of pool-boiling multiple-effect type plant and of vapour-compression type plant is 1 million gallons per day, while that of multi-stage flash distillation is about 1.7 million gallons per day. When such figures are viewed against consumptions of water in major cities of many hundred million gallons per day they appear small, and this fact, combined with the well-known experience in engineering generally that unit cost of product can be expected to reduce with increasing size of plant, has led to many expressions of interest in still larger unit capacities as a major line of advance.

Now there is no doubt that increase in mere size is a necessary and important part of further desalination advance. But to concentrate too much on such increase is undesirable, for several reasons. First of all the contribution to main public water distribution systems is only one aspect, however important, of desalination progress.

Another probable line of development is use by small communities, such as small isolated villages, or even family units, and temporary installations for construction and exploration teams and the like. It may well be that in some territories in the future high standards of living will be maintained in small communities and not necessarily in the vast conurbations which have tended to characterize past and present concepts of civilization. Such dispersed civilization may well find water economy best achieved by small-scale local desalination. The importance of such possibilities is that they may well determine the type of desalination process that is viable. Thus, for example, Professor Howe of California has rightly emphasized that solar distillation will probably have its main field in the provision of small capacity units for selective communities.

Already family units working by electrodialysis or by reverse osmosis have been suggested. It is quite obvious that any process which uses power energy input instead of heat energy input has advantages for family unit design, - so much so, that even distillation plants for laboratory use are usually electrically heated. Vapour-compression family units are also obviously possible. The economics of such cases of individual supply as against town distribution, or small community supply as against regional distribution, must obviously be rather complex and site-dependent, and no generalizations are possible. But at least this first criticism of too great concentration on ultra-large unit desalination capacities should be borne in mind.

Secondly, even when we are considering contribution to main public distribution systems, it should be remembered that multi-unit installations are not only possible, but also traditional. Most desalination plants throughout the world consist of many units to make up the total capacity. Such installations have grown by addition of units, sometimes adding two or three at a time, and usually adding larger sizes as they become available. Thus, in practice, most desalination installations involve practice and experience in operating as a group many different sizes of units and in some cases different types, such as multiple-effect pool-boiling units working together with newer multi-flash units. I respectfully suggest that such variety of operational and design experience of actual commercial installations is the best "demonstration", if any were needed, of the utility and practicability of multi-unit installations. The lesson to be learned from this is that to make an installation now of 100 million gallons per day capacity, it is not necessary to wait until a single unit is designed for this amount. It is perfectly practical to install and operate a bank of $\frac{100}{n}$ units each of n mgpd capacity, where n mgpd is the largest safe unit design figure possible from existing technology. At present n is possibly in the range 6 to 12.

Thirdly, it is doubtful whether the rate of unit product cost reduction with increasing plant size is as rapid as has been assumed. In a paper to the Institution of Mechanical Engineers last year, I gave details which showed that the technological effects of increasing unit size on costs were quite rapidly asymptotic, so that as between a unit of 1.2 mgpd and an infinite unit capacity the product water cost reduction was only of the order of 12 per cent, of which the first 8 per cent was used up in going to 12 mgpd. Thus, for technological cost factors, it is not very promising to seek beyond 12 mgpd unit size. When we come to commercial cost considerations, there would obviously be an advantage in bulk ordering of materials for a large installation even if based on multi-units, and indeed the incentive offered by producing several units to one design could make a substantial effect on cost.

C. The effects of power development

To the classic enunciation of man's basic requirements as food, shelter and clothing, we now have to add the requirement of power. Nothing is as characteristic of modern life as the rate of increase of power capacity in all countries. This is so rapid that in some typical developed territories, the relative consumption of water and electricity, which was about 100 gal/kWh 40 years ago, has fallen to about 10 gal/kWh today. This trend leads us to the question of whether as civilization develops this ratio can continue to decrease. Can we have, for example, a civilization which consumes only 0.01 gallon of water for every kilowatt hour of power which it uses? Or is there some higher limit to which we are rapidly approaching? In the paper already referred to, I gave some reasons for suggesting that in modern civilization we cannot go below about 2 gallons of water consumption with every kilowatt hour, excluding agricultural water. This would be down to one-fifth of the present value of this sociological statistic in the United Kingdom and in the United States. Perhaps a more realistic limit would be 5 gal/kWh. If this argument is valid, then any developing country which has an industrial programme leading to say, 1,000 MW of power, should also plan to be able to satisfy a non-agricultural water demand of at least 48 mgpd and perhaps up to 120 mgpd. In particular areas it might be quite possible to see such satisfaction coming entirely from conventional catchment or well development, but in some cases it will be necessary to consider the contribution of desalination. Hence it is particularly valuable to consider the interrelations between different methods of desalination and power production.

It is at once obvious that we must distinguish in principle between power consuming processes, such as reverse osmosis, freezing, electrodialysis and vapour compression, on the one hand, and thermal-energy consuming processes like multiple-effect or multi-stage flash distillation on the other. The former make inroads on the available power, the latter have only power requirements for auxiliaries. On the other hand, some electric power supply is bedevilled by the load factor problem, and the power consuming processes may help by consuming power when other loads are below the peak demand. This load factor problem is discussed in some detail in the paper referred to.

So far as thermal distillation is concerned the position may be generally assessed using the background information given in the first part of this paper. It was seen there that the Carnot rejection ratio for distillation plant supply temperatures is about 0.48 as compared with 0.36 for normal condenser rejection temperatures. The following table shows the consequent differences in the production of 1 MW of power.

Table 1

Carnot rejection ratio	Power production	Thermal input (MWth)	Thermal rejection rate (MWth)
0.36	1 MW	1.56	0.56
0.48	1 MW	1.92	0.92

Thus 0.92 MWth can be obtained as input energy to a distillation plant per MW of power production. This is approximately equivalent to the latent heat of evaporation of water at a rate of 7,500 gpd. Hence using a distillation plant with a performance ratio of say, 8, the production of 1 MW can be associated directly with the supply of 60,000 gpd - i.e. 60 mgpd for 1,000 MW. Thus, by an apparently fortunate coincidence, the possible water supply available from rejected heat from power supply comes right into the range of probable water requirements. (This may not ultimately be a coincidence. It can be speculated that, since all our power use is ultimately dissipated, and since all our environment maintenance ultimately involves transpiration, the two are related and this speculation gives somewhat greater confidence in the significance of the water/power statistics, at least as an order of magnitude.) Now since any real cycle must have a higher rejection ratio than Carnot, we shall in fact always have a greater water availability.

Thus, while individual sites and individual steam cycle design will cause some variation, it does appear from these arguments that the combination of power supply with complete backpressure operation and a distillation plant with a performance ratio of 8 or greater will be particularly apt to meet the general joint power and water needs of a developing territory. For smaller powers the figures can be taken pro rata.

In cases where only a portion of the water requirements is to be met by desalination - as for example in most developed countries - it will usually be preferable to work with only a fraction of extracted steam instead of 100 per cent backpressure. This will tend to be cheaper than working with a lower performance ratio, but the situation can be optimized. Where the water requirements in relation to power are particularly large, as for example in a "water only-" installation (which is a misnomer since some power is always required), it may be worth while raising the cycle rejection temperature, to give a poorer cycle efficiency and greater thermal rejection. But this depends on the ability of the distillation plant to accept higher temperatures. Again for such higher water demands, a higher performance-ratio distillation plant may be worthwhile. Optimization studies for the actual requirements are essential.

No process other than distillation has this same quality of inherent relevance to fundamental water and power needs. Other processes may well become competitive with distillation quite quickly for small capacity or special purpose use, but this "built-in" situation means they have formidable economic obstacles to overcome before they can challenge distillation for major general use.

Finally, under the heading of this section we must include the impetus given by the development of nuclear energy. It is evident that one of the main effects of this is to emphasize the large installation. Nuclear reactors are very largely capital, and are peculiarly prone to the reduction of product cost with increasing size. Hence the use of nuclear energy for desalination tends to be directed mainly towards the large public distribution aspect of water supply and so, for the reasons already discussed, has been particularly linked with distillation. This has tended to be discussed in terms of large units, but we have seen in the section entitled "The effects of capacity" that this need not follow.

At one time it was considered that nuclear energy might be particularly appropriate to "water only" installations, since the heat could in principle be produced at a low temperature. Subsequent developments in nuclear technology, particularly the United Kingdom advanced gas-cooled reactor, have now shown the ability of nuclear engineering to produce steam conditions as good as those produced with fossil fuels and giving more economic power production. This circumstance will almost certainly lead to emphasis on combined power/desalination schemes with nuclear energy.

D. Research and development in distillation

The conclusions of the preceding section lead obviously to my final point, that is, the query - What can be done to improve the economics of the distillation process still further? Now it is clear that I can only review this very briefly, since much will be said on this in detail at Washington next month.

The fact that emphasis on distillation research and development is worthwhile is well illustrated in the United States Department of the Interior Report to the President in September 1964. Previously the proportion of work under this head was 25 percent of a budget of 12 million dollars. The new proposals increase it to 41 percent of 37 million dollars. In the United Kingdom, the Committee on Desalination Research and Development, which advises the Ministry of Technology, has likewise placed special emphasis on distillation work, which it envisages as being predominant for at least the next ten years. Since quite a number of United Kingdom designs of distillation plant are in satisfactory commercial operation, what are the objectives of further work?

The research and development problems fall into the three classic divisions of chemistry, physics and engineering, and are all directly related to the basic cost considerations of supplying a smaller quantity of material, and/or cheaper material, and/or arranging it in a preferential way. Some are basic, and likely to respond to fundamental research. Some are secondary, and likely to respond to particular experience, know-how, or inventive ingenuity. Obviously, those companies already in the field with accumulated know-how and facilities for research have many advantages.

The chemical problems relate chiefly to the field of scale deposit formation, adhesion and prevention and to that of corrosion, with its correlate of finding substitute materials. A wealth of material has already been published on these fields and there will certainly be much more reported at Washington. The general situation in scale studies is that carbonate scale prevention is now fully effective and work is centred on calcium sulphate scale, which is the main problem preventing advance to higher distillation temperatures. Studies of calcium sulphate equilibrium in sea water are in hand, and also of the kinetics of its deposition from saturated solution. Another chemical approach is to the pre-treatment of the feed sea water, to see whether an economic method of ion exchange can be found as a preliminary to distillation. (Such an exchange would not in itself demineralize the feed, but would render it less scale forming.) Still other predominantly chemical studies are related to the behaviour of materials such as concrete, timber, plastics, etc., which might form cheaper substitutes for the metals predominately used at present for distillation plant structures. We can expect much new information on such work at the Washington Symposium.

The physics problems of greatest relevance are those of adiabatic two-phase flow. How do bubbles nucleate in flashing brine and how rapidly do they grow? What forces are exerted on them by flowing brine, and what forces do they in turn exert? How do droplets form and behave? What is the size distribution of droplets which may be projected above a flashing river of brine? Can they be controlled? How can they be collected and prevented from being carried out in the vapour? How rapidly does a droplet evaporate or a bubble grow? How does condensation heat transfer occur? How is it affected by surface conditions, materials or the presence of non-condensable gases? In general, a better understanding of all the basic hydrodynamics and thermodynamics of two-phase flow would be of value in improving the certainty of distillation plant design, whether boiling type or flashing type.

Such problems are of course closely intertwined with the engineering problems. At present we design the spaces, the apertures, and the dimensions of our heat transfer surfaces, flash chambers and flow passages on incomplete knowledge of the fundamental physics. We succeed fairly well, but undoubtedly we require more exact knowledge to obtain proper optimization and minimum cost. Moreover, such greater knowledge is an essential prerequisite to designing with confidence for new types or new sizes of distillation plant.

This range of physics and engineering research has, despite its importance, received surprisingly little attention in the published literature - at least in that relating specifically to desalination. There are far more papers on chemistry in desalination, perhaps because the problem of scale formation really impinges on the heat transfer situation. So long as even carbonate scale formation was not under control, scale problems dominated. Now that for certain temperature ranges scale can be controlled, other aspects of heat transfer are really worth attention. Again, so long as distillation plant was of relatively low thermodynamic efficiency, precise temperature and pressure differences were unimportant. Now they are vital. It happens however that in Heriot-Watt College, Edinburgh, we have a special interest in the hydrodynamics and thermodynamics of condensation and evaporation processes and it is to these aspects of desalination work that our particular research programme is directed. We have been studying particularly pressure drop in condensation and equilibration phenomena in flashing flow. An account of this work and its results to date will be given at Washington. The resources of the United Kingdom Atomic Energy Authority are now being marshalled to extend the attack on this work. Simultaneously, engineering design studies are in progress to take advantage of such forthcoming research-based information. I am quite sure that complementary work is being done elsewhere and we may hope that it will also be published soon.

However, before concluding, it is perhaps desirable to sound one slight note of warning. Certainly further studies of the type described will enable us to design more surely and precisely, and will enable us more correctly to optimize the cost. But the foremost manufacturers already have a great deal of experience and know-how - and one characteristic first result of fundamental research when applied to a well-established technology is that it merely tells you why you have to do the things you alreasy know you have to do. Only then does it guide you how to do better. Hence, no one should expect, as a result of the very active research on distillation now in progress, sudden or dramatic reductions in water cost, and no one requiring water supply by desalination should withhold an order for fear of a sudden obsolescence of his plant. The future certainty of desalination as a standard means of water supply stares us in the face - as an essential in a world of increasing population - almost whatever its cost. It is our task as scientists, engineers, planners and economists to see that the cost is brought as low as possible, by improved scientific understanding, good engineering practice, and sound industrial and commercial planning and budgeting.

I have limited myself mainly to distillation, not only to carry out my task as defined by your organizers, but because it is still our main hope at present for large capacity water supply. But I believe that the exigencies of the future will demand not only that we develop distillation to its best utility, but also that there will be real scope for other processes to meet particular needs.

This may seem rather a pedestrian termination to such a lecture. It may seem neither very visionary nor very inspiring. Yet it is my belief that here, in the future satisfaction of a basic necessity of human existence, there is a challenge to and a growing point for applied science and engineering.

The challenge is rather more stark than the pretty fancy of making the deserts blossom with flowers. It is the challenge of preventing the sufferings of thirst and starvation in a growing world, in short of preventing the failure of human life. Let us hope that it does not fail from any other reason either.

VIII. ELECTRODIALYSIS: PRESENT TECHNOLOGY AND RELATED PROBLEMS

by R. Matz

Electrodialysis, though known since the nineteen-thirties as a laboratory tool, obtained its impetus as a potentially useful desalination process with the publication in 1936, by Meyer and Sievers, of the paper in which the multi-compartment system is proposed, with the use of permselective membranes. Practical development began in 1947 when the TNO of Holland began active research and development on this process. At about the same time, Ionics Inc. in the United States began development work which led to the first commercial electrodialysis units in the early nineteeen-fifties. Since then, developments have been rapid, with increasing numbers of manufactures interesting themselves in the process in many parts of the world.

There are at present in operation about 200 electrodialysis units, desalinating brackish waters in widely distributed parts of the world. The large majority have outputs of below $100m^3$/day; several have outputs of up to $1,000^3$/day, while at least one larger plant is in operation, and more are now being projected.

Table 1 gives a partial list of some of the past and present operating plants, with their capacities, desalination ranges and approximate investment costs.

The electrodialysis process utilizes direct electric current to separate soluble salt ions from the saline solution. The principle of operation has been sufficiently described and will not be given in this paper.

The energy requirement is a function of the amount of salts removed, and hence precludes at present the application of the process to concentrated saline water sources, such as sea water, though experimental work now in progress at the Negev Institute for Arid Zone Research in Israel may lead to the possibility of an electrodialysis process for sea water, which may be competitive with other present methods.

A consideration of the range of applicability of electrodialysis for any country or region is intimately related to the seriousness of the water problem, and the availability of alternative sources and methods of supplementing water reserves in that region. In general, it can be stated that, with normal population, agricultural and industrial growth, the cost of providing additional quantities of water for any use in the above three categories will follow the well-known demand-cost relationship, in which each incremental amount will cost relatively more than the previous increment. This is quite logical, and is a function of the distribution of the water reserves, and the increasing needs of conveyance from source to consumer, with increasing development. This means, in effect, that for all natural water sources, there will be a gradual increase with time of water supply costs, and the rate of rise will increase as the limit of availability of natural supplies is approached.

Subsequently, there must be recourse to means of water conservation, such as the impounding of runoff water; waste and sewage water reuse; evaporation control;

Table 1

Technical and economic characteristics of electrodialysis plants

Location	Manufacturer	Capacity m^3/day	Investment $ cost	$/$m^3$ day	Desalination range ppm. T.D.S.	Remarks
1. Welkom, South Africa	S.A.C.S.I.R.	10,900	800,000	73.5	400/3,000 to 1,000/500	Shut down since 1961
2. Buckeye, Arizona United States	Ionics Inc.	2,500	305,000	122.0	2,100 to 500	Operating at 50 per cent capacity
3. Webster, S.D. United States	Asahir/Austin	950	560,000	590.0	1,800 to 400	High sulphate water
4. Tzeelim, Israel	Negev Institute	500	150,000	300.0	2,500 to 500	Experimental plant Start-up July 1965
5. Dharan, Saudi Arabia	Ionics Inc.	436	200,000	460.0	3,000 to 400	
6. Rotterdam, Holland	Bronswerk	5,700	250,000	44.0	1,200 to 800	Out of commission
7. Awali, Bahrain	Ionics Inc.	325	426,000	1,310.0	3,400 to 500	
8. Coalinga, California United States	Ionics Inc.	106	80,000	755.0	2,200 to 300	

Note: There are many electrodialysis units of capacities between 20-300 m^3/day operating at military bases (mostly United States and British) and oil wells. The majority have been constructed by Ionics Inc. and a much smaller number of Wm. Boby Ltd.

more economic water use in agriculture; and ultimately the application of desalination techniques. Even before these various methods are fully developed, the water cost may exceed the level of economic viability for certain uses, particularly in agriculture, and thus, the additional costs must be borne by Government or State subsidies.

On the other hand, during the past several years, the technological development of various means of desalination has been reflected by a consistent decrease in product costs for all methods, though in recent years, with no serious breakthrough in desalination technology, a relatively steady cost level has been reached.

The relationship between the cost of natural and converted water supplies with time, may be illustrated graphically as shown in figure I.

The general realtionship illustrated may be applied to water supplies on a national or a regional basis, and to specific desalination methods, with the appropriate displacement of each of the curves.

It may be anticipated, therefore, that in time, with increasing complexity in the development of natural water supplies, some form of desalination can become competitive, and ultimately more economic.

Sea water desalination is necessarily confined to coastal areas, and, logically, should be utilized near the centre of production if the already high costs are not to be inflated further by additional transportation charges. On the other hand, suitable sources of brackish water which can be desalinated by electrodialysis may exist both in coastal and inland regions, and these can provide a local source of supply, or provide a centre for the development of an agricultural or industrial community.

The economic basis for an assessment of the relative merits of different water supply methods for inland areas, assuming the presence of adequate brackish water reserves, will be the respective costs of desalination on the spot, and water conveyance to the area from some more distant source. The cost of desalination will be relatively constant while that for pipeline supply will increase with distance. Referring to figure I, brackish water desalination, regionally, will be viable in the areas beyond the meeting point of the two curves.

A. Applications of electrodialysis

Electrodialysis is potentially capable, with the present state of its development, of fulfilling the following functions.

(1) Desalination of brackish underground water in order to provide the main or a supplementary source of regional water supply.

(2) Salinity reduction of marginal waters, where the comparatively low, but excessive salinity, may be injurious to certain agricultural products, and can be reduced by a relatively uncomplicated application of the process.

(3) Salt rejection from coastal aquifers of high or relatively high salinities, by disposal to the sea of concentrated brines from electrodialysis plants and returning the partically desalinated water to the system.

(4) Salinity control of reclaimed sewage water which, after biological treatment, increases in salt concentration.

The feasibility of each of the above applications will naturally depend upon the relative economics of the process, and of alternative methods of fulfilling the water requirement. Each evaluation will be valid only on a restricted regional basis.

The technical and economic feasibility of the above applications will be discussed in greater detail below.

B . The present technological development of electrodialysis

During the past two decades, electrodialysis has become a commercial process, and several industrial concerns are today manufacturing plants of greater or lesser capacity for various applications. The process has been developed to include industrial chemical purification methods, such as metal and salts recovery, and, in Japan, has been used to make concentrated salt brines in the industrial preparation of common salt from the sea water.

In the provision of desalinated water, brackish waters of relatively low salinity have been used as feed, though a limited number of installations, of very small capacity, have been designed to desalinate sea water as well.

The majority of plant units in use today have a capacity of under 100m^3/day, and only a small number have capacities approaching 1,000m^3/day and more, though this number is increasing, and several large plants are in the design and construction stage, and will operate in the near future.

In the majority of cases, the water produced has been for drinking purposes, and a very large number of the small plants sold have been placed in military bases, petroleum drilling and producing installations, and refineries, in arid areas, chiefly in North Africa and the Middle East. Several installations are now in operation, providing water for municipal use in the United States. The first municipal plant was operated in Coalinga, California in 1959, and since then, Buckeye in Arizona, and Webster in South Dakota have installed electrodialysis units.

The largest capacity unit operated to date was commissioned at Welkom in South Africa in 1958, and operated for about 1-2 years on brackish mine water. The designed output of this plant was about 10,000m^3/day, but it was never operated beyond 75 per cent of its design capacity.

At least one large plant was installed to provide water for industrial purposes (by Bronswerk in Holland), though this was never successfully operated for reasons which will be discussed below. More recently, it has been reported that plants for industrial water are being constructed for use in several European countries.

C. Limiting factors in electrodialysis plant design

1. Unit plant size

The basis components of any electrodialysis plant may be grouped into the following:

(a) Electrodialysis stacks and associated equipment. This consists of the stack components such as membranes, electrodes, frames and separators; closing frame and sealing mechanism; and inlet and outlet manifolds. These components comprise the actual part of the plant which effects the desalination.

(b) Hydraulic equipment and auxiliaries. Pipes; pumps; valves; filters; raw water supply; concentrate disposal; hydraulic and control instrumentation; buildings; and site preparation.

(c) Power supply. Transformers and rectifiers; and associated electrical instrumentation.

Of the above, the relative investment associated with the electrodialysis section may be about 20 to 30 per cent of the total.

It is to be expected that one of the factors influencing product cost of electrodialysis will be plant output.

In many chemical and other industrial processes, the effect of size scale-up can be expressed in the following form.

$$\text{Investment B} = \text{Investment A} \times \left[\frac{\text{Product capacity B}}{\text{Product capacity A}}\right]^{n}$$

where n = 0.6 - 0.7 for scale-up of increasing unit size.

= 0.8 - 1.0 for scale-up of increasing multiple units of the same size.

= 0.3 - 0.5 for pilot plants.

This relationship can be found to be more or less valid for electrodialysis plants as well.

An analysis has been made of the cost/capacity relationship of some existing and projected plants and the results are shown in figure II.

In order to make the comparison valid, the plant outputs were expressed in terms of salt extracted instead of water produced, since these plants operate at varying desalination rates. Table 2 gives the data from which the comparison was made.

Though the data presented is meagre, very definite trends can be noted in the two curves presented. The curve for plants in which the unit membrane area is about $0.5m^2$, shows that increased capacity has a marked effect on relative cost.

Table 2

Electrodialysis plant cost-output relationship

Plant	Total investment cost	Capacity m^3/day	Salt transfer kgm/day	Unit membrane Total area m^2
Welkom, S.A.	800,000	10,900	27,300	1.46
Buckeye, Ariz.	305,000	2,500	4,000	0.465
Webster, S.D.	560,000	950	1,430	1.25
Rotterdam, Holland	250,000	5,700	2,280	0.400
Coalinga, Calif.	80,000	106	201	0.233
Tzeelim, Israel	150,000	500	1,000	0.600
Proposal A*	800,000	4,800	9,600	0.900
Proposal B*	300,000	3,000	10,000	0.75
Proposal C*	170,000	1,500	5,100	1.25

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* These values have been obtained from manufacturers' quotations and detailed engineering estimates.

On the other hand, for plants where the unit size lies between 1.0 - 1.5m^2, a relatively small advantage can be gained by scale-up. The value of "n" in the equation given above has been calculated for the two curves. For the smaller unit membrane areas, n = 0.45, while for the larger unit membrane areas n = 0.92. These results are quite consistent with the values given above for industrial plants.

The results are significant in that they appear to indicate that the standard electrodialysis unit is limited in size, and that plant costs are influenced by auxiliary equipment. The Webster plant falls outside the general trend because of the unique quality of the raw feed water necessitating exceedingly low current densities and hence, relatively larger investment costs.

The trend illustrated in figure II shows that beyond a particular output, scale-up of plant must be effected by means of the use of multiple units of limited size. This is a limitation which is based on several practical considerations. The multiple-compartment electrodialysis stack (see figure III) consists of a large number of parallel flow compartments defined by gasket frames, membranes, and separators placed between a set of electrodes. In an operating plant, several such units are arranged in parallel-series connexion, as shown in figure IV.

The throughput of any single stack is a function of the necessary linear flow rate, the compartment geometry, and the number.

Of these parameters, the compartment thickness and number are fixed by the resistances of the system and the maximum permissible DC voltage which can safely be applied. Linear flow rates are governed by consideration of maximum permissible current densities and pressure drops, so that the remaining parameter of compartment width is the only one which can be independently varied to increase or decrease the throughput.

The length of the compartment is the other geometrical variable which can define the stack size. With the limitations for thickness, number of compartments, etc., given above, increase in length will result in increasing desalination.

Scale-up of an electrodialysis stack is therefore a matter of increasing the active surface area of the membranes composing the stack. One of the very practical limitations to large scale-up in this direction is the fact that membrane stacks need, at periodic intervals, to be dismantled, in order to remove solid deposits formed during operation. While each stack can immediately be replaced by a stand-by unit, so that the interruption of the plant need not be very long, it is nevertheless necessary that the stacks removed should be relatively small in order to be conveniently handled. The subsequent dismantling, cleaning, and reassembly will take labour time, and the larger the size of the membranes and other stack components the more time-consuming and difficult this is, while, in addition, the membranes which are generally mechanically weak tend to tear and break more readily in the larger sizes during handling. The tendency today is to limit the unit surface area to a maximum of about 1 - 1.5m^2, and to design the stacks to comprise a number of relatively small sub-units to facilitate handling.

Table 3 gives the characteristics of a unit membrane stack of optimum size in accordance with the limitations described above.

Table 3

Characteristics of unit electrodialysis stack

Over-all voltage drop	500 Volts
Voltage drop/compartment pair	2-3 Volts
Number of compartment pairs	150-250
Active membranes surface	1 m^2
Membrane surface utilization	70 per cent to 80 per cent
Compartment thickness	0.75-1.3 mm
Linear flow velocity in compartment	10 cm/sec
Total volumetric throughout	60-100 m^3 hour
Maximum desalination capacity	800-1,200 ppm/pass.

2. Polarization

Operation of an electrodialysis system is affected by a number of phenomena which are as yet imperfectly understood, and are generally included in the collective term "polarization". Such polarization effects are generally attributable to the properties of the membranes and the composition of the feed water, and result in limitations in operating conditions which will vary with varying waters and different types of membranes. In recent years, many technical papers have appeared describing polarization phenomena and these effects are still being intensively studied.

Polarization, without defining its mechanism, is expressed by a gradual increase in over-all membrane stack resistance, resulting in decreased desalination, increasing power consumption, the formation of scale and consequent mechanical blocking of the system.

It can be controlled to some extent by the use of lower current densities and increased turbulence of flow in the compartments, though the effects are governed by the physical characteristics of the membranes as well.

The presence in natural brackish waters of such contaminants as organic materials, iron and manganese, and sulphate leads to difficulties in operation, and the need for the installation of pre-treatment plants in order to reduce or eliminate them.

In many of the major electrodialysis plants operated to date, some specific quality of the water has led to difficulties in operation.

(a) The Welkom plant in South Africa. This plant was operated on underground brackish mine water containing 3,000-4,000 ppm T.D.S. The concentration of scale-forming components was relatively low. A gradual increase in stack resistance occurred over a period of weeks to months, with the final resistances reaching a value of three times the starting resistance. The cause was finally found to be due, in addition to scale formation, to the accumulation in the cationic membranes of a double salt of strontium and barium. These ions were present in the feed water only as traces. The effect was originally picked up during pilot plant operation, and means to overcome the effect were introduced in the large operating plant. This consisted in the periodic cessation of operation and flushing the plant for several hours with the polarity reversed, to restore the original conditions.

(b) The Bronswerk plant at Rotterdam. This plant was to have operated on treated Rhine river water having an approximate mineral content of 1,200 ppm T.D.S., reducing this to about 800 ppm T.D.S., as a feed to a subsequent ion exchange demineralizer. The feed water was obtained directly from the Rotterdam municipal supply. In operation, the stack resistance increased rapidly, resulting in current drop and decreased desalination. The current dropped to about 10 per cent of the starting value. The membranes originally used were the AMF type. When these were replaced by membranes manufactured by the ASAHI Glass Co., the resistance increase was less severe but nevertheless resulted in a current drop to about 50 per cent of the operating value. Subsequent investigation showed that this effect was due to the presence of organic contaminants in the feed water, originating from industrial wastes pumped into the river. The presence of as little as 2.5 ppm of organic materials can produce this effect. An experimental plant subsequently operated on the same water, but the feed water was initially passed through an ion-exchange scavenging column to remove organic materials, which reduced this effect to a very large extent.

(c) Webster, South Dakota. The presence of iron and manganese in the brackish water required the installation of a chemical pre-treatment plant to remove these components from the Webster plant feed water. The brackish water is essentially sulphatic in type, and this has necessitated the use of exceedingly small current densities in order to operate under condition of minimum polarization. Nevertheless, scale formation continues to occur, and necessitates the use of various means to reduce its effects. These include periodic flushing, with and without acid, and reversed polarity, the application of pulsating current and stack dismantling for cleaning.

3. Scale formation

All natural waters contain components (calcium, magnesium, bicarbonate and sulphate) to a greater or lesser extent, which, under appropriate conditions, will produce insoluble precipitates. Such conditions exist in the concentrate compartments of membrane stacks, and operation of the plant is usually accompanied by the formation of such scales, which precipitate on the membrane surface, and may ultimately block the free flow of water in the compartments.

Several means for reducing scaling have been developed, but none is entirely successful, and it is necessary to employ a combination of techniques to obtain the best results appropriate to the particular plant. The following methods have been used for scale control:

(a) Pre-treatment by cation-exchange. This requires all the feed water to be passed through a cation-exchange bed, in order to remove calcium and magnesium. This may be effected partially by a preliminary lime or lime-soda treatment followed by filtration. Such a pre-treatment was in fact used in the operation of the pilot plant at Welkom which preceded the large operating unit. However, the hardness of the raw water was comparatively low initially. With waters of high hardness, such chemical pre-treatment adds considerably to operating costs and would be unjustifiable economically except for specific applications.

(b) Acid treatment of concentrate. This is the general method used in practically all the operating plants today. The recirculated concentrate is maintained at a low pH value by means of controlled acid addition. Under these conditions, scaling may be considerably diminished but is never entirely eliminated.

The conditions for scale formation, high ionic concentration and high pH exist at the boundary layer at the surface of the anion membrane in the concentrate compartment. This is generally the focal position for scale formation which spreads into the body of the compartment. The conditions of hydrodynamic flow existing at this surface are such that a comparatively stagnant fluid film exists there. Under these circumstances, acid distribution is poor so that even at relatively high, acid dosages (low pH) scale can nevertheless be formed.

Higher flow velocities can cause better turbulence and hence better acid distribution, but such conditions increase considerably the pressure drop across the compartment length and require greater pumping energy. Electrodialysis stacks of Ionics design operate at much higher flow velocities and with greater turbulence. This results in comparatively lower acid consumption and enables higher current densities to be used, but at the cost of increased pumping power consumption, and much more robust and hence costly stack construction.

(c) Reversed polarity. By reversing the polarity of the system at periodic intervals, the process causing increased polarization and scale deposition is reversed, and with time transferred to the opposite membrane surface. This may be effected either by stopping production and flushing the stacks with feed water with the polarity reversed until the original conditions are restored, and then continuing with the desalination, or introducing a regular polarity reversal cycle with uninterrupted desalination. In the latter case, each polarity reversal requires rerouting the diluate and concentrate streams, and this may involve the installation of elaborate and expensive equipment. In small capacity automatic plants this is done, but larger installations cannot be easily adapted to this form of operation. In either case, loss of production will occur, and the plant will be operating at a mean resistance which is intermediate between that for the clean and the contaminated stacks.

Many of the plants operated today provide means for some form of reversed polarity cycles at periodic intervals, as an additional means of extending the period between stack dismantling.

(d) Pulsating current. Concentration polarization is caused by the development of a concentration gradient between the membrane surface and the flow compartment. In the concentrate compartment the highest concentration occurs on the membrane surfaces and this drops rapidly over the thickness of the boundary layer to the normal value in the body of the compartment. It is there that the reactions occur which lead to scale deposition. Work at the Negev Institute has shown that, by the periodic introduction of a short reversed polarity pulse in the operating direct current, the maximum concentration is shifted to a position within the flowing concentrate stream, away from the membrane surface. The formation of insoluble materials is not affected, but these can now be flushed away in the stream, leaving the membranes' surfaces clean. Experiments have shown that operation can be extended to several hundreds of hours under these conditions.

The separators within the compartments, however, tend to act as a filter medium and inhibit the free passage of the sludge suspension from the stack so that there is a slow accumulation within the body of the compartment particularly towards the exit end of the stack, and often within the exit channels. While this is a disadvantage, such sludge accumulations can more easily be controlled by acid addition since the problem of acid distribution to the membrane surface no longer exists.

Some success has been met with the application of this method in the demonstration plant at Webster, South Dakota, but mechanical difficulties have been encountered in operating the pulsating current mechanism.

None of the methods listed above can control absolutely, or prevent entirely, a gradual accumulation of scale, which ultimately necessitates stack dismantling. The aim in successful plant operation is to extend as far as possible the period before a stack must be dismantled, by a combination of operating techniques involving some of the above methods. The actual operating cycle of reversed polarity, the quantities of acid treatment, or the frequencies of reversed polarity pulsations are closely connected to the plant design and quality of the feed water.

As has been stated previously, the use of much lower current densities will reduce considerably the magnitude of these effects, but this, on the other hand, requires much greater membrane surfaces and hence plant investment cost.

The geometrical characteristics and shape of the flow compartments can affect scale formation considerably. It is of importance that the solution flow should be exactly distributed over the active surface of the membrane. The presence of stagnant areas where flow rates may be considerably lower than the average in the compartment will create focal points for scale and polarization development which will then spread with time. In this respect, there is every argument in favour of a long path length but this again is related to pressure drop and increased pumping energy, so that a careful assessment of each of these factors is essential in considering any specific design.

The success of any scale and polarization control system lies in the length of operating time it is possible to obtain between stack dismantling. In order to achieve this maximum period, a number of measures may be introduced into the operating schedule which includes scheduled periodic flushing of the stacks with and without acid addition, and periodic polarity reversals, with the products of the plant discarded.

The contribution to production costs, of the effects described above, are manifested in increased investment costs for pre-treatment plant, increased operating costs for chemical and other treatment, and additional labour costs.

In general, pre-treatment will take the form of some ion-exchange process, e.g. iron and manganese removal in Webster, and organic material control at Rotterdam.

Operating costs involve the continuous dosing of sulphuric or other acids, and the regular dismantling, cleaning, and reinstallation of the membrane stacks, the latter requiring additional labour. An undesirable result of such cleaning operations is the consequent membrane damage which will inevitably occur. In Webster, for example, during the period 1963-1964, 40 per cent of the membranes were replaced owing to breakage or damage due to scale formation and handling.

4. Membranes

The majority of the commercial ion-selective membranes manufactured today have very similar electro-chemical properties, though their physical characteristics, particularly mechanical strength, may vary. In operation, however, distinct differences in behaviour are noted, many of these being associated closely to the quality of the feed water to be desalinated. A striking example is the comparative behaviour in operation of membranes installed in the Rotterdam plant, in which raw water, though comparatively low in mineral content, had a high content of organic materials. Details of this have been given in the section above entitled "Scale Formation" (b).

Additional variations which may be encountered include:

(a) Dimensional instability in use. Some membranes will either shrink or swell in use, depending upon operating conditions and water type. This may lead to blockage of some compartments, and difficulties in realigning the distribution channels when reassembling a membrane stack after cleaning.

Generally, membranes which have been manufactured with the incorporation of some reinforcing material, e.g. glass or polyester fibre fabrics, are stronger mechanically, but in some cases the membrane matrix has been found to break away from the reinforcing material.

The choice of suitable membranes, for operating in any specific condition, is a matter of preliminary experimental trials in which final plant operating conditions must be duplicated as closely as possible.

D. The economics of electrodialysis

Generalizations regarding investment costs of electrodialysis plants cannot readily be made. There are too few operating plants today of any reasonably large size, and in any case, investment costs are connected to problems specifically related to the type of water treated, such as composition, concentration, etc., as shown in the previous paragraphs. Arbitrarily, a large-scale plant may be defined as one which produces 1,000 m^3/day, or more. Only very few such plants have been constructed to date for which information has been published. For these, the range of investment costs varies between \$50-\$600/m^3/day. This large variation is a result, in part, of the widely differing conditions of operation required for these plants.

Some relevant information regarding plant investment costs is given in Table 1.

It has been shown in the section above entitled "Limiting Factors in Electrodialysis Plant Design - Unit Plant Size", that at the present state of technological development, there is only a comparatively small economic advantage to be gained from the scale-up of plants, in view of the size limitations of each individual unit. In any event, it is unlikely that the availability of natural brackish water in any one area or region will warrant the construction of the very large output plants visualized for sea-water conversion processes.

Production costs present an equally variable picture and a direct comparison between any two plants should not be made without considering the particular circumstances of operation. Variations in production cost allocations are influenced by water quality, the cost of electrical energy and the particular system used for capital charges and plant depreciation. Generally a fifteen-year depreciation period is allowed for. In the examples given in Table 4, the actual costs based on plant operation are in every case affected by some specific factor, e.g. operation at only part of full design capacity for the Buckeye and the Welkom plants, and the experimental nature of the Webster plant. However, predicted values for full capacity based on operating results provide estimates which may be acceptable. Production costs are of the order of about 8¢/m^3 for the more normal types of waters (e.g. Buckeye and Welkom). The Webster plant, even on a normalized basis, must be accepted as being specific to the treatment of a purely sulphatic water.

These values are particularly significant in this respect. Capital charges represent over 50 per cent of the production costs compared to 25-30 per cent for the other plants. Power consumptions are low, owing to the low current densities used, but operating charges are high.

Generally, then, the best expectation for electrodialysis costs, which are based on these few working examples, are from 8-10¢/m^3 for chloridic water, up to about 30-35¢/m^3 for highly sulphatic waters.

The foregoing discussion on the experience and economics of electrodialysis shows quite clearly the difficulties involved in attempting to produce generalized figures for the process, and shows the need for a careful evaluation of each of the specific requirements for any particular application. It is possible, however, to classify many of these parameters and to indicate quite generally and qualitatively their contribution to, and influence on, plant costs.

1. Raw water quality

High chloride to sulphate ratio. Relatively higher current densities can be used, and hence lower investment costs. With decreasing chloride/sulphate ratio, lower current densities, and hence higher investment costs, will be necessary. On the other hand, higher current densities will require higher energy costs, but this is likely to be offset by the reduction in capital costs.

High hardness (scaling) components require reduced current densities, increased pre-treatment and acid dosing, increased stack replacement and hence labour costs, and increased membrane replacement costs.

The presence of polyvalent ions, heavy metals and organic contaminants result in the need for reduced current density, increased pre-treatment costs and increased membrane replacement costs.

Table 4

Operating costs of various electrodialysis installations

(Values in $\$/m^3$)

	Webster, South Dakota				Buckeye, Arizona				Welkom, South Africa	
	Demonstration plant	%	Normalized plant	%	Present throughput	%	Designed throughput	%		%
Electrical energy	0.014	3.8	0.013	3.9	0.033	20.6	0.036	41.9	0.015	18.3
Other energy	0.004	1.1	0.003	0.9		-	-		0.003	3.7
Acids and chemicals	0.017	4.6	0.019	5.8	0.002	1.3	0.002	2.3	0.002	2.4
Operating and maintenance, labour and supervision	0.069	18.6	0.057	17.3	0.017	10.6	0.004	4.7	0.009	11.0
Supplies and maintenance materials	0.006	1.6	0.012	3.6	0.021	13.1	0.010	11.6	0.008	9.8
General and administrative expenses	0.057	15.4	0.015	4.5	0.004	2.5	-	-	-	-
Capital costs and insurance	0.172	46.3	0.178	54.0	0.065	40.6	0.023	26.7	0.025	30.4
Membrane replacements	0.032	8.6	0.033	10.0	0.018	11.3	0.011	12.8	0.020	24.4
TOTAL	0.371	100.0	0.330	100.0	0.160	100.0	0.086	100.0	0.082	100.0

2. Scale of operation

As has been shown, beyond a particular basic unit stack size, increasing capacity has only little effect on investment costs. The limit of size, for which scale-up is no longer economically effective, corresponds to a plant output of about 2,000-5,000 m^3/day, with unit stacks having the characteristics given in Table 3 above.

3. Cost of electrical energy

Low electric power costs will affect production costs considerably for most applications. Where circumstances, such as water quality, require low current densities, this factor will not be significant, but in many cases it may be important. Since electrodialysis plant requires comparatively little start-up time, operation at off-peak hours, as for example at Buckeye, proves economically attractive, but this must be considered in relation to the disadvantage of operating at a reduced capacity.

It has been stated in (b) above, that from the point of view of a reduction in relative investment cost, scale-up of plant has only a small advantage; however, where very large plants can be envisaged, it is likely that direct current generation will be economically preferable to rectification, so that such an electrodialysis plant will economically justify its own D.C. generation, both from the point of view of investment, and because of the considerably lower cost of each D.C. kwh. This could be economically justifiable for plants of about 10,000 m^3/day where the power requirements would be about 1,500 kW.

4. Capital costs: interest and depreciation

We may consider an electrodialysis plant as consisting of these sections:

(1) The membrane stacks;
(2) Hydraulic equipment - pumps, pipes, tanks, instrumentation, etc.;
(3) Power supply - transformers and rectifiers.

Items under (2) and (3) are more or less conventional, and will together represent up to 80 per cent of the total investment cost. The technical literature provides tables for average depreciation of plant equipment, and if this information is weighted on the basis of the relative investment costs for each section, a value of about twenty years is obtained, excluding the membrane stacks.

In view of some of the particular aspects of electrodialysis operation, a safe value of fifteen years can be assumed, although no experience is available for any plant over this length of time. The stack components will have varying life-times which are likely to be much shorter. This refers in particular to the gaskets, separators and electrodes.

Membranes are dealt with separately below.

Interest rates will obviously affect costs considerably, and a realistic approach is imperative if reasonably accurate cost estimates are to be made.

5. Membrane cost and lifetime

The relatively high cost of membranes, between \$10-\$30/m^2, does not appreciably influence the initial investment for any electrodialysis plant, but it is an important component of operating costs. The relatively short lifetime, estimated at about 3-5 years by manufacturers, requires their frequent replacement. In practice, this mechanical fragility leads to frequent replacement as a result of breakage and tearing. Water quality and plant operation conditions require frequent dismantling and cleaning of stacks, and increase the breakage and rejection rate of membranes. This has been noted particularly at Webster, and as a result normalized plant estimates give only a two-year lifetime for membranes.

In South Africa, the choice of the parchment type membranes used was influenced by the concept of a short-lifetime membrane of cheap manufacture. While these membranes lasted about six months to one year only, the expected low manufacturing costs were never realized, and resulted in a very high operating cost, owing to frequent replacements.

It must, however, be remembered that the present market price of membranes, which is influenced by a limited demand, does not necessarily represent the true picture. The application of electrodialysis on a large scale and resulting requirement for large membrane areas is likely to lead to a substantial reduction in price, and this will in time reduce the process costs.

6. Waste disposal

For any sea-water desalination process, concentrate disposal is a relatively minor problem and contributes little to operating costs.

For inland-based electrodialysis plants, this problem may become serious and will contribute substantially to first investment costs, and possibly to operating costs as well.

About 20 per cent of the feed water to a plant will have to be disposed of as a concentrate having up to 10,000 ppm T.D.S. or more. Where such a plant is sited it is to be assumed that there will be no rivers or streams available for disposal. Distribution over the ground may contaminate arable soil and uncontrolled percolation may return to the water source the salts which have been extracted. Two possible solutions are available:

(1) Complete evaporation;
(2) "Deep-well" injection.

In the former case, sufficient area must be made available to enable all the waste concentrate to evaporate completely. In hot dry climates, this may be a satisfactory solution, but the area required, site preparations and distribution may make this expensive. The deposited salt will moreover render the land unusable for agriculture.

The second method involves the disposal of the wastes into sub-surface strata isolated from the brackish water or other sources of useful water. While effective, this may involve considerable preliminary effort and expense in hydrological and geological surveys and drillings.

The costs involved in both cases could be substantial.

E. Other applications of electrodialysis

In the introductory paragraphs to this paper, several additional applications of electrodialysis were mentioned. These require some more detailed explanation since they may become increasingly important with time. Their economic feasibility will vary with the particular circumstances, and the gravity of the water need, either on a regional or national basis. Some of these applications may have almost immediate applicability in situations such as, for example, exist today in Israel where the water position is critical, and sea-water desalination is being considered for implementation in the immediate future.

1. Salinity control of marginal waters

Water for municipal, domestic and industrial application can be used over a relatively wide range of salinity, but many agricultural products are extremely sensitive to chloride salinity. Among these are deciduous and citrus fruits, which are particularly valuable to many countries as export crops.

The particular circumstances in Israel provide an example of this problem of high salinity in relation to citrus culture, and the possible solution which electrodialysis may present.

While citriculture is developing rapidly as a major export activity, the salinity of irrigation water is increasing, particularly in the south of the country, where new groves are being planted. The chloride salinity of this irrigation water is about 250 ppm and is likely to be exceeded in the future.

The irrigation requirement of citrus is a function of irrigation water salinity and has been extensively investigated, particularly by the United States Salinity Laboratories. Table 5 gives an indication of this relationship.

Table 5

Irrigation requirement as a function of water salinity (Citrus)

Chloride concentration (ppm)	Irrigation requirement (m^3/hectare/year)
100	7,800
150	8,400
200	9,150
250	10,000
300	11,000

If we consider, as an example, the comparison between 250 and 100 ppm Cl^-, the better quality water will require 25 per cent less for adequate irrigation. This means that it can tolerate a 25 per cent increase in cost over the more saline water. Where such waters must be conveyed over substantial distances, as is the case in Israel, and the cost is therefore relatively high, this increase could be about equivalent to the cost of water desalinated by electrodialysis. For high initial salinities, the advantage becomes increasingly greater.

The physical conditions for desalination are more favourable for low cost treatment since:

(1) There is a comparatively small amount of salinity to be removed, and hence investment costs and energy requirements will be low.

(2) Because of the low concentration range, recoveries can be much higher, up to 95 per cent, and hence waste disposal problems much less acute.

(3) Problems of scale deposition are likely to be less severe. Experiments in the laboratory have shown that for this range of desalination, power consumptions of considerably less than 0.5 kWh/m^3 can be obtained.

2. Sewage water re-use

Biological treatment of sewage waters, which may convert it into a potentially useful product, increases its salinity. Many of the arguments given above apply to the treatment of biologically treated sewage water by electrodialysis, but additional problems may arise due to the presence of organic contaminants. This can be handled by pre-treatment processes, but will add to the cost. However, as is the case in (a) above, the increase in cost can be low in relation to the primary treatment.

3. Salinity control of water sources

The exploitation of coastal aquifers at rates close to the annual natural recharge results in a slow but definite salt accumulation which will lead, in time, to the deterioration of the water. The re-establishment of the original water quality will be a very slow process, even if no further withdrawal is made.

Potentially, electrodialysis may provide a convenient method of effecting salt rejection of such coastal aquifers. Since, in this case, the object is not to provide a high quality product water, but to remove salt, the conditions for the process may be chosen to provide the optimum operation and cost conditions.

Figure V shows the optimal condition for electrodialytic salt rejection from waters of varying salinities at different rates of salt rejection.

The ideal conditions would apply to relatively concentrated feed waters at limited desalination rates. In view of the limited desalination and the convenience of waste disposal, the process could be operated at relatively low cost. From the values shown in the figure, the optimum cost would be equivalent to about 3-5¢/m^3 of treated water.

There is no doubt that the implementation of such a process would not be undertaken except as an extreme measure, and that all other possible alternatives would have to be thoroughly investigated first. Nevertheless, Israel is an example where such a system could be considered as a necessary measure in the not too distant future.

4. Sea water desalination

Electrodialysis has never been considered to be competitive with evaporation as a means of sea water conversion principally because of the unfavourable energy requirements for the system and the relatively complex plant involved.

However, recent developments at the Institute for Arid Zone Research in Israel have indicated that the energy requirements can be very considerably reduced, by operating the process at relatively high temperatures.

While it has been known that higher temperatures, by reducing the electrical resistance of the system, lower the energy requirements considerably, the economics of the process are nevertheless unfavourable if the additional heat energy must be supplied from an external source. In electrodialysis the major proportion of the electrical energy used is transformed into heat and this is usually discharged with the various effluent streams. It may, however, be recovered by heat exchangers and recycled to the system so that the process may be operated up to 90°C and above. Under these conditions, the energy requirement may be reduced by one-third to one-quarter of that at normal temperatures.

An economic comparison with evaporation processes is not possible at this stage, but it has been shown experimentally that the membranes can function effectively at such temperatures and that the indicated energy reduction can be effected.

F. Conclusions

In a country faced with a national water shortage, the ultimate solution, when all natural resources have been exploited, is sea water conversion. At the present state of technological development, sea water evaporation appears to provide the most advanced system for such conversion, particularly when coupled with electric power production.

There is, however, a considerable economic gap between the cost of natural water exploitation and sea-water conversion. This gap can potentially be filled by the desalination by electrodialysis of naturally occurring underground saline water.

The process is economically viable where it can be utilized in regions where alternative supplies must be provided by long-distance pumping.

More specifically, the economics of brackish water desalination by this system are influenced to a very large extent by the characteristics and concentration of the raw water available and the necessary operating methods required to overcome problems of scale formation etc., which may vary from one water to another. For this reason, while many of the plant components can be standardized, the design and method of operation must take into account the characteristics of the water treated.

The size of any electrodialysis plant is related to the capacity of the raw water supply, but is also limited by the size of the standard unit which can be designed conveniently.

Economically, therefore, there is only little advantage to be gained by size scale-up, since very large plants will require the installation of many parallel lines of standard units. This may, nevertheless, be an advantage since the plant may be increased in stages in accordance with the increasing local demand up to the maximum capacity of the raw water source.

Only a limited number of large-scale electrodialysis plants are presently in operation, and the experience gained with them has confirmed the great influence of water composition on the process. Where the raw water available is substantially chloridic, reasonably low product costs may be expected, but with increasingly sulphatic waters product costs increase. First investment costs for electrodialysis plants are generally lower per unit of product than for other desalination plants, but may increase in cases where the water feed requires special pre-treatment or operating conditions.

The major proportion of the product cost is attributable to capital charges, while energy costs and membrane replacement costs contribute somewhat less.

Process costs are at present influenced by high membrane costs and limited life expectancies. However, the present high cost of membranes is due to the limited nature of demand, and it may be expected that with increasing application this will drop and hence reduce operating costs.

In addition to the desalination of underground brackish water, electrodialysis may be foreseen as providing a method for controlling aquifer salinity by salt rejection, for treating marginal waters to render them suitable for specialized agricultural applications, and for the treatment of recovered biologically treated sewage water.

A possible future application is seen in the desalination of sea water by utilizing the heat produced in the process to reduce electrical energy requirements.

The development of the process can be foreseen in the following stages:

(1) The provision of municipal and industrial water in developing regions where brackish water is available and where consumer centres are removed from sources of better quality water.

(2) The general exploitation of all underground brackish resources to implement natural supplies and contribute to the national water budget.

(3) The utilization of waste and marginal waters such as industrial wastes and sewage.

(4) The control of salinity of natural coastal aquifers, where the salinity increase is due to total or near total exploitation.

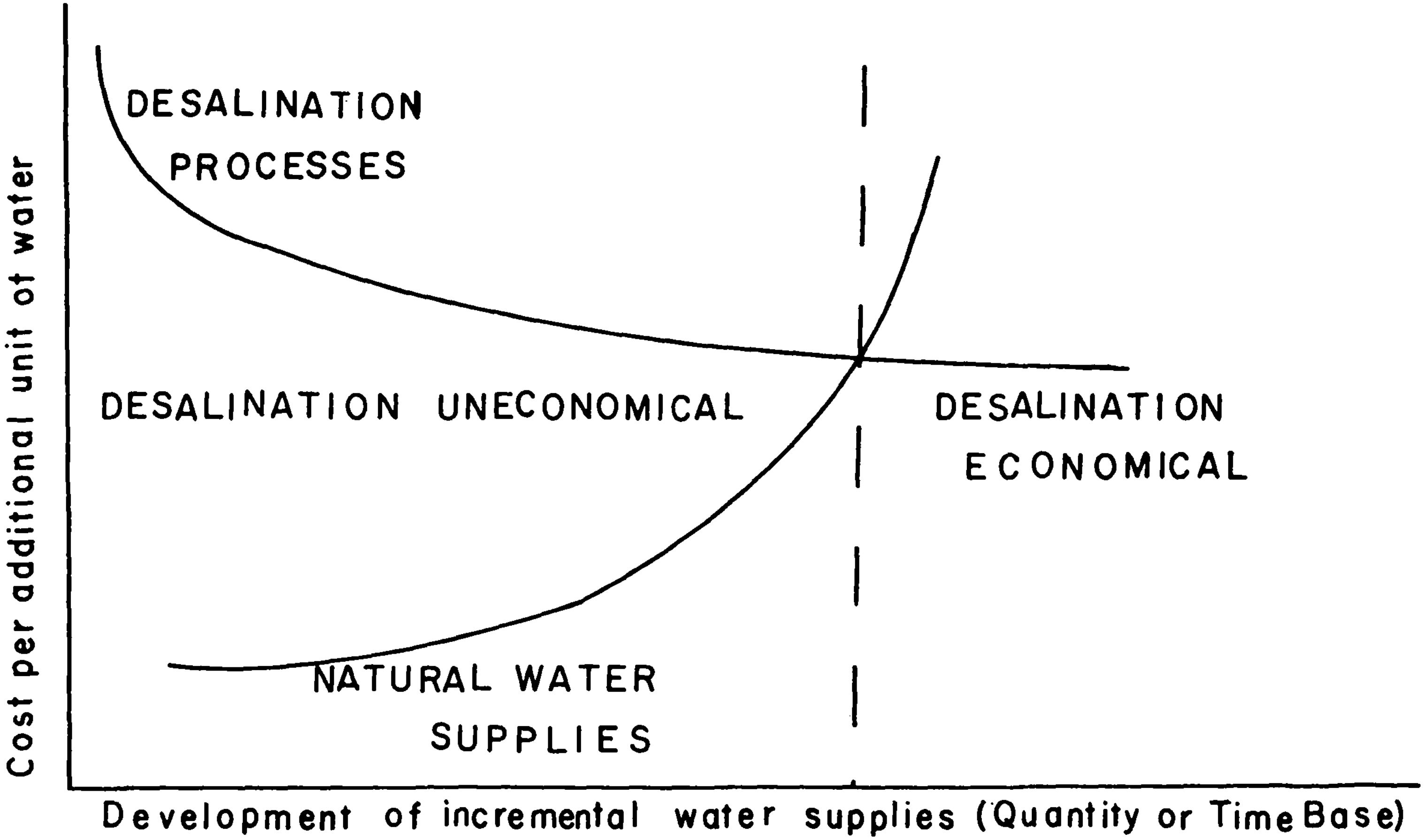

Figure I. Comparison of water supply economics

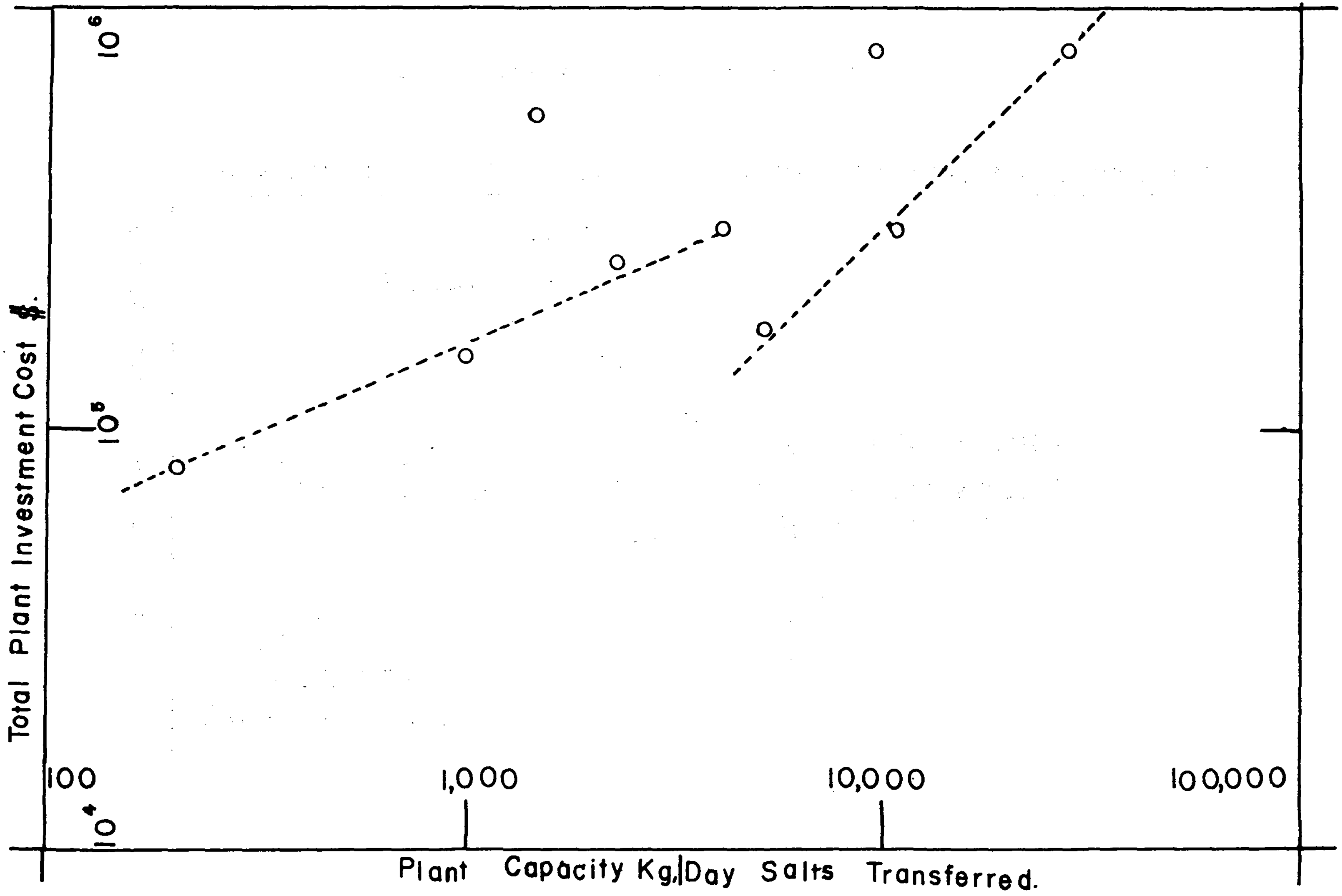

Figure II. Electrodialysis plant cost - capacity relationship

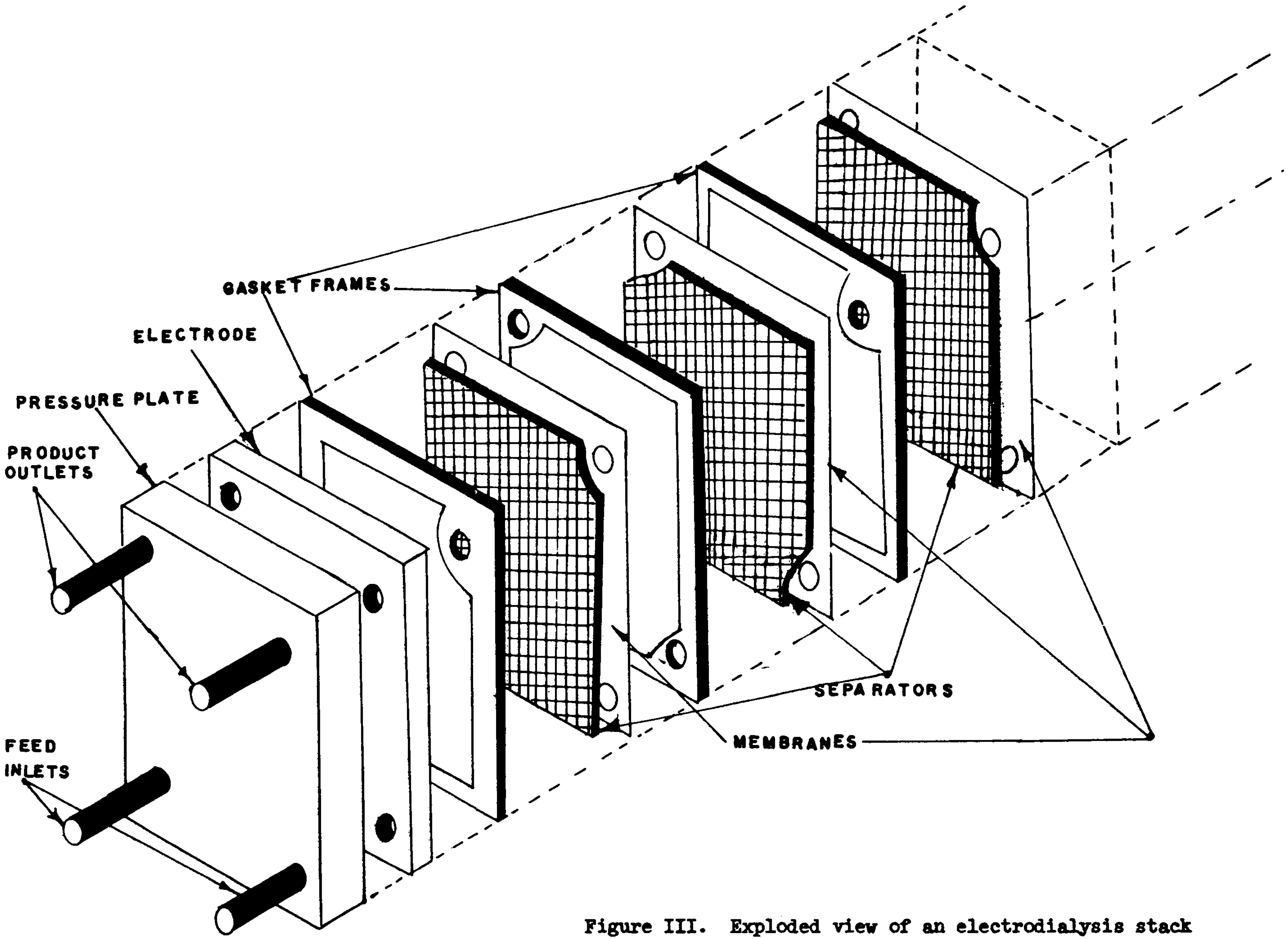

Figure III. Exploded view of an electrodialysis stack

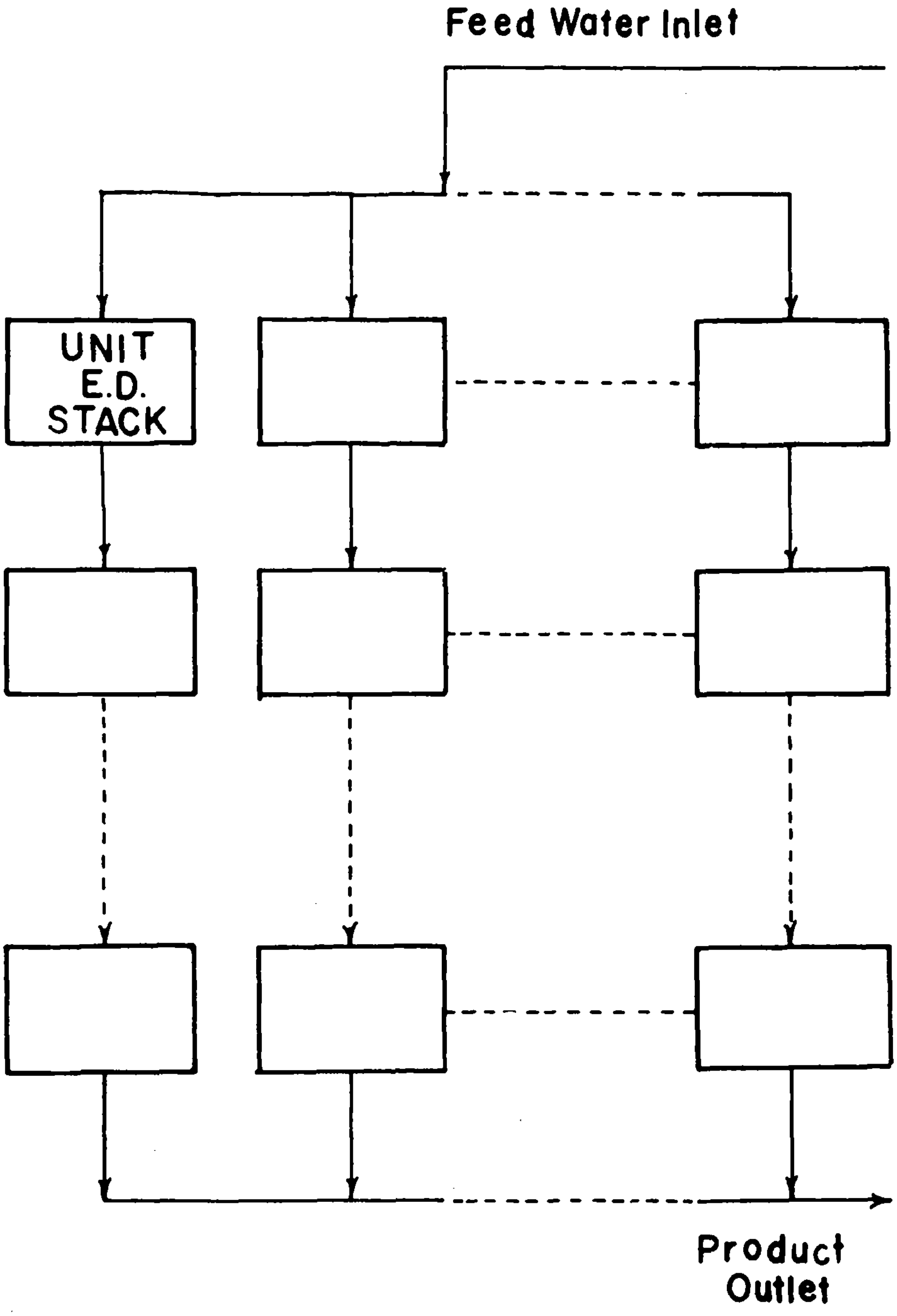

Figure IV. Flow diagram of electrodialysis plant
(Arranged in series - parallel connexion)

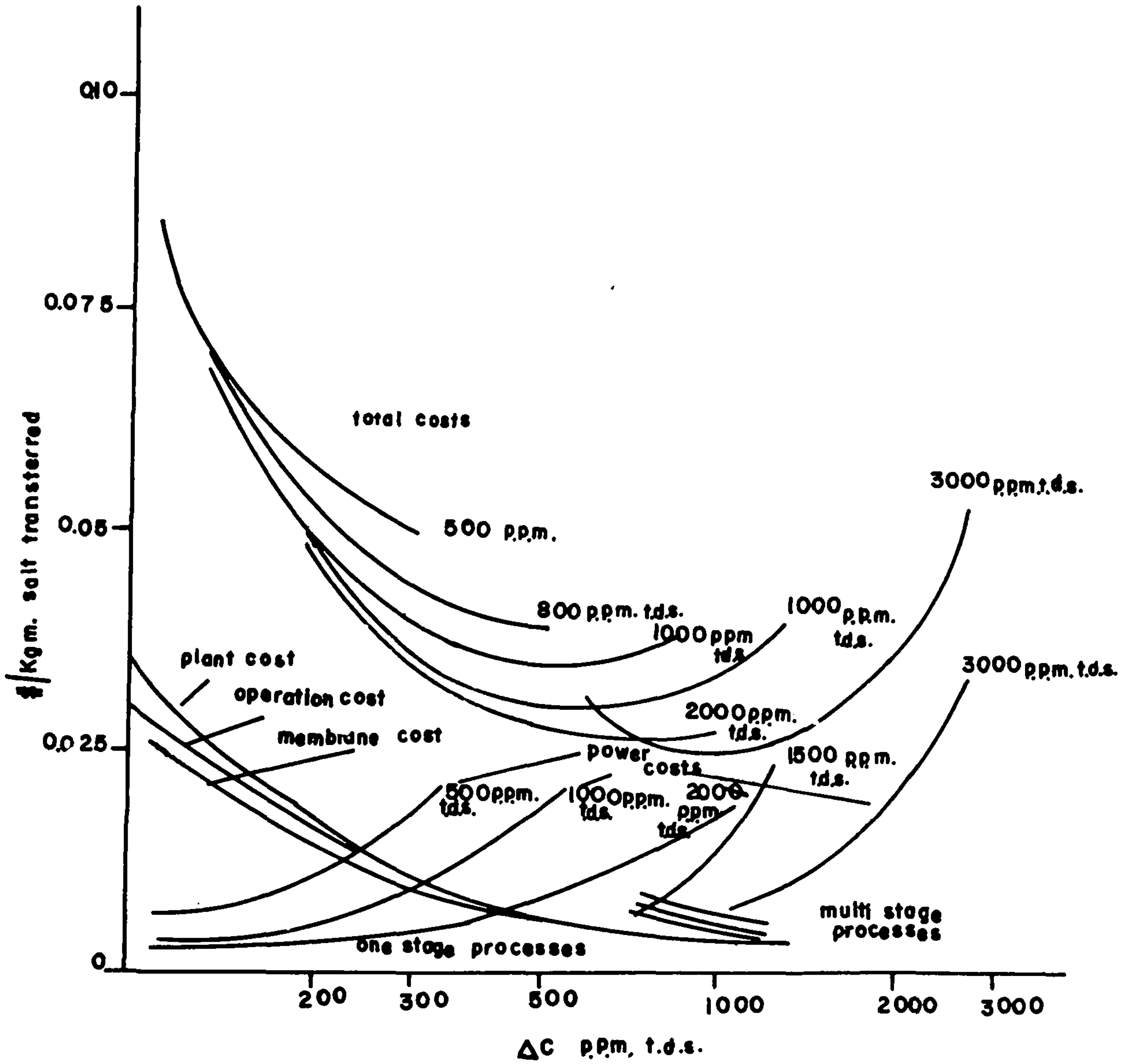

Figure V. Optimal conditions for salt rejection by electrodialysis

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IX. FREEZING PROCESSES:

PRESENT TECHNOLOGY AND RELATED PROBLEMS

by W.W. Rinne

From thermodynamic considerations, the freeze-separation method is potentially capable of achieving economical conversion of saline water. Apart from the successful development of an ice-brine separation method, the freezing system must operate in a closed cycle, integrating the ice-making and ice-melting steps so that a minimum of energy is consumed. In order to preserve the inherently low energy requirement of the system, direct heat interchange is employed in the freezing and melting steps thus eliminating costly metallic surfaces. This facilitates heat removal at the highest possible temperature and heat rejection at the lowest possible temperature. In order for the system to be economical, the heat removed, 144 BTU per pound of ice produced, must be recovered to melt the ice. Assuming a 50 per cent conversion of sea water feed, the freezing point depression is of the order of 7.6°F. For a continuous process using direct methods of interchange, heat is removed at 24.4°F and rejected at 32°F. The temperature range through which heat is pumped, therefore, is minimized and the net energy consumption of the system is that required for thermodynamic irreversibilities, heat leaks, and mechanical and electrical inefficiencies. The power requirement for the direct contact freezing process has been estimated to be in the range of 26-42 kWh per 1,000 gallons of potable water produced.

In addition to its energy advantage, freeze-separation, because of low temperature operation, exhibits little tendency toward corrosion and the formation of scaling compounds. These advantages afford possible use of low-cost materials of construction, and equipment of relatively simple design which may ultimately reduce investment costs.

Direct freezing may be accomplished by the flash evaporation of sea water at reduced pressure, or by vaporizing an immiscible refrigerant such as butane in direct contact with the feed. In the former method, the resulting water vapour may be absorbed chemically or compressed, while in the latter the refrigerant vapour is compressed. In either case, the heat of crystallization is recovered to melt the ice. Direct freeze-separation methods involve three basic operations: (1) partial freezing of the feed stream, (2) separation of the ice and brine, and (3) melting the washed ice.

A. Historical background

The freezing of sea water has been under study for a number of years. Early work was concerned with the concentration of sea water to brine for commercial production of salt and for use by the fishing industry. In recent years, attention has been focused on the application of freezing to the conversion of sea water as a means of producing fresh water for industrial and municipal uses. The change in emphasis from a brine-producing method to a water-producing method pointed up the need for a good ice-brine separation step. As subsequent development work indicated, the separation of a pure water phase posed a rather formidable technological problem.

The successful application of freezing techniques is dependent upon the efficiency of the washing operation. It is now recognized that in no freezing process can all of the ice produced be made available as fresh water. The incomplete physical separation of ice from brine requires that some ice must be melted and used to reduce the concentration of mother liquor adhering to the crystals.

Washing must be accomplished with a minimum use of product water, otherwise the economic advantages of the system cannot be realized. Early attempts at developing a freezing process pointed up the difficulties of the wash-separation step. Ice formed by direct methods of refrigeration generally produced very small ice crystals. Separation of brine by filtration was not a satisfactory solution. The large surface area provided by small particles enhanced the attraction between the crystal and the mother liquor. In other words, entrainment and adherence of brine by the crystal is understandable assuming the ice is 100 per cent pure water and the brine about 93 per cent pure water. Hendrickson investigated centrifugation, gravity draining, vacuum filtration and compression as methods of brine separation. 1/ He concluded that compression offered the most effective method. Rose found that countercurrent washing of ice beds would offer a satisfactory method of displacing entrained mother liquor. 2/

Since 1957, the Office of Saline Water has pursued the development of freezing processes in an effort to demonstrate the economic potential of the freezing principle. More recently, work by Wiegandt 3/ and Sandell, et. al., 4/ demonstrated that ice crystals could be washed countercurrently by employing the principle of hydraulic piston bed displacement. This system of wash-separation which employs either a cylindrical or a rectangular-shaped column has been employed successfully in both the vacuum flash and the secondary refrigerant processes.

Other methods such as pressure filtration and centrifugation have not as yet been successfully demonstrated in pilot plant operations.

1/ H.M. Hendrickson, Refrigerating Engineering, Vol. 66, p. 31 (1958).

2/ A. Rose, Proceedings of the Symposium on Saline Water Conversion, 1957, National Research Council publication, No. 568.

3/ H.F. Wiegandt, An Integral Processing Unit using a Secondary Refrigerant, Research and Development Progress Report No. 41 (1960).

4/ D.J. Sandell, W.J. Hahn, R.C. Burns and R.S. Fullerton, Development of the Direct Freeze Separation Process, Research and Development Progress Report No. 113 (1964).

B. Freezing systems

1. Secondary refrigerant method

The vaporization of a refrigerant such as butane, in direct contact with precooled sea water, was suggested to the Office of Saline Water by Wiegandt in 1957. The use of an immiscible refrigerant, under these conditions, permits operation at temperatures of about 24°F. Low molecular weight hydrocarbons are acceptable refrigerants from the standpoint of availability, cost and low solubility. Preliminary studies, carried out in the laboratory, were used as a basis for the design and construction of a 35,000 gallons per day pilot plant located at St. Petersburg, Florida.

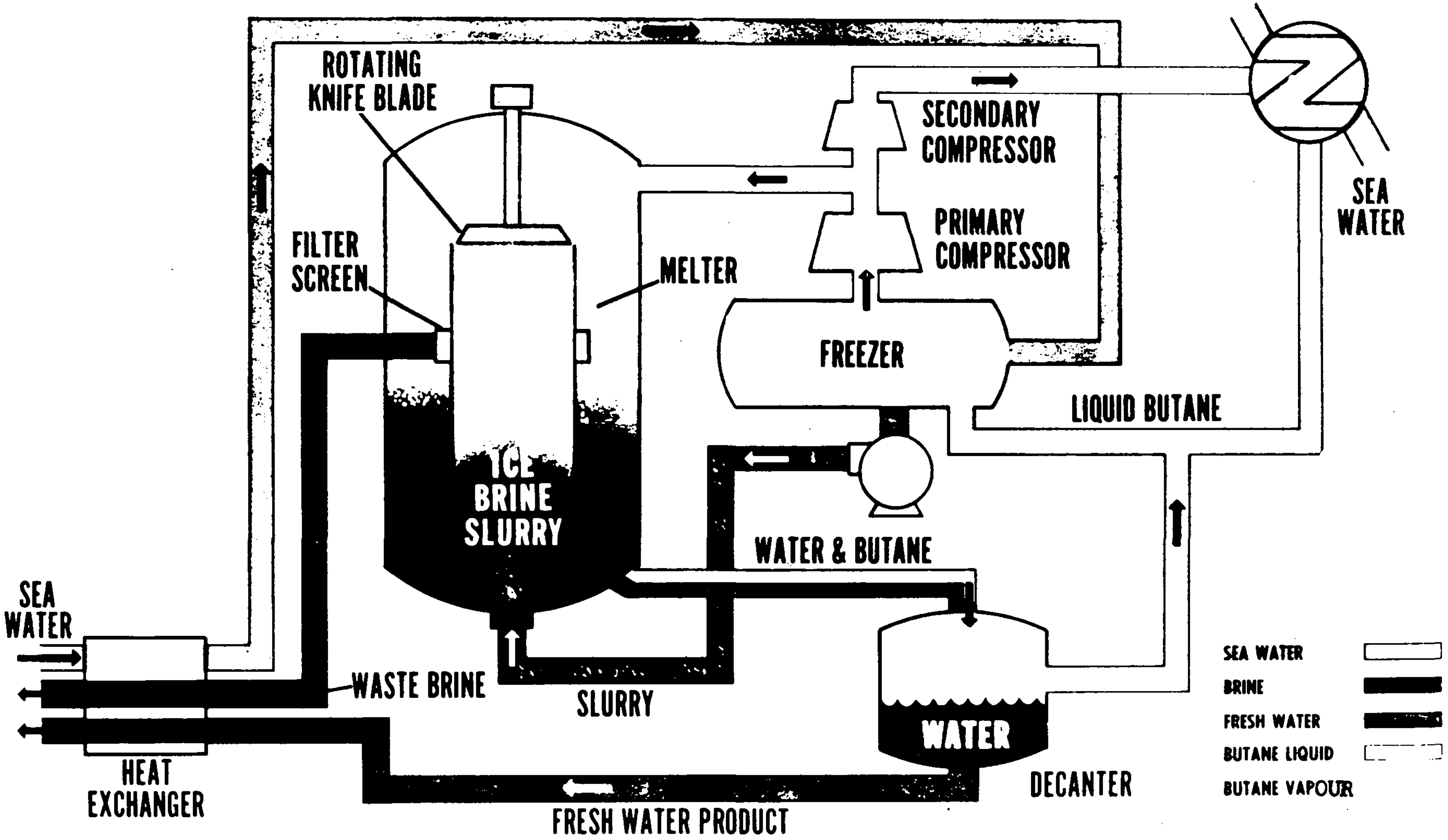
One of the major problems experienced in pilot plant studies was that of separating and washing the ice free of brine. Initially it was found that uncontrolled freezing led to the formation of very small ice crystals which were difficult to separate and wash. Subsequent developments resulted in the design of a torus freezer equipped with good agitation. This permitted sufficient residence time for growth of large crystals of uniform size. Diameters in the range of 1.0 to 1.5 mm appear to be optimum for wash-separation. The butane is introduced into the freezer by sparging.

The salient feature of the process is the wash-separation column, designed to separate ice-brine mixtures by means of hydraulic piston bed displacement. A diagrammatic sketch of the column is shown in the process flow, Figure I. The wash-separator consists essentially of a column within a column. The slurry from the freezer is pumped into the bottom of the inner column where the ice is compacted into a porous bed. Brine is drawn off through filter screens located slightly above the mid-point of the inner column. The flow of brine upward is at a rate of 0.8 ft/min. and the ice moves at a rate of 0.3 ft/min. The actual velocity upward, therefore, is 0.5 ft/min. The pressure drop caused by the brine flowing through the bed propels the bed upward. As it approaches the top of the column the bed is flooded with fresh water to effect removal of residual brine. A rotating knife blade scrapes ice off the top into the outer column or annulus where the ice is melted by head liberated in the condensation of butane vapour. The lower part of the outer column serves as a decanter separating water product from immiscible butane. The column consists essentially of a piston formation zone below the filter and a washing zone above the filter. Operating the washing zone in a flooded condition gives somewhat better washing efficiency whereas operation in the so-called drained-bed manner gives better ice-cutting efficiency. The rate of brine flow through the ice bed is referred to as piston leakage. This rate must be optimized with respect to the ice particle size produced in the freezer.

Other features of the process are the primary and secondary compressors which bring about vaporization of the refrigerant and compression of the vapour to complete the thermodynamic cycle of abstracting heat from sea water and cycling it back to melt the washed ice. Because of the irreversibilities inherent in the system, more vapour than ice is produced. Therefore, the secondary compressor handles the excess vapour which is condensed in an auxiliary or secondary condenser against sea water. The butane refrigerant is recycled to the freezer.

Figure I

BUTANE SECONDARY REFRIGERANT PROCESS



Since butane is not completely insoluble, trace quantities present in the water product and waste brine must be recovered by some form of degassing. This can be done by conventional methods under reduced pressure. The debutanizer is not shown in the flow diagram.

The 35,000 gpd plant at St. Petersburg, Florida, was evaluated over a period of several years. Numerous changes and modifications were introduced in order to optimize the process. Production rates up to 55,000 gpd of product were achieved yielding salinities of about 500 ppm.

Although present data indicate that further work is necessary to finalize the design features of the process, it is believed that the simple and practical design of the torus freezer can be extrapolated without difficulty to large sizes. Ice slurry is pumped around and out of the freezer without difficulty, and there is every indication that the slurry can be handled on a large scale. Ice is cut from the washer by an oscillating pendulum cutter. This type of cutter was installed after converting the inner cylindrical column to a rectangular column. The melter, with no moving parts, gave reliable operation and had good capacity for storing ice to give stability to the process. It is interesting to note that the melter operated with as little as 1°F driving force.

In general, the freezer and the washer-melter showed the capability of being co-ordinated into a combination of equipment that would operate smoothly, reliably and with low energy input. It is hoped that future work will demonstrate additional capacity, especially if the freezer is enlarged, since the retention time of the existing freezer determined the capacity. It is recommended that a plant of 300,000 gpd capacity be built to demonstrate the performance of the over-all process.

2. Secondary refrigerant: controlled crystal growth

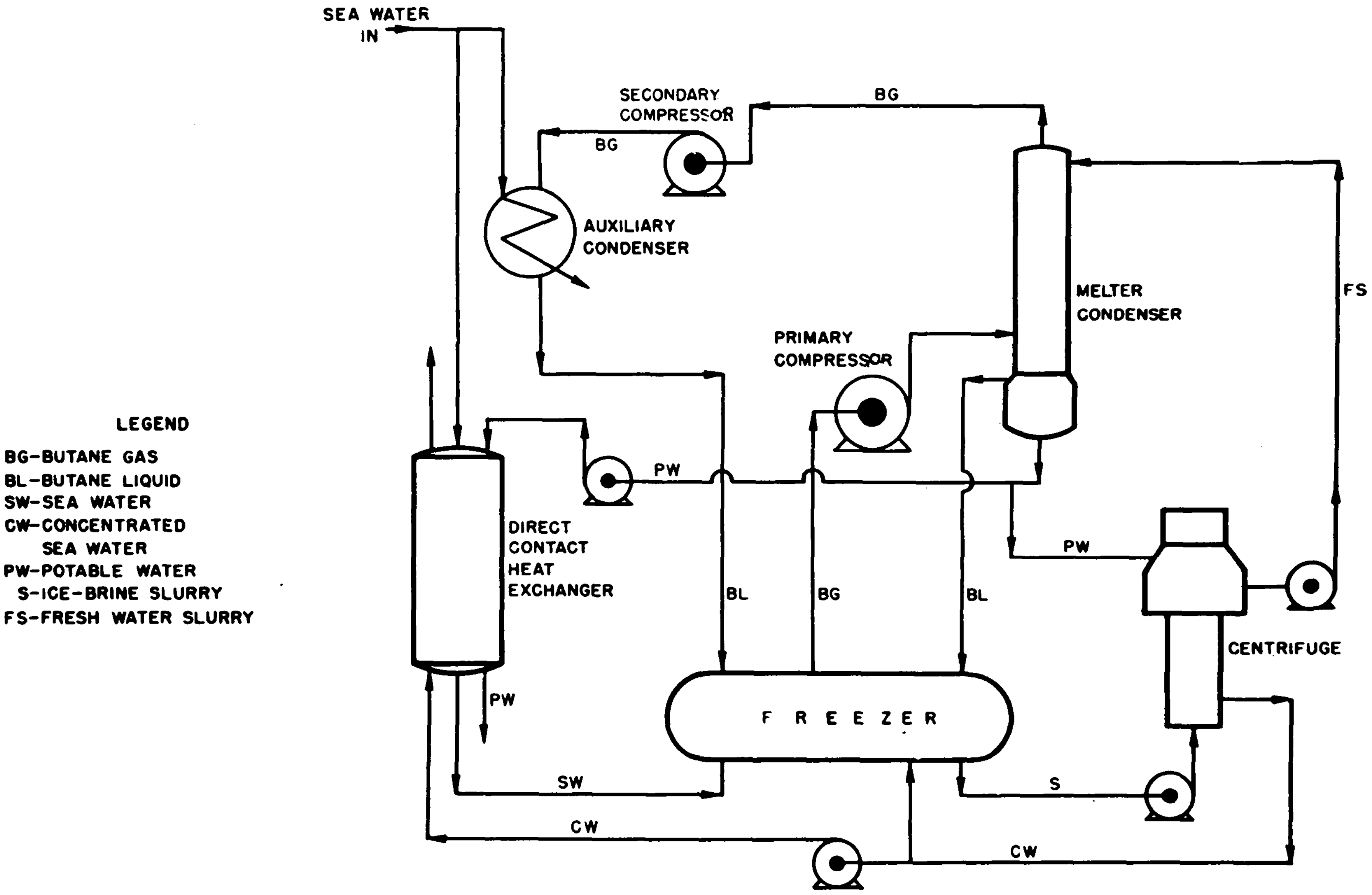
Other variations of the secondary refrigerant process have been suggested. One of these currently under development features the growth of a larger crystal size in order to facilitate wash-separation. By controlling the degree of sub-cooling, the number of nuclei can be reduced and thus permit, by increasing residence time, the crystals to grow to a large size. The system also permits a more uniform distribution of crystal sizes.

Ice crystals are generated in a specially designed freezer by retaining a large inventory of liquid refrigerant (butane-isobutane mixture) on top of the sea water. Paddle-type agitators provide sufficient agitation for freezing which takes place at 25°F. The freezer is maintained at a pressure slightly in excess of atmospheric (Figure II).

Under optimum conditions the crystals formed are hexagonal in shape and measure 0.5 to 2.0 mm in diameter. Other variables which control nucleation and crystal growth are degree of supersaturation, residence time in the freezer and degree of agitation. The evaporation rate of refrigerant controls the rate of nucleation. Growth depends on residence time and the control of sub-cooling depends in part on agitation.

The ice-brine slurry is separated in a centrifuge where the ice is washed and then pumped as a fresh water slurry to the melter-condenser. By means of direct

Figure II


SEA WATER IN
SECONDARY COMPRESSOR
BG
BG
AUXILIARY CONDENSER
MELTER CONDENSER
FS
PRIMARY COMPRESSOR
PW
DIRECT CONTACT HEAT EXCHANGER
BL
BG
BL
PW
CENTRIFUGE
PW
F R E E Z E R
SW
S
CW
CW
LEGEND
BG-BUTANE GAS
BL-BUTANE LIQUID
SW-SEA WATER
CW-CONCENTRATED SEA WATER
PW-POTABLE WATER
S-ICE-BRINE SLURRY
FS-FRESH WATER SLURRY

contact, compressed refrigerant vapour is condensed by countercurrent flow, melting the ice. Product water and refrigerant are separated in the lower part of the condenser-melter by decantation.

In order to further minimize driving forces, and to achieve low approach temperatures, direct contact heat exchangers are employed. The lower investment cost and greater efficiency of these units should aid in reducing the cost of freezing processes.

This system is presently being evaluated at Wrightsville Beach, North Carolina. Centrifugal separation has not been successfully carried out. However, the incorporation of a wash-column similar to that described in the previous process has produced potable water in conjunction with the freezer. There is some indication from this work that the growth of a large-size crystal increases the efficiency of the wash-separation column.

The performance of the direct contact heat exchangers has demonstrated operation far below design specifications. Present data indicate an over-all volumetric heat transfer coefficient of about 2,000 BTU/hr/ft^3/^{o}F in contrast to the design value of 10,000. A low hold-up condition of about 8 per cent water dispersed in hydrocarbon has been observed. This is believed to be the principal cause for the poor performance. Poor internal circulation is also believed to be an additional factor involved. A programme is being implemented to study the various parameters associated with the operation of the direct contact heat exchangers.

The major problem encountered in the operation of the 15,000 gpd pilot plant is that of separating ice-brine mixtures in the centrifuge. This device has not functioned because of ice glazing on the basket screens. Coating the basket with Teflon and the use of steam to partially melt and wash the ice has given some improvement. It is believed, however, that the problem is one of size, i.e., the centrifuge is too large for the flow rates of slurry from the freezer. Consequently, insufficient ice in the basket is the primary cause for poor performance.

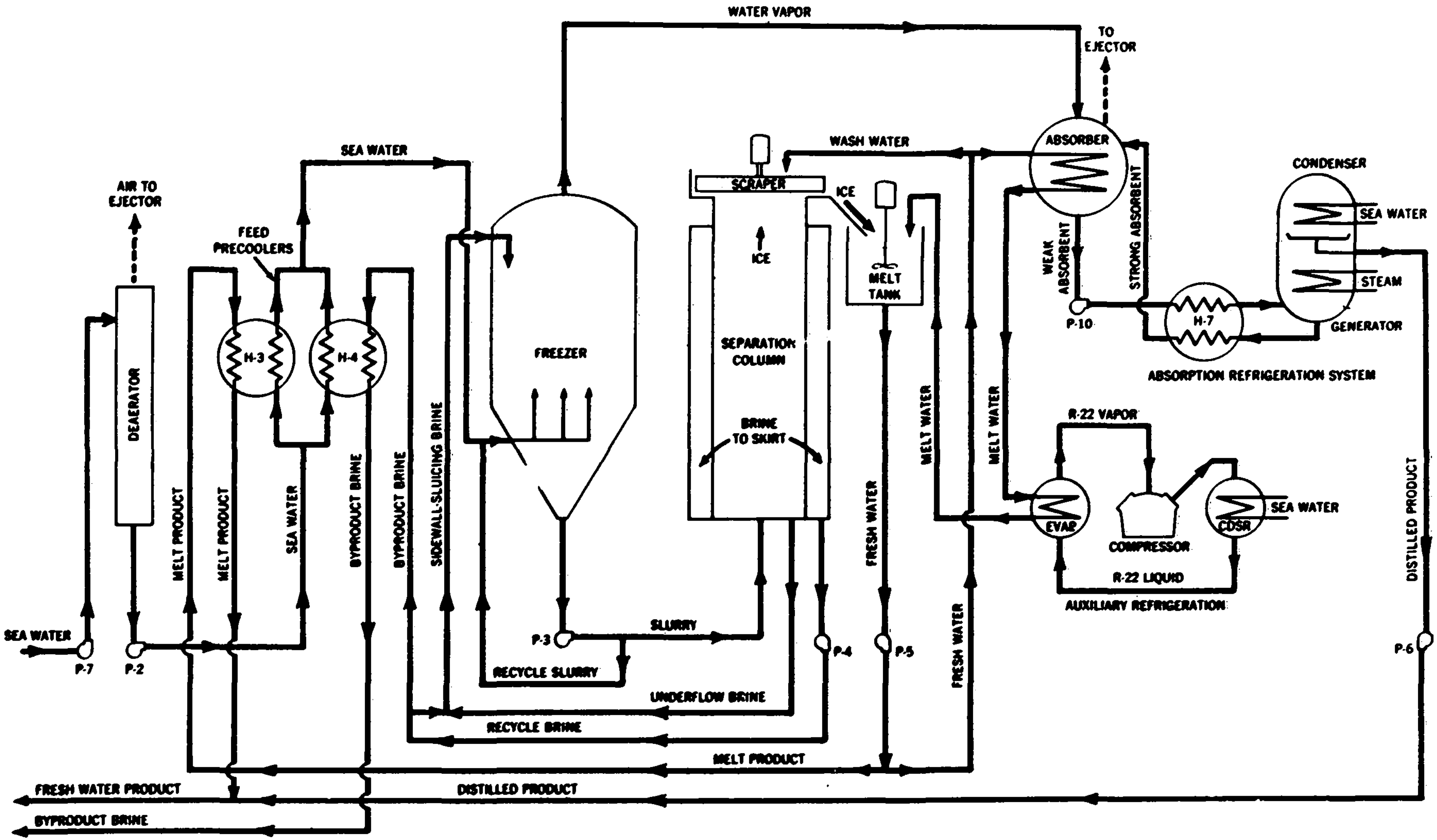
The crystallizer or freezer has shown somewhat erratic performance; at times large uniform-size crystals are formed while at other times poor crystal growth rates are observed. Additional studies are planned to determine major factors controlling crystal growth phenomena.

Other unit operations such as melter-condenser, auxiliary condenser, and debutanizer have been operated successfully but no tests have been made to verify their efficiency at design production rates.

3. Vacuum freezing: vapour absorption process

One of the first direct freezing methods investigated by the Office of Saline Water was based on vacuum flashing and the chemical absorption of the resulting water vapour. The process flow is shown in Figure III. Sea water feed is deaerated and cooled by heat interchange with waste brine and product water. It is then pumped to the freezer where at 3.3 mm of Hg pressure (absolute) boiling occurs and ice crystals are formed. Roughly six pounds of ice are produced for each pound of vapour formed. The resulting slurry is pumped to a wash column

Figure III



15,000 GPD PILOT PLANT
WRIGHTSVILLE BEACH, N. C.

similar to that described under the secondary refrigerant process. The formation of a porous ice bed, its propulsion upward through the column by a hydraulic piston-type displacement, and its subsequent washing countercurrently with fresh water constitutes the ice purification step. The ice is cut off the top of the bed by a rotating knife blade and is flushed into a melting tank via a chute. Here the ice is melted in effect by the heat of absorption to preserve the thermodynamic cycle.

The vapour stream which passes from the freezer is conducted to the absorber where it is absorbed by a lithium bromide solution. The deluted absorbent passes through a surge tank, a heat exchanger and then to the generator-condenser vessel where it is reconstituted by distillation. The distillate or condensate joins the melt product downstream from the heat exchanger. Approximately one sixth of the product is distilled water and the remaining five sixths is from melted ice.

Waste brine from the wash column is in part rejected through heat exchangers and in part recycled to the freezer.

Fresh water from the melt tank is split three ways as: (a) wash water stream to top of column, (b) recirculation stream through absorber, and (c) product stream through heat exchanger.

Heat balances are preserved by means of an auxiliary refrigeration system and by exchanging product water and reject brine against incoming sea water.

4. Vacuum freezing: vapour compression system

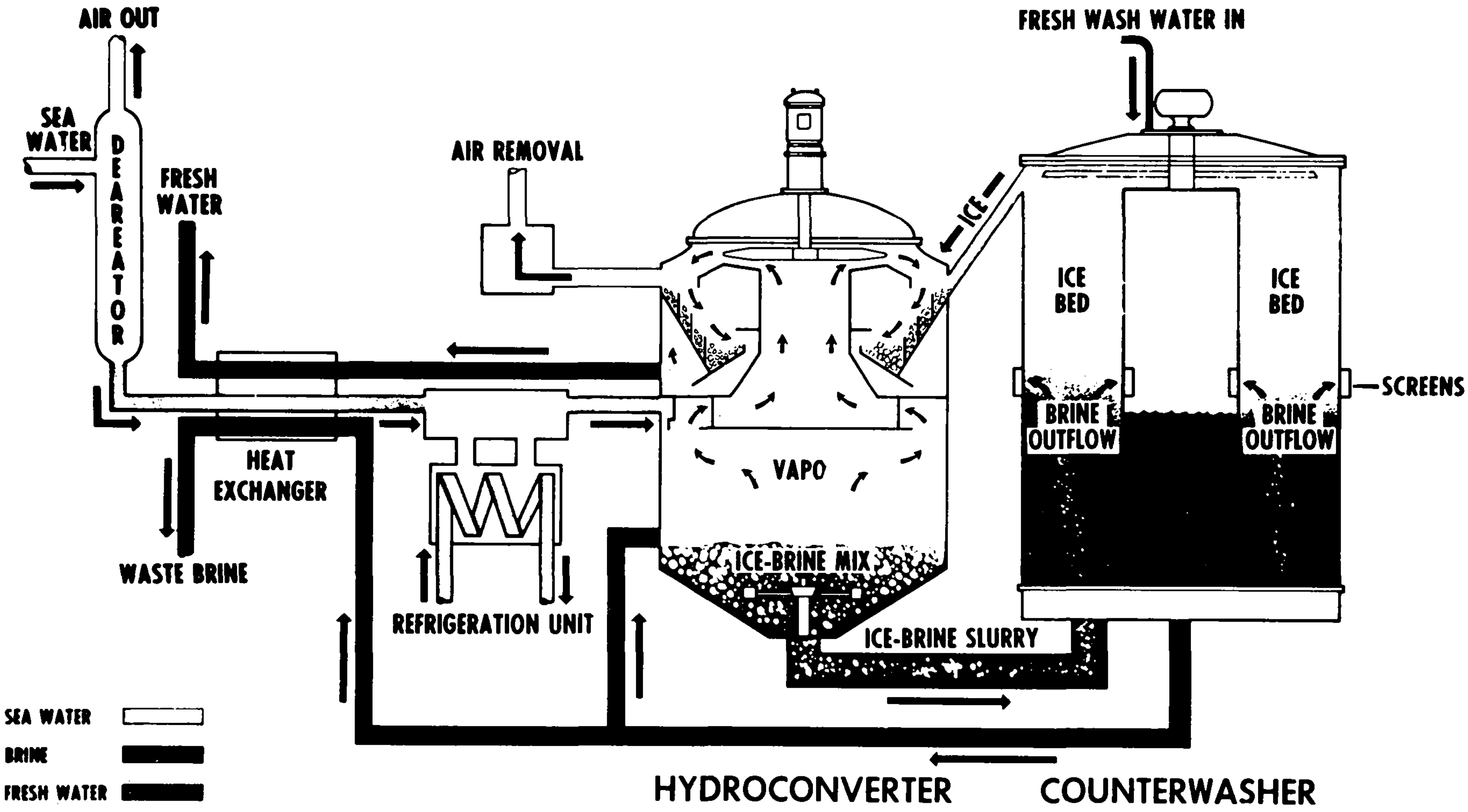
Filtered sea water enters the system at about 60-75°F, is passed through a deaerator and then through heat exchangers where it is cooled by product water to 32.3°F and by waste brine to 28.6°F (Figure IV). Deaeration of the feed stream to remove air and other non-condensible gases is necessary for the maintenance of a vacuum in the freezing and melting steps and for the promotion of good direct heat transfer in the melter.

The cold sea water is introduced into the freezer or hydroconverter at about 30°F through a nozzle assembly on the wall in the upper part of the freezing vessel. Thus a thin layer of water is distributed on the wall giving rise to a large surface area to facilitate vaporization. At a pressure of 3.2 mm of Hg absolute, a portion of the water vaporizes, removing heat and converting a portion of the water to ice. The mass ratio of ice to vapour is 7.5:1, since the latent heat of vaporization is 1,075 BTU/lb and the heat of crystallization is 144 BTU/lb. An agitator is positioned in the bottom of the freezer to maintain a good mixture of ice crystals and brine. The slurry is pumped out of the freezer and into a separation column designated the counterwasher.

The principal feature of the vacuum freezing-vapour compression system is the compressor. It consists of a slotted rotor to which thin, flexible stainless steel blades are attached. The blades assume a radial position when rotating due to centrifugal forces. The rotor operates at 36 rpm and has a top speed of 1,200 ft/sec. The compressor housing consists of two glass fibre shrouds mounted within the pressure vessel. The shrouds provide a vaneless ring chamber diffuser to convert part of the kinetic energy into static pressure. A flat baffle plate is positioned in a manner to prevent carry-over of salt water droplets into the

Figure IV

Vacuum freezing vapour compression process



compressor. Moreover, the rotational motion imparted to the vapour by inducer blades aids in removing any remaining droplets by centrifugal action.

The upper portion of the hydroconverter contains the melting chamber. This consists of a rotating basket of conical configuration which rides on a circular track by means of three rollers, one of which provides the driving force. Vertical panels are positioned in the basket to catch and retain the washed ice which is delivered via a chute from the counterwasher. The vertical panels assure even distribution of ice to provide a large area for melting. The unique arrangement of the melter in the upper part of the hydroconverter permits water vapour from the compressor to flow over the ice in the basket at 5 mm of Hg pressure, melting the ice and condensing vapour, to produce fresh water. The water flows out of the bottom of the melting chamber through heat exchangers to storage. A portion of the fresh water, less than 10 per cent, is used to wash the ice.

The counterwasher is a vertical cylindrical vessel into which slurry is pumped from the hydroconverter. The ice compacts into a porous bed which is propelled upward by a positive pressure exerted on the bed by the flow of brine through the pores and out of the column via filter screens located around the periphery and at the mid-point of the vessel. As the bed moves upward it is washed countercurrently with a stream of fresh water. A rotating knife blade scrapes ice off the top of the bed into a chute and into the melter basket of the hydroconverter. In effect, the column operates on the principle of a hydraulic piston, i.e., the upward thrust being provided by the pressure drop caused by the liquid flowing through the porous bed.

The design of any given plant is based on the modular concept of the counterwasher being sized to operate in conjunction with one hydroconverter. The capacity of the module, though not firmly established, is 60,000 gpd. The advantages of this type of ice purification system are (a) simplicity, there being no moving parts other than the cutter blade; (b) low power consumption; and (c) good efficiency, less than 5 per cent of the net water produced being required for washing.

Process auxiliaries consist of a heat removal system and an air removal system. Heat-leaks into the system generate vapour in excess of that which can be condensed on the ice produced; therefore, supplementary means of heat removal are necessary. This is accomplished by use of a condenser coil, the surface of which is maintained by an auxiliary refrigeration unit slightly above 32°F to condense vapour without production of ice.

Air and non-condensable gases must be removed from the system in order to achieve high efficiencies. This is accomplished by means of a deaerator of conventional design, which lowers the oxygen content of the feed to less than 1.0 ppm and a vacuum pump which removes non-condensables reaching the hydroconverter.

The heat exchangers used in the process are of the dimpled sheet design, consisting of Alclad sheets. These units provide heat interchange between waste brine and feed and between product water and feed. An approach temperature of about 1.6°F can be maintained during operations. Compared to the conventional shell and tube design, these exchangers are relatively low-cost items which reflect a lower investment cost.

C. Economics of freezing processes

The stringent economic requirements for the production of fresh water present a formidable problem to engineering disciplines associated with the development of desalination processes. Although the demand for water in many areas of the world is increasing, the short-range outlook for desalination is dimmed by traditionally low-cost natural water. Because of the paucity of information available today on the true cost of natural water, it is difficult to determine just when desalination will become competitive. If cost comparisons between desalted and natural water supplies were based on the true or on the replacement cost of the latter, judgements on the economic merits of desalination would be more significant. It is predicated that desalination costs will equal those of many natural water sources in the early seventies. However, in certain developing areas of the world where natural water supplies are not within the practical range of pipeline transmission, desalting plants may be competitive even now.

Studies of existing 1 million gpd multi-stage distillation plants indicate fresh water costs of about $1.18 per 1,000 gallons. 5/ The capital cost per gallon of daily capacity is $1.41. For a 1 million gpd normalized long tube vertical evaporator plant, water costs of $1.46 are obtained. The capital cost per gallon of daily capacity is $1.84. 6/ For electrodialysis plants of 0.25 million gpd capacity, operating on brackish water of about 1,800 ppm total solids, the cost is $1.40 per 1,000 gallons with a capital cost per gallon of daily capacity of $2.52. More recent data on a 650,000 gpd plant, operating on a feed of about 2,100 ppm, a cost of $0.52 per 1,000 gallons is reported. 7/

It is predicted that dual-purpose distillation plants of multi-million gallon per day capacities utilizing nuclear energy will show a substantial reduction in water costs. However, a more extensive market is emerging for small and intermediate-size plants capable of producing fresh water in the range of 35 to 45 cents per 1,000 gallons. Production plants of 3 to 10 million gpd definitely have a place in any long-range programme of development. It is believed, therefore, that freezing processes can be made to be competitive with distillation within this range of capacities.

Distillation processes have reached an advanced stage of development; electrodialysis is well established especially for the demineralization of brackish waters; hydrate systems are being evaluated in pilot plants; and freezing processes are believed to be commercially feasible. The Israeli plant at Elath, Israel, a 250,000 gpd vacuum freezing plant, is operating at 75 per cent of rated capacity.

Because of the favourable economic potential of freezing, it will be the purpose of this report to assess the possible cost of water produced in freezing plants of 500,000 and 3 million gpd capacities. These may be designated as intermediate-size installations applicable to the water needs of the average-size American community.

5/ Office of Saline Water, Research and Development Progress Report No. 114.

6/ Office of Saline Water, Research and Development Progress Report No. 72.

7/ T.A. Kirkham, Report on design, installation, start-up and operation of Ionics 650,000 gallons per day electrodialysis plant, Buckeye, Arizona.

In general, desalination involves two major items of cost, viz., energy and plant depreciation. Together these two items amount to about 60 per cent of the cost of producing water. The development of low-cost methods, therefore, will depend upon the degree to which investment and energy costs can be reduced.

D. Estimation of costs

The cost estimates of the various freezing processes described in this report were prepared in accordance with the costing procedure published by the United Nations. 8/ This procedure has been employed primarily as a guide and actual costs as determined by plant capacity, location, site conditions, electrical power rates, design parameters, interest rate on invested capital, labour rates, and quality of materials, when available, were used in preparing the data.

1. Items of investment

1.0 Preliminary research and project design.

This cost is computed on the basis of 3.0 per cent of equipment cost.

2.0 Land.

A value of $5,000 is used for the cost of land for both the 500,000 and the 3 million gpd plants.

3.0 Equipment.

3.1 The cost of equipment items is based on vendor's prices when obtainable; the cost of special items of equipment are extrapolated from pilot unit costs. Instruments, piping, buildings, electrical (other than motors), foundations, footing, and similar items are estimated or extrapolated from pilot plant costs.

3.2 Erection and installation was computed as 30 per cent of total equipment cost. This includes civil engineering associated with the foundations, intake facilities and brine disposal system.

3.3 The cost of water storage facilities, pumping equipment, pipelines for conveyance of product are estimated.

3.4 Complementary installations such as site access roads, drainage systems, fencing, and security facilities are based on extrapolations from pilot installations.

3.5 The main control building and office space, small laboratory, and maintenance shop are extrapolated from costs of similar facilities for 1 million gpd distillation plants.

8/ United Nations, Water Desalination: proposals for a costing procedure and related technical and economic considerations (United Nations publication, Sales No.: 65.II.B.5).

4.0 Engineering supervision.

Computed at 10 per cent of the above total investment costs.

5.0 Interest during construction.

Computed at 4.0 per cent of above investment costs and engineering supervision.

6.0 Performance testing.

Estimated at $25,000 for plants of both 500,000 and 3 million gpd capacities.

7.0 Contingencies.

Computed at 10 per cent of items 1.0 through 6.0.

8.0 Total investment.

Summation of items 1.0 through 7.0.

9.0 Net rated daily capacity.

Two plant sizes are considered, viz., 500,000 gpd and 3 million gpd.

10.0 Investment cost.

Investment cost in dollars per gallon per stream day is determined by dividing item 8.0 by item 9.0.

Fixed costs

11.0 Depreciation.

Based on a plant life of twenty-five years, depreciation rate is computed at 6.25 per cent of item 8.0 minus item 2.0.

12.0 Interest.

Interest rate at 3.5 per cent per annum. This rate is included in item 11.0.

13.0 Insurance and taxes.

Computed at a rate of 2.0 per cent of item 8.0 minus item 2.0.

14.0 Operation.

Salaries, wages, and materials such as lubricating oils, cleaning materials, log-sheets, office supplies, etc., costs are computed in accordance with a study carried out by the Bechtel Corporation for the Office of Saline Water. This study included actual costs incurred in the operation of the 1 million gpd distillation plants at Freeport, Texas, and San Diego, California. Costs were based on a two-man-per-shift operating requirement, one regular day man and one relief operator for vacations and sick leave. Base pay was taken as $3.09 per hour with 3 per cent bonus for swing shift and 5 per cent for midnight shift. A one-half-time supervisor was allowed at $4,800 per year. Operating labour will vary considerably depending on the location of the plant.

15.0 Maintenance.

Labour requirements were considered standard for all freezing processes studied and are computed at 1.25 per cent of the total plant investment.

16.0 Rent.

This item of cost is omitted from the cost estimates of freezing plants.

Variable costs

17.0 Energy.

Energy costs are computed on the basis of horsepower requirements, thermodynamic irreversibilities, electrical, and mechanical inefficiencies. With the exception of the vapour absorption process, the systems studied are powered by electricity.

18.0 Cost of raw water.

It is assumed that a constant source of raw water is available at no additional cost.

19.0 Raw materials and chemicals.

The cost of refrigerants are computed at their prevailing market price plus freight. Losses of refrigerant are also taken into consideration. The freezing process does not require pre-treatment chemicals as scaling is not encountered during operations.

20.0 Total annual costs.

Summation of items 11.0 through 19.0.

21.0 Effective annual output.

This item is a function of the load factor and daily production. Costs are computed on the assumption that a freezing plant will operate 330 days per year. The load factor is expected to vary depending on location of the plant.

22.0 Average cost per unit of production.

This value is obtained by dividing item 20.0 by item 21.0 and expressing the result in dollars per 1,000 gallons.

2. General

Estimated costs are given for several variations of freezing processes including two secondary refrigerant systems, a vacuum freezing-vapour absorption system and a vacuum freezing-vapour compression system. The half-million gallon per day plant is selected for study because it is believed that this size will meet the needs of a large segment of communities in water-short areas. The 3 million gallon per day plant is included to show the economic advantage of scale-up.

The vacuum freezing-vapour absorption process was extensively evaluated in a 15,000 gpd pilot plant and shown to be economically unfavourable. It is included because it represents a variation of direct contact freezing and except for the manner in which the water vapour is handled it is similar to the vacuum freezing-compression process.

Because of the promising application of freeze-separation to plants of intermediate size, cost estimates of plants designed to demineralize brackish waters of 5,000 ppm total solids are included for comparison. It is believed that such plants would be especially attractive for locations in the south-western United States and in those areas where large supplies of brackish waters as well as low-cost electrical power are available.

3. Cost of water

A typical example of the method used in costing a process is shown in table 1. As indicated above, the values assigned to the various items considered in the cost estimating procedure are based on the best knowledge and data available at present. The values are subject to change as more and more large-size plants are built and operated. As would be expected, these values will vary throughout the world. Therefore, cost differences with respect to labour, materials of construction, freight, power, etc., will modify to some degree the cost figures presented in this report. These figures serve only as temporary benchmarks of comparison and are subject to change as freezing technology advances.

The cost of producing fresh water, in cents per 1,000 gallons, by means of the various freezing processes is presented in table 2.

The energy requirements of each system are given in table 3.

Table 1

Costing of single-purpose desalination plant

Vacuum freezing-vapour compression

Items of investment		500 MGPD ($ X 1,000)	3 MMGPD ($ X 1,000)
1.0	Preliminary research and design	15	50
2.0	Land	5	5
3.0	Equipment	510	1,810
3.2	Erection and installation (30% of item 3.1)	153	543
3.3	Storage, pipelines, and pumps	15	50
3.4	Complementary installations	25	50
3.5	Buildings	20	30
4.0	Engineering supervision	74.3	253
5.0	Interest during construction (4% of items 1.0 through 4.0)	32.6	111.6
6.0	Performance testing	25	25
7.0	Contingencies (10% of items 1.6 through 6.0)	87.5	292.7
8.0	Total investment	962.4	3,220.0
9.0	Net rated daily capacity	500 MGPD	3 MMGPD
10.0	Investment cost ($/gal/day)	1.90	1.07

Annual operating costs

Fixed costs		500 MGPD ($ X 1,000)	3 MMGPD[a] ($ X 1,000)
11.0	Depreciation, 25 years Item (8.0 - 2.0) X 6.25%	60.0	201
12.0	Interest - 3.5% per annum. Included in item 11.0	-	-
13.0	Insurance and taxes 2.0% of item (8.0 - 2.0)	19.0	64.3
14.0	Operations, wages, salaries and materials	68.5	68.5
15.0	Maintenance, 1.25% of item (8.0 - 2.0)	12.0	40.0
16.0	Rent	-	-
Variable costs			
17.0	Electricity at 7 miles/kWh	35.8	142
18.0	Cost of raw water	-	-
19.0	Raw materials and chemicals	-	-
20.0	Total annual costs	195.3	515.8
21.0	Effective annual output	165 MMGPD	990 MMGPD
22.0	Cost per 1,000 gallons ($)	1.18	0.52

M = thousand gallons.

MM = million gallons.

[a] Brackish water of 5,000 ppm total solids.

Table 2

Cost of producing fresh water by freezing

				¢ / 1,000 GALLONS				
Process	Capacity GPD	Investment \$ X 1,000	\$/Gal/Day	Depreciation	Power[a]	Operations	Miscellaneous	Product
A	3 MM	4,445	1.48	28	22	14	12	76
B	500 M	869	1.74	35	22	50	15	122
C	500 M	790	1.58	33	16	48	14	111
D	3 MM	4,406	1.46	29	22	14	13	78
E	500 M	896	1.79	37	22	50	15	124
F	500 M	962	1.90	36	21	49	15	118
G	500 M	913	1.83	37	14	49	15	115
H	3 MM	3,220	1.07	20	14	11	9	52
I	500 M	1,250	2.50	51	63[b]	52	18	184

A - Butane secondary refrigerant - sea water.

B - Butane secondary refrigerant - sea water.

C - Butane secondary refrigerant - brackish water.

D - Butane controlled crystallization - sea water.

E - Butane controlled crystallization - sea water.

F - Vapour compression - sea water.

G - Vapour compression - brackish water.

H - Vapour compression - brackish water.

I - Vapour absorption - sea water.

[a] 7 mills/kWh.

[b] Includes steam costs.

Table 3

Energy requirement for freezing processes

	kWh/1,000 gallons
Butane refrigerant - sea water	34.5
Butane refrigerant - brackish water	24.3
Butane refrigerant - controlled crystallization - sea water	31.0
Vapour absorption - sea water	46.0
Vapour compression - sea water	31.0
Vapour compression - brackish water	20.5

E. Problems associated with the development of freeze-separation processes

1. Butane freezing process

The use of butane as a secondary refrigerant in the direct contact freeze-separation process has been brought to a relatively advanced stage of development. Pilot plant studies up to 55,000 gpd production rates have pointed up design features that might prove advantageous for large size plants. It is proposed, for example, to design the washer-melter as a long horizontal tank, with washing taking place in the space between parallel walls rather than within a cylinder.

Variables affecting performance of the freezer are brine retention, brine concentration, slurry concentration, slurry circulation rate, temperature differential for butane vaporization, and ice flow. Washer performance depends on control of brine and wash water flow rates and of hydraulic pressure at the brine filter screens, proper distribution of ice slurry, a satisfactory method of ice cutting from top of the bed and mechanical design of the washer to assure smooth ice flow. It is expected that the torus shaped freezer would be a relatively low cost item compared with the washer-melter.

Because of the strong tendency of brackish waters to cause scale formation in distillation processes, freeze-separation, which is unaffected by scaling, has been suggested as a method for desalting waters of high hardness values. Although little or no experimental work has been carried out using brackish water feed, there are a number of factors which offer good supporting evidence that freezing may offer a favourable economic potential in this area of desalination.

That the cost of conversion of brackish water by freezing is less than that for sea water is indicated by the following observations:

(a) Product yield is higher. Heat interchange surface which is directly proportional to the feed rate may be reduced by a factor of 0.6.

(b) Primary compressor CFM remains essentially the same; however, compression ratio is reduced from an average of 1.26 to 1.17.

(c) Secondary compressor duty is reduced because there is less heat added to the system at the interchanger as a result of reduced feed rate, and because there is a correspondingly smaller refrigeration load.

(d) The capacity of the washer is increased because there is less salt to remove.

(e) Because of the lower salinity of the feed, the crystals made in the freezer are larger and, therefore, easier to wash. The washer-melter of a corresponding sea water plant may be reduced by a factor of 0.75.

(f) The debutanizer may be reduced in capacity by a factor of 0.24, the ratio of brine flow in the brackish water plant to that in the sea water plant.

As a result of the reduction in equipment size (feed and brine pumps may be reduced in size), investment costs are expected to be lower. Likewise, a reduction in energy requirement from 34.5 kWh to 24.3 kWh/1,000 gallons of product water (table 3) is to be anticipated on the basis of a smaller freezing point depression and lower horsepower requirements in the brackish water plant.

The temperature of the feed stream also affects the energy requirements, in investment and operating costs. In a temperate climate the feed stream may vary from 40°F in the winter to 85°F in the summer. Operation in colder climates favours the economy of freezing systems since investment costs in heat exchangers and secondary compressors are reduced. However, in climates where sub-freezing temperatures are experienced, some added costs would be expected because of the need for winterizing the equipment.

Cost of water

For the butane process, cost estimates for 3 million and 500,000 gpd plants were prepared. The higher operational cost for the smaller plant would be expected. A 3 million gpd plant of the same design would effect a considerable reduction in the cost of product water. This reduction would be reflected principally in a lower operating cost. A 500,000 gpd brackish water plant using a feed of about 5,000 ppm salinity would produce fresh water at $1.11 per 1,000 gallons. Plants in this category would operate largely at inland locations and in non-sea water atmospheres. This may result in an added advantage of less corrosion than plants located on the sea coast. If so, a thirty-year life instead of the usual twenty-five-year period of depreciation may be applicable and thus reduce the cost of depreciation.

2. Butane freezing: controlled crystallization process

It was believed that better wash-separation could be brought about if the size of the ice crystals were larger. Studies showed that crystal growth could be induced by controlling the degree of nucleation. This was accompanied by special type agitation and by increasing residence time in the crystallizer.

Ice crystals of 0.75 to 1.5 mm could be obtained by this procedure. To facilitate wash-separation a centrifuge was used. Experiments to date, however, have failed to demonstrate the technical feasibility of the centrifuge. A 200,000 gpd conversion plant equipped with two centrifuges is being evaluated at Wrightsville Beach, North Carolina.

Cost of water

A cost estimate of this process based on plants of 500,000 and 3 million gpd capacities is included in this study for comparative purposes. As indicated in table 2, the cost of product water compares favourably with that of the butane secondary refrigerant process.

3. Vacuum freezing: vapour absorption process

The vapour absorption process was evaluated at the small pilot plant level and cost estimates were prepared from data obtained over a 2-1/2 year period of operation.

The cost estimate is based on the most advanced designs which were considered feasible at the time. The largest single unit considered practical for this type of refrigeration is about 500,000 gpd.

Cost of water

Cost projections assumed that additional improvements would be possible in the future. However, investment cost for a 500,000 gpd plant was much larger than that of the secondary refrigerant process. It was concluded that the vapour absorption process supplying fresh water at $1.84 per 1,000 gallons was commercially non-competitive.

4. Vacuum freezing: vapour compression process

The major advantage of vapour compression over vapour absorption is that the large volumes of water vapour are compressed directly on the ice rather than being chemically absorbed. Thus no steam or regenerating equipment is required in vapour compression. Both methods, however, share the advantage that the product water contains no traces of refrigerant, thus eliminating the degassing operation.

The vapour compressor which is an integral part of the hydroconverter is a feature of the process which contributes to the low cost and high efficiency of this system. All other components are more or less standard items. The counterwasher functions on the hydraulic piston bed principle and its design features are very similar to wash columns developed by others for the freezing process.

The heat removal system is designed to maintain equilibrium of the process. The difference in temperature between incoming sea water and outgoing brine and product water is the principal source of heat leakage into the system. The plate-type heat exchanges of low-cost construction have been designed to keep approach temperature small.

Since the amount of water vapour produced is in excess of the amount that can be condensed on the washed ice, a supplementary heat removal system is employed. Originally, this consisted of a Pac-Ice machine which removed heat from the feed before it entered the freezer. Currently the excess vapour is condensed on a refrigerator coil placed in the melter. The coil surface is maintained slightly above 32°F and condenses vapour without producing ice.

Cost of water

Present data for the estimation of costs were obtained from the operational evaluation of a 60,000 gpd module at Beloit, Wisconsin. One of the features of the vapour compression system is that no chemicals or refrigerants are required. The product, therefore, requires no clean-up treatment as is the case with the secondary refrigerant process. The cost of chlorinating the product was not included in the figures given in table 2.

The vapour compression system would appear particularly attractive for brackish water conversion. For a 3 million gpd plant the cost of water is $.58 per 1,000 gallons.

F. Future of freezing processes

The earliest desalination method employed by man was based on evaporative methods. This technique was familiar to ancient societies. Today, evaporation remains the principal method of desalting sea water and as a result claims more man hours of research and development than any other process. The technical and economic merits of distillation have been extensively reviewed. It is well recognized that of all processes or systems currently under investigation, distillation is perhaps the only process ready for escalation to plant sizes of 25 to 50 million gallons per day capacities.

The freezing process has elicited attention because of its inherently low energy requirements. The power requirements shown in table 2 for the various freezing systems are relatively low when compared with values for distillation processes calculated on the same basis. As was indicated above, all development work was carried out in a manner that would take advantage of this relatively low energy requirement.

Operational experience in several locations has demonstrated that corrosion of equipment in contact with sea water is minimized because of the low temperatures employed by the process. This feature, together with the fact that no scaling or fouling of equipment surfaces by inorganic constituents of sea water have been observed during a number of prolonged periods of operation.

Because of the high concentration of salts contributing to formation of scale which is found in many brackish waters, the freezing process has been recommended for use in the arid southwestern United States where there is a plentiful supply of brackish water. The lower salinity of brackish waters should also assist in minimizing costs. The smaller freezing point depression should give a lower kWh energy requirement and the less concentrated mother liquor sent to the wash column should facilitate separation of ice-brine mixtures.

For sea coast operation, a low temperature sea water feed would be advantageous; however, freezing process plants operating in sub-freezing temperatures would require additional winterizing to preclude freeze-up in the event of operational difficulties.

Wash-separation presents a problem not encountered in distillation, viz., a part of the product must be utilized for washing traces of mother liquor from the ice. Thus, if 5 per cent fresh water is required for washing, a total of 105 pounds of ice will have to be formed for every 100 pounds of fresh water produced. To date no solid phase separation process has yielded fresh water without using a portion of the total product formed.

The freezing process would be amenable to automated control. What the future cost of increased automation would be in terms of reducing operating labour costs remains to be determined. However, it does point up a potential savings.

Operation in conjunction with a power or other processing plant in which operating labour could be shared offers a possible way of reducing over-all labour costs.

A countercurrent, staged heat exchanger for transferring heat between two aqueous streams has also been proposed as a means of minimizing approach temperatures. This may be carried out by vaporizing an immiscible transfer agent from the stream being cooled and condensing it in the stream being warmed. Preliminary studies showed that heat transfer coefficients in the range of 150,000 BTU/hr-ft^2-^{o}F., at a liquid rate of 40,000 lbs/ft^2-hr., were obtained. This could result in greater energy economies because a lower driving force could be used.

The cost of desalting water by freezing might be lowered by combining operations with the production of by-products. For example, waste brine may be processed for the recovery of such elements as magnesium, bromine, fluorine and salt. Multiple-purpose operations of this nature would result in the allocation of the total joint cost over a wider range of products. Chemical complexes of this type would be considered for areas having a good potential for industrial growth.

In dual-purpose plants designed to produce both water and electricity, the waste brine could be used to produce chlorine and hydrogen chloride. Caustic soda and hydrogen gas, products widely used by industry, could also be produced in dual purpose plants.

Freezing plants designed to operate at a low load factor could be employed to provide cooling water for air conditioning and cold storage. The allocation of joint costs in a combined water and cold storage operation has not been determined. However, most American communities would require operations at an 80-90 per cent load factor.

G. Conclusions

(1) Desalination of sea water by freezing techniques appears economically attractive because of a low energy requirement. The use of low-cost electrical energy would contribute appreciably to a reduction in the cost of product water.

(2) Desalination of brackish waters indicates even more favourable economics than that of sea water. Cost reduction stems from a higher yield, larger crystal size, lower compressor load, and smaller size equipment.

(3) Scale formation and corrosion are minimized in the operation of a freezing process. Cost reductions are reflected, therefore, in the longer life of the equipment.

(4) The vacuum freezing-vapour compression system designed on a modular basis and employing a relatively inexpensive compressor offers a favourable potential for the construction of intermediate-size conversion plants.

IX. FREEZING PROCESSES:

OPERATIONAL DATA AND PRESENT STATUS OF TWO FREEZING-PROCESS DESALINATION PLANTS

by A. Peled

In my presentation, I should like to dwell specifically on the actual results obtained in two plants, and refer subsequently to the various possibilities latent in general in the freezing process.

The history of these two plants is as follows:

A company, jointly owned by the Government of Israel and Colt Industries, Inc., has been engaged since 1960 in the development of the vacuum freezing-vapour compression process. Following the laboratory, unit operation and pilot plant states of development, a full size, 10 m^3 per hour test unit was built in Beloit, Wisconsin in 1962. After this unit had been in operation for a few months, a four-module plant was built to the same design, and erected at the Red Sea port of Eilat, Israel. This plant was started up in January 1964, and has been in operation ever since.

Before reporting on the Eilat plant, let me first describe briefly the evolutionary process undergone by the test unit at Beloit. In this unit, which has been operated for test purposes only, and in closed circuit, great strides have been made in the following directions:

- the agitation and general operation of the freezer were greatly improved, signified by reaching heat transfer coefficients of over 75,000 kcals/hr x m^2 x °C. An effective carry-over separator was developed.

- the over-all efficiency of the vapour compression system was appreciably raised.

- the operation of the "dumped" ice melter was perfected, resulting in very high heat transfer coefficients.

This unit finally reached almost double the nominal production rate, with commendable reliability. It has recently been transferred to Wrightsville Beach, and is at present being operated there under contract with the United States Office of Saline Water.

The plant at Eilat is situated where high salinity, corrosive feed water and a hot climate (up to 45°C) pose the most severe testing conditions for the freezing process. In operating a full-scale plant under such conditions, we wanted to test the various design features, the different items of equipment, the instrumentation and control system and the various operational characteristics. The original design and choice of components were found wanting in a number of ways. We found that deaeration of the feed water was ineffective - but also unnecessary; many pumps were found to be inadequate - but quite a few could be dispensed with altogether; the heat removal system using ice-making machines was found to be unreliable and to be a high energy consumer, and so on. But we also proved that the process was definitely operational.

For over a year the plant was run under varying operational conditions, with only minor modifications, supplying drinking water to the town of Eilat, which had until then subsisted on brackish water only.

Recently, however, we started a thorough modification programme, based on the experience gained at Eilat, on improvements introduced and proved at Beloit, and on several innovations evolved in our pilot plants at Tel-Baruch, Israel.

Thus a substantial modification has recently been completed on Module No. 1.

Its operation has since shown much improved reliability, and a lower energy consumption. Module No. 2 is now scheduled for an even more extensive modification, including a new brine drainage system, aimed at a higher production rate and a better over-all performance.

Let me refer more specifically to energy consumption figures.

Theoretically, the freezing process may be developed to consume 6 to 7 kWh/m^3. The original Eilat model consumes about 22 kWh/m^3 at nominal capacity. Improvements carried out at Beloit, and the intermediate modifications carried out on Module No. 1 at Eilat have reduced this figure to about 15 kWh/m^3. The design currently being prepared for our next modifications ensures a total energy consumption per m^3 of 12 kWh or less.

The present-day "standard" unit is thus a 400/500 m^3 per day module. Plants consisting of one to four or more such modules may be built, costing, on a turn-key basis, roughly from $300,000 for a single-module plant to $850,000 for a four-module, 1,800 m^3 per day plant.

As for the salinity of the product, we can without difficulty regularly produce water at 250 ppm of total dissolved solids. A 100 ppm product can be reliably produced with only about 1-2 per cent drop in production. In fact, at Eilat we have provided the starting-up water for the local power plant with a salt content of less than 30 ppm.

Our present design has the following features:

- Production - 400/500 m^3 per day per module.
- Conversion ratio: about 40 per cent.
- No deaeration is required.
- Wells are recommended for raw water intake.
- Sheet-type heat exchangers are used.

Each module consists of two cylindrical vessels, four metres in diameter and five metres high.

The main vapour compressor is of the flexible blade type, driven directly.

A combined heat and air removal system (comprising a vapour compressor, a refrigerated condenser and a vacuum pump) is used.

Energy requirements

Main vapour compressor	4.7 kWh/m^3
Secondary vapour compressor	0.8 "
Refrigeration compressor	2.8 "
Various pumps and auxiliaries	3.7 "
Total	12.0 kWh/m^3

Operation and maintenance crews (including shifts) may be taken at seven to eight men for one and two module plants, and eleven to twelve men for the three and four module plants. It must be remembered that in a multi-module plant, seasonal variations in demand may be met by operating only some modules - with no penalties of higher running costs.

To sum up, the general characteristics of the freezing process may be stated as follows:

(1) An energy consumption of 12 kWh/m^3 is obtainable today in 400 m^3/day units, using the vacuum freezing process. Appreciable improvement to this figure may reasonably be expected. Larger units are being designed.

(2) Scale and corrosion problems are negligible.

(3) Freezing plants in the small and medium-size range have a relatively small investment cost.

(4) In the secondary refrigerant process, which is also being developed by our company, single modules for up to 20,000 m^3/day are now being studied, with a calculated energy consumption of 7-8 kWh/m^3.

(5) The possibility of utilizing low-price electricity provided from the central grid in plants located close to consumer centres is a decided advantage. Even with local diesel generating plants, energy costs come to no more than United States $0.12-0.15 per m^3 at the present stage of development.

(6) The freezing process thus offers an efficient and reliable solution for small-size plants today with prospects of widening the range in the future.

X. OTHER DESALINATION PROCESSES: REVERSE OSMOSIS, HYDRATES, ION EXCHANGE

by J. J. Strobel

There are several desalting processes in addition to those of distillation, electrodialysis, and freezing which, through extensive laboratory and some pilot plant work, have emerged as possibilities for practical and economical applications in the future. The use of osmotic membranes to effect separation through application of pressure greater than the osmotic pressure, i.e., reverse osmosis, is one of these. The use of a hydrocarbon such as propane to form propane hydrate to separate fresh water from saline is another. Ion exchange processes to completely demineralize waters of very low salinity have been in use for many years. Developments recently announced by several commercial organizations in this field indicate that these may be economically attractive on brackish waters up to 3,000 ppm total dissolved solids.

It is the purpose of this paper to describe briefly these other processes, to indicate the status of their development, and to provide some very preliminary consideration of conversion costs.

A. Reverse osmosis

The principles of the process and the origin of the term "reverse osmosis" are illustrated in Figure I. If a saline solution is separated from pure water by a semipermeable membrane (one which permits the passage of water but prevents the passage of salt), pure water will flow into the saline solution with the necessary driving force being provided by the difference in salt concentration between the two solutions. This flow will continue until the hydrostatic pressure on the salt solution is just sufficient to prevent the further flow of pure water into the saline water chamber. The movement of pure water into the saline water is called osmosis, and the pressure at which the flow of pure water ceases is known as osmotic pressure of the saline solution.

The normal process of osmosis can be reversed if sufficient pressure is applied to the saline solution to overcome the osmotic pressure and thus cause pure water to flow out of the saline solution in a direction opposite to the osmotic flow, hence the term "reverse osmosis". The driving force in this reverse case is hydraulic pressure.

This principle can be translated into a conversion process assuming that appropriate membranes are available. The essential features of a reverse osmosis desalination system are illustrated in Figure II. Feed water is pumped to a pressure in excess of its osmotic pressure and passed through a separation unit which contains semipermeable membranes. A portion of the water permeates the membranes, and is collected as desalinated water at atmospheric pressure on the other side of the membrane. The concentrated brine, still at essentially its entering pressure, is passed through a recovery turbine to conserve its contained energy, and discarded.

Potential advantages of this process include the following:

(1) Low energy requirements. No phase change is involved which inherently makes for a lower thermodynamic energy requirement and tends to simplify the operations. This is in contrast to the distillation, freezing, and hydrate processes where phase changes are necessary.

(2) Possible simplicity of required equipment.

(3) Normal temperature operation resulting in minimum corrosion and scaling problems.

(4) General applicability to both sea and brackish waters.

An initial research programme was undertaken in 1953 at the University of Florida. The salt reject properties of cellulose acetate were discovered and it was shown that purification of saline waters by this method was technically feasible. 1/ However, the available films which showed this property also had too low a transmission rate of the desalted water for practical and economical applications.

Developments in 1960 2/ of an improved technique for fabricating cellulose acetate membrane made possible greatly increased transmission rates in excess of 10 gpd per square foot per day with salt rejections of 95-99 per cent. Further improvements in membranes and techniques for using them have been accomplished in recent years through Office of Saline Water contracts with several industrial contractors. 3/ 4/ Small pilot units with capacities of 1,000 gpd have been operated for extensive periods of time on both sea water and brackish water. Several design concepts are under investigation including a plate-and-frame method and a spiral modular concept. Recently the University of California has announced installation of a 3,500 gpd pilot plant to operate on brackish water at Coalinga, California.

As with other conversion processes in relatively early stages of development, it is possible to make only a preliminary cost estimate based on a great many assumptions because of the lack of prototype plant or even extensive pilot plant data. Parametric studies now under way of a 1 million gpd reverse osmosis plant operating on sea water feed indicate cost in a range of 60-90 cents per 1,000 gallons using the Office of Saline Water process comparison cost criteria of an annual capital charge factor of 7.4 per cent and a power cost of 7 mills/kWh. An earlier projection for a very large 1,000 mgd plant for the 1980's projected a

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1/ J.B. Burton, Jr., Office of Saline Water Research and Development Report No. 16 (April, 1957).

2/ S. Loeb, UCLA Department of Engineering Report No. 61-42 (August, 1961).

3/ Aeroject General Corporation, Office of Saline Water Research and Development Report No. 117 (1965).

4/ General Atomic, Office of Saline Water Research and Development Report No. 111 (May, 1964) conversion cost of less than 25 cents per 1,000 gallons. 5/ The development steps planned for the years immediately ahead wherein reverse osmosis test bed plants up to 250,000 gpd would be built and operated should provide needed data on both plant and operating costs so that firmer extrapolations and projections can be made.

B. Propane hydrate process

One of the more recent approaches to saline water conversion is that of chemically separating pure water from salt solution by the use of hydrate forming materials. Certain compounds such as low molecular weight hydrocarbons or their halogen derivatives combine with water to form solid clathrate compounds which are inclusion complexes in which molecules of one substance are contained or enclosed within the crystal lattice of another component. Like ice crystals, clathrates reject ionic constituents and accept only pure water molecules in their lattice. The crystals are separated from the mother liquor either by filtration, column washing employing the hydraulic piston bed technique, or cyclone separation, then washed free of mother liquor and decomposed into two immiscible liquids: the liquid hydrating agent which is recycled and salt-free water. The process flow for the hydrate system is shown in Figure III.

Sea water feed is heat-exchanged against product water and reject brine steams. It then enters the reactor where it is mixed with liquid propane at 35°F. and 57-pounds-per-square-inch gauge. Propane hydrate crystals form as a solid phase. The propane serves both as hydrate former and a secondary refigerant to control the reaction temperature. The hydrate-brine slurry is pumped to a filter-washer where hydrate is separated from the mother liquor and then pumped to the melter. Liquid propane from the melter is recycled to the reactor. Propane vapour from the reactor is compressed and condensed on the washed hydrate crystals to effect decomposition to liquid propane and fresh water. Excess propane vapour which does not condense on the hydrate crystals is removed and compressed by a secondary compressor. The vapour is then condensed by heat interchange with sea water, potable water, and waste brine streams. From the melter a portion of the fresh water is cycled to the washer to wash the hydrate crystals and the remainder is sent to storage after heat exchange with the incoming sea stream. A portion of the reject brine is recycled to the reactor to control viscosity of the reaction mixture while the remainder is heat-exchanged against incoming sea water and then discarded.

Like freezing, the hydrate has several potential advantages over other methods of desalination. It is similar to freezing in that the separation of water involves the formulation of an insoluble phase which must be washed free of brine. Since the hydrate process is operable over a range of modern temperatures, depending on the hydrating agent used, problems of scale and corrosion are minimized. From the standpoint of energy considerations, the hydrate process has an advantage over freezing. For example, in pure water ice exists at 0°C, whereas propane hydrate exists at 5.7°C. This difference of 5.7°C is also maintained in salt solutions irrespective of concentration. Thus, the propane hydrate process, operating at temperatures above those employed in freezing, offers the potential advantages of lower energy requirement and investment costs.

5/ Office of Science and Technology, An Assessment of Large, Nuclear-powered Sea Water Distillation Plants (Report of Interagency Task Force, 1964).

In 1959, the Office of Saline Water supported, under a co-operative contract, the development of a hydrate process based on a patented process. Most of the work 6/ was carried out in bench-scale equipment including a 10-gallon reactor-crystallizer with a capacity equivalent to 150 gallons of potable water per 24 hours. In addition, laboratory research was done on the hydrate forming reaction and calculations were made to evaluate the processing steps. In this process, two methods of washing the hydrate crystals have been investigated at the bench-scale level. These methods are (1) filtration and (2) column washing using the hydraulic piston bed technique.

In view of the promising bench-scale work, a 10,000 gpd pilot plant to evaluate this process is being built. Scaled-down experiments will be conducted in the pilot plant on the two different methods of wash separation in order to determine which method will be used for additional pilot plant studies. The pilot plant is expected to be completed about September 1965.

Also being investigated is another hydrate process which employs cyclones for washing the hydrate crystals and which is based on a different patented version. 7/ This process had an initial development by industry in a small 700 gpd pilot plant. After supporting further development of the process in the 700 gpd pilot plant, the Office of Saline Water contracted for the design and construction of a 20,000 gpd pilot plant at the Research and Development Test Station, Wrightsville Beach, North Carolina. Operational evaluation of the pilot plant has started.

The hydrate processes, using propane as the hydrate former, are less advanced than freezing processes. Although problems similar to those experienced in freezing studies will undoubtedly arise, it is expected that the technology will move ahead more rapidly because solutions to freezing problems will in part be applicable to hydrates.

In regard to cost, it can be expected that water cost from this conversion process will be in the same range as that predicted for the secondary refringement processes which have been discussed in Lecture 9 "Freezing processes: present technology and related problems."

C. Ion exchange

Ion exchange processes pass saline water through an ion exchange material. Figure IV is a typical ion exchange flowsheet. This material has the ability to exchange one ion for another, hold it temporarily in chemical combination, and give it up to a regenerating solution. Salt can thus be removed from saline water. Ion exchange desalination has been used effectively to obtain small quantities of fresh water from sea water in special applications, such as emergency kits for life-rafts. A few United States Department of Defense installations, such as radar warning stations, have successfully used ion exchange desalination for producing limited quantities of potable water from brackish water. Also, ion exchange

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6/ Koppers Company, Office of Saline Water Research and Development Reports Nos. 90 and 125 (March, 1964 and 1965).

7/ Sweet Water Development Company, Saline Water Conversion Report for 1964 (Office of Saline Water), pp. 190-192.

demineralization has shown advantages for obtaining fresh water of very low dissolved solids for special industrial and other uses. Ion exchange processes have been too costly to consider for desalination of appreciable quantities of sea water or highly brackish water. However, there have recently been announcements of several developments by commercial firms 8/ 9/ which make use of newly developed ion exchange resins together with new approaches to low-cost regeneration of the resins, with predictions that ion exchange desalination can be lower in cost than electrodialysis when applied to waters up to 3,000 parts per million total dissolved solids.

8/ R. Kunin and Vassiliow, Industrial and Engineering Chemistry, vol. 3, "Process Design and Development" (1964).

9/ Nalco Chemical Company, Chemical and Engineering News (22 February 1965).

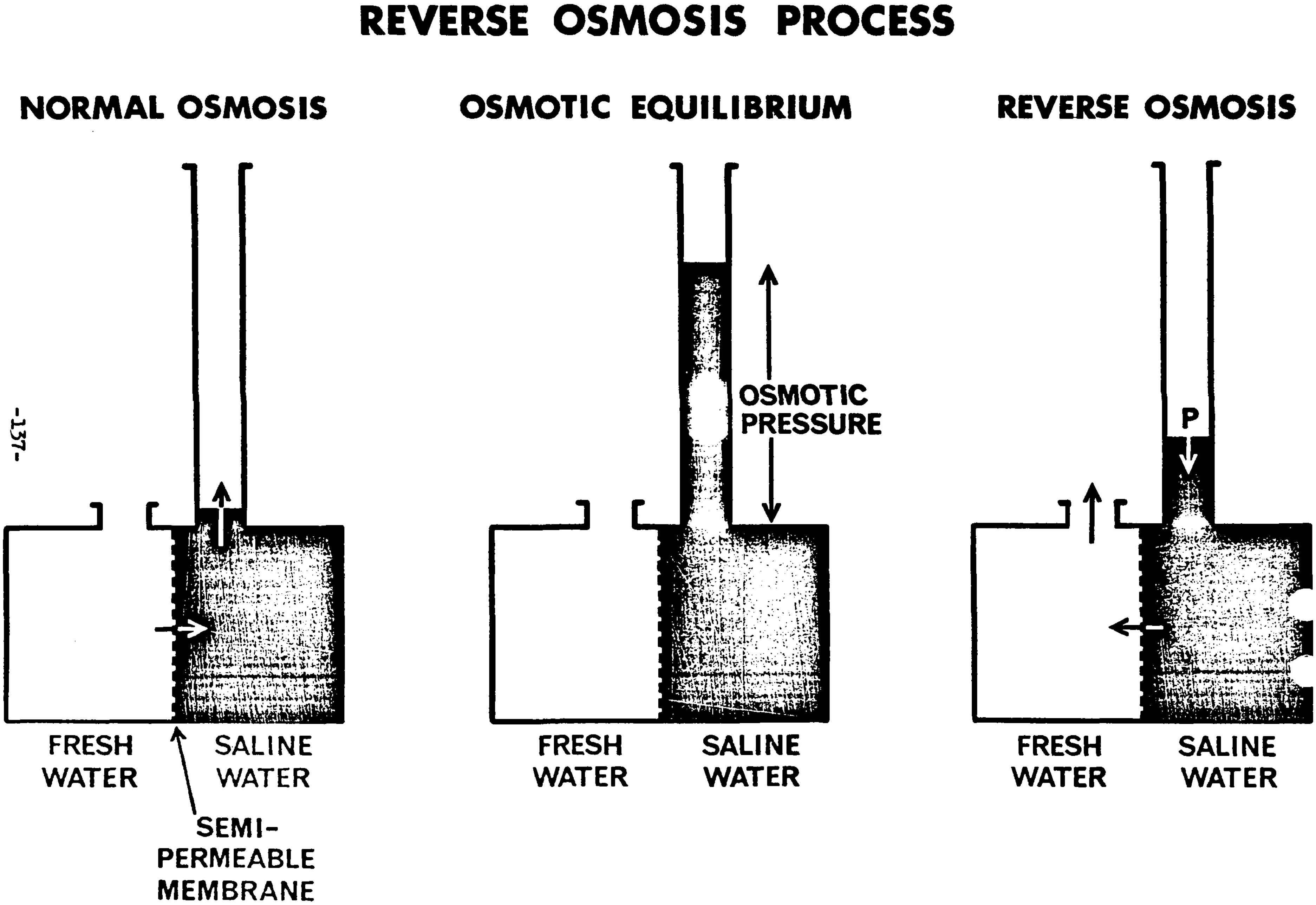
REVERSE OSMOSIS PROCESS
NORMAL OSMOSIS
OSMOTIC EQUILIBRIUM
REVERSE OSMOSIS
OSMOTIC PRESSURE
P
FRESH WATER
SALINE WATER
SEMI-PERMEABLE MEMBRANE
FRESH WATER
SALINE WATER
FRESH WATER
SALINE WATER

Figure I

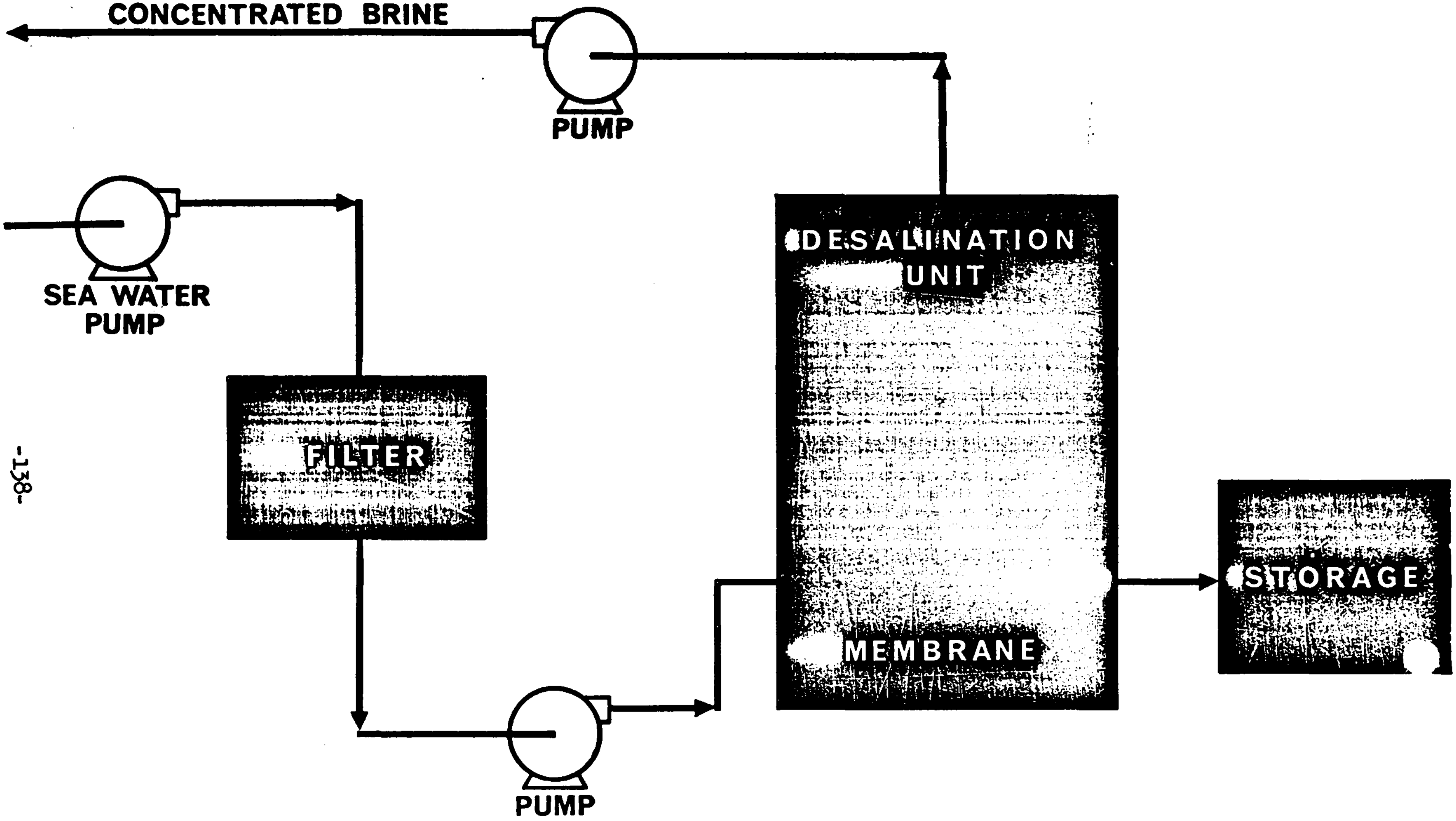
CONCENTRATED BRINE
PUMP
SEA WATER PUMP
FILTER
DESALINATION UNIT
MEMBRANE
STORAGE
PUMP

Figure II

PROPANE HYDRATE PROCESS

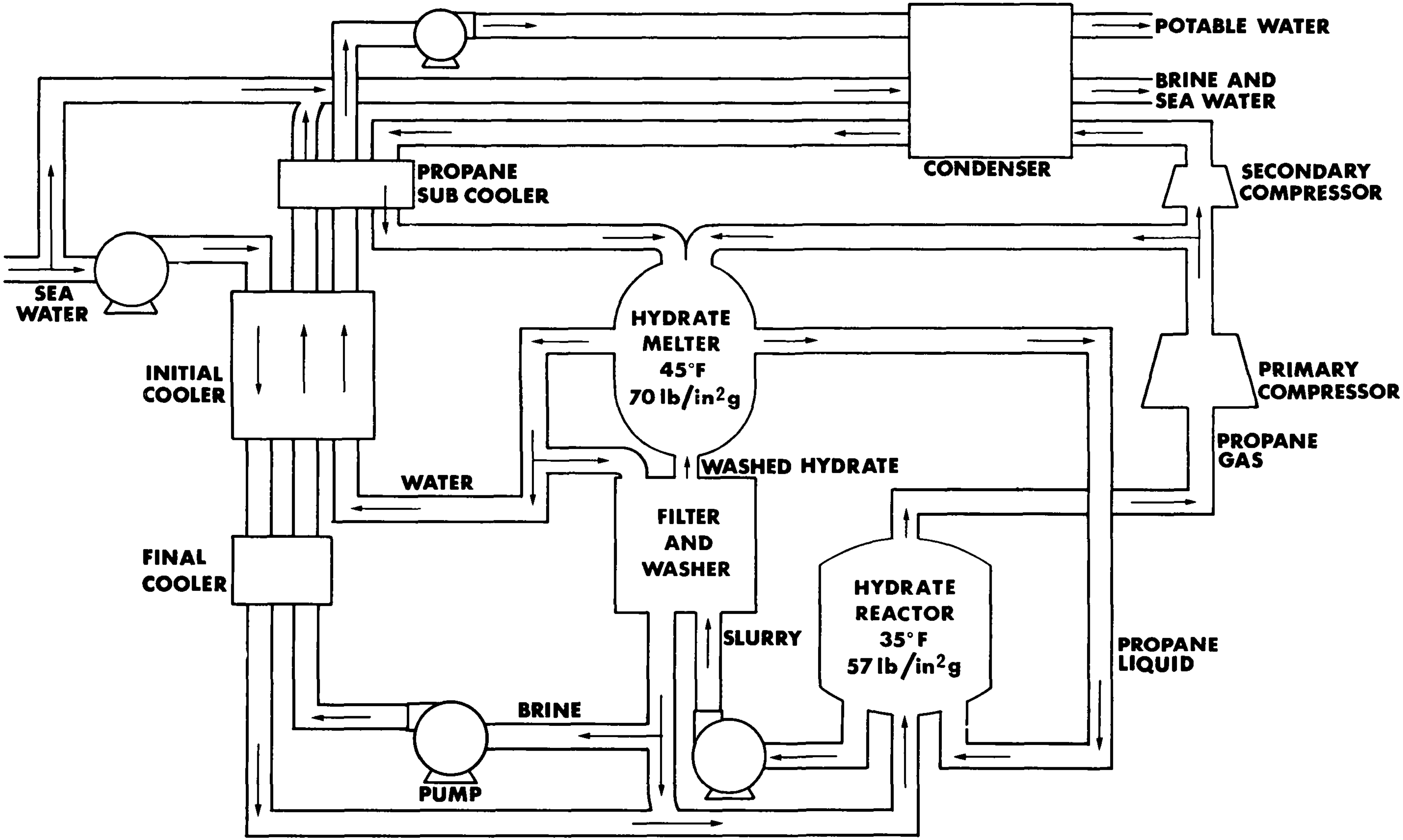

Figure III

TYPICAL ION EXCHANGE DESALTING PROCESS

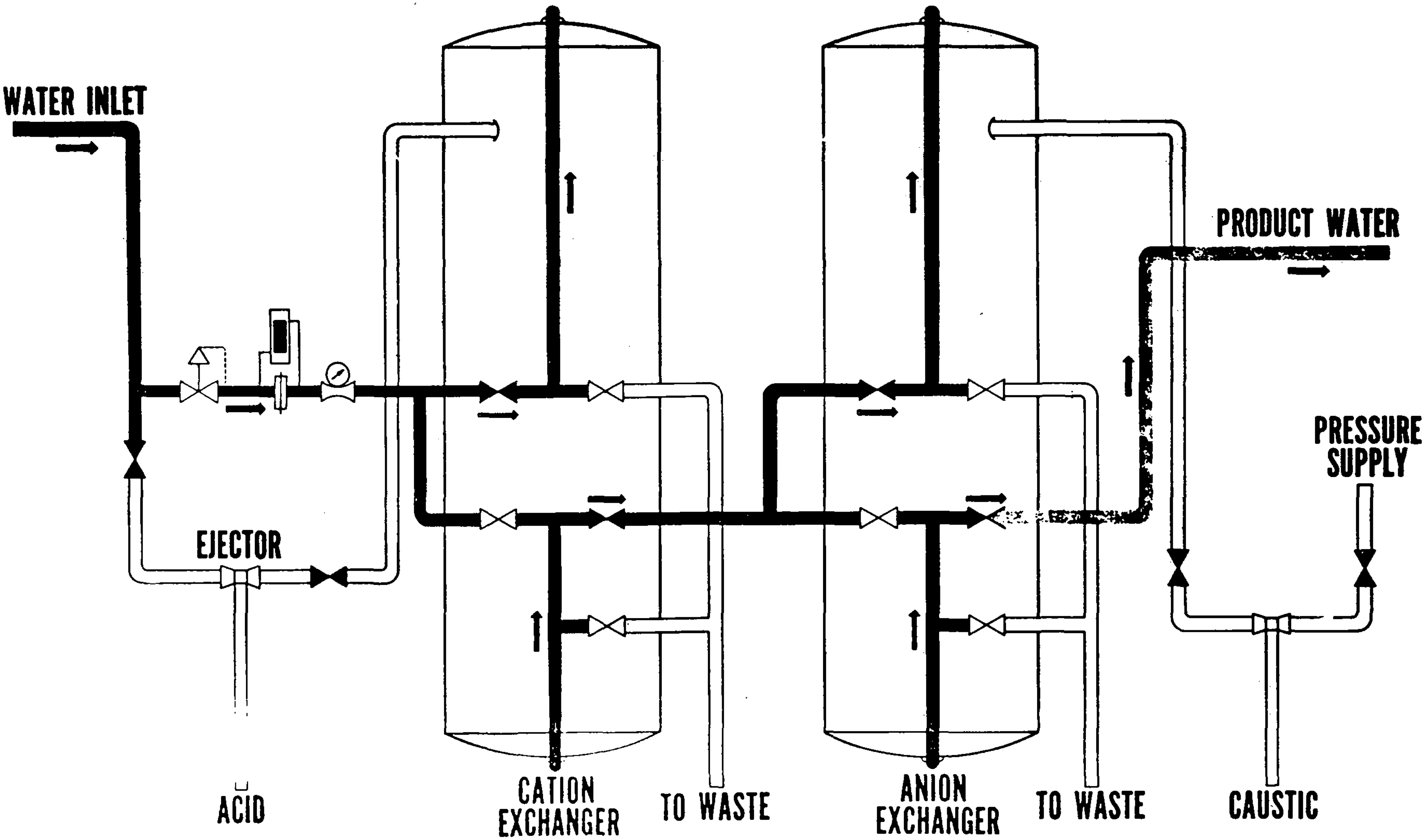

Figure IV

XI. DESALINATION AND ENERGY

by G. Costes

Sea water may be considered as a "product of disintegration of energy", more stable, less orderly and therefore of greater entropy than the elements from which it is made. There can therefore be no hope of separating these elements without "going back up the hill", in other words without deducting something from our resources of energy and injecting it into the desalination system.

Energy is a constituent of all the problems arising from desalination of sea-water or brackish water.

It is a main concern of basic research under two principal headings:

(1) How to get over the energy barrier created by the thermodynamic minimum required for reversible exchanges; and

(2) How to find systems for conservation of energy which would lead to better exploitation of available natural energy and smaller consumption of natural energy.

On the question of technology of conversion processes there must be a continuing search for practical means of reducing both consumption of energy and investment in its application. The problem is how to use as little energy as possible with the lowest possible investment.

For the engineer who must come to grips with the realities of industrial life when designing and setting-up a plant, it is no longer a question of minimizing expenditure of energy, but of defining the economic optimum. In each case this will be the best possible compromise under local conditions between decrease in expenditure of energy and the corresponding increase in investment costs.

Finally, in the operation of an existing plant, energy is a constant worry, since it must be watched in order to maintain the yield guaranteed at the beginning and to ensure economic functioning of the whole. There is indeed scarcely any science or technique which does not affect the relationship between desalination and energy, at least in the potential or theoretical stage. This is true even of the sciences of living matter, since living matter can apparently desalinate water with a minimum expenditure of energy.

The present essay cannot therefore be other than extremely summary. Its main purpose is to supplement other papers submitted to the seminar which are directed to the energy aspects of desalination processes.

Rather than emphasizing any particular point, it seemed to us more useful to give a general review based on the enormous documentation published in the last few years. This documentation is easy to refer to since the subject is not secret.

A. Energy and basic research

All of us here are concerned with the practical, and sometimes urgent, application of scientific knowledge. Nevertheless, I believe that we should bear in mind the major problems of basic research. It has been often noted that every year millions of dollars are spent on a vast expansion of technological research, as compared with the scanty resources available to basic research laboratories. Technicians, indifferent to anything which does not immediately open the way to practical application, are certainly responsible in part for this disparity. Yet the need to give priority to basic research is all the more urgent because of a general phenomenon common to all branches of industry, but especially clear in desalination problems. Industrial plants are becoming more and more complex and difficult to work, more and more frail inasmuch as they must be used at a fixed rate if they are to give satisfactory results and more and more short-lived as they become "obsolescent" before they have paid for themselves. Big capacity is often the only means of parrying these difficulties. That, however, works against general progress, since it leads to a concentration of modern industry in the very rich and very big countries.

Basic research, therefore, seems more and more necessary if the poor countries are to move forward at a satisfactory pace.

As we have said above, there are two sides to this question:

(a) Elementary energy, which must be overcome in order to separate the elements dissolved in sea water; and

(b) External energy to achieve this end.

In the present state of knowledge, we do not have to resort to subtle experiments or to the abstractions of modern mathematical physics in order to describe the main energizing properties of sea water.

It is unlikely that one day we shall be led to separate the elements dissolved in water by breaking their atomic nuclei; the Rutherford-Bohr model of the atom will therefore suffice for our purposes.

Creation of the molecule of water releases enormous energy in the form of heat at the rate of 200 kcal/mole.; this is proof that stronger bonds are established at the molecular stage than existed before. The molecule of water thus goes unaltered through all the changes encountered in the process of desalination. The molecule is not symmetrical, however; it behaves like an electrostatic doublet with two poles because the centre of gravity of the electrical charges does not coincide with their geometrical centre. These electrical properties are very important in desalination.

Dissolution is not a reaction, but a "molecular pulverization" without mechanical action; there is no joining of electrons to provide a primary chemical bond. It results in purely electrostatic cohesive bonds which release very little energy, as:

1-10 kcal/mole. with a relatively great distance of 3-4A^o between the atoms concerned, as compared with the 200 kcal/mole. on the creation of water, with distances of 1-2A^o between the atoms.

We shall confine ourselves to examining the properties of sodium chloride in solution. This salt accounts for 80 per cent of the salts dissolved in water and at first sight explains the energizing properties of sea-water. Solid sodium chloride is an ionized crystal, [1] with the electron belonging to the sodium providing the only fixed link between the chlorine atom and the sodium atom. This exchange of an electron results in an electric change and leads to stability of the Cl^- and Na^+ atoms, which is why they are called ions.

The free chemical energy existing originally in the Cl atom and the Na atom together is thus transformed by this valency electron into free electrostatic energy, which is no longer localized, but radiant.

The stability due to this redistribution of the valency electron leads to chemical inertia in the ions and as a result they react only to electrical energy. Fortunately, very weak electrical fields are enough to set the ions in motion. Moreover, contrary to general belief, liquid water at ordinary temperatures has a lacunose structure closer to the structure of solids than to that of gases. This is important because it makes it easier to dislodge the dissolved bodies.

Such water is not inactive; because of the **asymmetry** of the electrical charges, some molecules or water cling to the ions. [2]

This is the extremely complex and still little known phenomenon of hydration. It is not to be confused with chemical hydration since in the case of sea-water salts it is purely electrical. The atoms dissolved in ions assimilated by the water behave as if they were part of the water itself; these ions have an electric charge which radiates, but is absorbed by the direction of the polar molecules of water attached to them. The ions thus acquire a relative kinetic independence as against the opposite ions and increase the chemical inertia just mentioned because of the isolating power of the water. Hydration consequently makes it more difficult for outside agents to act on Cl^- and Na^+.

However, hydration has one happy result. It causes a considerable reduction in dissolution energy. This energy would normally be equal and opposite to the reticular energy of the sodium chloride crystal which must necessarily be provided from outside in order to break up the crystalline network and pass on to the liquid state.

The Born-Haber cycle [3] shows that this energy is of 187 kcal/mole., but the dissolution in water entails hydration and the electricity this causes in molecules or water provides an almost equal energy: 100 for Na and 85 for Cl. Thus the external energy, the dissolution heat, amounts to no more than 2 kcal/mole.; in the case of ClNa it is exactly 1.7 kcal/mole.. Thus, the low ratio of dissolution energy, and consequently the minimum energy required to separate the salts from the water, is due to hydration, provided of course that the separation is made without dehydrating the ions.

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[1] See figure II.

[2] See figure I.

[3] See figure III.

Thus we come again upon the minimum of thermodynamic energy required for separation under Raoult's Law. However, the theoretical value of 0.70 kWh/^{3} is applicable only to changes using a solution of infinite dilution and therefore without effect on the hydration phenomena.

Wegelin has provided a more accurate formula [4] for the work theoretically required in a reversible exchange when concentration is increased.

It will be seen that at saturation point, when all the salt is concentrated in 1/10^o of the original amount of water, the theoretical energy is 1.8 kWh/m^3, provided again that the ions are not dehydrated. If a practical exchange is considered, such as that produced in distillers where the water drawn off has twice the concentration of the water drawn in, the minimum energy is about 1.5 kWh. This is very poor for heating purposes and would scarcely be enough to raise the heat of a cubic metre of water by 1.3°C. From the mechanical point of view, however, it would make it possible to raise the level of a cubic metre of water by 5.50 m. It is astonishing to reflect that, since practical processes require from 20 to 50 kWh, they could raise the level of the cubic metre of water to at least 10 kilometres.

These brief considerations on the energizing properties of salt solutions lead to some general observations:

All processes for the extraction of salt in the dry state must provide the energy for dehydration. This is the main reason why it has never been possible to use electrolysis economically in desalination; electric current cannot in fact be passed through the electrodes unless the hydrated ions are changed into dry ions. As we shall see, electrodialysis has made it possible to overcome this handicap.

On the other hand, processes such as distillation and freezing do not require hydration and therefore start with a certain advantage.

Nevertheless, the fact that these processes cannot go below 20-50 kWh/m^3 provides a strong incentive for continuing basic research, since there is theoretically no reason why a minimum energy of 0.70-1.8 kWh/m^3 should not be reached. There are many sectors of modern technique where it can be said with assurance that we are as close to maximum progress as can ever be hoped. It cannot be too strongly emphasized that this is not the case with desalination.

It seems to me a proper deduction from what has just been said about the electrostatic properties of solutions, that priority should be given to any research into the action of electrical fields on solutions which can displace ions with very little energy. At the same time it will be seen how unsatisfactory it is to have recourse to the extremely complex technology of nuclear energy in order to achieve this displacement.

Although nuclear energy may be the most economical source of energy in the years to come, it is difficult to believe that it can provide a final solution for the problem of desalination when a means of direct action on ions is perhaps within our reach. It may indeed be hoped that new means of acting on ions will be found.

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[4] See figure IV.

The search for cheap and inexhaustible sources of energy is especially important to future desalination plants; in any case, the creation of new sources of energy is known to be absolutely necessary.

Even if the increase in consumption of energy does not continue indefinitely at the present exponential rate and even if there were to be a slowing down, it is practically certain that fossil resources, including present nuclear energy, will be exhausted by the next century. There is of course talk of perfecting "super-regenerating" piles which will produce more fuel than they use and so multiply present fossil reserves by 2,000 or more. (And is there not already serious talk of tapping the energy resulting in the difference in temperature between the two faces of the moon for earthly use!)

In any case, something else must one day be found, and recognition of this fact is the origin of the very widespread research now being undertaken in order to find new methods of converting energy. It might be said that the year 2050 is influencing the year 1965.

Table 1 sums up the main known sources of energy as well as the methods of conversion used or possible in order to pass from one source to another. The fact that many methods of conversion are not listed does not prove they might not be possible in the future but merely that they are not considered of present interest to desalination.

Most of the indications in table 1 are obvious and well known to everyone. Some observations may still be of interest:

Geothermal energy is being more and more exploited. Everyone knows what magnificent results have been achieved in Italy and New Zealand, but it is often forgotten that geothermal energy is very widespread. In practically all deep sedimentary land there is hot underground water; often it is very brackish, which means that it carries within itself the energy needed to desalinate it, at least in part. This is the case with the water table of the Saharan "continental intercalary". The water there reaches 65°C; it is thought by the mere action of the geothermal degree. We shall see an example of treatment of such water later.

Photovoltaic energy at present costs $10,000 per kilowatt, as compared with about $100 for energy from conventional thermo-electric plants. The price might be brought down to $5,000/kW, but a big effort to reduce the price of silicon cells would have to be made before this process could be competitive with conventional processes. The process has, however, one great advantage when used for desalination. It cannot be extended to production of electrical energy for general use until cheap accumulators have been perfected. But when this form of electrical energy is used directly for desalination, the accumulators are not needed; it is therefore obviously possible to work the plant only during the hours of sunshine, since the water can easily be stored.

The process nevertheless has the great drawback of giving a maximum theoretical yield $\leqslant$ 20 per cent (practical yield at present 10-14 per cent). Perfection of cells better than silicon will be needed before this can really be a process with a future.

The MHD process for ionization of fuel gas is less advanced than the former in so far as practical achievements are concerned, but will certainly make it possible to improve the yield of natural resources. An improvement of 10-20 points is foreseen, which would mean fuel economies of up to 30 per cent in combination with conventional thermo-electric plants. There would, however, be a relatively small decrease in the cost of production because of the complex machinery required.

Fuel piles have been the subject of many patents and of many experiments. The best known is the REDOX H and O pile; the most practical for mass production of electric energy is the liquid methane pile electrolyzed under pressure. The great diversity of models at present is proof that none has taken the lead, and it is not yet clear which will prevail. In all the arsenal of energy converters this device is the most direct. It is also the most promising not only from the point of view of yield, which might reach 90 per cent, but also from the point of view of cost, which might not exceed that of conventional plants: $100 kW.

The first industrial plants are already being established or will be very soon.

It should be noted that the process will be especially adaptable to desalination by electrodialysis for the following reasons:

(1) It produces a continuous current;

(2) The yield does not depend on the size of the units; and

(3) It is easy to install at the point where the energy is consumed.

Moreover, it is to be hoped that the fuel pile and the desalination electrolyzer may soon be combined in the same installation and so produce the energy needed for ionization right at the electrodes, without passing through electric conductors.

Thermo-electric conversion might offer the same advantages in desalination as the preceding system and provide yields of 30, perhaps even 50 per cent, but its cost is much too high for it to be used at present.

Thermo-ionic, or rather thermo-electronic, conversion certainly has a much bigger future because of the high yields resulting from the high temperatures it makes possible, but for a long time to come its use will be limited to special purposes. It will be the basic source of energy for interplanetary journeys, but its use in industry seems rather unlikely at the moment.

The means of converting natural energy now being developed will certainly have a good efect on the cost of desalination as soon as they become competitive. However, even if we have confidence in the eventual perfection of energy derived from fusion of atomic nuclei, these modern methods will certainly not bring a sharp and lasting fall in the price of energy, since their application is complex and delicate. Here again we come across the objections to application of modern techniques cited above.

In short, it seems more and more clear that the sun is the real source of energy for the future. The sun dissipates its energy at the tremendous rate of 4.10^{15}kWh, $1.8.10^{14}$ kW reaching the earth's outer atmosphere, in other words an average of 1 kW/m^2 of earth in full sunlight. If all this energy could be recovered with a yield of 1, rather less than 10,000 km^2 would be required to provide for all the world's present needs.

This means that the greater part of the solar energy which reaches the ground is lost in radiation into space.

This is certainly the last stage in the use of any form of energy and we shall never change anything in it. But at least we can hope to change it for the benefit of mankind before we arrive there. Research into direct use of solar heat is becoming more and more active and promising; the results are not yet competitive, but such processes as the photovoltaic pile are only beginning to develop. Desalination is especially adapted to direct use of this form of energy; it can use it when it is available because of the ease of storing water.

B. Energy in the technology of various processes

We shall now examine the various processes from the point of view of limitations on the supply of energy in order to determine what is the minimum expenditure of energy that may be hoped for in each case.

The limitations may be technical or economic, although in most cases the technical and economic limitations overlap.

Solar distillation is obviously a special case. Since the energy used in it is free, it might be said that there are no technical limitations properly so called. There is indeed one limitation, in the yield to be expected from a given insolated surface. The yield is extremely important in comparing various systems, but in fact it constitutes an economic limitation since an inadequate yield can always be compensated by adding more surface. With regard to the yields in energy of various solar distillation processes, I have thought it better not to overburden the present statement, but to refer you instead to the United Nations Conference on New Sources of Energy of June 1961. The Conference's published papers are an excellent review of the question and, because of the very slow development of this technique, are still quite up to date.

When the maximum possible solar energy does not exceed 1 kWh/m^2, the average production of distilled water scarcely goes beyond 4 to 6 litres per m^2/day of insolated surface; the heating load does not in fact exceed 100 $kcal/m^2$ per hour, as compared with 6,000 $kcal/m^2$ per hour for tubular distillers (exchange coefficient of 2,000, with a variation of 3 to 5°C). The cost of distillers brought up to the exchange surfaces is roughly in the ratio of 1 to 5 : 500 francs per square metre for LTV tubular or flash distillers instead of 150 f/m^2 for the cheapest glass solar distillers or at most 0.5 f/kcal per hour with tubular distillation as against 1.5 f/kcal/h installed with solar distillation.

The inclusive cost of distilled water in the end proves much the same in both cases - of the order of 1.20 to 1.50 f/m^3, but generally higher with solar distillation. Thus we come up against the question of price.

It is now the turn of the researchers to perfect new materials and of the manufacturers to lower prices by assembly-line production. Whatever progress may be achieved, the exhaustion of fossil fuel resources will make solar distillation economic in the future. It is worth noting that the resulting economic burden will not be very heavy since solar energy is already close to being competitive.

Silver and Tribus have shown that specific consumption cannot be decreased without investment being increased in any process using paid energy.

When K is the cost of desalinated water;

A the capital investment;

B the unit cost of energy; and

E the specific consumption of energy,

then the formula: $K = \frac{A}{E} + BE$

holds good for all processes.

The formula shows that the consumption corresponding to the economic optimum is: $E = \sqrt{\frac{A}{B}}$

Obviously, the energy is weaker when the capital required to produce it is less than the unit cost of the energy higher.

A formula of this kind is especially interesting when the economy of a project as a whole is being considered or when the economic optimum of a process is being sought at a given moment of technological development. Naturally, the aim of technological research is to minimize factors A and E.

Thus we come back to the technical and economic limitations mentioned above. These limitations have been brought out in the reports on the nature of various processes which have just been submitted. Nevertheless, it would seem worth while to review them again, more particularly from the point of view of energy. In doing this we shall consider two big classes of process: those which use heat exchangers and those which use membranes. This classification is of course arbitrary, but would appear well suited to the consideration of energy.

In all processes using heat exchangers, whether distillation, freezing, hydration, solvents or absorbents, it is clear that the consumption of energy is primarily linked to variations in the final temperature of the exchangers. But such connected factors as pumping expenses, waste of heat to the environment and load losses may change the classification of the various processes on the scale of energy consumption. In fact such a classification is neither of theoretical nor of practical importance in all these processes, since the only question of interest is the over-all economic cost of a specific consumption of energy.

For example, let us take the various kinds of heat exchanger.

In most cases, the simplest kind, the conventional tubular exchanger, is the most economical; it has not been dethroned by any of the other systems invented. Among them are:

- Exchangers without exchange surface: mixing of non-miscible liquid and solids in grain or powder; and

- Centrifugal force exchangers with rotating and vibrating exchange surface, etc., as well as all the processes intended to improve the heat exchange coefficients: fins, ultra-sound, anti-dampening surfaces, swept films, etc.

These systems should not be subjected to blanket condemnation. On the contrary, a decision can be made only after study of each particular case and this decision must be continually reviewed in the light of continuing progress. It may merely be stated in general terms that there is a use for all these apparatuses where they are already competitive, but that they in no way represent any marked progress. The complexity of these special kinds of exchangers entails a higher investment by comparison with simple tubular exchangers, and, although this investment is amortized over a longer or shorter period by economies in energy and some related advantages, there are never free advantages.

Let us therefore confine ourselves here to conventional tubular exchangers.

The limitations are economic and not technical; with the usual cost of energy and normal periods of amortization, it is not worth while to go below 3.5°C for liquids or to the temperatures usual in desalination processes.

The same can be said of most of the technical limitations; it would simply cost too much to overcome them. This is true, for example, of the main limitation encountered in distillation: salt deposits.

Systems for scraping deposits of thermal shock treatment, of chemical treatment and of special metals could be used, but up to now these methods are too laborious. It is more economical to limit temperatures to a maximum of 95 to 120°C.

It should be noted, however, that if one day the maximum temperature used in distillation processes could be multiplied by two, the expenditure of energy would be divided approximately by two.

Indeed, within the same temperature range twice the effect or stages of expansion can be obtained. The loss from the final exchanger would be the same, but would be related to a distillation flow multiplied by two.

It would probably thus be possible to go down to 20-30 kcal/kg in LTV or flash evaporators. The question is whether this would be economical and at the moment no prediction can be made on this score.

Technical limitations linked to the internal properties of matter will always be insurmountable obstacles. Such are:

- The rapid diffusion which hampers formation of steam bubbles and crystals and the fusion of crystals;

- Loss of charges through liquid or gas friction;

- Loss of heat to the environment; and

- Losses due to delay in vaporization, freezing, etc.

These losses become more and more important as the economic limitations which constitute the main losses are overcome. But they are still far from being a major obstacle on the road to the theoretical energy barrier.

Let us now consider the processes which make use of membranes.

Electrodialysis is an extraordinary invention and its possibilities have certainly not been exhausted.

Since the discovery of electrolysis - in which the passage of electric current is accompanied by movement of matter - it has been obvious that this process was adaptable to desalination. But a hundred years had to pass before the discovery of electrodialysis made the process commercially possible.

There is a considerable consumption of energy at the electrodes. The discharge there cannot be considered a simple electronic exchange. As we have seen, energy is needed to dehydrate the ions, a step required so that they may lose an electron at the positive electrode and gain one at the negative electrode.

Electrodialysis has made it possible to decrease this loss of energy considerably. Although electrodes are still there, everything happens as if the corresponding loss were divided by the number of compartments: the ions set in motion are discharged as soon as they pass through the electrodes and only a very small percentage of them reaches the electrodes.

The results so far obtained cannot, however, be considered a satisfactory ending. There are strong technical and economic limitations which still prevent this process from being competitive for sea water.

The technical limitations are linked to:

- Chemical potentials for diffusion;
- Osmotic pressure; and
- Membrane resistance.

Obviously the last factor is the one in which most progress can be expected. Moreover, at present it is also the economic limitation; the electrical losses due mainly to the resistance of the liquid can be reduced by reducing the strength of the current, but the surface needed for a given result is then increased. We come back to the formula:

$$K = \frac{A}{E} + BE$$

Besides this economic limitation, it is well known that as yet there are no membranes which work satisfactorily for a long time in sea water. However, the rapid progress of organic chemistry in producing new materials of all kinds should make us very optimistic for the future. If there were membranes which held at 100°C, the expenditure of energy would be divided by two since this expenditure is reduced by 2 per cent per additional degree centigrade.

It may be noted, however, that there are several ways of getting around this difficulty right now.

Recycling 5/ makes it possible to demineralize sea-water without exceeding 6 g/l in the cells to be deconcentrated. The presence of water at 35-40 g/l in the concentrated cells has some secondary drawbacks and the increase in membrane surface is considerable. A system of this kind is not competitive, but might show the way to progress.

Another possibility would be to mix in converted water of inferior quality. For example, water of 2 g/l mixed with distilled water obtained through another process could give drinking water of 0.5 to 0.7 g/l.

With reverse osmosis we enter the field of mechanical energy, which obviously seems tremendous. However, although a pressure of 100 kg/cm^2 produces a considerable flow of reverse osmosis, the final result is only 3 kWh/m^2 of energy. This is much lower than what other processes now promise.

As we say in France, "the stamp is not dear." 6/

Is it not wonderful to find out, as is now being done in laboratories, that all the fall in pressure inside the membranes and all the work of separating the salts are conducted within a bed 2 microns thick, the rest of the membrane serving only for support!

Does it not encourage inquiry into the possibility of living membranes?

Even if, as is quite certain, industrial membranes will not have the property of self-regeneration, an acceptable length of service will be enough to make this process economic.

Table 2 sums up the minimum expenditure of energy required in the main processes of practical interest. It will be seen that the way the energy is consumed is very important. Electricity produced from fossil fuels uses at best only about 40 per cent of the original energy because of the limitations imposed by the Carnot Cycle.

In practice the yield scarcely exceeds 30 per cent because of losses along the line and working with variable loads; often it does not exceed 20 per cent, particularly in small power stations.

From the point of view of a country's general economy, it may be said that the electricity used per unit of desalination is always produced in thermal form, and even by the thermal station with the lowest yield, so that the cost of the marginal kilowatt is certainly rather high.

Indeed, whatever progress may be achieved in the thermo-electric equipment of any country, there will necessarily be a number of obsolescent power stations, providing "peak" or "balance" services, which determine the cost of the marginal kilowatt-hour.

5/ See figure V.

6/ The "stamp" is the tag riveted to pressure tanks to certify their maximum pressure. A thin metal cylinder will contain high pressures.

To sum up, the cost of electrical energy, even when it is of hydraulic origin, is still linked to cost per calory.

Table 2 shows fuel calory consumption for an average yield of 30 per cent. It will be seen that:

Processes using electrical energy cost more. It must however, be remembered that these data give only a general notion. The cost in individual cases must be calculated by the formula:

$$K = \frac{A}{E} + BE$$

which makes it possible to determine the optimum expenditure of energy in relation to its cost.

Figures VI - VIII show the result of calculating costs for flash evaporators in a particular case, according to the price of energy: 0.5 to 1 centime per therm. It will be seen that above 4000 m^3/day, a performance ratio of 9.7 results in a lower cost price with a fuel cost of 0.5 centime a therm. With a fuel cost of 1 centime, the higher performance ratio becomes significant after 1,200 m^3/day.

Obviously, local conditions could lead to very different conclusions from these calculations. The following general conclusion, not obvious a priori, may be drawn, however:

The higher the capacity, the more the economic optimum results in low expenditure of energy. In other words, there is more point in economizing on energy when the plants are more powerful. This is obviously linked to the fact that the relative proportion of investment to total cost decreases when capacity is increased. In fact, investment generally increases only in the proportion of 0.7 - 0.8 of capacity, at least for capacities below 2,000 - 4,000 m^3/day.

The United States Government's Office of Saline Water has devised a standard method of calculation which makes economic comparison of the various processes easier. It must, however, be borne in mind that the data on basic prices of energy and rules for amortization apply to the United States and may be different in other countries.

The last figures published on the comparison between multi-stage and staggered expansion plants clearly favour the latter.

Cost of plant for 1 million gallons a day: $1.41 gallon/day
as against: $1.60 " "
Cost of converted water : $1.18 per 1000 gallons
as against: $1.51 " " "

Although the divergence is considerable, it is by no means certain that it might not be reversed in certain local conditions. It would certainly be most unfortunate to see one process dominating the whole market because it has shown a marked advantage in one particular case. Moreover, published information does not take account of progress achieved in between times. It is rather like the struggle between the breastplate and the cannon; progress in one calls forth progress in the other. This is the case, for example, with the multiple effect it is proposed to achieve in a caisson like the flash evaporator. 7/

Calculations are all the more difficult because there are obviously many more processes than those mentioned in Table 2. We are now in a period when the enormous impetus to research has resulted in perfection of many industrial processes between which it is more and more difficult to choose.

The choice is the more difficult because every engineer holding a certain number of patents for a particular process proposes a complete and homogeneous system.

It should be noted that often a combination of various processes offers very promising possibilities. These possibilities should not be forgotten when a process is being chosen. The choice is difficult, however, for the combination depends on patents held by various engineers and it is thus difficult to obtain precise proposals for dual purpose systems. For example:

(1) Heat pumps which can be used with any process employing calorific exchanges, solar distillation, freezing, etc.

By compressing an intermediate fluid it is possible to tap the heat in a cold medium providing heat and transmit all of it, including the calorific equivalent resulting from compression of the fluid, to a reheating medium. The yield of the heat pump, defined as the ratio of the heat transmitted to the heat used in compression, is extremely significant because it may exceed 4 or 5. In other words, the total expenditure of energy for reheating may be less than direct use of calorific energy when the electrical energy is cheap and the source of heat is free. The heat pump may therefore be considered in utilization of solar heat.

The heat pump is especially adaptable to desalination because, when there is a variable tariff, storage of desalinated water makes it possible to use it only when it is not required for other purposes.

(2) Freezing inspires an infinite variety of designs. One interesting example, requiring low expenditure of energy, is given in Figure X. It uses vacuum freezing combined with multi-stage evaporation of caustic soda.

It is true that the equipment required is complex. But the relatively high investment is compensated not only by the low expenditure of energy, but also by the fact that salt deposits are not formed at the temperatures used. This process should be of interest, but to the best of our knowledge has not yet been industrially applied.

(3) The immense range of dual-purpose plants for production of electricity and fresh water is the subject of a special paper. We shall therefore consider only some special applications.

7/ See figure IX. Kestner patent.

(a) Peak-load stations

In all distribution networks, and especially in the networks of developing countries where there are few stations continuously in service and consequently few fixed loads, the problem of peak consumption is one of the main causes of the high cost of electric power. This problem is likely to become even greater in the future as nuclear power stations with a constant load provide the basic load cycle. The result is that the full power of some electric generating stations is used for only a few hours a year. Such stations can be grouped with sea-water distillation plants by using the power available when the station is not distributing over the network.

There is an infinite variety of possible designs. Figure XI shows one. It is not the best that could be imagined, but it seems to us to be of interest.

Its design could be applied to a European coastal town of 50,000 inhabitants which uses 5,000,000 m^3 of water a year and a maximum of 10,000 kW. The peak load is 20 per cent, or 2,000 kW. There would then be an unexpended balance of 3,000-5,000 kW for the peak of the general network.

It thus appears that the price of fresh water is lower than it would be from an independent plant, whatever the sale price of the peak energy (which has little influence on the price of the water) and even assuming that amortization of the station is charged to the water.

Such a station could therefore sell peak energy very cheaply, with a resulting maximum of five favourable factors:

- A machine working 7,000 hours a year (compressor) takes the place of one working 1,000 hours (alternator);
- Since the distillation plant is not always working at full capacity, the extra investment needed is very small;
- The storage of fresh water needed to compensate for the times when the compressor is not working is negligible since distribution of the water in any case requires a minimum reserve of one day's supply;
- Heat is used to the maximum; and
- Direct operation by the compressor by a gas turbine with synchronized coupling could result in a noticeable economy.

It will be seen that the ratio kW/m^3 of water is determined by the design; obviously this ratio must be favourable. Many different designs could be thought out, giving a great variety of ratios.

(b) Free piston generating groups[8]

This system is competitive with Diesel motors over a range of power between 1,500 kW and 10-20 mW. In combination with the production of fresh water, it could attain a higher $\frac{kW}{m^3}$ ratio which might be of interest in certain cases.

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[8] See figure XII.

(c) Large boilers in thermo-electric stations

Large boilers in thermo-electric stations discharge combustion gases into the atmosphere at ever lower temperatures. At present the temperature does not go below 100-120°C for two reasons:

(i) In order to avoid the heavy corrosion resulting from some fuels at low temperature; and

(ii) Under present economic conditions the extra investment required to bring gas temperatures below 100°C could not be amortized within an acceptable period. There is, however, no doubt that development of the technique and economy of energy is clearly directed along these lines and that in the near future the big power stations will recover the difference between high heating and low heating value by condensing the water contained in the smoke. When such a process is perfected, it will be easy to transform boilers into distillers of sea water; all that will be needed will be to inject the sea water at a carefully chosen point in the gas circuit and to collect the fresh water at the end of the circuit. The final result might be that the boiler would produce as much fresh water as steam. Obviously a number of technological problems would be raised, particularly that of preventing the salts being carried along with the gases; perhaps they could be discharged while in a melted state. 9/

A final example, which we mentioned before, is hot (65°C) brackish underground water, such as that found in a great part of the Sahara.

Figure XIV illustrates the principle of distillation by expansion, which makes use of the difference between air and water temperatures. In the Sahara night temperatures rarely exceed 25°C. Furthermore, experience with the gas turbines in service at Hassi-Messaoud has shown that the air temperature fifteen metres from the ground rarely exceeds 35°C, even when the temperature one metre from the ground reaches 45°C. There is thus available for distillation purposes a divergence of temperature between 65°C (it freezes in the Sahara in winter) and 20°C, allowing for heating of the air by 10°C. This is a small divergence and heavy investment would be needed to make use of it. This is why up to now attempts to use the thermal energy of the seas have failed (although there the source of cold had to be sought far away). It is also the reason for the high cost of investment in solar distillation. In the present case the result is that, although the energy is free, the cost price exceeds one franc a cubic metre. Progress is possible, however. For example, the Heller system of finned tube exchangers with natural draft used at the Rugeley power station in England might lead to a noticeable improvement. It is also possible that local conditions might be especially favourable. For example, if there were a bore-hole producing hot brackish water close to the sea, the economics of the process would be definitely more favourable. If brackish water at 65°C were continuously available alongside a cold spring at 20°C, the cost of fresh water would fall to 30 centimes a cubic metre.

9/ See figure XIII.

These considerations are doubtless commonplace. But it often happens that the possibilities of variations in temperature offered us by nature are lost to sight. Generally speaking, not enough advantage is taken of them.

These few examples give some idea of the immense variety of possibilities. These possibilities entail great difficulties in research because existing plants will never be able to try out more than a very small number of the possible processes. After studies which will become more and more complex and difficult, decisions will have to be made "on paper", in order to direct the development of new processes and to choose among them those capable of industrial application.

C. Planning and establishment of industrial desalination plants

A United Nations document[10/] has brought out very well the energy aspects to be taken into consideration when designing and creating an industrial plant. We cannot do better than refer to it, as well as to the publications of the United States Office of Saline Water concerning standardized costs. I shall therefore add only a few observations.

The first problem to be solved is capacity. Forecasts are difficult and in the case of isolated plants a big margin of error can hardly be avoided. Capacity is more easily defined in the case of plants running in parallel with other sources of fresh water. But, as we shall see later, operation with part loads cannot be avoided and this always results in a poor yield of energy. In many processes, partial operation may be impossible and recourse must be had to intermittent operation, which also causes extra expenditure of energy. The extra cost of starting and stopping must be carefully calculated.

The following section of this study deals with:

- The local cost of power;
- Choice of the source of power;
- Specific consumption of power;
- Rules of technical amortization (depreciation); and
- Interest rates.

These five factors cannot be separated and must be determined at the same time, since they react upon each other in deciding the optimum cost, in accordance with the formula:

$$K = \frac{A}{E} + BE$$

Optimum utilization of the energy available in a given country at a given time is possible only if prices are not artificially established, but are on a correct scale based on cost of production.

[10/] United Nations, Water Desalination: proposals for a costing procedure and related technical and economic considerations (United Nations publication, Sales No.: 65.II.B.5).

Unfortunately this ideal is often difficult to attain, if only because of the difficulty of defining cost of production. Is it the average cost or the marginal cost? - a question still being widely discussed in Europe in connexion with coal. Sale at marginal cost is more favourable to the community. But should it be long-term marginal cost or immediate marginal cost?

In the case of oil the question is still more complicated because marginal prices certainly vary by more than one to ten according to zone. The question was, however, solved more than twenty-five years ago by agreements between the big companies and it may be said that since that time oil has been the great unifier of the cost of energy throughout the world. The fact that prices are not very different in the producing and non-producing countries is obviously because the two main producing zones, the Persian Gulf and the Gulf of Mexico, are admirably situated from the point of view of the users; it is also due to the practice of "posted price". Under this system, buyers pay a c.i.f price which takes actual freight charges into account, but with Venezuelan or Persian Gulf prices f.o.b. so calculated that the c.i.f. price New York is the same for both sources. This tariff scale is favourable to the arid zone countries, most of which are close to the two points of departure. It should also be noted that the posted prices are generally much higher than the real prices because of the practice of giving big rebates. It has often been observed that the cost of oil is not as low as it could be. However, it was stated at a recent conference that the producing countries in the Middle East had lost more than two billion pounds sterling because New York, rather than a Western European port, had been selected as the site for basic prices.

Transportation costs obviously result in differences running from the single to the double. Figure XV shows that the price electric power stations in the United States pay for fuel varies from 20 to 35 cents per million BTU or 0.40-0.50 francs the 10^6 kcal. Arid countries not too far from the fields get prices of the same order. In Europe, and in countries a long way from the source of supply, the prices may reach \$0.50-\$0.60 the 10^6 BTU or 1.00-1.20 francs the 10^6 kcal.

These variations are important, but desalination plants on the coast are obviously in a position to get the lowest prices. Figure XVI shows the advantages of transportation by tanker.

It is good to know that for the near future, that is, for the lifetime of a desalination plant now being designed, there will certainly be an accelerated development of oil without any increase in its price. Indeed, in all probability this development will continue for at least one or two generations afterwards.

Natural gas may produce even more favourable conditions. In many parts of the world there are enormous quantities of gas, lost or unexploited because they are too far from centres of consumption, which could provide low-cost power for desalination.

Having determined the local cost of oil, gas, coal and electricity, it remains to determine the cost of nuclear fuels. As this subject is dealt with elsewhere, I will merely draw your attention to the fact that it is very difficult to make an oil-nuclear cost comparison for the following reasons:

- Arbitrary fixing of the price of uranium;

- Variable rate of irradiation;

- Arbitrary resale price of irradiated uranium; and

- Difficulty of forecasting the cost of storage.

Fortunately, in most cases local conditions permit definite conclusions, although these conclusions must of course be continuously reviewed because of the rapid development of nuclear technique.

The cost of solar energy must also be taken into account when considering the cost of energy for a desalination project.

As we have seen on first examination, solar energy is not yet competitive. Because of this, attempts have been made to approach the problem in another way.

For example, it had been noted that the price of solar distillers per m^2 was much lower than the price of housing per m^2. It was therefore proposed to increase the capital investment in the houses by a sum equivalent to a fraction of m^2 and to provide solar distillers on the roofs. While this method does not appear economically orthodox, it can be justified, for example, if it makes possible the mobilization of individual savings which would otherwise be unemployed. The heavy investment needed for solar distillation would not then be a burden on the community.

Solar energy might be made competitive when:

- Brackish water is available on the spot and there is consequently no need to build a network for public distribution;

- The time available makes rapid action essential; and

- Forecasts of consumption are so high as to make considerable equipment in addition to tubular distillers, inevitable.

This last consideration seems to me to be especially important. Solar distillers can be extended more easily than others, whereas tubular distillers are greatly lacking in flexibility. It must not be forgotten that, if a plant of a given capacity is installed ten years too soon in a dear money country - which many poor countries and indeed others are - it is as if the plant had cost twice as much. The heat from a tubular distiller then ends by being as dear as the heat from a solar distiller.

It therefore seems that in any plans for a desalination plant there should be one part in the form of an expandable solar distiller. Such a system would offer the many advantages described below:

It would assure the desalination plant a heavy rate of load, and therefore maximum profitability, from the first year it was put in service.

It would provide help in case of a breakdown, since each part of the plant could be used separately in case the other was not available. There would thus be no need to split up the plant and the biggest appropriate unit capacities could be used.

There would be no need to allow exaggerated margins for error. It is very difficult to forecast water consumption and allowing a margin at each stage in planning often results in unprofitable plants. Addition of a solar distiller to a fixed-capacity tubular distiller might therefore help to overcome the main difficulty in drawing up a plan.

With regard to technical amortization, or depreciation of the plant, the United Nations document quoted above estimates a period of twenty-five years, including a special provision for economic obsolescence. It is impossible to predict technical progress, but it will certainly take place. The figure of twenty-five years thus seems reasonable. However, it should be noted that, if technical progress should be still more rapid, a plant might have to be replaced before it was completely depreciated. Most of the time it will even be possible to avoid burdening the new plant with the remaining depreciation of the old. Provided durable materials are used in construction, the case of solar distillation should in our opinion be considered separately and looked upon as if it were a real estate investment depreciating in forty years, for example. There is certainly no cheaper source of energy, and with proper maintenance the plant will certainly last fifty years, like a house or a hydro-electric dam. Indeed, since maintenance of a distiller amounts in fact to constant renewal of part of the material, the very principle of depreciation might be brought into question.

Moreover, technical progress may result in a better yield from the surfaces of the solar distiller and a consequent reduction in operating costs. In that case a new investment would be very difficult to justify, since a great part of the cost price comes under the heading of depreciation.

All factors we have just rapidly reviewed constitute the basic data for a study of desalination; it is extremely important to determine them correctly. In many cases they will lead to several alternatives, combined with the technological variants (choice of process and materials, etc.), and the result will often be a great number of possible solutions.

While more or less thorough calculations may point to certain choices, judgement based on experience will still have to play a great part. In the period of preliminary study it will obviously be necessary to work with the contractors since technology is constantly developing. It is precisely at this moment that an independent expert can play a specially important part.

D. Exploiting energy

To end this statement I shall merely say a few words about the cares of the operator in charge of a desalination plant. If the plant is isolated, his only care is to obtain the best possible yield. For that, big reserves of converted water and many kinds of measuring apparatus are essential. There is already talk of complete automation by means of a computer.

The difficulties are much greater when a plant works in parallel with other sources of fresh water. For the load then depends not only on the need, but also on the capacity of the other sources.

The cost price of a desalination plant is sometimes calculated on the assumption that it will work 8,000 hours a year, the needed balance being supplied from other sources. In practice such reasoning does not hold good for long because the other sources may be, and in fact generally are, more economical.

In a complex of producing units, distribution is optimum when the marginal cost of each unit is the same. Now this marginal cost is almost entirely composed of proportional charges; in the case of desalination the charges include expenditure on energy which is generally higher than that in other sources of water supply.

So long as the cost of the extra cubic metre of water from the other sources is lower, these sources must be used first. This practice often grows more frequent; the price of 0.50-1.00 franc per cubic metre resulting from permanent operation will be multiplied by two or more because the end result is operation at peak. The cost of a desalination plant operating at lower loads thus increases.

Obviously, the time to take note of this disadvantage is not the moment when the plant starts working, but at the very beginning of planning.

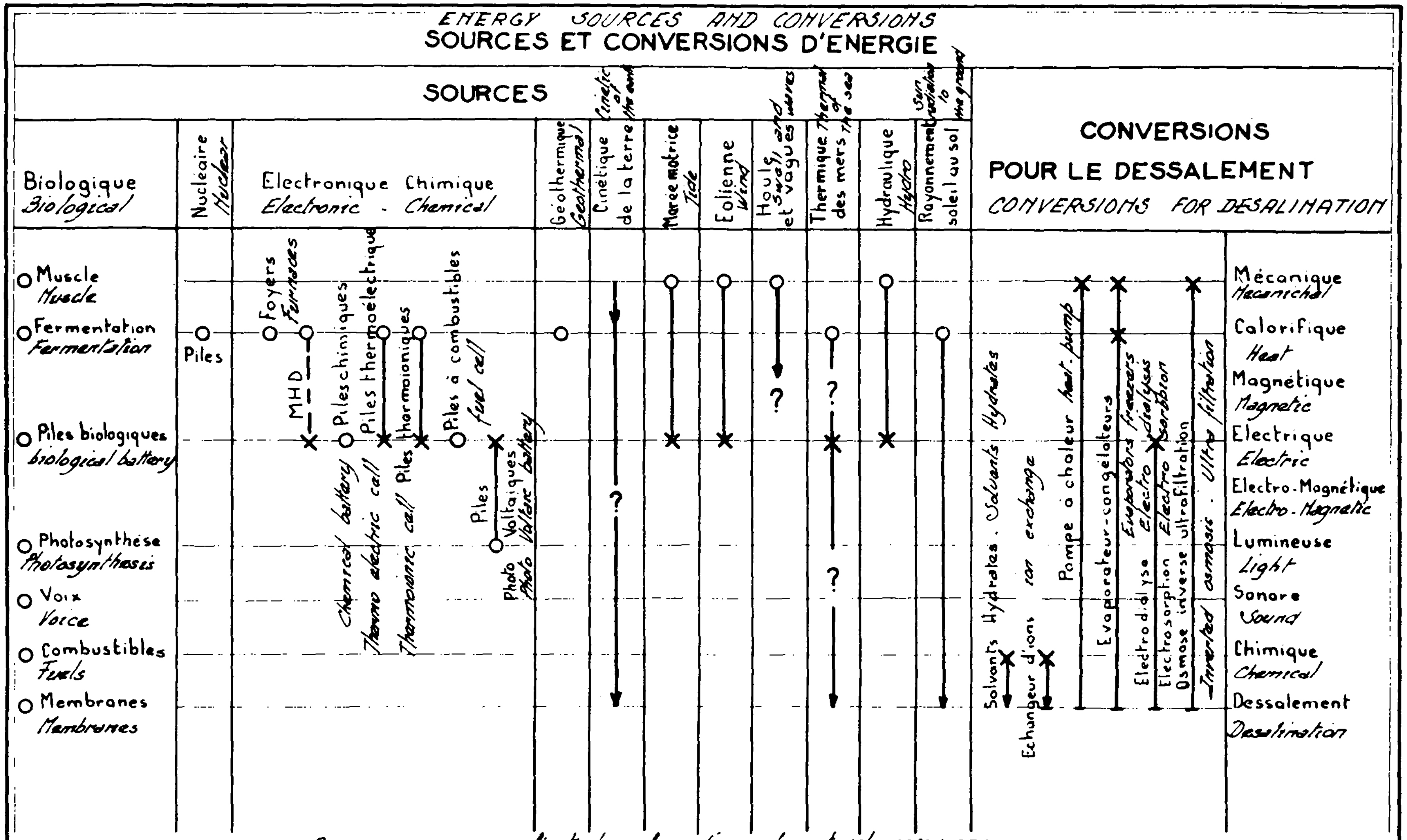
E. Conclusion

Throughout this statement we have seen that economizing energy is not an end in itself. While energy is omnipresent in all human activities, its importance should still not be overestimated. In relation to the total value of a country's production, expenditure of energy represents scarcely 8-10 per cent. We have emphasized the fact that the scarcity of energy in the world will entail an increase in its price in the future. That is not necessarily a reason for its importance to increase. Indeed, many earthly resources are exhaustible; steel, for example, does not exist in unlimited quantity. Shall we in future have to economize on steel or on energy? This may appear an idle speculation, but it may help in understanding the place of energy in the problem of desalination. The present situation is not satisfactory, with the percentage of energy in the cost of desalinated water often reaching 30-40. This is a very high percentage, even higher than in the big consuming industries such as iron-smelting, where the percentage does not go above 30.

Many tend to believe that technological progress and an increase in plant capacity will suffice for the production of desalinated water at a suitable price and everyone more or less consciously approves of the following reasoning:

If water can be produced at 0.20-0.50 franc a cubic metre, is it not natural that it should cost three or four times as much in arid countries, where there are no resources? Certainly not! It is precisely there that very cheap water is needed, for water alone can make the deserts blossom again. We should not be satisfied until we can produce water at 0.05-0.10 franc per cubic metre at most. But free energy will no more suffice than free water to increase the production of the arid countries in vast proportions. The energy of men will also be needed. It is comforting to think that we are fortunately certain not to lack that kind of energy.

Table 1



Primary energy : first transformation of natural resources

○ Energies primaires qui sont la 1ère transformation des ressources naturelles

✕ Energies secondaires après une 1ère transformation
Secondary energy after a first

Table 2

Energie en kWh/m3

Energy . kwh/m³

	Evaporation Evaporation		Congélation Congelation	Electrodialyse Electrodialysis
	par réchauffage with external heat	par compression with compression		
Energie à mettre en oeuvre Energy to be used	625	625	93	0,7
Energie pratique Energy of partical process	50	12	10	18
Sous forme	calorifique heat	électrique electrical	électrique electrical	électrique electrical
Dépense de combustible fuel consumption	50	36	30	54
Rapport de performance Performance ratio	12,5	17,5	20,8	11,5

1 - le rapport de performance utilisé dans la pratique de l'évaporation est égal au nombre de kg d'eau déminéralisée produite par kg de vapeur. L'énergie par kg de vapeur étant 540 kcal = 0,62 kWh, le rapport de performance 1 correspond à une dépense de 625 kWh/m3 d'eau douce. Par analogie, on peut utiliser la même définition pour les autres procédés qui ne mettent pas en oeuvre l'évaporation.

1 Kwh/m³ = 0.255 Kwh/1000 U.S. gallons

$$\text{Performance ratio} = \frac{\text{Quantity of demineralised water}}{\text{Quantity of steam used for the process}}$$

Performance ratio = 1 corresponds to an expense : 625 kwh/m³ of demineralised water

This definition can be used for other processes than evaporation

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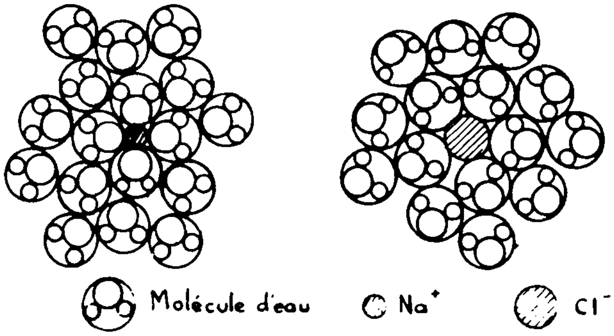


Figure I REPRESENTATION SCHEMATIQUE D'IONS HYDRATES

SCHEMATIC VIEW OF HYDRATED IONS

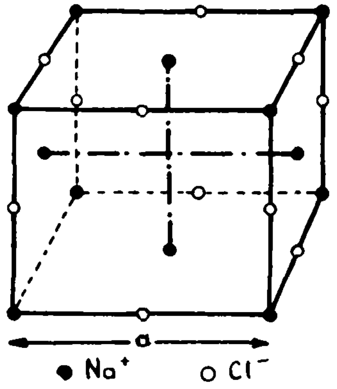


Figure II MOLECULE DE Cl Na

ClNa MOLECULE

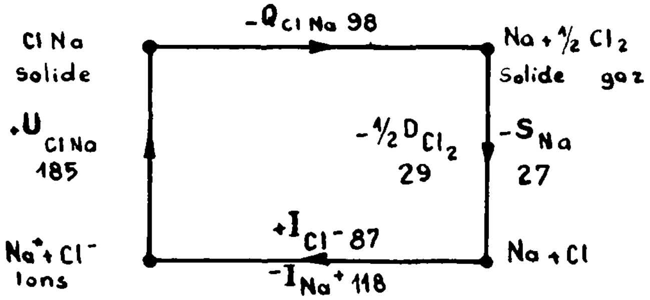


Figure III

CYCLE DE BORN-HABER

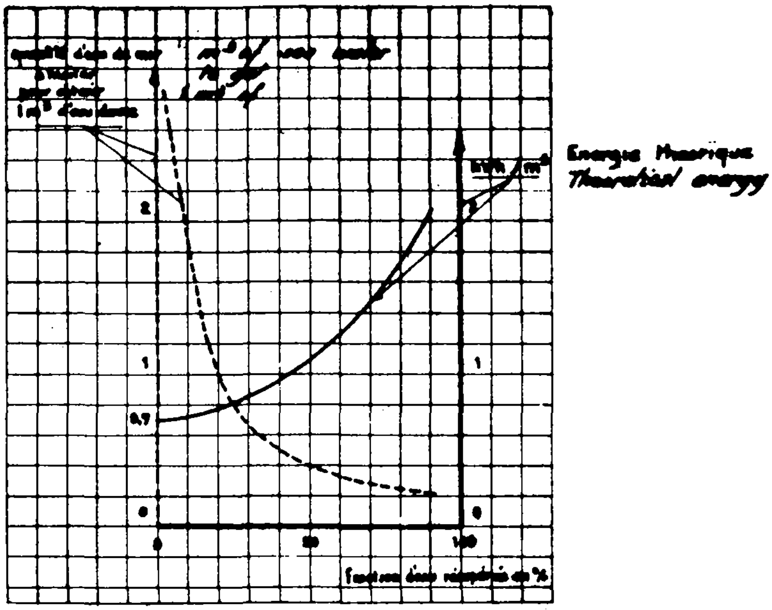
BORN. HABER CYCLE

On part de Na solide . On le vaporise en dépensant S = 27 kcal
solid Na is vaporised spending
On enlève l'électron ⟶ Na^+ en dépensant I_{Na} = 118 -
an electron comes off spending
On dissocie Cl_2 pour former un atome de Cl D = 29 -
" is dissociated to form an atom of Cl
On ajoute un électron a Cl en recueillant I_{CL} = 87 -
an electron is added to Cl producing
Na^+ et Cl^- se combinent en recueillant U = 185 -
are combined producing

$$U_{ClNa} = Q_{ClNa} + \frac{1}{2} Cl_2 + S_{Na} + I_{Na} - I_{Cl}$$

1 BTU = 0.25 Kcal

Figure IV



$$W = 2mRT\left(\frac{Ln\beta}{\beta - 1}\right) - \left(\frac{Ln\alpha}{\alpha - 1}\right)$$

Formule de Wegelin
pour une eau de concentration C
transformée en une de $\frac{C}{\alpha}$ $\alpha > 1$
et une de $\frac{C}{\beta}$ $\beta < 1$

Energie pour séparer m moles

Formula of Wegelin
a water of concentration C
is transformed in a water of concentration $\frac{C}{\alpha}$ $\alpha > 1$
and one of $\frac{C}{\beta}$ $\beta < 1$

Figure V **ELECTRODIALYSE A RECYCLAGE**

ELECTRODIALYSIS OF SEA WATER WITH RECYCLING

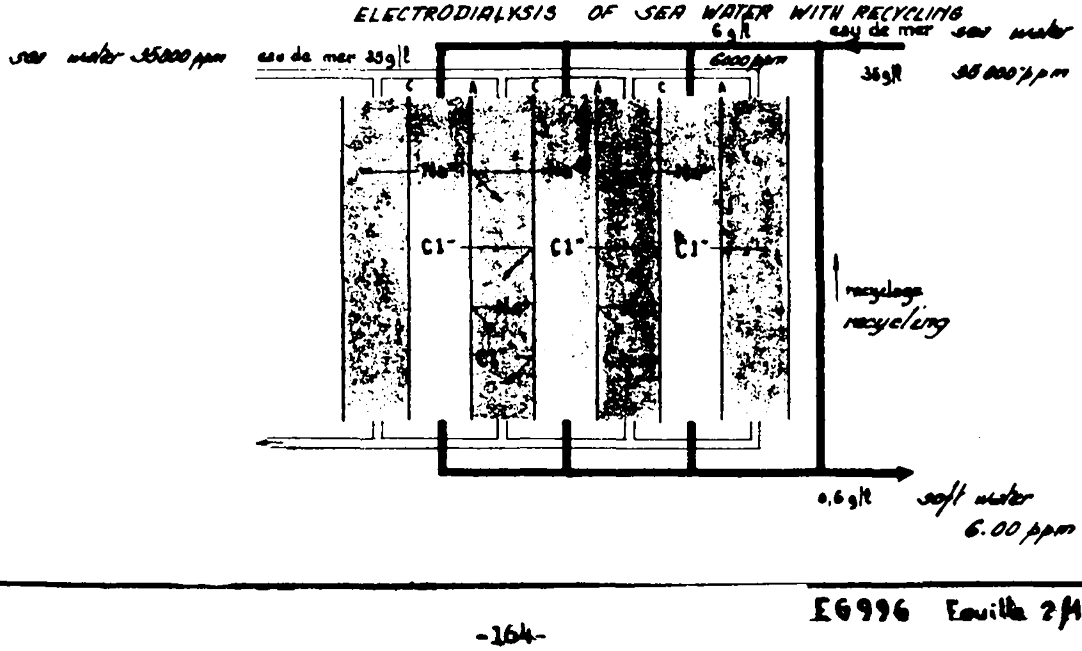


Figure VI. **Figure VII** (V)

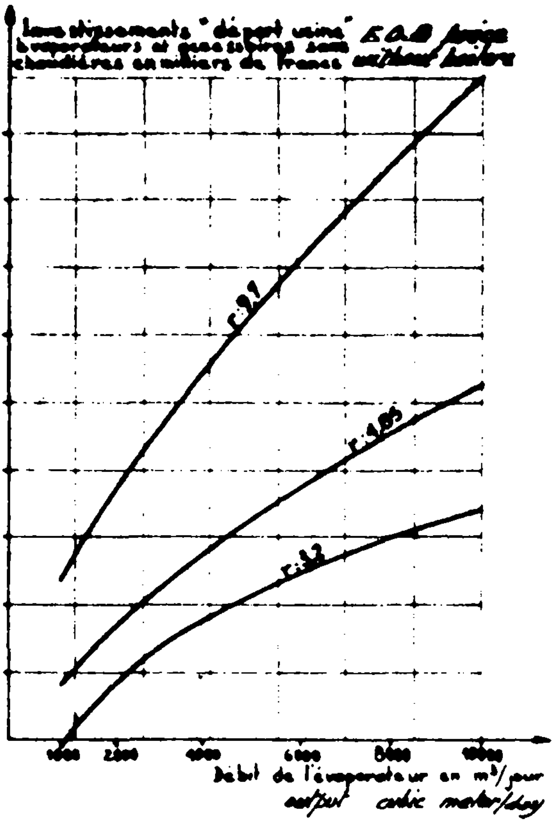
FLASH EVAPORATORS

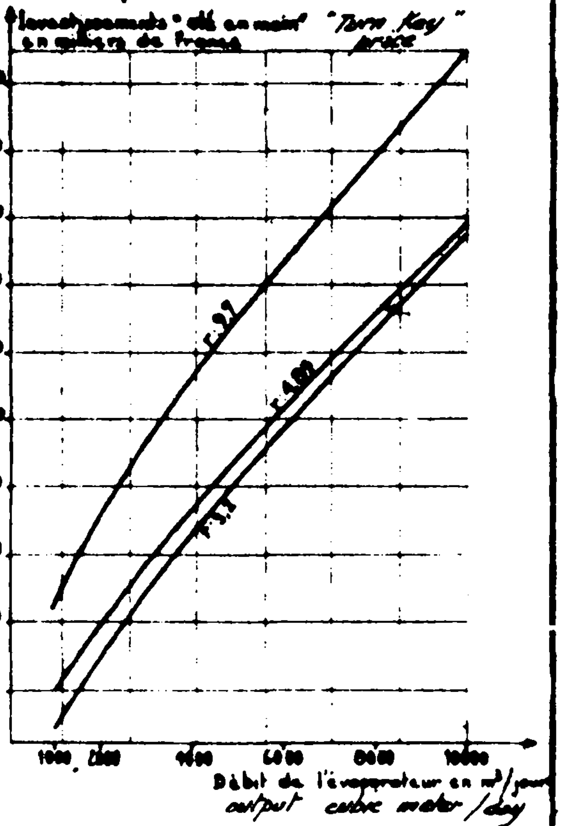
EVAPORATEURS A DETENTES

COMPLETE INSTALLASTION WITH BOILERS

INSTALLATIONS COMPLETES

(évaporateurs à détentes et chaudières)





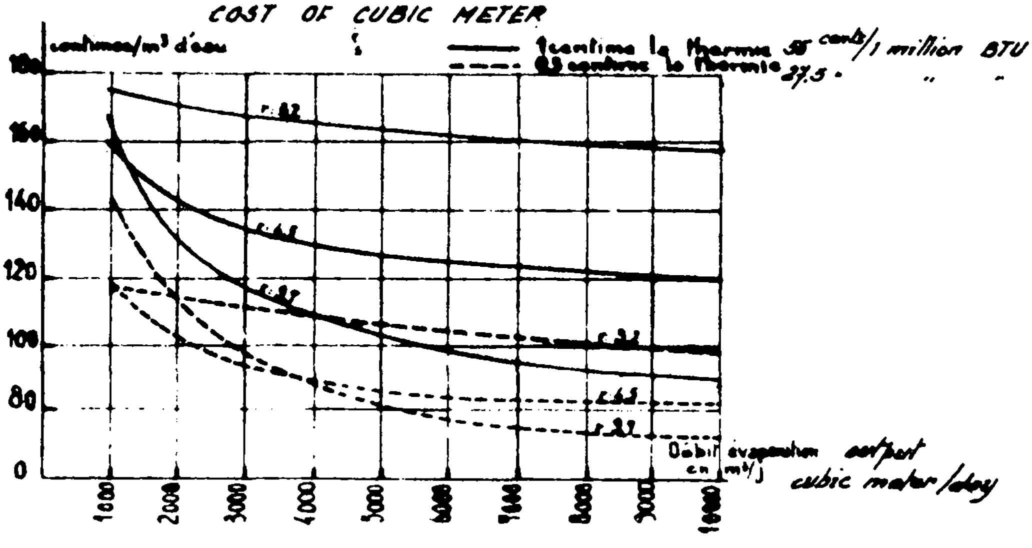
r: rapport de performance net : T d'eau par T de vapeur
(tenant compte de la consommation des auxiliaires)

r = performance ratio (including auxiliairies consumption)

4500 F = 1000 Dollars

Figure VIII **PRIX DE REVIENT DU m³**

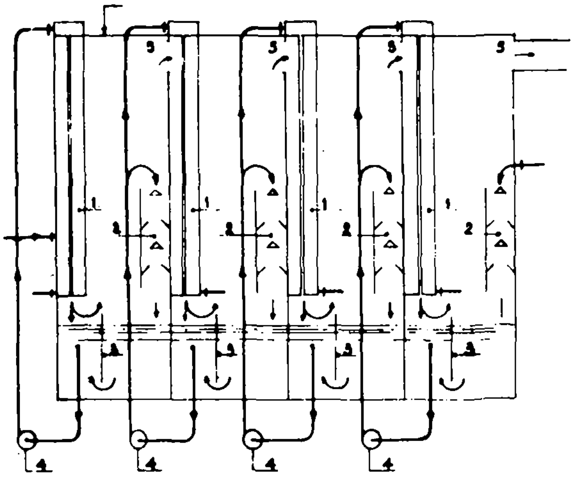
COST OF CUBIC METER



100 centimes/m³ d'eau = 0,84 dollars/1000 gallons

Figure IX

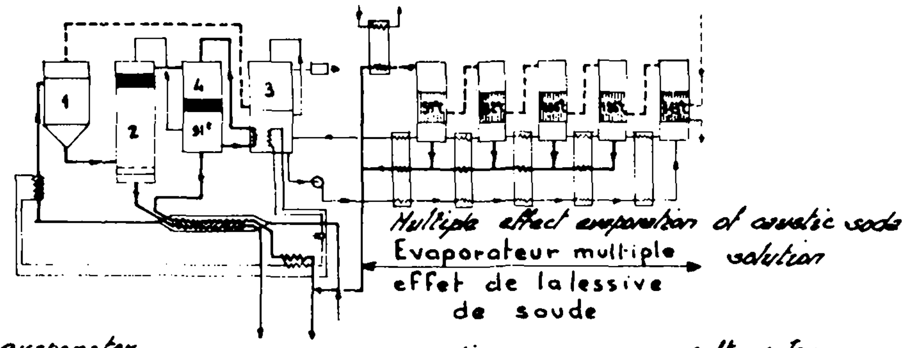
EVAPORATEUR LTV
LTV Evaporator



LEGENDE
1 . Faisceaux tubulaires . *Tubular bundle*
2 . Réchauffeurs à mélange - *Direct contact heater*
3 . Cloisons médianes des séparateurs - *Separators*
4 . Pompes de circulation - *Circulating pumps*
5 . Passage de la vapeur - *Steam*

ECHANGEUR EN CAISSON
INTEGRAL CONSTRUCTION OF LTV EVAPORATOR

Figure X EVAPORATEUR CONGELATEUR
EVAPORATOR - FREEZER



Vacuum evaporator
1 Evaporateur sous vide

2 Séparateur des cristaux
Separating device
3 Condenseur-absorbeur à lessive de soude
Condensor absorber with caustic soda solution
4 Fondoir
Melter

Consumption for 100T soft water
Consommation pour 100 T d'eau douce

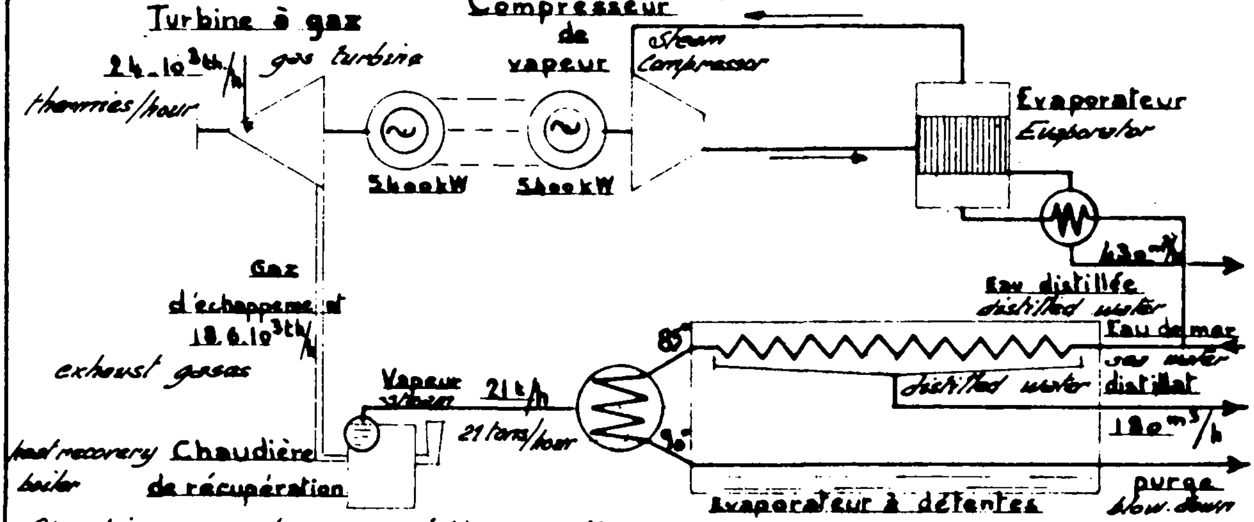
vapeur *steam*	3,7 tonnes
kWh	960 kWh
eau de réfrigération *cooling water*	400 tonnes

Figure XI

GROUPE TURBO-ALTERNATEUR à GAZ de 5400 KW utilisé en Centrale de pointe, échappant dans un évaporateur de 4300 m3/jour et alimentant un compresseur de 5400 KW

GAS TURBO GENERATOR 5400 KW

operated as a peak power station, with recovery of exhaust gases in an evaporator of 4300 m³/day and supplying energy to a steam compressor of 5400 KW



Operation as peak power station supplies hours every day hours per year
Marche en Centrale de pointe exporte 5400 kW pendant 4 heures par jour – 1000 heures par an

Marche en Evaporateur seul *Operation as evaporator only*

L'adjonction d'une installation à thermocompression utilisant la totalité de l'énergie électrique produite par le turbo-alternateur permet de produire en plus 430 m3/h d'eau distillée soit 3.100.000 m3/an en 7000 heures.

The steam compressor increases the water production by 430 m³/hour

- **Investissements** .... **20.000.000 F**

Investments

Production *Output*

- **Production kWh** .... **5400 x 1000 = 5.400.000**

Water : compression

- **Eau : compression = 3.100.000 m3**

Flash

détentes = 1.340.000 m3

4.440.000 m3

Bilan économique

Fixed charges (interest-depreciation)

- **Charges financières** .... **2.000.000 F**

Maintenance - Insurance

- **Entretien assurances** .... **500.000 F**

Man Power

- **Main-d'Oeuvre** .... **150.000 F**

Fuel

- **Combustible** .... **1.920.000 F**

4.570.000 F

Price of electric energy

Prix de l'énergie électrique : *0,06 F/kwh*

5.400.000 x 0,06 = ... **325.000 F**

Price of water

Prix de l'eau :

$$\frac{4.570.000 - 325.000}{4.440.000} = 0,95 \text{ F/m3}$$

Figure XII

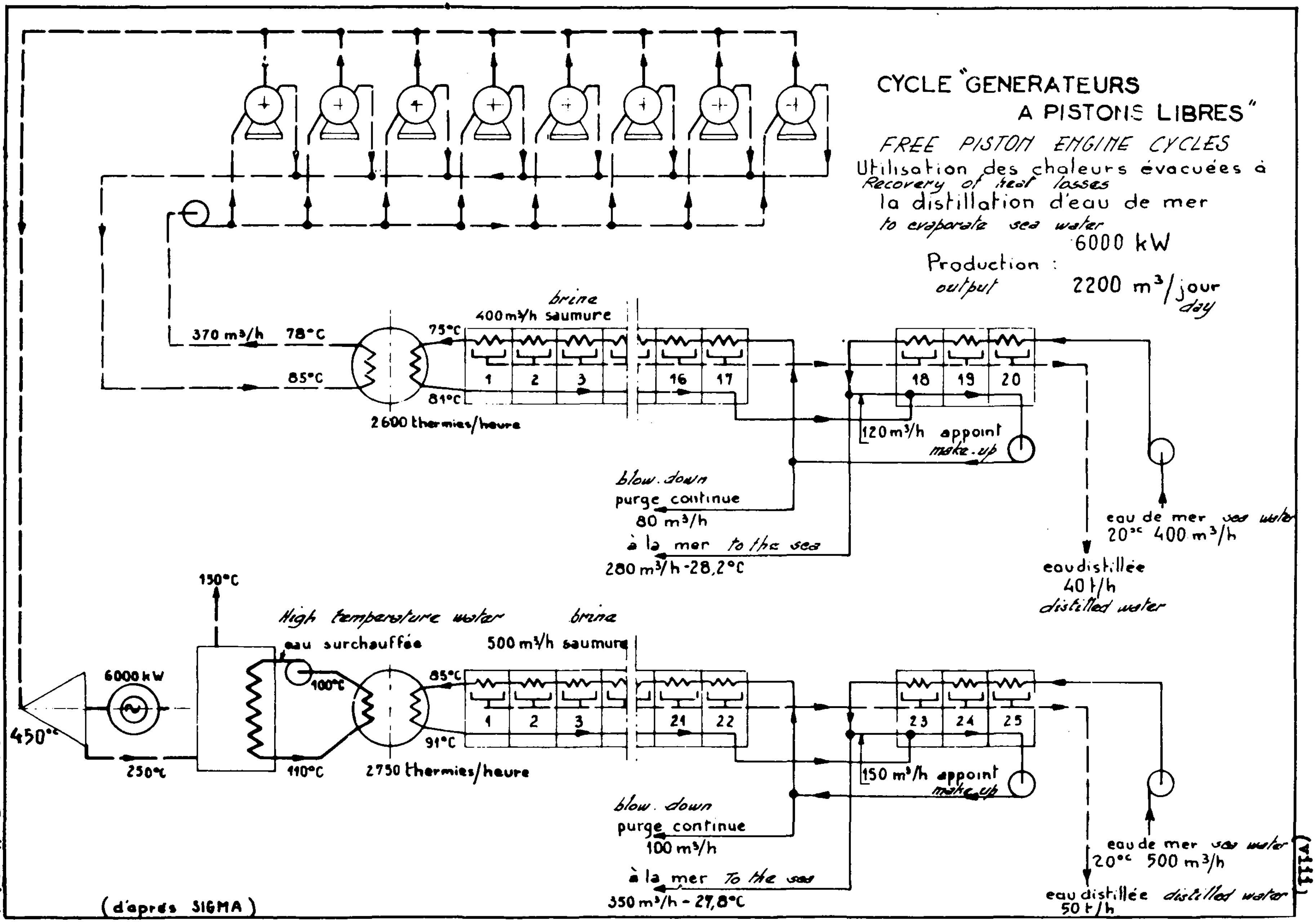
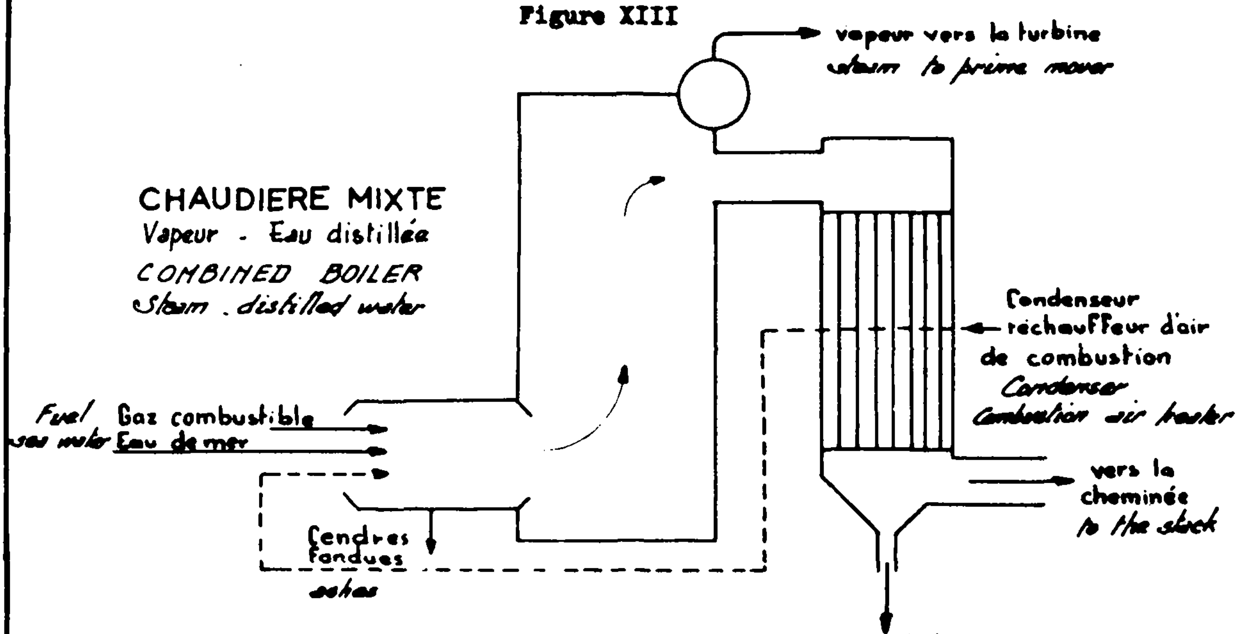
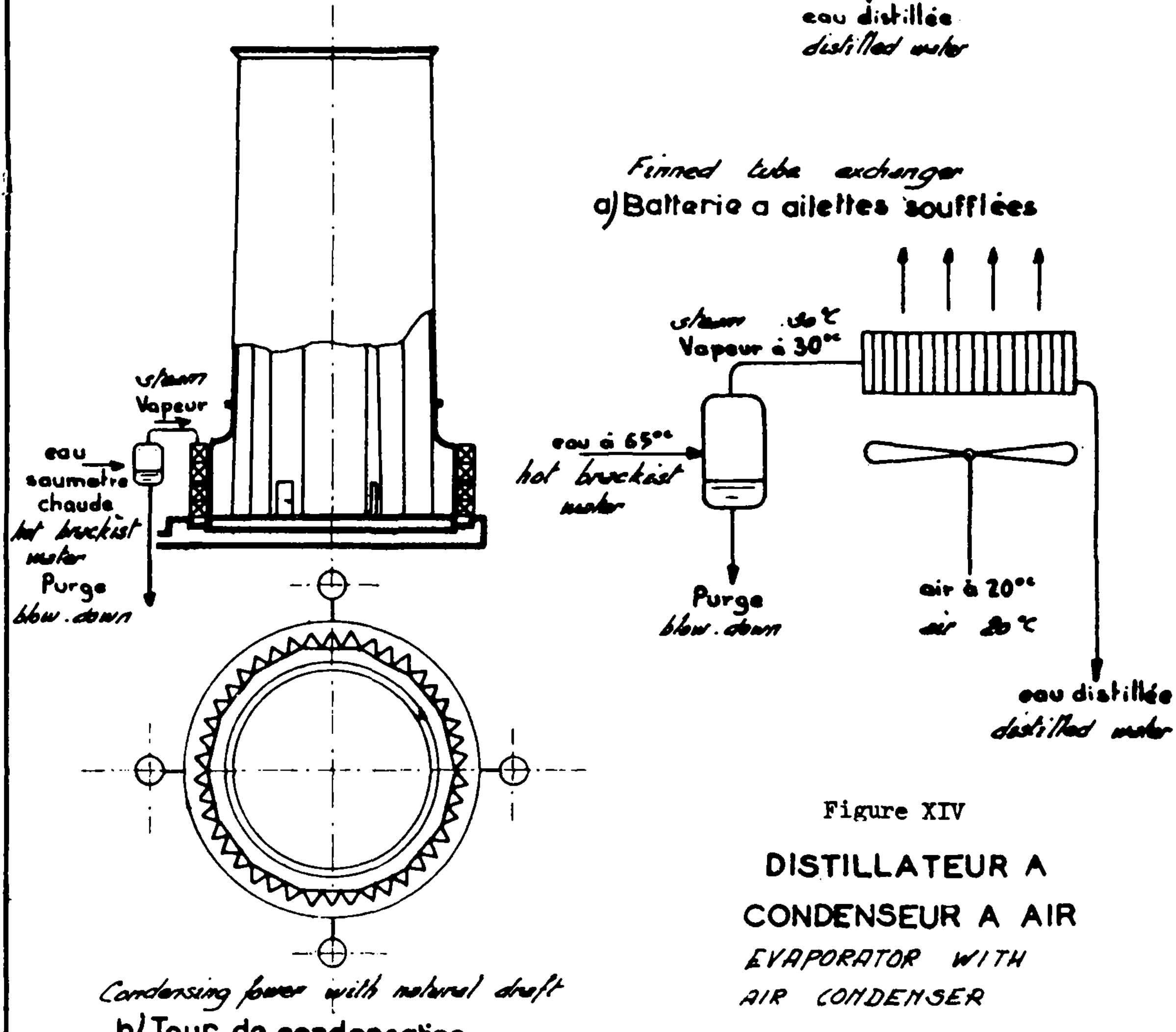

CYCLE "GENERATEURS A PISTONS LIBRES"
FREE PISTON ENGINE CYCLES
Utilisation des chaleurs évacuées à
Recovery of heat losses
la distillation d'eau de mer
to evaporate sea water
6000 kW
Production :
output
2200 m³/jour
day
370 m³/h
78°C
85°C
75°C
81°C
brine
400 m³/h saumure
1
2
3
16
17
18
19
20
2600 thermies/heure
120 m³/h appoint
make-up
blow-down
purge continue
80 m³/h
à la mer to the sea
280 m³/h - 28,2°C
eau de mer sea water
20°C 400 m³/h
eau distillée
40 t/h
distilled water
150°C
High temperature water
eau surchauffée
brine
500 m³/h saumure
6000 kW
100°C
85°C
91°C
450°C
250°C
110°C
2750 thermies/heure
1
2
3
21
22
23
24
25
150 m³/h appoint
make-up
blow-down
purge continue
100 m³/h
à la mer To the sea
350 m³/h - 27,8°C
eau de mer sea water
20°C 500 m³/h
eau distillée distilled water
50 t/h
(d'après SIGMA)

Figure XIII



CHAUDIERE MIXTE
Vapeur - Eau distillée
COMBINED BOILER
Steam . distilled water



Finned tube exchanger
a) Batterie a ailettes soufflées

Condensing tower with natural draft
b) Tour de condensation
a tirage naturel (Système Heller)

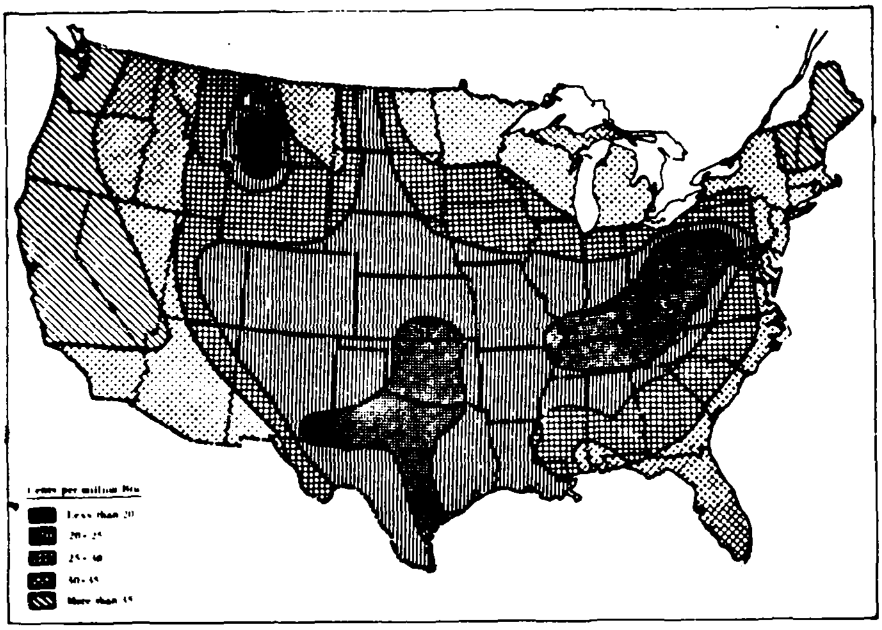
Figure XIV

DISTILLATEUR A
CONDENSEUR A AIR
EVAPORATOR WITH
AIR CONDENSER

Figure XV **PRIX DU COMBUSTIBLE PAYE PAR LES CENTRALES ELECTRIQUES AUX U.S.A**

FUEL PRICE OF UTILITIES IN U.S.A

55 cents/million de BTU = 1 centime la thermie



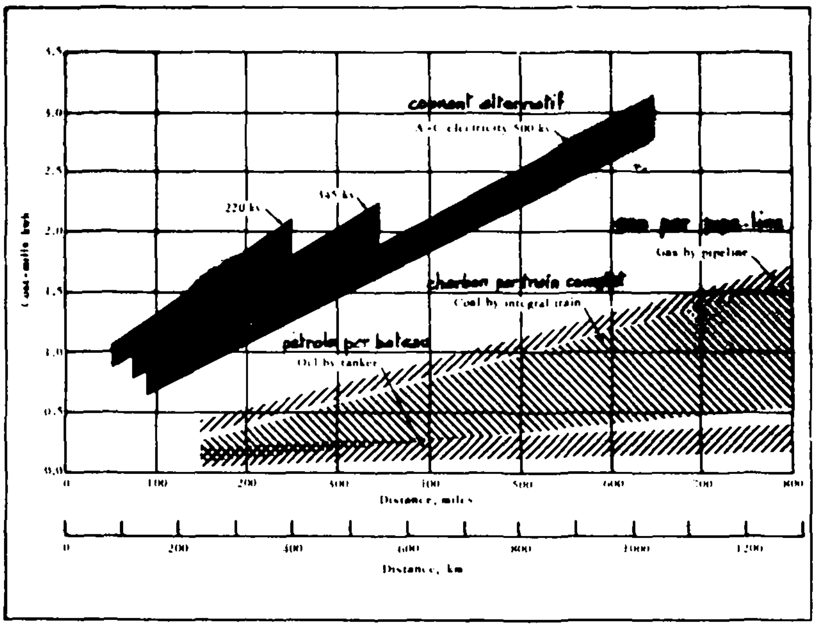


Figure XVI **COUT DE TRANSPORT DE L'ENERGIE AUX U.S.A**

ENERGY TRANSPORTATION COST IN U.S.A

d'apres World Power Conference

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XII. APPLICATIONS OF NUCLEAR ENERGY TO WATER DESALINATION

by R. Krymm

In many respects, economic analysis of the future prospects of nuclear desalting has to proceed today in the same climate of confidence in ultimate achievement and uncertainty on operational data as that which prevailed in the field of nuclear power costs in the early 1950's.

The rapid growth of nuclear power capacity which we are witnessing ten years later shows that this is not a cause for doubt or misgivings. Yet, a look taken today at the forecasts made ten years ago on the role, time scale of introduction and costs of different nuclear power reactors clearly emphasizes the dangers inherent in sweeping extrapolation.

In the case of desalting we are clearly in a field where the first word belongs to development engineers, where several processes have only reached the pilot plant stage, and where water desalting installations, capable of being economically coupled to power reactors, would be of a size many times greater than the largest unit operating today.

The economic analyst peering into the future must therefore guard against quoting costs for conceptual plants without an indication of the margins of uncertainty affecting these figures or engaging in large-scale extrapolations which almost always tacitly assume as constant some variables which would certainly change as a result of the massive programmes sometimes contemplated. Furthermore, while economic and costing methodology has an essential role to play, it should give priority to the analysis of plants or combinations of plants most likely to be developed in the near future on an industrial basis, and engage in refinements only to the extent that their impacts upon final results exceed the possible variations arising from uncertainties on basic input data. What is needed, in one word, is some sense of perspective restricting forecasts to qualitative and therefore tentative appraisals when the technological base is still in a state of flux and allowing the quotation of cost figures only in cases where they rest, if not on operational data, then at least on advanced design studies.

The scope of the present paper was therefore limited to the possible role of reactors as sources of heat for water desalting through distillation or evaporation. This does not reflect in any way a doubt as to the future prospects of freezing, vapour compression, electrodyalisis, and reverse osmosis, but the fact that as a result of engineering development the basic technical and cost data relevant to the former processes are known with a lesser degree of uncertainty than those of the latter. Furthermore, since the subject of costing methodology, the economics of different processes and the general problem of dual-purpose plants are dealt with separately within this co-ordinated seminar, the present report will merely review briefly the general relative positions of nuclear and conventional heat sources, the prospects of nuclear reactors in single-purpose and dual-purpose installations and the present national and international activities initiated in this field.

A. Cost of heat from proven reactors

A first attempt to determine roughly an area of competitiveness between nuclear and conventional plants as heat sources usually may take the form of estimating the cost of steam produced by those plants in terms of monetary units per unit of heat. If serious distortions are to be avoided, however, these comparisons should be made with steam of similar parameters. It would, for example, be quite misleading to compare steam costs of advanced fossil fuel stations with those of a low temperature reactor having the same electrical output, a procedure which would certainly penalize the conventional alternative. Furthermore, even if made for similar steam conditions, this type of comparison can only lead to approximate conclusions, considering on the one hand that a full economic comparison of desalting installations involves a series of optimizations in which steam costs are only one variable, and on the other that such conditions as siting of the plant and its availability may seriously alter the competitive status.

It is with these reservations that the curves of Figures I, II and III are to be interpreted. The data used are taken from a recent study and based on information supplied by equipment makers. The curves give the variation with plant size of the cost of steam produced by light water reactors of present design and by fossil fuel plants of two categories: the first, producing steam with parameters comparable to those of the reactors, the second, with parameters typical for advanced power plant boilers. All plants are assumed to be operated at an 80 per cent plant factor.

It should be clearly realized that these steam production costs at the outlet of the heat sources are roughly equal to the cost of heat for the water plant, only in the case of single-purpose systems. In the case of dual-purpose installations, there would of course be only one parameter in the costing procedure used. In the power credit approach, for instance, the cost of heat to the water plant would be obtained by adding to the steam cost, at the heat source exit, the cost component relevant to the electric power installations and subtracting the credit assumed for the saleable electric power output.

Without discussing further the underlying input data which are in accord with general information available at present, there appear to be thresholds of competitiveness for the reactors ranging from 300 MWth (for fossil fuel at 35 cents/1,600 BTU and 7 per cent fixed charge rate) to 1,600 MWth (for fossil fuel at 25 cents/10^6 BTU and 14 per cent fixed charge rate) in the case of comparison with fossil fuel stations producing steam of similar parameters. In the case of comparison with high temperature fossil fuel stations, the competitive size is, as expected, decreased. Without labouring further the expected sensitivities to size and fixed charge rates, a few comments on the validity of such estimates for even a preliminary appraisal of the competitiveness of nuclear heat for water desalting seem to be required.

First of all, the comparison was restricted to light water reactors in order to extend the range of competitiveness to as low a size as possible, and to simplify the presentation of this very general estimate. Clearly, both gas-cooled and heavy-water reactors would have to be considered in the middle and upper ranges covered by the curves. Data available indicate that only a detailed analysis could make it possible to establish the economic merits of the three reactor types as steam producers in the 1,000 to 1,500 MW thermal region.

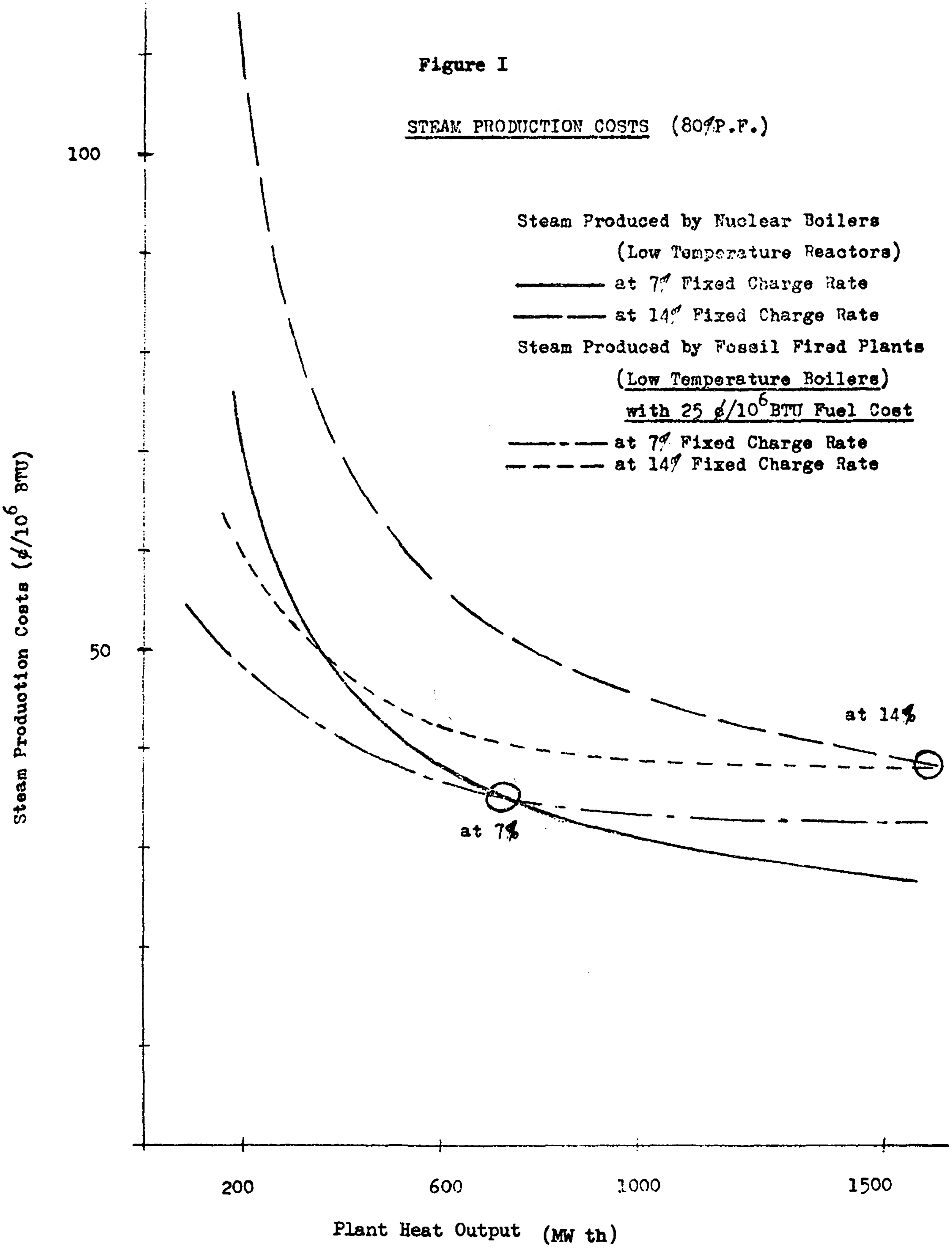


Figure I

STEAM PRODUCTION COSTS (80% P.F.)

Figure II

STEAM PRODUCTION COSTS (80 % P.F.)

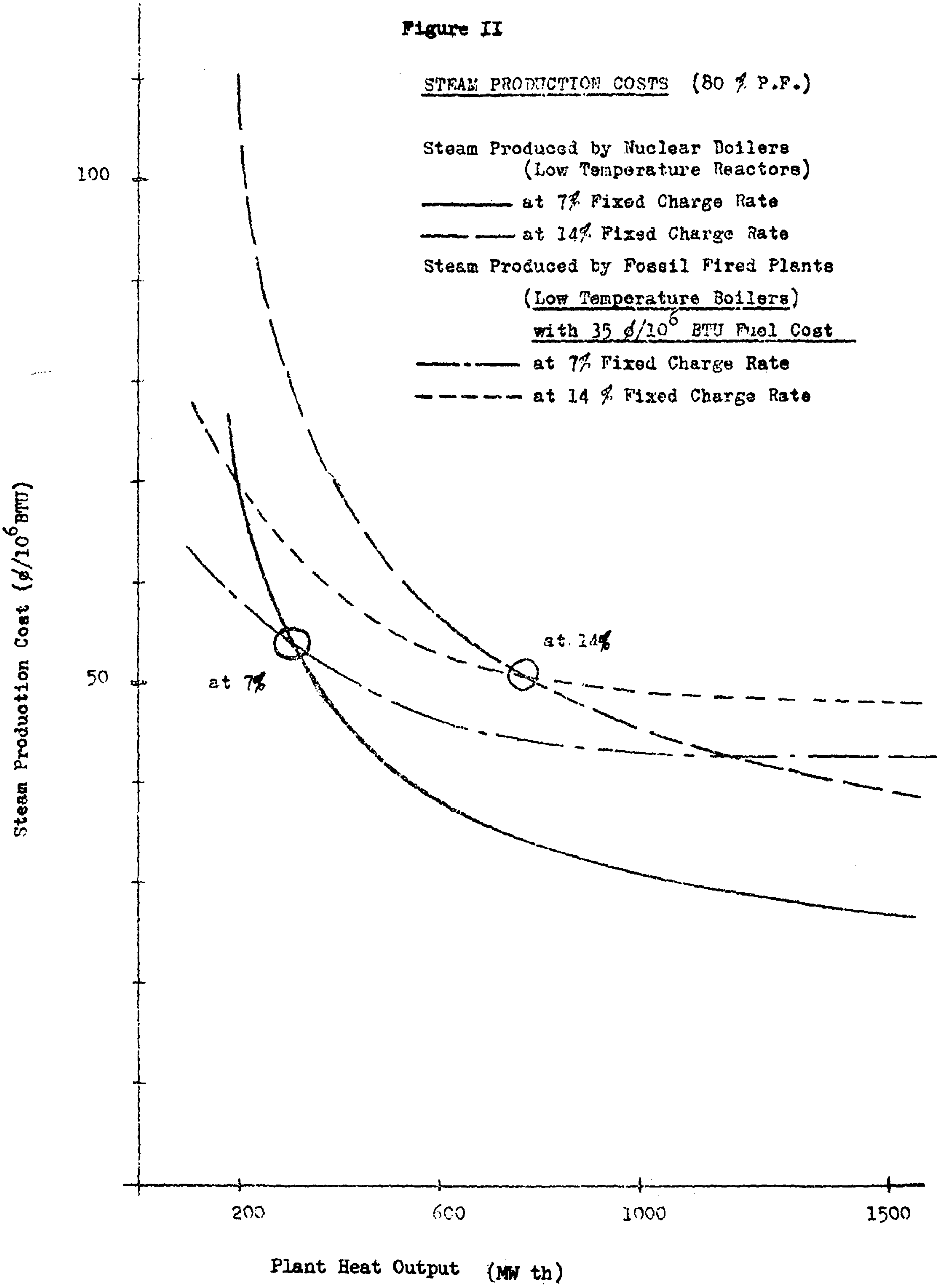


Figure III

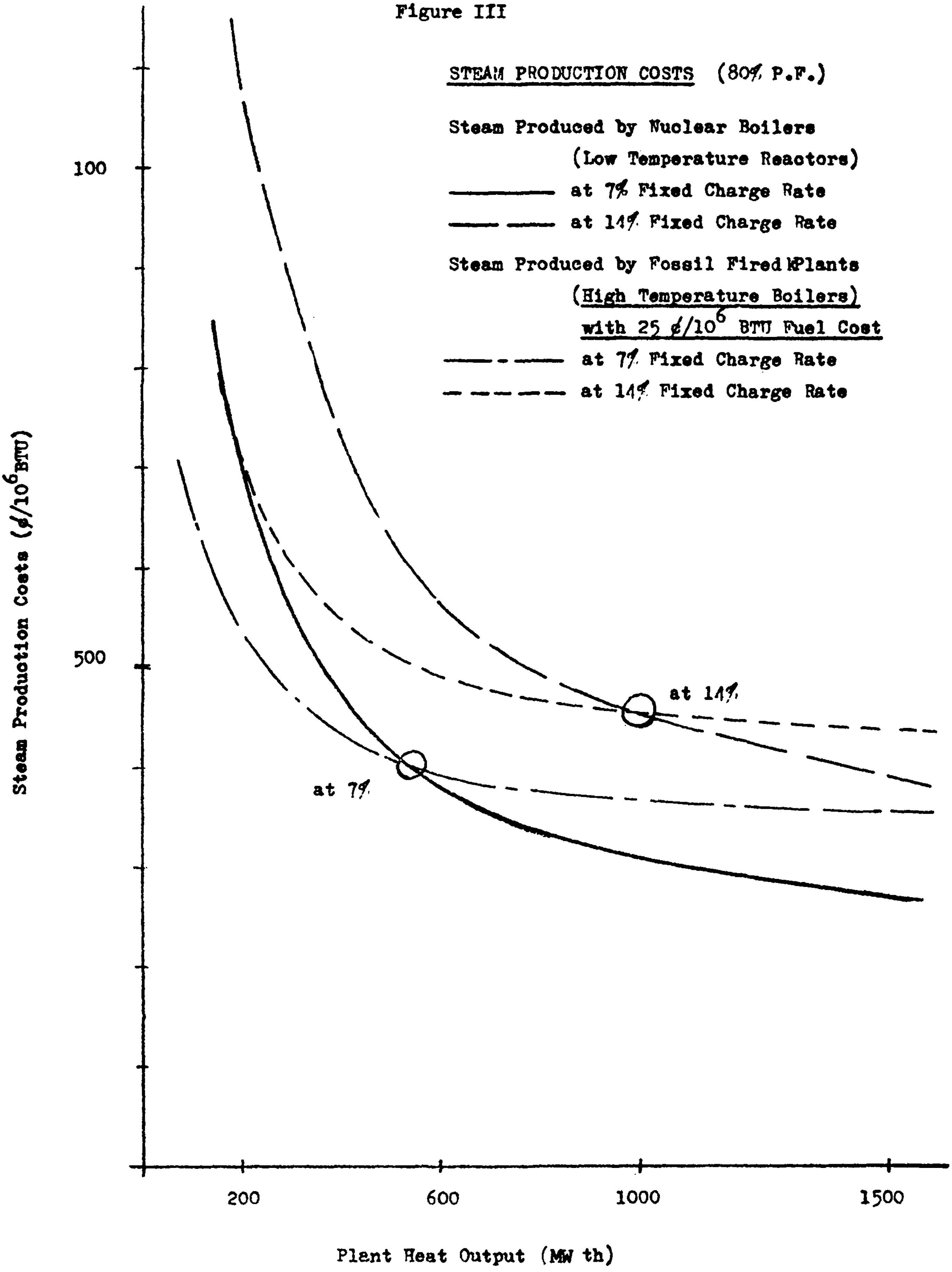
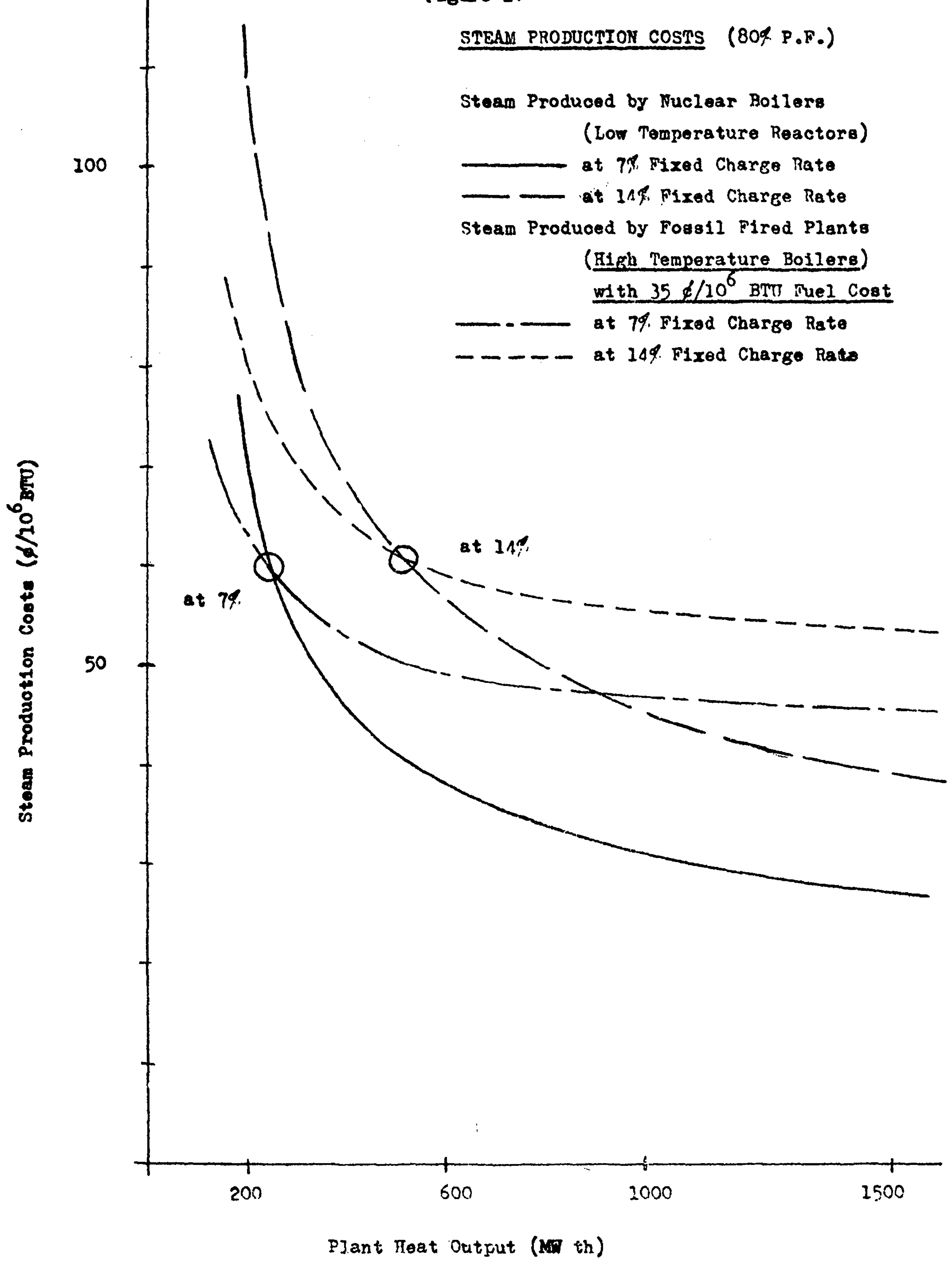

STEAM PRODUCTION COSTS (80% P.F.)
Steam Produced by Nuclear Boilers
(Low Temperature Reactors)
at 7% Fixed Charge Rate
at 14% Fixed Charge Rate
Steam Produced by Fossil Fired Plants
(High Temperature Boilers)
with 25 ¢/10⁶ BTU Fuel Cost
at 7% Fixed Charge Rate
at 14% Fixed Charge Rate
at 14%
at 7%
100
500
Steam Production Costs (¢/10⁶BTU)
200
600
1000
1500
Plent Heat Output (MW th)

Figure IV


STEAM PRODUCTION COSTS (80% P.F.)
Steam Produced by Nuclear Boilers
(Low Temperature Reactors)
at 7% Fixed Charge Rate
at 14% Fixed Charge Rate
Steam Produced by Fossil Fired Plants
(High Temperature Boilers)
with 35 ¢/10^6 BTU Fuel Cost
at 7% Fixed Charge Rate
at 14% Fixed Charge Rate
at 14%
at 7%
100
50
Steam Production Costs (¢/10^6 BTU)
200
600
1000
1500
Plant Heat Output (MW th)

Second, the figures used are of course based on certain assumptions on nuclear fuel costs. Considering that the installations are expected to operate for several decades, doubts have been sometimes expressed as to the stability of the former over such extensive periods. While it is true that the presently proven 600,000-700,000 tons of low-cost uranium reserves would come under pressure if the nuclear power industry expands at a rate presently forecast, it should be remembered that the recent conditions of over-supply have led to an interruption of prospection and there appear no grounds to expect a shortage of uranium ore but only a gradual shift to higher cost deposits. On the opposite side, fabrication of fuel elements is only beginning to reap the benefit of standardization, mass production and automation. This applies to an ever greater extent to the reprocessing of irradiated fuel. Finally, the speed-up in the development of plutonium-fuelled fast breeders is likely to guarantee a substantial value to this element perhaps exceeding the present assumed value. At the same time, the radically improved utilization of nuclear fuels in the next generation of reactors, whether advanced converters or breeders, will relieve whatever pressure may arise on presently proven supplies. To sum up a situation which can only be dealt with in qualitative terms at the present stage, it can be said that nuclear reactors of the present proven type are not likely to be penalized over their lives by higher fuel costs than those estimated today for their first years of operation.

Another element which might seriously change the competitive status of nuclear heat for water desalting is the question of siting. Clearly, if safety requirements were to force a nuclear desalting plant to be located along a coast-line at a distance substantially greater from the collecting or consuming point than its conventional alternative, the comparative costs of heat production at the plant site might lose much of their relevance. It has often been argued, in this connexion, that safety criteria will systematically handicap a nuclear station. Rapid engineering developments are, however, already beginning to offset this handicap. Without going into an analysis which would justify a report of its own, the example of the use of pre-stressed concrete pressure vessels, containing the complete coolant circuit for certain reactor types, represents a greater step forward in the field of safety since such a vessel depends for its integrity on a very large number of separate high tensile steel pre-stressing cables and many of these would have to fail simultaneously to provoke a sudden accident. On the other side, the problem of air pollution by conventional stations will increase in importance at an accelerating rate. The only conclusion which can be drawn in this field as in many others is that no general affirmation can be made at the present stage. As a matter of fact, enhanced nuclear safety and fossil fuel pollution control can both be achieved at additional investment costs, and only a detailed study of a specific case can decide what additional economic costs are to be attached to the two alternatives as a result of site restrictions.

Still another qualifying factor affecting comparative heat costs is that of availability. The steam costs presented in the charts were based on an assumed 80 per cent plant factor. In many situations, however, the plant factor, at least in the early years, is likely to be limited not by fluctuations of demand but only by the availability of the station. In this connexion, power reactors have a short but remarkable availability record. They have in most cases shown availabilities superior to those of conventional boilers and exceeding 90 per cent. Nevertheless, there are inherent differences between availabilities of on- and off-power refuelling reactor types. This does not mean necessarily that the latter should be penalized by the full time of their shut-down for refuelling, since in many situations the reactor stoppage might be scheduled to coincide, at least partially, with the maintenance of the evaporators and in dual-purpose installations with that of the turbine.

B. Extrapolation from present technology reactors

These extrapolations proceed along two lines which are sometimes combined together: size increase and development of low temperature reactors specially suitable for desalting.

With regard to size extrapolation, there is no question that unit capital costs contribute to a decrease for nuclear power plants in size ranges much higher than those for which unit investment costs of fossil-fuelled stations become practically constant. Furthermore, there appear to be no insuperable technical obstacles to proceed to sizes of 10,000 MWth and more, for certain reactor types at least, as for example those using pressure tubes. The size limitation rising from steel containment vessels can also be lifted by the substitution of pre-stressed concrete. It is, however, quite another matter to extrapolate investment costs by an order of magnitude and estimate them for reactors in the 100,000 MWth range. However fine the breakdown of the cost function, it seems difficult to admit that reliable industrial estimates can be made as to the costs of the components of a plant of this size.

Another line of investigation, on which there is unfortunately some scarcity of data, proceeds from the theory that low pressure steam-producing reactors could offer an attractive solution as heat sources. There appears, however, little reason to believe that this is the case. For the presently proven reactor types, major cost items would be little affected by a lowering of temperature. On the other hand, serious problems would arise in the heat exchangers because of the increase of exchange surface and of the pumping power required. As a matter of fact, it seems that the progress made in this field is irreversible and that nuclear reactors which will supply heat for desalting will be based on the progress achieved and expected for electricity-producing nuclear power plants. The inherent advantages of dual-purpose installations can only reinforce this point.

C. New advanced converters and fast breeders

There is no question that both types will be able to produce steam with nuclear fuel costs in the 5 to 10 cents/10^6 BTU and with expected scale-ups of the fuel elements fabrication, and processing industries, even lower costs might be conceivable. The essential parameters of these reactors are, however, still affected with margins of uncertainty which make an economic analysis of their role as heat sources for desalination fall outside the scope of the present paper.

D. Nuclear and conventional heat sources in dual-purpose plants

The general advantages of dual-purpose water and power-producing plants are the topic of a separate paper presented to this seminar. The present remarks are therefore restricted to the expected economic merits of nuclear and conventional stations in dual-purpose installations.

It should be stressed from the beginning, however, that the economic comparison of two dual-purpose plants involves a highly complex process of comparing two installations usually rendering different services, say, for instance, the same output of electricity for different outputs of water, each alternative being optimized for the achievement at minimum cost of the objectives required. Under these conditions, there is obviously little room for sweeping generalizations and the following comments can only be taken as qualitative indications of trends.

The general argument that the competitive status of nuclear reactors will be enhanced in the case of dual-purpose stations is of course true, but the measure of this improvement can only be determined in each specific situation.

If we take the somewhat unrealistic case of a fossil and nuclear power plant of the same efficiency, which produce electricity only, and which are barely competitive, and consider what happens if we want to convert to dual-purpose water and electricity production while maintaining the same electrical output, it will appear that, as a first approximation, the end result will be equal electricity and water production for both plants with a larger boiler or reactor. Since unit capital costs decrease much faster with increasing size for nuclear than for conventional boilers, an improvement in the competitive position of the nuclear alternative will thus have been achieved. The validity of the general conclusion of this somewhat theoretical argument that the savings of scale will favour nuclear plants in dual-purpose desalting installations still holds good in real cases where relatively high efficiency conventional plants are usually competing with relatively low efficiency reactors, and is borne out by a very detailed study of dual-purpose installation.

Another and somewhat more complex advantage of nuclear stations arises from the wide range of water to power ratios offered by them at present. Once again, the argument has to be simplified but in summary it amounts to the following: Present reactors competitive for the production of electricity have efficiencies ranging all the way from 29.5 per cent in the case of heavy-water stations to about 41.5 per cent in the case of advanced gas reactors, the latter figure being comparable to that of modern fossil fuel stations. If these stations are investigated for dual-purpose installations with a required electrical output, optimization studies could yield water outputs differing by a factor of the order of 2 for the same electrical capacity. In large size dual-purpose installations, economically competitive fossil fuel plants are likely to be restricted to high efficiency units, and hence to relatively low water to power ratios. Different reactor types, on the other hand, will offer a wide spectrum of possibilities in this regard and could be selected to fit each specific situation.

The competitive status of reactors in dual-purpose may further be affected in a somewhat less objective way by the costing procedure used for economic comparisons. Although the important topic of costing methodology is outside the scope of the present paper, an example of how a particular procedure may penalize one of the alternatives can be mentioned in connexion with the widely used method of the power credit. Under this method, the cost of water is obtained by adding the total annual costs of all the components of the dual-purpose installations, subtracting from them a credit for the electric power produced, computed on the basis of either the generating cost of electricity by the most economic single-purpose electricity-producing plant, having the same saleable output as the electric part of the dual-purpose plant, or on the basis of the lowest electricity production cost in the system. Furthermore, it is usually assumed that both installations will operate at full capacity throughout their lives. In the marginal but very real case where the nuclear and conventional dual-purpose stations are barely competitive, while the most economic single-purpose reference plant for the determination of the power credit is conventional, the method contains an element of penalty against the nuclear alternative, inherent in the assumption that the single-purpose reference conventional plant would remain on base load throughout its life, while it will, in fact, be displaced in the load diagram within a few years of operation by conventional or nuclear units with lower fuel costs. This example may be considered as purely illustrative and as involving only second order effects in the results; however, much more serious consequences would arise from, for instance, using different fixed charge rates for costing the power credit and the total dual-purpose plant annual charges, a procedure which would completely distort any economic analysis of alternative schemes.

The sketchy consideration of some of the problems arising in assessing the position of nuclear stations in dual-purpose installations was only designed to underline the complexity of a subject which can only be adequately analysed through detailed studies, some examples of which are given in the list of references. Yet, the conclusion that nuclear reactors will have a major role to play in dual-purpose installations is inescapable, and one of the best guarantees of its validity is the variety of projects and studies recently undertaken in the field of desalting on a national and international basis.

E. National and international projects in the field of nuclear desalting

Let us now review briefly the present state of nuclear desalination. While there is at present no nuclear desalination plant in operation, one is under construction in the Soviet Union near the Caspian Sea, and will generate 150 MW of electricity and produce 120,000 m^3 (30 mgpd) of fresh water per day. This reactor is of the breeder type and will be completed by 1968/1969.

A feasibility study for a nuclear dual-purpose plant with two light water reactors of 750 MWe each and a water production of 600,000 m^3/d (150 mgpd) is under way. This plant would be located in California and owned by the Metropolitan Water district. The study will be completed towards the end of this year, and the plant could be operating by 1970.

Another detailed feasibility study is being carried out for a joint United States-Israel project. It evaluates a reactor of 1,500 MWth producing 200 MWe and 400,000 m^3/day of fresh water (100 mgpd). The results of the study will be known by next December, and the plant could be operated by 1971. The water would be fed to a distribution system and be used for domestic and agricultural purposes.

The state of advancement of other projects is somewhat less defined. Thus, the United Arab Republic has sent an invitation to bid for dual-purpose nuclear plant producing 150 MWe and 20,000 m^3/d (5 mgpd). The water would be used for a pilot irrigation scheme.

Tunisia received preliminary bids for a dual-purpose plant producing 50 MWe and 20,000 m^3/d (5 mgpd). The water would be intended for industrial and domestic use in the region of Gabes (South Tunisia).

A joint United States-Mexico project is under consideration. Its purpose would be to dilute a part of the water from the Colorado River which presently has a salt content too high to be used for irrigation. The size of the reactor would be of 3,000 MWth and several units might be considered.

It might be worth noting that some cities such as Mexico, Athens and New York, are reported to have or to expect a water shortage. In these cases, nuclear dual-purpose plants might be considered as an alternative.

Finally, the recent report to the President of the United States of America issued by the Office of Saline Water and the Atomic Energy Commission proposes to build a prototype reactor having about 1,000 MWth capacity. This reactor would be heavy-water-moderated and organic-cooled, and could be operated by 1970. It would be followed by a second plant of the same type of about 3,500 MWth operating by 1974/1975. The first unit would not be coupled to a desalination plant, in order to minimize the possible interference by one prototype plant with the operation of the other. If both reactor and desalination plant of about 200,000 m^3/d (50 mgpd) would prove successful, the proposed 3,500 MWth reactor would be coupled with a large sized prototype desalting plant. It is also interesting to note that the Atomic Energy Commission considers that this type of reactor should either be developed for a large-size power-only plant or for a dual-purpose desalination plant.

F. The role of the International Atomic Energy Agency

The intensive nuclear desalting development programmes undertaken at a heavy cost by some industrialized countries and the keen interest in their possible application evidenced by developing States, lends special significance to the role of an international organization. The International Atomic Energy Agency, whose responsibility for the applications of nuclear energy to desalination clearly arises from its statute, has already participated in a series of studies and convened several panels of international experts, designed to keep its members abreast of the latest developments in the field. It intends to expand these activities from the collection and analysis of information and the preparation of general studies on such topics as, for instance, costing methodology and prospects of different reactor types for desalting to the lending of technical assistance to Member States with regard to the analysis of their specific situations.

G. Conclusions

It may perhaps seem surprising that no figures for water costs have as yet been quoted in a paper devoted to the prospects of nuclear desalting. Enough has been said, however, to show that such figures are sharply dependent on basic cost input data, involving size extrapolations of one or two orders of magnitude and, especially in the case of dual-purpose plants, on the costing procedure and the economic parameters used. By combining extreme assumptions and selective costing procedures, variations of more than 100 per cent in water costs can easily be achieved and any quotation out of the context of the specific feature of a given situation has therefore little meaning.

However, in assessing the possible role of nuclear desalting over the future, some idea of the order of magnitude of the costs of water produced is necessary. The water costs quoted by studies involving nuclear power reactors of proven types and sizes and extrapolated water plants extend over a range of 7 to 14 cents/m^3 (25-50 cents/10^3 gal), depending on the costing procedure and parameters used and leaving extreme assumptions aside. The advent of breeder reactors with extremely low heat-producing costs and the consequent savings in the investment costs of the water plant, whose optimal number of stages would decrease with the cost of heat supplied to it, are likely to bring the above cost range to substantially lower levels.

Meanwhile, however, a forecast on the role of nuclear desalting in the future must necessarily distinguish between the time periods involved. Over the short term, nuclear desalting involves the coupling of two rapidly progressing technologies which have, up to now, been developed for quite separate objectives. Their combination in the immediate future depends on a wide research programme, covering, on the reactor side, the study of units particularly suitable for dual-purpose operation and, on the water side, the construction of evaporator plants of sizes 10 to 100 times larger than that of the units operating today. In this initial phase, economic desalting is likely to occur only in special situations of acute water shortage and nuclear competition in the subcategory of cases where relatively large dual-purpose plants can be considered.

Over the medium term, the development effort undertaken in the first phase is likely to lead to the construction of a series of large dual-purpose installations, where the combination of the size effect with the cost characteristics of advanced reactors will ensure a major role to nuclear energy.

Finally, over the long term, the technology of flash evaporation and distillation is likely to be supplemented by other means of water desalting. Indeed, it will have to be, if desalination is expected to make a major contribution to the world water supply without exerting a serious pressure on fossil and even nuclear fuel resources. A short calculation would show that with the performance ratios of the order of 12 pounds of water per 1,000 BTU heat input available today, and the expected growth of water demand in the world till the turn of the century, an attempt to meet a large fraction of the additional requirements by distillation or evaporation processes would involve quantities of fuel substantially exceeding those predicted for electricity production. Although it would be idle to speculate on which of the promising processes, at present in the research and development stages, will be economically successful, all of them are however bound to be, to varying extents, energy consumers and hence depend on the existence of a low-cost energy supply base which only nuclear fuels can ensure.

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XIII. RELATIONSHIP BETWEEN STORAGE CAPACITY AND LOAD FACTOR OF A DESALINATION PLANT

by A. R. Golzé

This seminar on the economic application of water desalination has already been concerned with a review of the several saline water conversion processes and energy requirements and with water demand and the evaluation of water resources. Lectures to follow this one will be concerned with selection of desalting plant capacity and desalted water cost.

The problem of the relationship between storage capacity and desalting plant-load factor has received little, if any, attention. Economic and engineering analyses have been limited mainly to determination of the feasibility of constructing desalination plants in specified areas where a demand for desalinated water is expected to develop. For purposes of this discussion it has been tacitly assumed that the construction and operation of a desalter was determined to be of benefit to the service area and the use of the water will be largely municipal and industrial.

This discussion is based on an economic cost analysis in which the least costly alternative is selected. In this analysis the selection of a desalter and the manner in which it would be operated depends on a comparison of the costs of alternatives. Comparisons of alternative sources of water supplies are done in this manner by my organization. Even though conditions may exist in some areas that might preclude an analysis based solely on economic alternatives, it is probable that the least expensive source of water would normally be developed first. The procedure outlined here should therefore be of general interest to those concerned with water development and the selection between alternatives.

As the cost of saline water conversion is reduced through technological developments and construction of larger capacity plants and test facilities, desalination will become economically feasible in many water-short areas, especially if water use is predominantly municipal and industrial because it is customary to charge a higher rate for this class of water. Consequently, it becomes more important to develop the most economical scheme for operating the facilities. This will include the determination of the optimum plant size, storage capacity, and load factor for each desalting system.

Before any decision can be made on a water resources development scheme, a survey of existing and future water use must be made for the particular service area. On the basis of data obtained in the survey, future water requirements can be projected by various statistical methods which undoubtedly would reflect population growth. This projection of future needs will permit the required capacity of the desalting plant and the schedule of construction to be determined, and indicate whether the desalted water will serve as the only, major, or complementary source of water supply.

In presently developed areas the existing water storage and distribution systems must be considered in evaluating the relationship between storage capacity and desalting plant load factor. At one extreme, it may be possible to blend desalted water into an existing network with little, if any, construction other than the desalter. At the other extreme, an entirely new network and storage facility must be designed and constructed so that the desalted water can be utilized effectively. The relationship between storage and plant capacity can thus vary over wide limits. Consequently, the schedule of water requirements must be carefully considered.

In this lecture some of the many relationships involved in comprehensive studies to determine the economic selection between alternative water supplies will be discussed. While these studies are complex and would require more time than is available to present completely, the lecture will show the types of relationships and their importance in developing a water supply system. The need for data on the water demand for a service area is explained and the type of information required is discussed. The relationship between water deficiencies and the resultant economic loss is also presented.

Several typical situations in which a desalter might be justifiably involved in a water supply and the utilization of its output are explained and illustrated analytically. The case where the desalter is the sole source of supply is selected to illustrate, by example, the type of optimization that can be accomplished. A procedure is programmed for computer solution to show the relationship between storage capacity and the desalting plant load factor. A model to determine optimum operation will be presented. A brief discussion of different types of storage facilities and of representative average cost of such storage facilities in California is presented in Annex A to the lecture.

A. Water demand

In many areas, at least in the near future, the relative price of a desalted water supply is expected to be higher than in areas where water from other natural sources is available. Since water use is sensitive to price, *per capita* consumption may be expected to be lower in areas where desalted water is used. Before establishing the size and capacity of a desalination plant, it is necessary to modify the estimate of water requirements by determining the demand for water as a function of various prices and time of use. This converts the physical potential of the water requirement schedule to an economic demand schedule. 1/

Data by which an economic demand schedule can be established are limited. There is, however, some information concerning prices charged for water and *per capita* use for a number of areas summarized in the United Nations publication, *Water Desalination in Developing Countries*. 2/ Differences in *per capita* income and possibly other factors affecting water use will have to be taken into account in deriving a demand schedule from such data.

1/ See "Definition of Terms".

2/ United Nations publication, Sales No.: 64.II.B.5.

The first step in sizing any water development, storage, or distribution system is the determination of the shape and size of the demand curve. Each service area will have its own regimen of demand on a daily basis as well as on a weekly, monthly, and annual basis.

Quantitively, figure I shows the type of curve which must be developed to show the relationship of demand with time. It is typical of a developing area. The figure shows the expected future increase in total water demand for the Coastal Plain of Los Angeles County in California. This information is developed on an annual basis and reflects the expected rate of growth and the increase in rate of water use per unit activity under the expected future costs of water for that area.

Figure II, the second step in developing information, shows the variation in water demand in any year as a monthly per cent of the average monthly demand. As you can see, the demand in the peak month is nearly twice that of the lowest month. In California, in the northern hemisphere, our peak month is July and the monthly variation follows the air temperature curve to a great extent. The average monthly water demand curve will vary from place to place and must be developed taking into account the conditions of the water distribution area. It will, however, have some relationship to air temperature. Such a surve is developed from empirical information either in the expected service area or in a similar climatic and water use area.

Figure III, the third type of information required, is the regimen of the hourly water demand during a day. In the Los Angeles area the large rates of water use occur during daylight hours, peaking at the time when people have returned to their homes from their place of work. This curve reflects an urban area with an industrial complex. This type of curve is developed from empirical information on a water-supply distribution system in the area or in a similar climatic and social environment. The social mores of the urban population greatly influence the typical hourly demand curve. The Los Angeles area is a widespread urban area consisting predominantly of single-family dwellings, each of which has its own lawn and yard. Lawn watering may account for the high peak at 6 to 7.00 p.m. in the evening. The high use during the day reflects not only the industrial activity but also the use of washing machines and other water-using appliances.

Since conditions and applications vary from place to place, the characteristics of the curves will vary. For each area it should be possible to develop such demand curves. The development of such curves is a necessary prerequisite to the optimization of storage capacity and load factor for a desalter. Later, by example, an illustration of the use of these curves will be made.

B. Economic loss

In order to balance the cost of auxiliary facilities against the economic need for them, it is necessary to have some expression of economic loss resulting from a failure to meet water demands fully. There has been very little study of these loss functions. Let us, however, state a loss function which is based

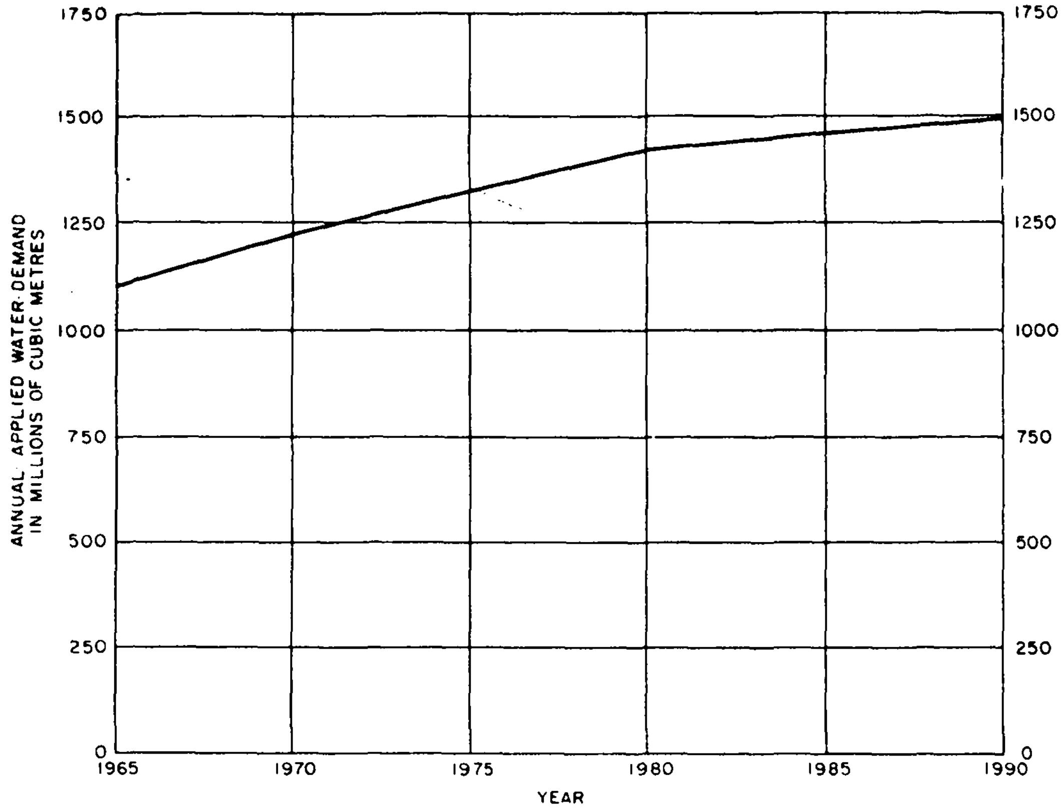

Figure I. Projected applied demand

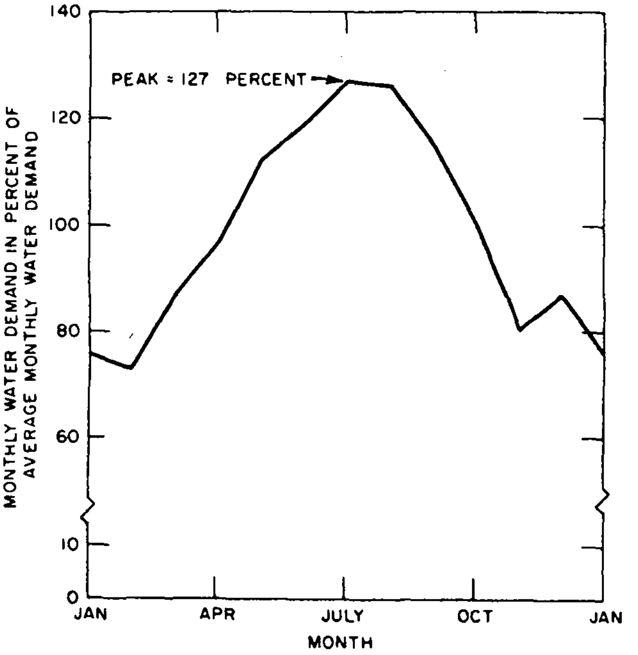

Figure II. Average monthly water demand

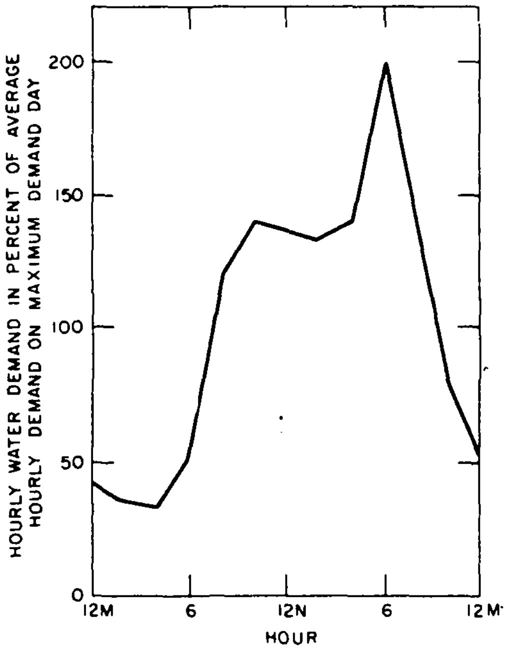

Figure III. Typical hourly water demand on a maximum water demand day

Note: Figures I,II,II, show water demands for the coastal plain of Los Angeles, California.

on some studies[3] of pricing policy versus municipal and industrial demand. Further, this loss function applies only when the shortage of water occurs over time periods long enough so that uses of water are not merely delayed but foregone. Such a function might have the following form:

$$\text{Economic loss} = \sum_{i=1}^{i=d} a \left(1 + \frac{i}{n}\right)^4 \qquad (1)$$

Where:

i varies from 1 to d
a = marginal price per unit of water normally supplied
d = number of units of water not supplied during shortage
n = number of units of water normally supplied

For any given water deficiency, at any one period of time, the economic loss in dollars is given by the solution to equation 1. The total shortage cost is the sum of the economic loss incurred by each type of shortage multiplied by the probability of that type of shortage. This requires an estimate of the degree of deficiency as a function of the duration of downtime and extent of storage in the system. Table 1 is a solution to equation 1 for several selected water deficiencies. In table 1 if the water deficiency in the service area is 10 per cent, the economic loss resulting therefrom in the same service area would be 12.44 per cent.

Table 1

Economic Loss for Percentage Water Deficiencies

Deficiency %	Economic Loss %
2	2.12
5	5.63
10	12.44
25	41.76
50	133.91
75	312.47

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[3] The elasticity of demand for water for short-term curtailments in supply is assumed to be .25 at the retail level for small shortages, and to increase as the degree of shortage becomes more acute. Various studies described in the California Water Industry study undertaken by Professors Bain and Margolis at the University of California, show an elasticity of demand of between .4 and .7 for residential water use. These estimates are based on a cross section analysis for data for various cities in the United States and reflect a long-run response to price. Consequently, the .25 elasticity estimate may more reasonably reflect the effects of a short-term curtailment of supply.

Per capita use must reflect long-term adjustment to high water prices rather than a temporary period of high prices. In the case of a temporary shortage, there would be lack of time for water-use adjustment. An increase in the price would be less effective in restricting use in an interim situation than that indicated by a demand schedule. Consequently, the economic loss attendant on such shortages would increase more rapidly than when long-term adjustments can be made. The loss per unit will be the average price between the price charged under normal operating conditions and the price required to ration use to the restricted amount.

1. Typical situations

Three situations which might be faced by water-deficient areas are as follows:

Situation A. The desalination plant is the only source of supply and therefore a breakdown of the plant would result in comparatively heavy economic losses.

If the desalination plant is the only source of water, the following factors, including shifts in demand schedule, primarily affect the size and capacity of a desalination plant and the need for auxiliary facilities:

(1) Month-to-month variations in water use.

(2) Scheduled non-productive maintenance and operation time.

(3) Unscheduled maintenance requirement which will halt water production at the desalination plant for a period of time.

Situation B. Desalination is a component, either major or complementary, of a water supply system but the demand for electric power is not sufficient to make a dual-purpose plant economical. This situation is especially relevant in areas where use of electricity is limited.

Situation C. The desalination plant is operated in a dual-purpose arrangement with electrical power production. This situation is particularly relevant in highly industrialized countries where there is a large-scale demand for power.

In the last two situations, nation-wide or region-wide water distribution networks may exist or be planned, so that reservoirs may be used for storage of water from the plant.

An optimization model, which minimizes economic costs (or maximizes net benefits) is presented in this lecture. It is applied primarily to Situation A, in which desalination would be the only water supply except for storage facilities. The economic costs included in this model are the costs of the desalination plant itself, the costs of storage, and the economic losses resulting from lack of sufficient storage to provide water at times of unscheduled downtime of the desalination plant.

2. Utilization of desalting plant output

Let us construct a series of examples, starting with a simple case and progressing to more complex cases:

Case 1. A constant output desalination plant with no maintenance requirements which must meet a varying demand schedule is shown in figure IV.

If the auxiliary facility is a surface water reservoir, its storage must equal the volume of water whose quantity is given by area B. If one were able to start operation at the most favourable time it would be possible to set the output level so that the area A (volume of water stored) equals the area B (volume of water withdrawn from storage) plus losses. One would seek to minimize the sum of storage costs and desalination plant costs. This may cause the output level to be set higher than that which would cause area A and area B plus losses to be equal.

If the auxiliary facility is a ground-water basin, the cost is principally related to the rates of withdrawal (r_w) and recharge (r_r). The volume withdrawn cannot exceed the volume recharged plus losses. This cost relationship may be considered nearly linear because a number of modules of recharge and extraction facilities are used.

Case 2. This is the same as Case 1, except that output of the desalination plant is variable within a limited range (see figure V).

The economic aspects of reregulation for this case are very similar to those discussed for Case 1, except that in this case one would also balance the cost of building variable capacity into the desalination plant against the reduction in cost of auxiliary facilities.

Case 3. The desalination plant has scheduled time for maintenance during which water is not produced. The relationship is shown in figure VI.

At this point it is desirable to introduce a more formal consideration of the regulatory requirements. In order to clarify the following algebraic statements, separate factors are shown to obtain costs that are normally calculated as a fraction of the particular capital investment involved. This is necessary even when the same interest rate is used for all capital investments, because interest is often but one part of each of these costs. For example, depreciation rates are part of these cost factors. The depreciation on desalting plants is usually taken over a period of twenty to thirty years, whereas pumping plants are depreciated in fifty years. Land normally does not depreciate at all and may gain in value. Interim replacement costs are also significantly different. These and other components of such cost factors normally require the use of different factors for each type of investment.

If only a surface storage facility is considered possible, one then wishes to minimize the annual cost expressed as the following quantity: 4/

4/ See "Nomenclature" for definition of symbols.

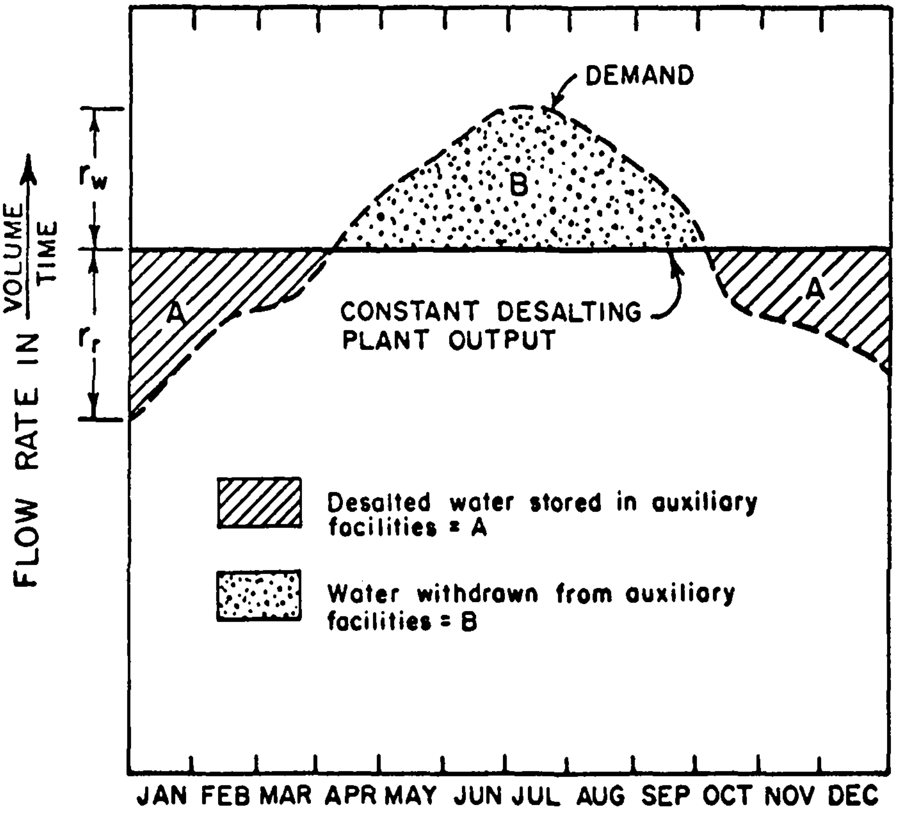

Figure IV. Constant output plant

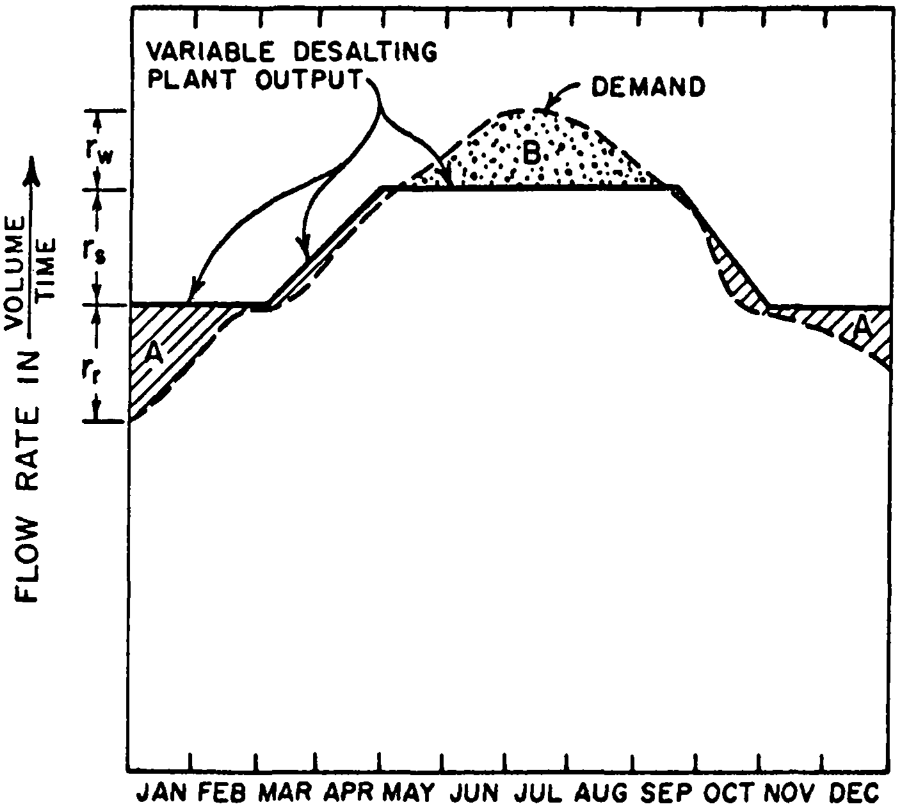

Figure V. Variable output plant

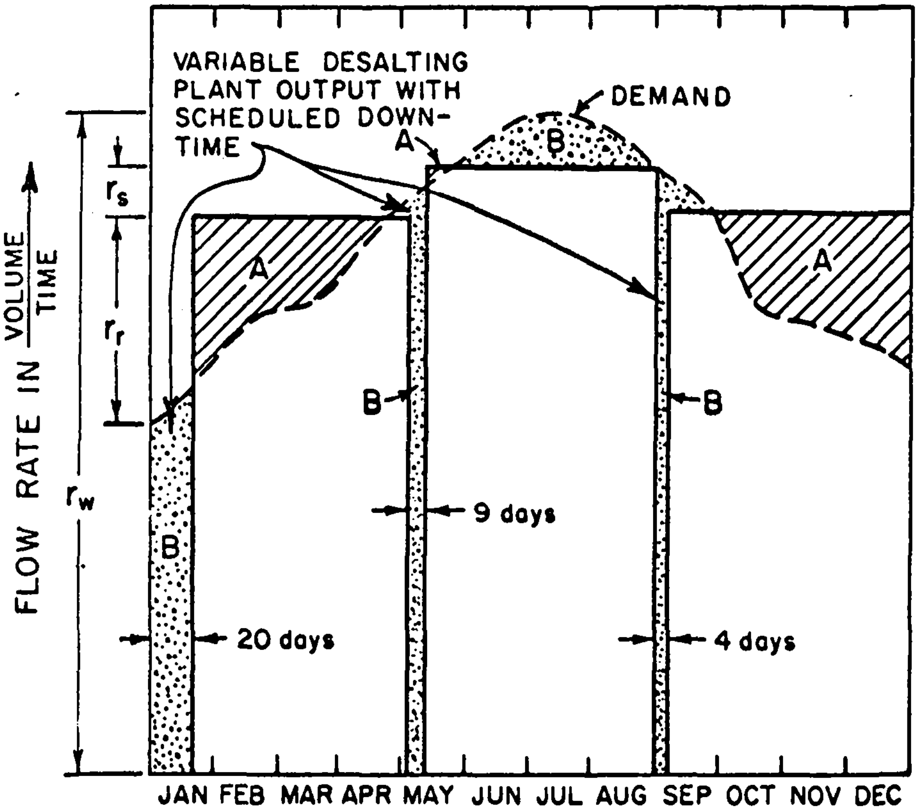

Figure VI. Variable plant output with scheduled downtime

$$(C_s \div C_{rs} \div C_{us})crfd \div F_d \div (C_q \div E_q)crfs \div F_s \div (P)crfl \div e_s w_s \div e_q w_q \tag{2}$$

subject to these restrictions:

$$w_s \geq D \div L_q \tag{3}$$

$$A \geq w_q \geq B \div L_q \tag{4}$$

$$Q \geq B \tag{5}$$

$$S(t-u_s) \geq w_s \tag{6}$$

It appears that incremental cost analysis will suffice for the solution of this case. At the margin:

$$\Delta\,[(C_{us})crfd] = \Delta\,[(C_s)crfd] \div \Delta\,[(C_q \div E_q)crfs] \div \Delta\,[(P)crfl] \div \Delta\,L_q \tag{7}$$

That is, the cost of reducing downtime should equal, at the margin, the cost of decreasing nominal capacity, the cost of decreasing storage capacity, the cost of decreasing property and right-of-way requirements and the value of the water not lost by virtue of reduction in storage.

Also

$$\Delta\,[(C_{rs})crfd] = \Delta\,[(C_q)crfs] \div \Delta\,(e_q w_q) \div \Delta\,[(P)crfl] \div \Delta\,L_q \tag{8}$$

the cost of increasing the variability of output from the desalting plant should equal, at the margin, the cost of decreasing the storage required, the water pumped into the storage, the cost of decreasing property and right-of-way, and the value of the loss from surface storage.

Additionally

$$\Delta\,[(C_s)crfd] = \Delta\,[(C_q)crfs] \div \Delta\,(e_q w_q) \div \Delta\,[(P)crfl] \div \Delta\,L_q \tag{9}$$

the cost of increasing desalination capacity ought to equal the value of decreasing storage, pumping into storage, the cost of decreasing property and right-of-way, and losses.

Similar considerations would apply if the only auxiliary facility were a ground-water basin and the means of management for the ground-water basin

$$\Delta\ [(C_{us})crfd] = \Delta\ [(C_g)crfg] \div \Delta\ [(C_s)crfd] \div \Delta\ (e_r r_r) \div \Delta\ (e_w r_w) \div \Delta\ [(P)crfl] \tag{10}$$

$$\Delta\ [(C_{rs})crfd] = \Delta\ [(C_g)crfg] \div \Delta\ (e_r r_r) \div \Delta\ (e_w r_w) \div \Delta\ [(P)crfl] \tag{11}$$

$$\Delta\ [(C_s)crfd] = \Delta\ [(C_g)crfg] \div \Delta\ (e_r r_r) \div \Delta\ (e_w r_w) \div \Delta\ [(P)crfl] \tag{12}$$

The difference here is that the cost of ground-water facilities and their use is a good deal more sensitive to the rates of withdrawal and recharge and much less sensitive to the amount of storage required than surface-water storage systems. If ground-water and surface facilities are combined, it appears that incremental cost analysis will suffice for use as planning guidelines. Detailed consideration of these problems by operations research techniques may be warranted.

Case 4. The problems of unscheduled downtime [5] and its relation to the foregoing optimization calculations have not yet been considered. In order to make other than an arbitrary judgement about measures to ameliorate the effects of such an event, the loss function for shortage and the probability of downtime needs to be further quantified. It is not economically feasible to protect against all untoward events.

In addition to surface and underground storage facilities, the economics of building two half-size desalination plants, in order to prevent a complete simultaneous loss of desalination capacity, should be considered.

This problem, as the problem in Case 3, can also be cast as a minimization problem. Here we seek to minimize the following expression:

$$\begin{aligned} &(C_s \div C_{rs} \div C_{us})crfd \div F_d \div (C_q \div E_q)crfs \div F_s \\ &\div (C_g)crfg \div (P)crfl \div e_s w_s \div e_q w_q \div e_r r_r \\ &\div e_w r_w \div e_h H \div \text{shortage cost} \end{aligned} \tag{13}$$

---

[5] Without careful initial planning, thorough preventive maintenance during scheduled downtime and the use of some duplicate equipment, unscheduled downtime can become a very great production loss. Depending on when unscheduled downtime occurs, the nominal plant capacity may have to be considerably larger than would otherwise be the case. In any event, even with the greatest care, some unscheduled downtime can be expected. Some of the items that should be given careful consideration to avoid excessive unscheduled downtime are properly designed sea-water intake facilities and process pumps. Interruption of the power supply to the plant can cause serious consequences because of the loss of production. Mechanical damage of the equipment may result, especially with thermal desalination processes. Careful consideration should be given to reliability of the external power supply and, depending on conditions, adequate safeguards to prevent serious damage should be designed into the plant.

Much the same restrictions as previously listed in Case 3 apply except that the deficiency must be subtracted from the right side of expressions 3, 4, 5 and 6 in each case. The shortage cost is a probabilistic quantity which is the sum of the products: loss incurred by each type of shortage multiplied by the expectation of that type of shortage. By expectation of a shortage is meant the probability that a water deficiency of a given magnitude will occur during the analysis period.

3. Illustrative example

A simplified problem which includes consideration of scheduled and unscheduled downtime and the use of surface storage facilities is presented. The technique of incremental cost analysis is used to provide a solution to the problem.

A demand of 37 million cubic metres per year is assumed. The possible facilities are assumed to be a desalination plant and a surface storage facility. The demonstrative computation which is done has as its objective the minimization of the sum of desalination plant costs, storage costs, and the economic costs associated with not fully meeting demand when the effect of desalination plant emergency maintenance is particularly adverse.

Several assumptions were made. The following costs were taken as reasonable approximations.

(1) Fixed-cost of providing desalination plant capacity = $63.2 per thousand cubic metres annually. 6/, 7/

(2) Variable-cost of desalting water = $62.4 per thousand cubic metres. 7/,8/

(3) Cost of providing surface storage = $40.5 per thousand cubic metres annually.

(4) Unit costs for water other than desalting costs = $6.5 per thousand cubic metres. 9/

It was also assumed that:

(1) Losses from surface storage could be neglected.

6/ Interest, 3.7 per cent; plant life, 30 years; interim replacement, 1 per cent; insurance, 0.25 per cent; single-purpose water plant.

7/ Steam at $0.60 per million kilogramme calories would reduce the cost of water at the plant site to about 80 per cent of 1. plus 2. or to about $100 per thousand cubic metres.

8/ $1.19 per million kilogramme calories for steam; $0.0062 per kilowatt hour (6.2 mills per kwhr) for electricity.

9/ Interest, 3.7 per cent; pumping plant and pipeline life, 50 years; pipeline length, plant to storage, 3 kilometres; elevation gain, plant to pipeline outlet, 160 metres; $0.0062 per kilowatt hour for electricity.

(2) There would be thirty-three days of scheduled downtime annually.

(3) One unscheduled downtime could be expected annually.

The demand bar graph used in the illustrative example is shown in figure VII. Also shown in figure VII is the distribution of scheduled downtime which is scheduled to occur at four month intervals. Twenty, nine, and four days' time are required.

The first step in the solution of this cost minimization problem is to schedule these downtime periods so that demand for water during the times when the plant is not operating is at a minimum. Scheduling them will permit us to minimize the amount of storage required for this purpose. As it turns out, if the demands are as we have assumed, the optimum scheduling placed the twenty-day maintenance period on the first twenty days of the year.

Emergency maintenance or unscheduled downtime can, by definition, occur at almost any time. It cannot, of course, occur during a scheduled maintenance period. For the purposes of this illustrative computation, the following assumptions were made:

(1) That only one event requiring emergency maintenance would occur during the year.

(2) That if this event occurred within a ninety-one-day period following a twenty-day scheduled maintenance period, the required emergency maintenance time would be twelve days.

(3) That if this event occurred within a sixty-day period following a nine-day scheduled maintenance period, the required length of time would be sixteen days.

(4) That if this event occurs outside these time periods, the required maintenance time will be twenty-two days.

(5) That if the time required for emergency maintenance extends into a scheduled maintenance period, the number of days common to both is subtracted from the time required for emergency maintenance.

These assumptions were built into a computer programme. It was assumed that there was an equal chance that an event requiring emergency maintenance could occur on any day of the year. Thus, there are assumed to be 365 equally likely possibilities. Thirty-three of these (occurrence during scheduled maintenance) have no effect. The varying effects of the other 332 possibilities on storage required and nominal capacity of the desalination plant were computed.

The storage required is the absolute value of the area between the demand curve and the output schedule of the desalination plant.

The nominal capacity of the desalting plant is the total assumed demand divided by the number of days that the plant is actually in operation.

The computation is done in the following manner:

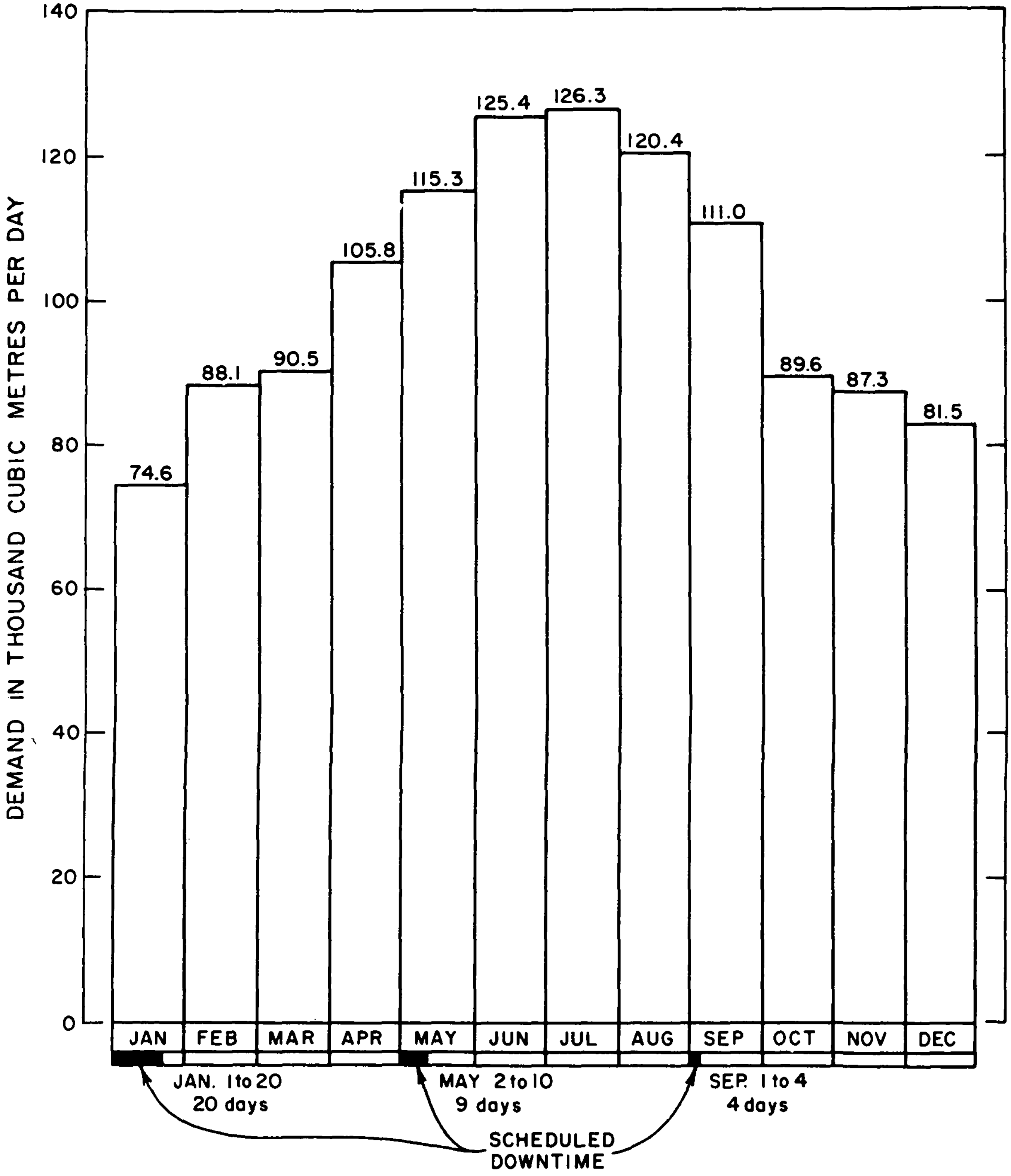

Figure VII. Average daily demand by month and scheduled desalting plant downtime

(1) The equivalent annual cost is computed for each indicated nominal desalting capacity and storage capacity; the highest of these is the cost that would be incurred if no possibility of shortage is allowed.

(2) For each other indicated nominal desalting capacity and storage capacity, the amount of shortage is computed for all cases in which higher nominal desalting capacities or higher storage capacities are indicated.

(3) The cost of each shortage is computed according to the previously discussed loss function (equation 1).

(4) For each case all the shortage costs are summed and divided by 365; this is the expected shortage cost.

The optimum facility is that facility for which physical costs and shortage costs are a minimum. Results of the above computation are summarized in table 2. On the basis of this computation and analysis, for minimum water cost, a desalination plant with a daily capacity of 115,600 cubic metres would be selected. A reservoir capacity of 2,884,000 cubic metres would be required.

Table 2

Storage capacity required Million cubic metres	Desalting plant output capacity Thousand cubic metres	Fixed cost of facilities $\$ \times 10^6$	Cost of desalting water $\$ \times 10^6$	Expected cost of shortages[a] $\$ \times 10^6$	Total cost $\$ \times 10^6$
4.269	119.4	2.928	2.550	-	5.478[b]
4.146	119.4	2.923	2.550	0.001	5.474
3.994	119.0	2.908	2.546	0.010	5.464
3.493	117.5	2.853	2.532	0.056	5.441
3.124	116.4	2.813	2.518	0.100	5.431
2.884	115.6	2.786	2.508	0.133	5.427[c]
2.626	113.9	2.734	2.476	0.236	5.446
2.724	111.5	2.683	2.432	0.388	5.503[d]

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a/ Computation of the cost of shortages was based on a marginal price of about $200 per 1,000 cubic metres.

b/ Highest cost facility.

c/ Lowest water cost.

d/ Lowest cost facility. Maximum water cost.

4. Desalter augments water supply

In cases where the desalination facilities represent only a portion of the water supply system, the problem becomes more difficult. Although a great deal of work has been done on the optimization of water resources systems through the use of mathematical optimization and statistical hydrologic techniques, no readily applicable method which does not involve a great deal of simulation study is as yet available.

It could be economic to run desalination plants to provide the base load to minimize the per unit desalinated water costs in areas where these plants are the major source of supply. But in areas where desalinated water is a supplemental source, minimization of the cost of the desalination plant is not a sufficient criterion for minimum cost operation. The costs of the entire system, including both desalination plants and conventional sources, must be minimized. Variables to be considered include the proportions in which the desalinated and conventional water supplies should be mixed or whether separate areas could be served by each. With a given desalination plant capacity, most of the desalinated water could be used near the plant with a comparatively small proportion of conventional water supplies added. Alternatively, the desalinated water could be mixed with a large proportion of poor quality water supplies and the blend distributed throughout the system.

In choosing a method of operation between these extremes, consideration would be given to water quality benefits. If the benefits increase proportionately to the amount of desalinated water in the blend, distribution throughout the system may be justified.

In estimating an economic loss function from shutdowns of the saline water conversion plant, consideration should be given to the effects of rapid changes in water quality that might give rise to expensive alterations in manufacturing processes. The loss per unit of time from a reversion to a lower quality of water might be greater than the long-run benefits from the improvement in water quality because the manufacturing processes would be adjusted to the improved water supply and the water treatment devices formerly used may have been scrapped.

The ground-water basin could be used as a storage facility for both conventional and desalinated water supplies. In this connexion, a model developed by the California Department of Water Resources to determine the most economical combination of primary feeder systems, well pumping and booster facilities, and surface storage facilities will be useful to study.

In the Department of Water Resources' model,[10/] a general cost equation was written to express the total cost of pumping, boosting, and surface storage. Equations were written to express the number of water supply facilities, in terms of booster flow capacity. These facilities are boosters, ground-water pumps, and surface storage reservoirs. The unit cost of facilities and the electrical energy cost were determined. An equation was developed to determine the most economic flow capacity of facilities.

[10/] State of California, Department of Water Resources, Bulletin 104, Appendix C, Attachment 9, to be published. This appendix describes the procedure in a number of cases in detail.

A method was developed for using the most economic flow capacity equation to determine the most economic combination of boosters, pumps and storage facilities, considering existing and additional facilities.

A period of five consecutive days with the maximum water demand was used as the maximum demand on water supply facilities. A sharp change in slope on the storage cost curve is caused by this criterion that the facilities must be provided to meet the demand at least for five days.

If the necessary data could be obtained at reasonable expense, the criterion that has just been stated could be modified by consideration of both the probability that such maximum demand will materialize and the economic loss that would result if this demand were not satisfied.

5. Dual-purpose plant

In a dual-purpose plant, savings in operating costs may result from use of low-value off-peak energy produced by the plant. If maximum output of water and electricity can be varied to some extent, according to fluctuations in demand for one or the other commodity, the justification of storage is increased. Since electric power cannot be readily stored, it would be economical to produce less electric power but more water during the off-peak period for electricity, and more electric power but less water during the on-peak period. In areas where the peaks on load curves of water and electricity overlap, this would require additional storage. The cost of this additional storage then would have to be less than the increased value of the electrical energy produced. Where the dual-purpose plant is a complementary source of water supply, the demand for electric power to pump the surface and ground water should be considered. This may shift the electric power load curve enough to affect the optimum operation pattern of the desalination plant and hence its optimum storage requirement.

6. Cost of storage

Annex A contains a discussion of the cost of water storage. The capital cost of surface storage cost versus storage capacity is presented in figure VIII. The relationship of the cost of withdrawal of water from ground-water storage and pump load factor is shown in figure IX.

Nomenclature

A = desalted water stored in auxiliary facilities

B = water withdrawn from auxiliary facilities

C_g = capital cost of ground-water facilities without land

C_q = capital cost of surface storage without land

C_s = basic capital cost of desalting plant without land

C_{rs} = capital cost of variability in desalting plant capacity

C_{us} = capital cost of reducing scheduled downtime

crfd = factor for the desalting plant capital recovery, interest cost, interim replacement and, if applicable, taxes

crfg = factor for the ground-water storage and pumping plant capital recovery, interest cost, interim replacement and, if applicable, taxes

crfl = factor for land and right-of-way interest cost and, if applicable, value depreciation and taxes

crfs = factor for the surface storage and pumping plant capital recovery, interest cost, interim replacement and, if applicable, taxes

D = total annual demand

d = instantaneous demand

E_q = capital cost of surface storage pumping facilities without land

e_h = unit cost of hauling

e_q = variable unit cost of pumping water into surface storage (not including fixed costs) [11]

e_r = unit cost of recharge

e_s = variable cost of a unit of desalted water (not including fixed costs)

e_w = unit cost of withdrawal

F_d = fixed operating and maintenance costs for a given capacity range of desalting plants

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[11] It is assumed that the surface storage is at a higher elevation than the desalination plant and the water service area.

F_s = fixed operating and maintenance costs for a given capacity range of surface storage and pumping plants

G = magnitude of ground-water facilities based on rate of recharge and rate of withdrawal

H = amount of water hauled

L_q = losses in surface-water reservoir or value of losses in surface-water reservoir

P = land and right-of-way cost

Q = volume of surface storage

r_r = rate of exchange

r_s = variability of desalting plant capacity

r_w = rate of withdrawal

S = nominal capacity of desalting plant

t = time

u_s = fraction of time that is scheduled downtime for desalting plant

w_s = number of units of water desalted

w_q = number of units of water pumped into storage

Definition of terms

Depreciation is a recognition that the capital investment made in a facility is generally worth less each succeeding year. It is usually due to the wearing out and outdating of plant equipment.

Downtime is the period of time a plant is not operating and hence not producing its product. This concept can be extended to the situation of the plant being partly "down" when parts of the plant are not operating but partial production is still possible.

Economic demand schedule is defined as the various quantities of an economic good that will be bought at all possible prices at a particular time.

Incremental cost analysis is examination of the increment costs of alternatives (cost for increasing capability an incremental amount) to determine which alternative is more economical. Example: given the same net amount of water to the user at the time needed, if the cost of an additional unit of installing variability in desalination capacity exceeds the cost of an additional unit of storage capacity, the optional procedure is to install another unit of storage capacity.

Interim replacement is replacement of parts of the plant during the life of the plant. This allows the plant to continue to produce at full capacity. An example of this for distillation type desalting plants would be the replacement of condenser tubes.

Nominal capacity is the full rated production capacity of the plant when it is operating. Thus, the more time during the year that the plant is not in production, that is to say, "down", the greater must be the plant nominal capacity to produce a given amount of product in the year.

Operations research is a group of mathematical techniques used in decision-making and process optimization.

Conversion factors - metric to English system

From	Operation	To obtain
Metres	Multiply by 3.2808	Feet
Kilometres	Multiply by 0.6214	Miles
Square metres	Multiply by 10.76	Square feet
Hectares	Multiply by 2.471	Acres
Cubic metres	Multiply by 35.32	Cubic feet
Thousands of cubic metres	Multiply by 0.8107	Acre-feet
Litres/second	Multiply by 0.03532	Cubic feet/second
Kilogramme calories	Multiply by 3.969	Btu

ANNEX A

Water storage facilities and their costs

Surface water storage

Surface water storage is usually of three types: concrete or steel tanks; excavated and leveed reservoirs, lined or unlined; and dams and reservoirs, usually unlined. The amount of water to be stored tends to determine the type of storage used. Another factor is prior treatment of the water and its value.

While considerable overlap exists between types, both as to size and cost, the foregoing types were stated generally in increasing order of size and decreasing order of unit storage cost.

Tanks. A variety of construction materials and corrosion prevention methods is found in tank construction. Generally, water tanks are basically either steel or concrete construction. Steel requires corrosion protection, inside and outside, and concrete is sometimes lined on the inside. Concrete tanks are of two kinds, reinforced and pre-stressed.

In larger tank sizes, say 4,000 cubic metres of capacity or more, the first cost of pre-stressed concrete tanks is closely competitive with steel water tanks. However, in this size first cost of reinforced concrete tanks is greater by a factor of two or more. Large-size pre-stressed tanks might be cheaper than steel over the lifetime of the tanks because of possible lower maintenance costs for the pre-stressed tanks. In some environments, however, corrosion of the pre-stressed tendons can drive the maintenance cost of a pre-stressed tank above that of a steel tank.

Steel water tanks can be protected from corrosion by a variety of means. Often a large steel storage tank can use a combination of protection involving cathodic protection and coatings. Such combination protection can be obtained for a cost including power of about $1 per square metre of tank surface per year.

Most steel water tank installations rely for inside protection on coatings or liners that completely cover the steel surface. The better ones are good for fifteen to twenty-five years. Outside coatings are also applied for protection of the installation. Cathodic protection may be used alone for protection of interior surfaces or in conjunction with protective coatings. Factors which determine the most economic type of protection include corrosiveness of the water, type of construction, and the operational characteristics of the water system.

The initial cost of tank coatings and liners, including inside and outside, will range from about $3 to $20 per square metre. Distilled water storage places the most severe requirements of almost any water storage on the inside tank protection. This is true of concrete tanks as well as steel tanks. Protection for tanks holding distilled water such as might be obtained from a desalting plant, especially if the purity of the water is to be maintained, will cost closer to the above $20 per square metre than to the $3 per square metre.

Excavated and leveed reservoirs. In the water capacity range of about 25,000 cubic metres to 10 million cubic metres, or more, excavated and leveed reservoirs are frequently used. Often the water stored in such reservoirs has been chlorinated and is ready for municipal use.

A construction often used for such reservoirs in California is that of asphaltic concrete lined with a relatively impermeable membrane. Reinforced concrete is also used especially for the smaller capacity reservoirs. Generally the asphaltic concrete construction is less expensive than the reinforced concrete. The membrane is often in the form of impermeable asphaltic panels one and one-fourth centimetre thick, one and one-fifth metre wide and six and one-tenth metres long, placed next to each other and sealed with special material. All the sides and the bottom are lined. Another membrane material is butyl rubber available in several thicknesses but often used at about twenty-three hundredths of a centimetre thick.

Dams and reservoirs. Tank construction is sensitive to such natural structural factors as soil bearing and earthquake forces. Constructed reservoirs are sensitive to these factors plus other soil properties and the geology of about the first six to thirty metres of earth. Dams and reservoirs, however, are so completely site-sensitive in construction of the dam and the amount of water impounded that they must be analysed on an individual basis. The value of the water lost through the ground must also be considered along with the value of the land inundated for the reservoir and the cost of the dam itself.

Covered reservoirs. Most surface-stored water ready for municipal consumption in California is covered. Water that might be consumed by people, as contrasted, for example, with only agricultural or industrially-used water, is subject to stringent health requirements. Water to be treated for domestic use in California is often stored in dam-contained reservoirs; but after treatment, by chlorination, for example, it is often stored in covered tanks or reservoirs to prevent algae, air-borne contaimination, and bacterial infection. A covering also prevents evaporation of valuable treated water. In California preventing evaporation of water, especially in water-short regions such as the desert areas, can pay for a part of the cost of the cover.

A net water loss of a depth of about one metre per year from reservoirs in the southern part of California corresponds to the actual situation for many uncovered municipal reservoirs. A water reservoir holding 1 million cubic metres with a surface area of 60,000 square metres will lose 60,000 cubic metres of water per year at the above one-metre loss rate. If this water were worth $70 per thousand cubic metres, the yearly loss of water is worth $4,200 per year. This sum will pay off over $65,000 worth of roofing or other cover over a period of twenty-five years at 4 per cent interest.

Tanks are often covered with material similar to the rest of their construction. Roofing for constructed reservoirs has used a variety of materials such as steel frame with aluminium or galvanized steel sheeting or wooden posts supporting a plywood asphaltic cover. A covering supported by floating members is presently being installed in California on a reservoir with a capacity of over 5 million cubic metres. It is estimated that such a covering will cost one-third of a normal roof structure.

Many California communities install underground concrete tanks. This type of construction costs up to twice that of covered surface storage and is used primarily for appearance.

Unit cost of surface water storage

Figure VIII shows the amount of storage in thousands of cubic-metre capacity versus storage-capital costs in dollars per cubic metre. It should be noted that this is storage capacity. Thus, if the storage is kept at one-half of capacity, the unit capital cost of storage will be twice as much as shown by the curves in Figure VIII. Both tanks and excavated and leveed reservoirs are included on the solid curve. Reservoirs with dams are not. For storage capacities of less than 10,000 cubic metres, the curve reflects costs of tanks. For storage capacities greater than 40,000 cubic metres, the curve reflects costs of excavated and leveed reservoirs. From 10,000 to 40,000 cubic metres the cost of both types is represented by the curve. Tanks are essentially steel ground tanks. Elevated tanks cost about three times as much. The larger reservoirs, from 40,000 cubic metres, are concrete asphalt type. Land is not included. Included are coverings, protective coatings for tanks, paving around the tank or reservoir, foundation ring for tanks, drains, and entrance tap to tank or reservoir. Water meters or extensive piping is not included. Tanks without roofs would be about 25 per cent less. Large reservoirs with dams would be only about one-half the cost without a roof type covering. The broken line in Figure VIII represents the cost of excavated and leveed reservoirs without roof type cover. Extension of this broken line upward can give some estimate of storage costs in large reservoirs with dams. An important point to remember about this cost information is that it is representative of average conditions in California.

Ground-water storage

Cost of using natural storage capacity in the ground consists of the sum of three separate costs: placing the water into storage, extraction of the water, and unavoidable loss of water. Because the storage capacity is available naturally, capital costs of using ground-water storage may be lower than the capital costs of other types of storage. Operating costs, on the other hand, may be higher than those associated with the use of other types of storage facilities. Moreover, the use of ground-water storage may be complicated in local areas by legal problems.

Costs of utilizing a ground-water storage area are greatly dependent upon the geological and soils conditions in and near the storage area. A thorough geological investigation of the area will be required to determine the geological structure, the stratigraphy, the soil infiltration rates, and the permeabilities and storage factors of the basin materials. This information on structure and basic characteristics will be used in selecting the type of recharge facility and size and spacing of extraction facilities. 12/

Artificial recharge facilities can be variations or combinations of any of the basic project types: basins, pits, or injection wells. A lack of near surface restrictions suggests use of basins or ponds. A near-surface aquifer may be recharged by use of pits which reach through the surface restrictions to contact the aquifer material directly. Injection wells would be used when the storage area occurs at depth.

12/ For a further discussion, see American Society of Civil Engineers' Manual No. 40, "Ground Water Basin Management", 1961.

Costs of the possible recharge facilities should be compared on a basis of rate of recharge since that, and not total storage capacity, will probably govern when using ground-water storage. Capital costs of acquiring right-of-way and constructing the recharge facilities should be expressed separately from operation and maintenance costs for ease of comparison.

The capital cost per litre per second is highly variable depending on specific land costs and on the amount of works needed to prepare the land for the recharge operation. When distilled water is being recharged, no de-silting works are required, and the amount of land required would be approximately the maximum rate of the facility divided by the infiltration rate ascertained from the geological study of the site. The design rate should be less than the rate at which water is available to the site if advantage is taken of the temporary storage of water in the basins themselves.

Land preparation costs can vary widely and, as a minimum would include levelling of the basin area, construction of levees around basins, observation wells, and fencing. Selling of gravel or soil removed from the site may offset some of the cost. Average land preparation [13] in California amounts to about $6,200 per hectare including 25 per cent for engineering costs and contingencies.

The other element of cost, operation and maintenance, will depend on the amount recharged. Operating costs in California vary widely but average about $4.00 per cubic metre of water spread. Some projects handling large volumes report operation costs of $1.00 or less per cubic metre. Todd has reported [14] operating costs of four spreading basins operated by the Los Angeles County Flood Control District (LACFCD) as follows:

Spreading grounds	Wetted hectares	Operation cost per 1,000 cubic-metre spread
Rio Hondo	150	4.90
Sawpit	1.6	12.50
Pacoima	49	3.90
Santa Fe Reservoir	54	1.90

Pits used as recharge facilities usually require less land and cost more per hectare to prepare. Operating costs also vary widely depending on the site. The LACFCD operating costs as reported by Todd varied from $2.10 per 1,000 cubic metres at the Buena Vista Pit to $17.25 per 1,000 cubic metres at the Peck Road Pit.

The highest costs for basins and pits reported above are for facilities recharging silt-laden storm water. Recharging of distilled water would not be as costly.

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[13] D.K. Todd, Economics of Ground-Water Recharge by Nuclear and Conventional Means, UCRL-7850 (University of California, February 1964).

[14] Ibid.

Extraction costs include only capital costs of drilling the well or wells, motor and pump. It is expected that wells would be located on the land acquired for the recharge facility. Capital costs of wells will depend on depth to storage area, permeability of aquifer material and drilling and equipment costs at the particular site. In the Los Angeles area a typical well of 60-metre depth with pumping level at 30 metres would carry a capital cost of about $14,400 and would produce 160 litres per second with a 75 kilowatt motor. The capital cost would then amount to about $90 for each litre per second required.

Operating costs include energy and maintenance. Cost of energy is the most significant item and the cost of energy for the above sample well in the Los Angeles area is a function of volume pumped per year from each well. The results are shown graphically in figure IX attached.

Irrecoverable losses encountered in using ground-water storage include evaporation from ponds, basins, or pits, and losses to irrecoverable ground-water storage.

Evaporation losses are dependent on area of basins, time flooded, and local evaporation rate. The amount of water lost through evaporation must be estimated and the cost of the water lost charged against the cost of ground-water storage.

Losses to irrecoverable ground-water storage are of two types. The first occurs only at the onset of use of the storage and amounts to the moisture required to bring the soil in both the percolating area and the storage area up to specific retention or soil capacity. The amount of this loss is dependent on the existing soil moisture. The second type is the loss of water from the storage area by movement through the lowly permeable boundary structures or simple migration outside of the zone reached by the extraction facilities. Little information is available on the amount of such losses but they may be estimated from ground-water hydraulics formulae and knowledge of the permeabilities and gradients expected.

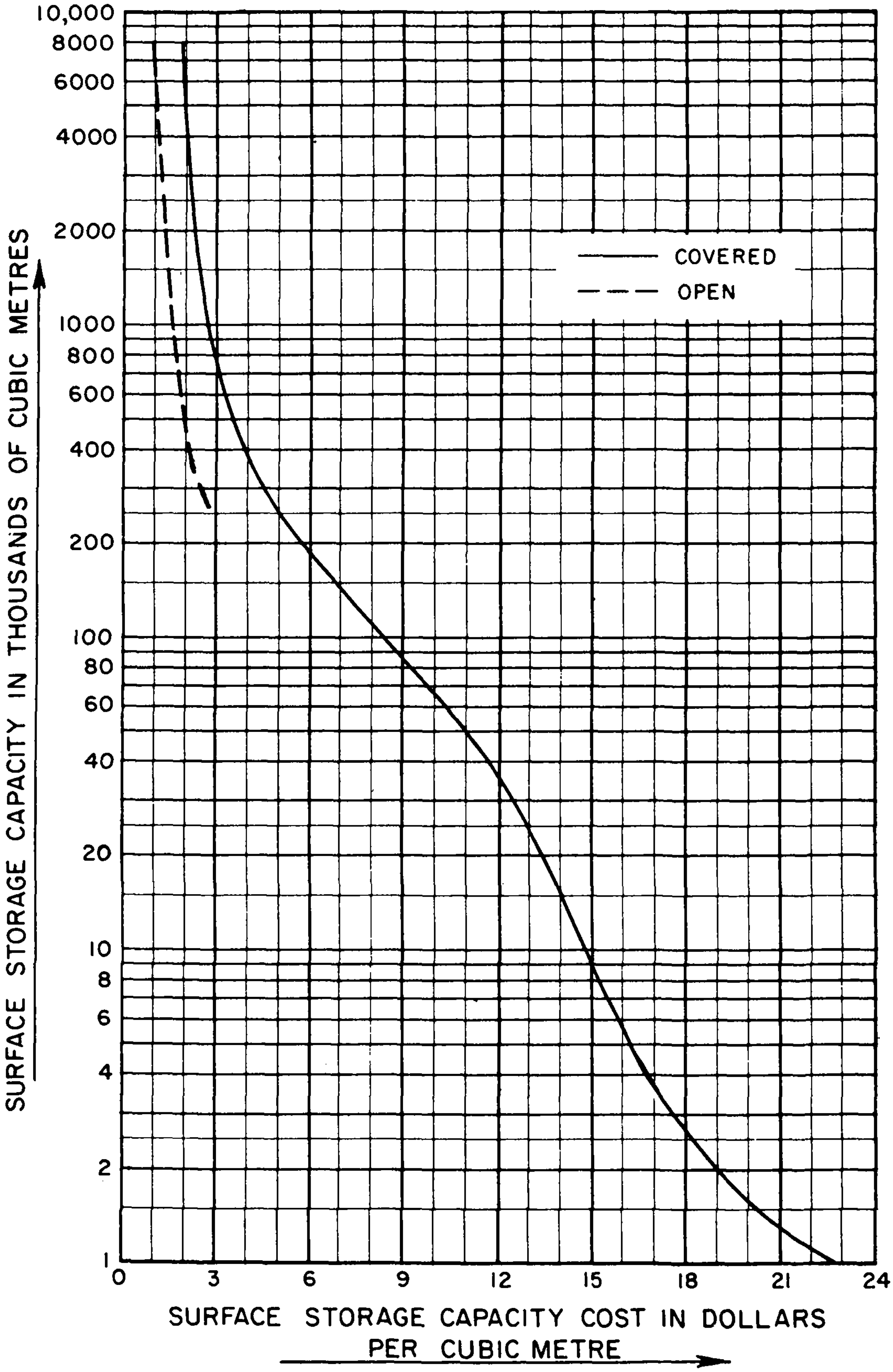


Figure VIII. Surface water storage
Storage capacity versus cost of capacity

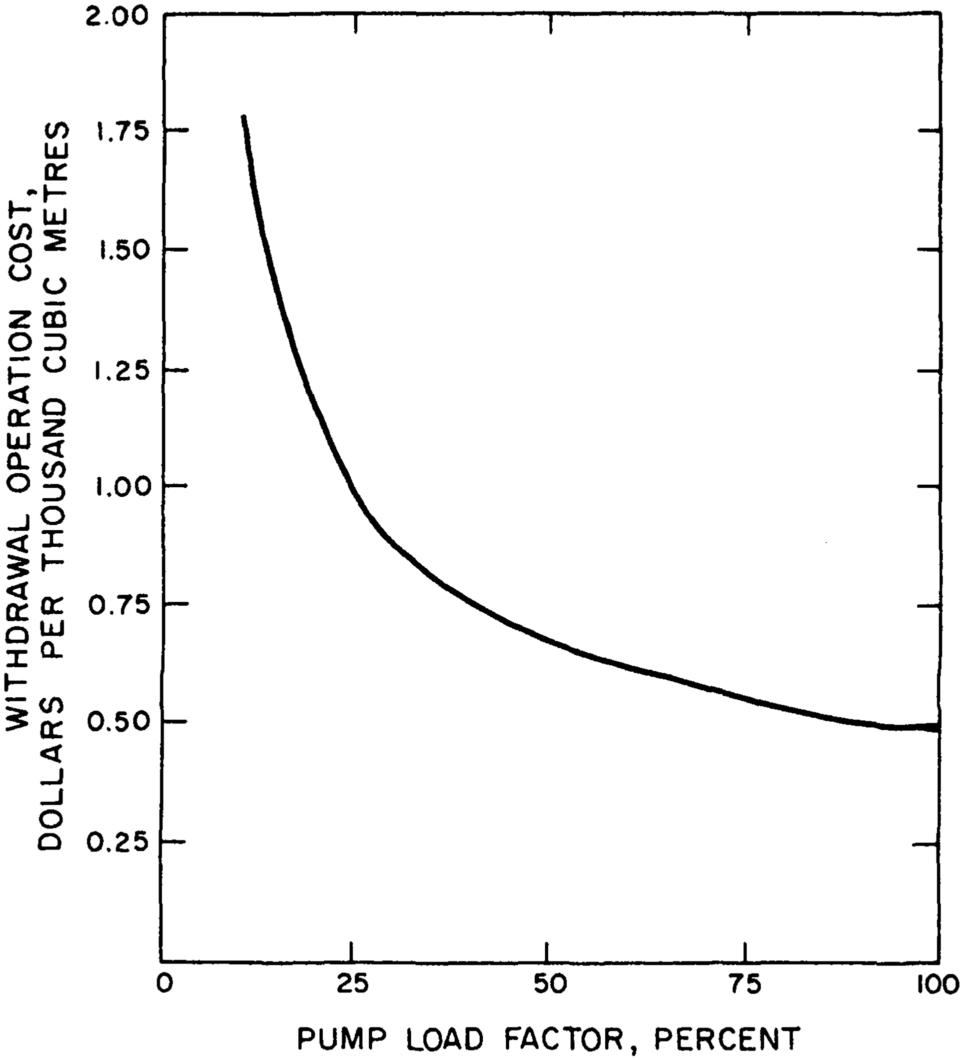


Figure IX. Ground water storage withdrawal operation cost versus pump load factor

XIV. DESALINATION PLANT AS A SOLE SOURCE OF WATER: SELECTION OF SIZE AND TYPE OF DESALINATION PLANT

by J.J.C. Bradbury

A desalination plant intended to supply the whole of a community's requirements of fresh water is in somewhat the same position as a power station supplying electricity without the benefit of interconnexion with other sources. This analogy cannot be taken too far since the provision of storage capacity is available to the water plant to smooth out daily peaks and short-term fluctuations, whereas this advantage cannot apply to electricity. However, it is not usually economically feasible to construct sufficient storage capacity to smooth out long-term seasonal fluctuations in water demand, and consequently the desalination plant must necessarily operate at a load factor closely corresponding to the load factor of consumers' demand.

Because of these special circumstances, it may not be possible to operate the desalination plant at any higher than a 60 per cent annual load factor, and there will be a consequent increase in the unit cost of water arising from plant under-utilization. Where desalination is used to supplement ground water, however, it is usual to run it on base load at 100 per cent load factor to spread the fixed costs over as large an output as possible and reduce the average cost of water supplied. It will be seen from the foregoing that any desalination project intended to provide a community's sole water supply must start with an economic disadvantage arising from the fact that the operating load factor will be imposed on the plant by the annual fluctuations of consumers' water demands.

A. Basic design parameters

Before choosing and designing a desalination installation intended as a sole source of water, it will be necessary to make a careful analysis of the pattern of water demand, both over short-term daily fluctuations and also long-term seasonal changes. An investigation of these aspects will provide an indication of the daily load factor expected from the plant, and also the annual load factor which will apply. Once the probable daily load factor is known it will be possible to assess the amount of water storage necessary to achieve a reasonable daily plant operating load factor.

Unless local geographical conditions are particularly favourable, it will not be possible to provide sufficient water storage capacity to accommodate the seasonal variations in water consumption and allow the desalination plant to operate at a high annual load factor.

The desalination plant must therefore be designed with a capacity capable of meeting the peak seasonal demand, and will therefore produce at lower capacities during off-peak seasons, with a corresponding reduction in load factor, and an adverse effect on the economics of operation.

In addition to ensuring that plant capacity is sufficient to meet seasonal peaks, some provision must be made for meeting the estimated increase in water demand in the future. This requirement will necessitate a careful analysis of past water demand peaks in order to assess the rate of rise of maximum demand. Once this rate has been established it can be extrapolated to give future estimates of demand. These future estimates will have a significant effect upon the size of plant which is installed, since it will be necessary to incorporate in the design a sufficient measure of pre-building to allow for future expansion. The requirement for pre-building will in itself further worsen the plant load factor and make operation even more uneconomic in the early period following commissioning.

Depending upon the actual shape of the annual water load curve, it might be economically feasible to incorporate a short-term overload capacity into plant design, even if this involves some temporary sacrifice of quality.

The amount of pre-building incorporated in a desalination plant design will be mainly a function of the interest rate which will determine the financial burden of the extra capital expense involved. However, in some developing areas the actual availability of capital itself may well be a further limiting factor.

B. Plant operation

As demand for water increases in a community relying solely on desalination, it will become necessary to construct additional desalination plants. It is a basic premise of this special situation that, as stated above, the over-all plant operating load factor approximately corresponds with the water demand load factor of consumers. With only one desalination plant in operation this circumstance necessarily precludes operation at the highest and most economic load factor which would normally be used, where alternative water sources were capable of carrying peak loads. However, with the commissioning of more than one desalination installation the opportunity presents itself of running one on base load at a high load factor, and using the other primarily for peaking purposes at low load factors.

These differing operational requirements can have a significant effect upon the plant designs. The initial installation can be designed primarily for low load factor operation, the chief requirement being to save capital cost and produce output at a relatively modest gain ratio, and consequently higher fuel cost of production. When this plant is operating as the sole producer of water, it will probably not achieve economies which would be available from a more expensive plant designed for base load operation. However, the second increment of desalination plant can be of a much more refined design intended for base load operation, having high thermal efficiency and consequent low fuel costs. The size of this second unit would be such that it would always run at base load, thus achieving the economies normally associated with the operation of desalination plant under these conditions. Meanwhile, with the commissioning of the second unit the original plant would be relegated to peak load operation, and this would constitute its main function for the rest of its life.

With a rising demand for water, the additional quantities required would have very little effect upon the second unit, which would be operating on base load, and the extra production necessary would therefore fall upon the original plant and improve its operating load factor. Thus the initial peaking desalination plant would experience a gradual rise in output over the years as water demand increased. This would continue until a position was reached when the installation of yet another base load plant was justified. With the commissioning of this further base load plant the output of the initial plant would again fall to a low level, and the cycle would be repeated as demand continued to grow.

It will be seen from the foregoing that it will be necessary for one installation to be used continuously as a peaking and stand-by plant. This fact should be recognized from the beginning, and the equipment designed as economically as possible to fulfil this function. In these circumstances the provision of desalination units in a sole source installation, each having a similar design, would be a mistake and not result in the most economic allocation of resources.

C. Reliability and flexibility

Where desalination forms the sole source of water supply, one of the most important considerations will be to ensure that plant reliability is such that it will be possible at all times to meet the demand for water.

The basic problem under this heading is concerned with assuring the continuity of water supply during periods of plant maintenance or unexpected plant breakdowns. In so far as the impact of plant maintenance upon availability can be anticipated, the provision of water storage capacity can be considered to cover these periods. However, unless geographical factors are particularly favourable the provision of storage capacity tends to be an expensive solution. This would be even more expensive in the case under consideration, where the storage would consist entirely of expensive desalinated water resulting in correspondingly expensive evaporation losses. These high evaporation costs might require the provision of expensive covered storage facilities.

Whilst it might be economically feasible to provide some short-term stand-by in the form of storage capacity, the solution to improve reliability would no doubt be found in the provision of stand-by plant.

There are certain units of a desalination installation, such as heat exchanges, which require to be taken out of service periodically for the purpose of cleaning. If stand-by heaters are provided, this cleaning can proceed without loss of output capacity. As an alternative, if several heaters are used in parallel it may be possible to take one out of commission and still maintain output at a significant level.

In the special circumstances of the case under consideration it may also be prudent to supply spare feed pumps and other auxiliary items, the loss of which would shut down the main plant.

In order to ensure a high plant availability it may also be necessary to carry a substantial inventory of spare parts in excess of what would be considered adequate for a plant integrated with other sources of water supply. This will increase the amount of capital tied up in stock, and constitute a further cost burden on the plant output. The requirement for a higher standard of reliability may also result in a need for highly qualified staff, who may be called upon to carry out a wide and comprehensive range of repairs without outside assistance.

It is obvious that the additional reliability required from a sole source desalination plant can only be obtained by the provision of either considerable storage capacity or else extra items of equipment, larger spare part inventories or a higher investment in trained staff. Each of these alternatives will result in an increase in capital cost, which in its turn will be reflected in the cost of water.

The flexibility of operation required from the plant will, as mentioned earlier, be dependent upon the load characteristics of the consumers' demand for water. Where water demand increases to the level necessitating the provision of more than one desalination plant, they must obviously be interconnected so that each can fulfil its intended function and operate at its designed load factor within the general scheme of supply.

D. Factors affecting choice of plant and cost of water

The size and type of plant selected as the sole source of water supply must aim at producing water at the lowest possible cost. In this assessment, the availability of cost of various energy sources will be a significant factor. Where desalination is the sole source of water supply there may be prospects for the application of a multi-purpose plant producing both water and electricity. However, the fact that it will not be possible to operate the desalination plant on base load will involve variations in process steam demand from an associated turbine installation, which will either preclude the use of backpressure turbines or else necessitate the provision of pass-out machines, each having a separate steam condenser allowing electricity generation to proceed independent of variations in the steam supplied to water production. Should the electricity system not be interconnected, there may be a further difficulty arising from differences in demand characteristics for water and electricity. Thus it may well be that during some periods the demand for electricity will be so low as to prevent the desalination plant output from meeting the corresponding demand for water. Under these conditions, some provision would need to be made of reducing valve facilities, allowing boiler steam to be supplied direct to the desalination plant.

The foregoing comments have drawn attention to the special factors associated with the design and operation of a desalination plant as the sole source of water supply. Certain factors, such as reliability, flexibility and pre-building for future demand can be incorporated in the plant design. However, all these requirements must involve additional capital expense which, when associated with the comparatively low operational load factor, will result in a comparatively high cost of product water.

XIV. DESALINATION PLANT AS A SOLE SOURCE OF WATER: DESALINATION ON THE ISLAND OF ARUBA

by H. Beck

Many systems are known to convert sea water or brackish water into pure drinking water. Yet many of these are still in a research stage or are being tried out in pilot plant installations. No doubt the next few years will produce many answers and solutions in this field. In the meantime this rapid development adds to the number of factors and circumstances which have to be taken into consideration when one is faced today with the problem of making a selection of desalination plants for a particular location. Pilot plants run with a capacity of some tens of thousands of gallons per day. The so-called "large" units of today are those producing as much as two million gallons per day, but requirements run to 25-50 and 100 million gallons of daily capacity. Economic life expectancy, therefore, plays a major part in any decision which has to be made concerning the installation of desalination plant. Over-capacity and stand-by policies may present an economic burden which may yet be fully justified when viewed in the light of individual circumstances. Pure water is one of the first necessities of life which has to be available, almost regardless of costs, and a community cannot wait for new techniques to develop particularly when desalination is the only source of water.

A. Historical summary

Aruba, which has only a few brackish groundwells driven by windmills, used to have to depend for the rest of its natural water on rainfall, or expensive imports. During 1930, the Lago Oil and Transport Co. decided to enlarge its oil bunker and switch station into a refinery. This in its turn brought a new urgency to the local water problem, since as additional jobs were created the demand for good drinking water increased. Possibilities for the commercial conversion of sea water were very limited with no substantial electric load outside the refinery. However, in 1932 the Government decided to build its own distillation unit at Balashi, on the south side of the Island. This unit was designed with a capacity of 250 tons per day (barely sufficient today to supply make-up water for the existing plant). Low pressure steam from 40-60 psi boilers was used in a multiple-effect submerged coil system. The formation of scale was the biggest problem, and was tackled in a very simple way by dismantling the copper coils when production had dropped too much, and beating off the scale by hand. This scale removal system was necessarily expensive.

With no substantial technical improvements, and only domestic water being supplied, the system expanded rather unspectacularly. By 1952, ten units were in operation and the sytem was fairly reliable and flexible, but costs were above $4.00 per thousand gallons.

In due course, the refinery was converted to automatic operation with a consequent increase in unemployment, which in turn emphasized the need to attract other industrial enterprises. Two essential prerequisites for the establishment of new industries were adequate and reasonably priced supplies of both water and electricity.

At this time the refinery needed to renew its own waste heat evaporators, and bigger and more economical units had also become available. This could result in cheaper water, which in turn would mean more connexions and increased consumption. Including part of the refinery usage, the demand for water had tripled over a short period of time. Since the private electricity company was concurrently willing to consider buying power, the possibilities existed for a dual-purpose plant supplying both water and electricity.

The specifications applying to water for industrial use were stringent (less than 5 ppm T.D.S.) and the amount formed 40 per cent of the total output capacity. It was therefore decided to instal one type of system that would produce only water suitable for industrial use. The addition of calcium and minerals would convert this into acceptable drinking water. Should small leaks in the sytem bring the T.D.S. of the industrial water above 5 ppm, it would still be acceptable drinking water. A double header system was also provided to give greater flexibility in operation.

This double header for drinking water also entered into the triangular relationship betweel old plant, storage and new plant.

B. Planning the expansion of the system

With a demand of 5,000 tons per day, planning centred around units of 2,000 tons daily capacity, which was a substantial increase over the existing sizes. Estimates indicated that with the new units in operation at over 80 per cent load factor, cost of water would come down to $2.00 per 1,000 gallons. Calculations showed that the provision of extra 2,000 ton units as stand-by could increase this to $2.40. It was calculated that the provision of stand-by capacity could be carried out more cheaply by relying on the existing older distillers. However, the very poor thermal efficiencies and excessive maintenance costs of these old units, many of which had seen fifteen to twenty years of service, prompted the decision to abandon them and they were therefore scrapped.

Decisions of this nature will vary for different circumstances and will depend upon conditions peculiar to a particular location. For example the availability of low-cost heat in the form of refinery gas would have a significant impact upon deliberations of this kind.

On Aruba the plant does not have access to waste gas, and boilers are fired with a bunker C type oil, which is bought on the basis of standard posted prices.

Because of rapid development, planning should be such that demand periods of not more than five to six years are taken into account to avoid the retention of antiquated equipment which jeopardizes the attainment of lower costs. Amortization was originally set at the usual level for condenser equipment of power plants, i.e., twenty to twenty-five years, but it was considered necessary to reduce this to fifteen years. Already the cost of sea water conversion installations has gone down considerably, and a greater improvement is to be expected when really large units become available, possibly combined with atomic power.

For smaller- and medium-sized installations using conventional fuel, progress may not be so spectacular, since atomic power in the range of 100 MW is still at a premium with commercial development progressing only slowly.

In 1958, even the flash-evaporator type installations were still in the trial stage, and because of the strict quality requirements for water for industrial use, multiple-effect submerged coil type units were selected for extension at Aruba.

In this type of design the free surface of the boiling sea water is relatively large, with a low static height of the liquid around the coils, and vapour velocities are small, thus limiting carry-over. Although the formation of scale was intended to be eliminated with the injection of ferric chloride, downtime for a complete overhaul was estimated at four weeks, bringing the storage requirement to four tanks of 12,500 tons, one for industrial water use, and three for drinking water.

C. The submerged-tube type distillation plant

Based on forward estimates, and taking into consideration additional industrial enterprises (including tourist hotels) over a period of six years, five units each of 2,000 tons daily capacity were installed. It was anticipated that this programme would include a certain measure of over-capacity. In retrospect, it appears that the provision of this excess capacity was most fortunate since difficulties were experienced in obtaining the designed performance. Scale formation proved to be a serious problem which not only adversely affected the economics of operation, but also reduced the amount of water available from the plants. This example stresses the need to supply adequate stand-by capacity in those cases where desalination provides the only source of water to a community.

One of the main disadvantages of the use of submerged tube distillers is the difficulty encountered when heater coils scale up. The whole plant has to be shut down and cooled before work can start. In order to speed up the exchange of coils, it is recommended that a complete set of spares should be kept. In the case of Aruba, this extra investment was amply justified since downtime was reduced from twenty-eight to three days on a double shift basis, and twenty-five days of production gained.

The somewhat cheaper system of flash evaporation was not selected at that time, because firstly not enough was known about it, and secondly no guarantees for water with salt content below 20 ppm were offered. The flash installation available at the time had few stages, and on looking back did not in any case offer an optimum solution.

Since Aruba is an island, and in a relatively isolated position, the question of spare parts for the distillers has assumed considerable importance. Whilst the dangers of tying up an excessive amount of capital in spare parts must be avoided, due regard must also be given to the consequences attaching to plant closures. In this way a satisfactory compromise may be reached assuring an adequate availability of spare parts without unduly prejudicing plant output.

D. Economic consequences of stand-by requirements

With no interconnexion possibilities for either steam or electric power, major equipment such as boilers, turbines and electrical equipment all need stand-by units to ensure continuity. In Aruba where full water production of four units approximately coincides with full electrical load for one 7.5 MW unit, this meant that virtually the entire installation for steam production was duplicated. This is not conducive to the achievement of lowest water prices, but represents the price paid for security.

E. Effects of expanding the island's power facilities

With the existing smaller units, boiler ratios are lower than for big installations, where efficiency could be improved with reheaters and economizers. As, however, the demand for water and electricity grows, there may be a need for larger generators and boilers at Aruba. These will be more elaborate and refined than the existing plant, and they may well bring a problem as regards the availability of suitable staff. With a population of under 60,000, Aruba might find it difficult to supply the necessary skilled operating and maintenance personnel from local sources.

The idea of large generating units may sound optimistic, certainly with units initially of 7,500 KW. However, the requirements of water of excellent quality for industrial use on a regular basis acted as a stimulus to further developments. In addition, some of the electrical generating plant in the refinery was due for retirement, whilst huge quantities of gas, which could be used in chemical and fertilizer plants, were flared from the refinery. All this activity added up to a load requirement of over 40,000 KW.

A further consideration impinging on development was the availability of concentrated brine which might be used to produce salt with additional fresh water as a consequence. Based on this 40,000 KW load and some of the future prospects, it became necessary to enlarge the existing power-plant with three units of 33 MW capacity. The water-plant had then become a power-plant with by-product water-producing facilities. It is indicative of the rate of development that all previous plans had been based on 9 MW extensions.

Two of the new turbines were equipped with a steam extraction mechanism, but also with full-size condensers, and the low pressure steam was interconnected with the backpressure system of the two 7.5 MW machines. This gives great flexibility for the steam supply to the water-plant. On the other hand, the present over-capacity in steam generation does seriously affect the price of steam. Calculations show that when a load of 70 MW is reached for the installation, steam will be available at a 25 per cent lower cost. In order to avoid working at present with a sliding cost scale, which somewhat complicates calculations, the water production is considered separately from the rest of the plant, buying steam and electricity from the power-plant portion. The price of steam is calculated on the basis of present load requirements plus a normal amount of spare capacity, which compares very well with the results which would have been obtained with the addition of a fully loaded 7.5 or 9 MW unit (15 per cent lower).

Whilst this method improves the basis for water cost calculations, at the same time it lowers possible credits to water produced with salt concentrators. Since this amount of water is substantial, it did enter substantially into the selection of the next water-plant increment.

The cost of steam could be further reduced if cheaper fuels were available.

With a refinery nearby, very heavy residual oils and pitch seem likely prospects. Studies were made which showed that, because of high sulphur and vanadium content, the fuel oil price would have to drop at least 20 per cent to offset the higher plant depreciation associated with its use. Transportation through a pipe-line over more than eight miles with an inlet temperature level of 500-600°F, and buffer storage in insulated tanks, offer a few more points for studies which are being conducted.

F. Matching the island's rising water demand with supply

Owing to rising demand and extension of the water-plant had become a necessity. Of the available systems of which there was experience, namely, flash evaporation, falling film and the freezing process, flash evaporation seemed most promising.

Freezing requires fewer BTUs per unit of output than evaporation, and because of lower temperatures no scaling should occur, but the energy required is mostly mechanical and the system is somewhat complicated. The crystals, which have to be of a fair size, need to be separated from the brine liquid and washed.

The objections against the falling film evaporator were that it is still based on boiling against a surface, which had formed the greatest disadvantage of the existing submerged tube installation. In addition, very few manufacturers now offer this type of installation and this necessarily restricts the range open to competitive public bidding.

As regards flash evaporators, interesting material is available dealing with the economics of sizes, and optimum conditions for the number of stages, terminal temperature differences and concentration ratio. All these point towards a favourable application of this type of system.

G. Specifications for the latest desalination plant installed

Specifications were therefore drawn up for a multi-flash type evaporator, incorporating the experience of the Kuwait, San Diego (Guantanamo) and Curaçao installations. All heater piping was of cupro-nickel 90-10, sea-water lines were of glassfibre reinforced polyester and the top temperature was limited to 220°F. Scale control was effected by acid injection and additional caustic treatment. Sulphuric acid was used, being the only type available in commercial quantities on the island. With a pilot plant installation the possibilities of higher top temperatures had been investigated. The results were very promising and verified other contemporary reports but were not conclusive enough to affect the design of the new installation. However, the installation can easily be adapted at relatively minor cost to incorporate this feature, and once proven will contribute considerably to a lower cost. Owing to the high increase in water demand, the production capacity was required in a relatively short period.

It can be shown theoretically that a rise in temperature from 220° to 250°F will result in a 20 per cent higher production and a 6 per cent lower specific heat usage, whilst requiring only 30 per cent more acid. This constitutes a potential over-all saving of 12 per cent.

The logical increment, based on the forecast figures, would have been a unit of 5,000 tons per day since the other five 2,000 ton units ensure sufficient flexibility. But with the possibility of brine concentration present, which could produce another 3,000 tons of water, the decision was difficult.

Therefore two alternate sizes were specified; one of 3,000 tons per day and the other of 5,000 tons.

Because of the characteristic differences between flash and boiling evaporators another variable has to be considered here, i.e., the number of stages. In a boiling evaporator when the temperature difference across the heating surface is fixed, the number of effects and the performance are fixed for a given temperature range. This is not so with a flash evaporator. For a given terminal temperature difference the number of stages can vary widely. The "Gain Ratio", which is the amount of distillate water in pounds per 1,000 BTU, depends on the electricity production, and should be high for an installation using extraction steam. However, with a higher performance ratio a tendency develops for instability. The evaporators also become increasingly more expensive with a higher performance ratio, to that the optimum situation depends on the economics of a certain case. For Aruba this worked out to be a performance ratio of ten with a thirty-six stage evaporator installation. For Curaçao, where steam is obtained from backpressure turbines, the optimum ratio is in the order of eight using thirty stages.

The prices received for the installation of the specified flash evaporators, varying from $1.00 to $1.50 per gallon capacity, opened interesting possibilities for future reduction in water cost, which may aid the development of new industrial projects, hence leading to even higher capacities.

Water being of the utmost importance, no import duties are levied on all equipment related to the production of both electricity and water.

The two alternatives of the lowest bidder concerned two different concepts in flash evaporation, the smaller one being a long tube design, the bigger unit a cross tube.

The pumping capacity for the 5,000 ton alternative was, because of this, much higher and energy charges per unit of output equalled the direct operating costs. However, with the possibility of a salt project the bigger unit lost its advantages.

With five units operating, it is not expected that many more personnel will be required. Therefore prorating the cost over the entire installation shows that the new unit will operate at a price of $1.02 per 1,000 gallons, based on 8,000 hours production per year. With a raised temperature level, this price could be further reduced to $0.93 per 1,000 gallons. At present it is only planned to use the design temperature level since the plant output is urgently needed and should the new unit scale up under test conditions a serious water shortage could arise. At a later date, the de-aeration and acid control on the existing units will be improved. Tests have shown that this can be done for a relatively small investment, and this will improve the production between 5 and 10 per cent. Following this, tests will be made on a full production scale with the new unit.

In order to facilitate future expansion, the civil work for the new plant included the pre-building of a double-sized inlet structure, extension flanges in steamlines and air systems. Only the main pumps at the inlet of the plant cooling canal were duplicated, and although they are also providing back-up for power-plant cooling water, they are charged entirely to the water-plant operation. Since these plants were bought initially second-hand their impact on water production costs has not been significant.

At Aruba an adequate amount of spares, etc., are available, yet all sulphuric acid needed for the important scale control of the units is bought from spare production capacity of the refinery. This situation led to a research programme to see how our own production of sulphuric acid compares with the use of other chemicals. Possibly the W.R. Grace process can be used, since limestone is available on the island.

Desalinated water being the only source of water supply, reliability comes first, but lower cost is a very close second.

H. Effect of the new installation on product water cost

At the present price level of $1.90 per 1,000 gallons the books have balanced for the Water and Power Authority for the last two years, whilst over a period of ten years the operating budget has increased from $600,000 to $5,000,000.

The new unit will upset the water-plant economy for the next two years, because the installation needs time to reach its optimum operating point, but with a 5 per cent growth in demand, and with new hotels going up and being planned, this is estimated to take place within four years, bringing the price level down to $1.75 per 1,000 gallons. This does not take into account a possible higher load factor for the power-plant, which would in turn reduce steam and electrical costs to a total of another $0.05/1,000 gallons.

The effect of lower prices on water use is hard to estimate. Water may get a little cheaper but it is still rather expensive for everyday use. Estimates do not run higher than an additional 5 to 10 per cent. The price is too high for normal agriculture, although farming on the basis of the hydroponics system has proved economically possible even at the present water price level of Aruba. Some of the products are even shipped abroad.

When the operation of flash evaporators at higher temperatures does prove reliable, then, based on the present available cost figures for 5,000 ton flash evaporator units, the replacement of the existing units with two flash evaporators becomes a possibility. Total charges for operation of these units plus capital cost of the five submerged tube evaporators will add up to a total cost of $1.50 per thousand gallons.

Should one start today with a new installation, prospects are a great deal better. For plants the size of the Aruba installation, with four to five million gallons daily production, operating as a sole source of water, a price of $1.25 is possible, reducing to $1.10 when back-up facilities are available.

For large plants of the order of 100,000,000 gallons per day using atomic reactors, prices of $0.30 and $0.40 are mentioned as possibilities, but much work remains to be done before these estimates can be translated into reality.

XV. THE DESALTING PLANT AS A COMPONENT WITHIN A WATER SUPPLY SYSTEM

by A. Wiener

A. The over-all economic impact of desalting

1. General

We are rapidly approaching an era in which virtually unlimited quantities of water, suitable for use in all spheres of human activity, can be made available by the desalting of sea and brackish waters. The problem of water resources will turn then primarily into an investigation of the economic feasibility of desalted water and the magnitude of its use will depend on the relation of the benefits achieved to costs incurred; the more favourable the ratio, the more attractive will be the investment. On the one hand, desalting sea water is at present a highly capital-intensive investment, and the water produced extremely expensive; on the other hand, the benefits resulting from the application of water in agriculture where it serves as a major production input are, under most circumstances, limited. General use of desalted water will become economically feasible only under special conditions in accordance with our ability to boost the benefits obtained from the application of water, and to reduce the costs involved in its production. The over-all impact of desalted water on the economy must therefore be considered and the appropriate measures applied to increase and multiply its benefits, as well as to minimize its costs.

2. Optimization of the use of desalted water

The use of desalted water may be optimized by the maximization of its benefits and the minimization of production costs. Various measures will now be considered for the attainment of these objectives.

(a) Selection of the right product

Only those products or services commanding high prices should be considered for the application of desalted water.

The selection of the right product will be considered separately for municipal, industrial, and agricultural sectors.

(i) Municipal use. Municipal use of desalted water will be highest in the scale of priority, although it is difficult to prove this formally by quantified economic analysis. Only part of the water supplied to municipal networks is consumed and not given to recovery. Considerable quantities ejected as wastes may be recovered for re-use and safe potable water may be obtained by use of up-to-date reclamation practices, such as recharging the wastes underground after complete treatment, and possibly the removal of some nutrients. The salinity content of these reclaimed waste waters will in all probability not be prohibitive, even after a number of use-reclamation cycles, in view of the negligible salt content of desalted water and especially if the reclaimed water is itself diluted. Reclamation of used desalted waters will generally prove to be worth while, even after taking into account the additional cost of the reclamation plant. Desalting for municipal use will thus often prove to be economically feasible - at predicted 1970 costs and where no alternative natural resources are available.

(ii) Industrial use. The cost of water is generally a very minor element in the production costs of most manufacturing industries, and will remain so even with desalted water. Although high-cost water may be a considerable burden on some "wet" low-cost commodity producing industries, such as the pulp industry, it will rarely be a determining factor in the economic viability of an industry. The ratio of consumptive to low consumptive use in industry will also be important for here, too, numerous reclamation cycles may be carried out, especially where water is used for cooling on a cycling basis. Air cooling will, of course, be preferable where low-cost water is not available. However, difficulties may arise in reclamation owing to the toxicity and refractory nature of some industrial waste streams.

(iii) Agricultural use. Water is one of the more costly inputs of agricultural production in arid and semi-arid zones, even where water is available from untreated natural sources, the application of desalted water for agricultural use is consequently most questionable. The cost of the water input, based on predictable desalting costs for the early 'seventies, will far outweight that of all other inputs and may even be higher than the value of the end product. A special combination of circumstances resulting in unique, specific advantage of location or off-season and multi-benefit application, together with the development of a highly efficient organization for production and marketing will be required to make the application of desalted sea water economically feasible for agricultural production in the early 'seventies.

(b) Choice of application and production technology

Water the world over is considered as a cheap expendable commodity, and as a result the technology of water application is geared to conceptions of low-cost water. The maintenance of subsidized low water rates, even after production costs of water have risen considerably, has even reinforced this low-cost technological approach which is at present taught in universities and almost universally applied by engineers. The application of desalted water, many times more expensive than the natural waters of projects - often subsidized - necessitates complete reconsideration of the conventional application technology. This would seem obvious, yet formidable mental blocks militate against any basic change, and, as a consequence, we may be tempted to adopt the most incongruous combinations of high-cost water and standard application technology derived from low-cost water economics. An advanced application technology based on high-cost water must, therefore, be adopted, if the use of desalted water is to be economically feasible.

Municipal supply systems should incorporate all techniques so far developed in the field of water conservation and waste reduction, such as metering, rate structure, leak suppression, piping and plumbing devices to conserve water, new methods of sewage handling, e.g. vacuum conveyance, etc.

In the industrial field, air cooling should be introduced instead of water cooling, wherever possible, and preference given to dry, instead of wet industrial processes, wherever these exist.

The impact of the change of application technology will be greatest in agricultural use. The integration of outdated methods of cultivation and irrigation practices with the use of desalted water is neither intelligent nor commendable. Only scientific methods of cultivation and irrigation, optimized for the anticipated water costs, can bring the application of desalted water in agriculture nearer to the point of economic feasibility. Agricultural technology must be based, first and foremost, on uniform and rational application of water, together with the use of developed, selected seed, highly intensive cultivation and optimum application of fertilizers in order to increase crop yield and quality. Measures should also be taken to optimize the maturation season and marketing services.

The appropriate technologies for optimizing the benefits of desalted water to make its use feasible in agriculture are not yet available. A number of techniques have recently been developed, but major research and development work remains to be carried out in order to adapt agricultural practices to conditions of high-cost water. This work must be conducted concurrently with research on desalting processes, and on a considerable scale, if desalted water is to be brought within the economic reach of the water-needy nations.

(c) Plurality of benefits

Water may be applied in situations from which more than one benefit may result. The benefits that may be derived from the use of desalted water may be subsumed under five headings:

(i) Direct use - in place of natural waters;

(ii) Dilutant use - diluting natural waters with desalted water to improve their mineral quality;

(iii) Integrated use - integrating a desalting plant into an existing natural water system;

(iv) By-product use - exploiting the by-products of the desalting process;

(v) Indirect benefit - the catalyst effect brought about by supplying additional water to an undeveloped region.

These benefits will be dealt with in greater detail in the following paragraphs.

(i) Direct use. The benefits that may be obtained from the direct use of desalted water have already been enumerated but it is necessary to add here some pertinent comments on the quantitative evaluation of direct productive benefits. Only direct benefits lend themselves to quantitative evaluation, although this evaluation meets with the same difficulties in predicting the future behaviour of the market that are encountered with most other commodities. This uncertainty may, however, have more serious consequences for agricultural production based on desalted water than for other production processes because of the long-term investment required. Further, agriculture and industrial products, sustained by desalted water, will have to compete with the production of other countries, fed by natural water sources or by more up-to-date and efficient desalting plants.

(ii) Dilutant use. The use of desalted water as a dilutant for slightly saline waters may be considered at present as its most important secondary benefit. The low salinity content of desalted sea water makes its use most suitable for this purpose.

High salinity contents of some natural waters may be put down to one of a number of factors:

(1) Natural processes taking place at equilibrium conditions, i.e. natural salinity of ground and surface waters;

(2) Disturbance by man of natural equilibrium conditions, i.e. change of ground-water flow gradients, and the lowering of ground-water levels or heads through excessive use;

(3) Re-cycling of reclaimed waters, i.e. sewage water;

(4) Gradual salt accumulation in closed or quasi-closed ground-water formations, i.e. "salinity creep".

Desalting of sea water and the salt extraction processes suitable for brackish waters, such as electrodialysis, may be applied for the improvement of water quality, although other more attractive water management measures are often available. Where such measures are either unavailable or uneconomic, the application of desalting processes by salt extraction or dilution may be the only course, if such substandard natural resources are to be exploited. In such cases, the development of the substandard natural resource and that of the supporting desalting process should be considered as one investment package, which will result in a combined water yield at a cost that will equal the weighted average of the costs of the two processes and thus lower considerably the over-all cost of the system. The pros and cons of these two basic desalting approaches to our four categories of salinity conditions cannot be analysed here in detail; we shall only mention here the main factors on which the selection of one or other - or a combination of both approaches - will depend. These are as follows:

(1) Local hydrological conditions;

(2) Relative costs of the alternative desalting processes;

(3) Possibility of alternative, selective, direct use of the substandard waters;

(4) Comparative cost of brine disposal;

(5) Quantity and location of the additional high quality waters needed;

(6) Extent of integration into the water system;

(7) Institutional authority available for integration.

Some policies, if practised continuously, will lead to qualitative equilibrium conditions; others will not reach such equilibria and will require an ever-increasing rate of intervention, in order to maintain tolerable qualitative levels.

At present, the quantitative evaluation of the benefits resulting from the improvement of the mineral quality of water for agricultural use is seldom possible. Such evaluation can only be made if the function correlating the salinity content with the value of the crop yield is known. This function is influenced by soil texture and structure, soil drainage, cultivation methods and fertilizer application, irrigation requirements and methods, the amount of natural rainfall, as well as other factors; this function is at present known only for a limited number of crops grown under highly specific local conditions; it is not as yet fully understood for orchards.

In order to evaluate the economic feasibility of dilution or salt extraction, we must first study the cost of the alternative approaches or a combination of approaches. This will generally be difficult and perhaps may not even be feasible at this stage of development. An alternative evaluation approach is to establish a salinity ceiling for the most salt-sensitive crops, based on available scientific and empirical observation, together with the exploitation of substandard waters that have undergone some desalting process - where these substandard waters cannot be improved by any less expensive method.

(iii) Integrated use. We shall confine ourselves to listing a few of the more important advantages of integrating a desalting plant or plants into an existing water supply system:

(1) The conveyance capacity of the system can be significantly improved by locating the desalting plants, to feed directly into strategic points of the system;

(2) Seasonal and short-term cyclical flow variability in the system will be decreased, and with it the relative storage capacity required for flow regulation;

(3) Long-term cyclical dependability of the yield will be increased by the incorporation of a desalting plant, operating independently of climatic cyclical variations.

These advantages, although real, are, nevertheless, difficult to evaluate quantitatively and in general can only be evaluated qualitatively.

(iv) By-product use. The possibilities of the utilization of by-products of the desalting process are as yet little known. Utilization of by-products may be combined with pre-treatment of sea water, e.g. the process proposed by the Grace Corporation; the concentrated brine discharged from the plant may also be utilized. Where the by-products of desalting are exploited by industry, it may be justifiable to attribute a value to such by-products and debit part of the costs to the desalting operation. Exploitation of by-products may, however, be economic only if they are not burdened with any of the costs of desalting. At present, and as long as there is no proof to the contrary, desalting costs should not be debited to these by-products.

(v) Indirect benefit. The supply of additional quantities of water or the introduction of water into an area which prior to desalting may have had no natural sources of water may bring about a far-reaching catalystic effect on all sectors of the economy as well as bringing in its wake important social changes. Some but not all these effects are given to evaluation.

(d) Maximum loading of plant

The methods of desalting anticipated for the early 'seventies will be capital-intensive to a very high degree. The investment - allocatable to water in a dual-purpose plant - may be as high as $US1.00 per gallon per day, and annual fixed capital charges at a 10 per cent rate may reach 55 per cent to 60 per cent of the total annual cost at full load. The plant-use factor, and its development over the life-time of the project, will therefore have a decisive influence on the economics of a desalting plant: the nearer the plant will operate to full load conditions on a daily, seasonal, and long-term basis, the more economic the plant. In a single-purpose plant no difficulties will arise from daily and seasonal fluctuations of demand, once the full capacity of the plant is called for, since the product water can be stored in surface or underground storage during off-peak hours or seasons of the demand curve. Difficulty will arise mainly during the maturation period of the desalting project when the full plant capacity is not yet required. In a dual-purpose plant, the local requirements of the electric grid must be co-ordinated with the requirements of the water system.

Operating at a low load during the maturation period of a single-purpose plant or reducing the production of water in a dual-purpose plant during the off-peak hours of the electric grid, will add a heavy and possibly unbearable burden to desalting. Hence, measures must be taken to ensure that the plant will operate fully from the date of its commissioning until its retirement; demand manipulation may provide a satisfactory solution to this requirement. As an example of this, part of the demand to be supplied by the proposed desalting plant may be developed a few years ahead of the commissioning of the desalting plant. Demand build-up may take the form of "pre-financing" the water needs of the economy through a properly planned and controlled "overdraft" from existing ground-water resources. This "pre-financing" can be carried on to a point where the instalments for "re-payment" of the "debt", together with the demand created, will approach the rated capacity of the plant. A less attractive alternative consists in using part of the unused capacity of the plant to create a water stock to be kept in storage for future use; drawing upon the stored water at a later date makes it possible to postpone for some time the investment required for the construction of a subsequent desalting plant.

The first approach has the double advantage of according benefits before the plant is actually commissioned and of allowing full capacity operation from start-up to retirement. Thus the burden of interest to the national economy during construction, as well as the cost of maturation, can be minimized. An attractive spacing in time of investment may be achieved by applying a similar procedure when a subsequent plant becomes necessary.

3. Conclusion

The programme adopted in planning desalting plants should embody all or a majority of the approaches outlined above. The adoption of only one approach will generally not be sufficient to make the plant economically feasible at present-day costs.

B. The economic justification of desalting

1. Marginal analysis of existing water allocation

So far, we have expounded the marginal analysis of new uses and the benefits accruing from them, implying, of course, complete lack of transferability of water from present uses. This does not, as a matter of course, constitute a full analysis of the impact of a desalting plant on the national economy; a complete analysis should consider all present uses of water in agricultural as well as non-agricultural sectors, together with the proposed new uses; we must then also consider the possibility of transferring water from less profitable to more profitable uses, from the over-all national viewpoint.

In reality, the mobility of water resources will depend on a number of political, social, legal, institutional and economic factors: in some societies this degree of mobility will be higher; in some, lower or even nil. Resistance to transfer is not static and immutable, but to some extent amenable to change. Where dramatic stress on resources develops - and no country would at present consider the construction of a large-scale desalting plant without the emergence of such stress - resistance to transfer will soften and some re-allocation of resources will be effected in the right direction, although even under such conditions a considerable hard-core of resistance will remain.

Let us assume at the outset and for the sake of simplicity, that our political universe is "frictionless" and that water can be freely transferred from one use to another without involving any cost to the economy. When all natural resources have been utilized and before we resort to desalting, we should investigate the economic feasibility of applying desalted water for the existing use that carries the marginally lowest benefit in the economy. Desalting should be adopted only to the extent that the use of the expensive product water would be justifiable for that marginally lowest use. Should such use of desalted water be unjustifiable - and this will normally be the case - desalting should be delayed and water switched from the lowest benefit use to the proposed, high-valued application. A similar analysis and subsequent re-allocation procedure should be applied when the first re-allocated amount of water becomes exhausted. The procedure will be repeated until what then constitutes the lowest marginal use justifies the use of expensive desalted water. Only at this point would desalting be justifiable from a theoretical point of view.

So far, our analysis has used static parameters of benefit, water cost, etc.; this is not warranted for the analysis of processes extending over long periods of time: to avoid the falsification of such simplification a number of variable parameters changing with time must be entered into the analysis; efficiency in the use of water and the value of benefits per unit of water will markedly increase; the forces of the market will exert a pull on low-value uses, tending to effect a gradual re-allocation of water resources to higher-value uses.

The following schematic diagram illustrates the relationship of these tendencies. Demand and supply curves have been plotted on the basis of the costs of natural and desalted water respectively. The broken lines represent demand curves for the years 1965, 1975 and 1985; the full lines represent supply curves for desalted water for the same years. We see from the diagram that desalting costs will decrease both with time due to technological progress and with an increase in the size of the desalting plant. Theoretically, desalting will be justified when the demand curve and the supply curve for a particular year intersect; the distance "a" on the diagram in Figure I represents the minimum desalting capacity justified for that year. The choice of actual plant capacity will not, of course, be based on the requirement for a particular year but for a considerably longer period.

Moving from our model to real-life conditions we must determine:

(1) the economic and social cost to the economy in suspending the allocation of water for a particular use;

(2) the cost of effecting the physical transfer from the original to the new application.

The transfer will be justified, from the purely economic aspect only provided that the benefits foregone as a result of the transfer and the costs of effecting the transfer per unit of water are lower than the cost of desalted water per unit of water transferred.

We must also determine the social, political, legal and institutional resistance to such a re-allocation of water resources. Uses which arouse considerable resistance to change will be excluded from our marginal analysis; they will remain islands of economically incompatible low use; in time, the forces of the market, or the softening of the resistance to mobility may erode part or all of these islands.

A similar analysis should be applied to quality aspects of water, and here we refer mainly to mineral quality. Again, the question of the mobility of the allocation of saline waters arises; in this context, mobility implies exchange of water of lower salinity content for water of higher salinity for crops that are not particularly salt sensitive. Generally, greater resistance against the re-allocation of the "salt-burden", resulting from agro-technical considerations, will be encountered than when trying to shift water to a different use. The cost of the installations required for the allocation of saline waters may also be relatively high. The procedures and approaches described for quantitative mobility - mutatis mutandis - apply also to qualitative mobility.

DEMAND AND SUPPLY CURVES

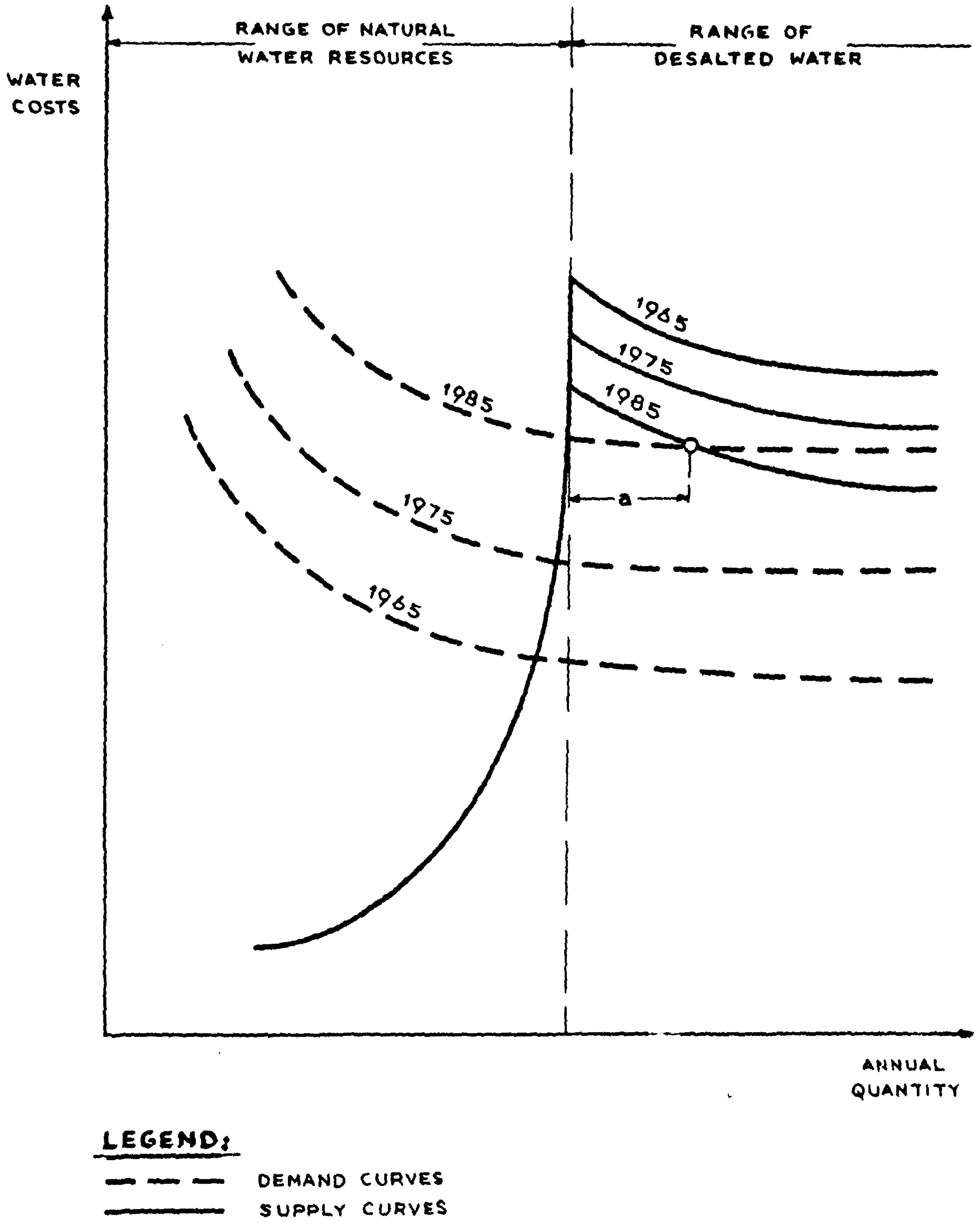


Figure I

Marginal analysis must then take in both aspects of mobility, where desalting is undertaken as a multi-benefit proposition, to include the quality improvement of natural resources among its benefits.

2. Resource expansion and efficiency of use

One last simplification must now be resolved. Up till now, we have considered the recoverable part of the natural water resources and the "duty" of water to be constant. Changes in these parameters, although very slow, cannot, however, be neglected.

Resources parameters are to some extent amenable to change; water systems can be designed for minimum loss and resources which have been left untouched or only partially developed in the past because of high development costs, may become attractive when their cost is compared with that of desalted water. All existing projects should be examined for the possibility of squeezing out some additional yield at costs below those of desalted water. Regional and inter-regional integration of water systems and regional and inter-regional management plans based on system analysis often allow a considerable increase in the water yield of a system. Reclamation of marginal resources, waste water, etc., may also play an important role.

Similar considerations apply to the application end - already referred to in section A.2(b) above.

3. Institutional constraints

We have commented elsewhere on the influence of institutional constraints: such constraints are, perhaps, nowhere as decisive and refractory as in the development of land and water resources.

Institutions take shape within socio-economic contexts, in order to facilitate the achievement of certain economic and extra-economic objectives; where contexts change, institutions should change accordingly. Gross incompatibility between traditional institutional patterns and the institutional requirements of development will tend to lower system efficiency and result in economic failure. It is the duty of the system planner to outline the minimum institutional changes mandatory for the introduction of desalting processes.

4. Conclusion

Large-scale desalting is at present a major capital-intensive, technological undertaking and everything indicates that it will continue to be so in the foreseeable future. Before resorting to large-scale desalting, existing water systems should be analysed, for possibilities of expanding the resource yield, minimizing losses, and reallocating or making better use of resources through their integration; further, possible improvements of application technology and the adequacy of the institutional framework should be examined.

Only after all the above approaches have been exhausted should the introduction of desalting plants be considered. When planning the scope and layout of such plants, all opportunities inherent in the geographical, technological, economic and social context should be adopted to maximize plant benefits and to minimize plant costs.

A similar problem exists with flash evaporator shells, presently built of carbon steel. The larger quantities of steel for vacuum construction will be costly, which explains the planned programme to study the suitability of substituting concrete. However, there will certainly be many problems with concrete from hot salt water attack as well as tightness in design to hold vacuum under thermal gradients. Whether concrete will prove out is still uncertain, and the economic gain may disappear if steel liners are necessary to maintain leak-tight shells.

Although there are many uncertainties in design, the economies of large scale still exist, particularly in mass production of tube material, as well as large pumps, evaporator shells, and large-scale piping, valves and circulating water systems. Realistic cost figures for these plants should be available by 1968, following the Office of Saline Water module testing programme.

E. Economic factors in dual-purpose plants

One must be very careful in using water costs from dual-purpose plants because generally no standardized methods are used for these calculations. Although both the Office of Saline Water and the United Nations have proposed standardized procedures, many water cost figures published to date are inconsistent in their assumptions.

To appreciate and understand water costs properly, let us examine some of the more important contributing factors:

I have made a number of references to the significant capital cost savings that are possible by scaling-up from 1 mgd to 50, 100 or 150 mgd. This factor is well known and has been amply demonstrated by experience in the power, chemical, and manufacturing industries, even in housing and office building construction. A number of design studies by equipment manufacturers and engineering organizations have been made of large-size flash evaporators during the past three or four years. Their results are shown on Figure VI, which correlates the unit cost of flash evaporators with size based upon a fixed performance of 12 lbs of water per lb of steam.

With currently known technology, a 1-2 mgd plant can be installed for around \$1.50 per gallon per day. By increasing the plant size to 50 mgd, the unit installed cost reduces to \$0.75, while 250-mgd plants will have an estimated installed cost of \$0.50 per gallon per day. These reductions in unit cost with size are actually modest and decrease at a much slower rate than power or chemical plants for comparable size increases.

The scale-up factor also reduces maintenance and operating costs. As a rule of thumb, in a 1-mgd desalination plant, about one-third of the production cost is in energy, one-third in capital cost, and one-third in operating and maintenance. Operating and maintenance costs do not increase in proportion to size - again, a factor well known in other industries. Therefore, where these costs for a 1-mgd plant in the United States may be 20-35¢/1,000 gallons, the comparable cost for a 50-150-mgd plant will probably be around 6-7¢. Of these costs, around 2-3¢/1,000 gallons are chemical costs, if brine temperatures are over 200°F.

Most economic evaluations of dual-purpose plants have been based on water-plant capacity factors of 80 per cent and 92 per cent. These correspond to 7,000 hrs and 8,000 hrs of operation. In operating flash evaporator plants, the scheduled shut-down should be one week a year to descale brine heater tubes and for pump maintenance. Therefore, the scheduled availability of the water plants is 97.5 per cent. Power-plant experience has been around 95 per cent scheduled availability, allowing two weeks for shut-down. Experience with fossil-fuel plants in the United States has generally shown a 90-95 per cent availability. Nuclear power experience has been limited, but their availability to date has been 80-85 per cent. By comparison, the United Nations report on "Water Desalination in Developing Countries" indicates that evaporators have been less than 80 per cent available. Although, in theory, there is nothing inherent in the flash evaporator design to keep availability below 80 per cent, appreciably more operating experience and design improvements will be necessary if these dual-purpose plants (particularly nuclear-fuelled) are to achieve an operating capacity factor of 92 per cent.

Another economic method generally applied to dual-purpose plants which favours water costs has been the cost of money. In some countries, water is financed at lower interest rates than power and in addition taxes are generally not levied against water, but may be levied against power. Where oil is imported, the duty charges are also added to power costs. Therefore, power plants bear a greater burden of financing charges than water plants. In some studies reported in the literature, the lower financing charges of the water plant are applied to the combined power and water plant, while the power is credited with the higher financing charges. This technique obviously gives a lower annual capital charge against the water-plant portion of the combined plant.

The recent United Nations report, "Water Desalination: proposals for a costing procedure and related technical and economic considerations", 2/ attempts to place water costing of dual-purpose plants on a more equitable basis by letting power production costs share in the economies normally all attributed to water costs. This United Nations report attempts to give proper balance in costing both products. However, water is also a social problem; if a country chooses to have another industry, such as power, assume some extra cost burdens to make water more reasonable, that is certainly its prerogative.

F. Dual-purpose plant water costs

After considering all the factors and limitations discussed in this paper, we can now examine water costs from dual-purpose plants. No attempt will be made here to give extensive cost tabulations, but rather to provide enough information to decide whether costs are low enough for particular situations to justify further detail analysis.

Water costs in this paper have been reported in previous studies and are all based on charging water only for the cost difference between the annual cost of a dual-purpose plant and the annual cost of a single-purpose power plant with the same net salable power. The water plant sizes have been divided into small plants (up to 10 mgd), medium plants (up to 150 mgd), large plants (greater than 150 mgd).

2/ United Nations publication, Sales No.: 64.II.B.5.

(a) Small plants

Table 1 summarizes the costs chargeable to water production for dual-purpose plants of 2 mgd and 10 mgd. The 2-mgd cost figures were presented in a talk by Phil Sporn to an investment group, but were corrected to 7 per cent fixed charges and 35¢/10^6 BTU fuel, rather than the reported 10 per cent fixed charges and 40¢/10^6 BTU fuel. In addition, maintenance and operation costs were increased from 10¢ to 20¢/1,000 gallons, to reflect United States labour rates and personnel needed for plants of this size. The 10-mgd cost figures are from the Burns and Roe Florida Keys Study for the Atomic Energy Commission and the Office of Saline Water. Water costs in the 2-10-mgd range, as these figures show, are between 52¢ and 78¢/1,000 gallons - a production cost generally too high for municipal or industrial supply.

(b) Medium plants

Table 2 summarizes the water costs in dual-purpose plants between 50 and 150 mgd as reported from the parametric study by Catalytic Construction Company for the United States Atomic Energy Commission. These water costs are based upon 7 per cent fixed charges, 80 per cent capacity factor and gas fuel at 35¢/10^6 BTU. Results of this study are based on optimizations which, surprisingly, show very small water cost reductions with increasing size for nuclear fuel plants, and increasing water costs with increasing size for fossil fuel plants. This unanticipated trend may be due to sensitivity to power credit as explained in the report, or by other factors not obvious at this time. The production costs are in the range of 26-37¢/1,000 gallons for either fossil or nuclear fuel. These costs are still higher than United States experience for municipal and industrial water production costs, which are generally 10-20¢/1,000 gallons.

(c) Large plants

The data in Table 3 is from the Office of Science and Technology Report, dated March 1964, entitled "An Assessment of Large Nuclear Power Sea Water Distillation Plants". The water costs are based on fossil fuel of 35¢/10^6 BTU, 7 per cent fixed charges, and 80 per cent capacity factor. The water-plant capacity ranges from 170-970 mgd and the power-plant sizes range from 180-680 MW. Water costs for these large plants range from 26-38¢/1,000 gallons, which is similar to the medium size plants. Although the costs are comparable, the methods of calculation and capital cost estimates are not.

For a consistent costing procedure, the water costs would continue to drop with increasing size, as shown in Figure VII. The data presented in Figure VII is based on light water reactors as the heat source, which can be reliably estimated for the range considered. The flash evaporator costs were taken from Figure VI, reflecting the scale-up cost reductions. The results of these calculations, as shown, in Figure VII, are typical of the values reported by other studies in the size ranges considered.

G. Over-all considerations in dual-purpose applications

The reported costs of water are all based on production only, and do not include costs for conveyance and distribution. Conveying water from large dual-purpose plants may add another 7-11¢/1,000 gallons to production costs, if conveyance distance is around 40 miles. In addition, one must add distribution costs and general administration overhead costs which may be around 15¢/1,000 gallons, so that the actual consumer price could be about 25¢/1,000 gallons higher than production costs. Consumer costs might be reduced by 10¢/1,000 gallons if the water plant is near an existing conveyance system.

It should be clear that, with agricultural water costs of 5-10¢/1,000 gallons, fresh water from desalination plants is too costly for agricultural use. The immediate application of desalted water is for municipal and industrial use where billing costs in the United States are in the 20-35¢/1,000 gallons range. Fresh water produced by evaporation is of high quality - generally below 50 ppm solids. In fact, 10 ppm water can be produced with insignificant cost penalties. Therefore, should existing water supplies have a high salinity, desalted water can be used as a diluent of existing supplies. This approach is being considered in Israel as well as the south-western United States, where the Colorado River water has a salinity of over 700 ppm.

The attractive economics of water production by desalination in Tables 1 to 3 and Figure VII are based on the non-condensing power generation shown schematically in Figure III. Such an arrangement gives the maximum ratio of water to power production. Whether the total water and power production of this arrangement can be used effectively and economically depends on the power and water system being served.

If a nation is highly industrialized, and requires large quantities of water, the large blocks of power generated can readily be absorbed in the power system. Even a developing country short in power and requiring large water production may be able to initially add a limited number of dual-purpose plants without affecting the power to water balance.

However, most of the arid and semi-arid regions of the world are not sufficiently industrialized to use all the power. Even industrialized nations will reach a point where either the power or the water produced in such dual-purpose plants will be greater than the demand. We then come upon one of the limitations of the dual-purpose plants; namely, limited flexibility in economic design to satisfy the proper balance of power and water demand.

When such a situation arises, the condensing power plant with extracted steam for water production as shown in Figure IV will be required or an oversized power or water plant will be installed. The condensing power cycle offers only little economic advantage over a separate single-purpose power or water plant. On the other hand oversized power or water plants of the high efficiency arrangement will hurt the over-all economies, either of the power system or the water system, because of over-production.

When considering the medium- or large-scale desalination plants, it is most important to consider what will happen to the power system or the water system, if the dual-purpose plant is shut down. In the case of the power system, it would be vital that there should be power reserve to take up the loss in load, either by existing units or through transmission inter-ties. This situation is normally planned in any power system.

However, in case of water production loss, the solutions may be costly and yet must also be considered in the over-all problem. If the water system is isolated from other water systems, it will be necessary to have sufficient water storage capacity to carry the period of desalination plant shutdown. Large reactors will require shutdown times of about three weeks for refuelling, while boilers and turbines are generally scheduled for two-week shutdowns for necessary annual repairs. The water storage capacity should then be sized to supply the daily output of the desalination plant for two to three weeks. If storage is very costly, consideration might be given for stand-by heat sources with smaller storage capacity or stand-by heat source and stand-by desalination plant with little or no storage capacity. If the water system is not isolated, possibility of an aqueduct inter-tie to an adjacent water system should certainly be investigated.

With desalination developments moving at a rapid pace, it is most important not to overlook the problem of obsolescence of design. The multi-stage flash evaporation with high performance ratios is a recent development. The units now in operation are based on low-performance ratio evaporators. With fuel costs generally high, the economies of low-performance ratio evaporators are not justified economically when compared with high-performance ratio units. Therefore, the low-performance ratio units cannot be justified for continued operation, and are being replaced by high efficiency units. Similarly, the older evaporators were operated below 200°F sea-water temperature, while present day units are being designed for 250°F and future units are being considered to operate at 300-350°F range. The multi-stage flash evaporator is also displacing the submerged tube and vapour compressor designs of the early installations because of their lower capital cost. These are typical examples of recent trends in desalination design which point up the potential problem of obsolescence because of a rapidly changing technology.

In the non-condenser power-plant cycle of dual-purpose plants, the heat energy is converted to power at almost 100 per cent efficiency. As discussed previously, the power is credited at the production cost of a single-purpose plant of the same output. However, as a power system grows, particularly in the case of developing countries, the cost of power production will drop as units get larger and the plants are designed more efficiencly. Therefore, a dual-purpose plant may have a power credit initially based on a value which may be too high after a few years because of the newer, more efficient units. Under such conditions, the power credit of the dual-purpose should be decreased, thereby shifting greater costs to water, or else the power portion of the dual-purpose plant should be shut down. Under these conditions, the cost of water production will increase because the available energy of the steam is decreased by bypassing the turbine.

The dual-purpose plant also limits the flexibility of plant location. It is unlikely that the water and power demand will be required in the same area. It will, therefore, be necessary to include in the over-all economics the additional cost of power transmission if the plant cannot be sited on an established power station and for water conveyance if the plant cannot be located near an established aqueduct or water distribution system. These cost penalties should be considered if the economics of dual-purpose are compared with single-purpose power, or single-purpose water plants, as well as alternate methods of water supply.

The use of large-scale nuclear plants may also impose additional cost penalties to power transmission and water conveyance above those enumerated. Since the reactor sizes required for dual-purpose plants are larger than single-purpose power plants, they become even a greater siting problem because of the increased fission product inventory. To solve this problem, it may be necessary to site the dual-purpose plant at even greater distances from the power and water demand centres thereby further increasing power transmission and water conveyance costs. To keep the distances at a minimum, an alternate solution would be adding double containment or increased engineering safeguards which again increase the nuclear plant costs.

Therefore, in any study considering dual-purpose application, it is important not only to examine power and water production costs of a plant, but also the effect of the dual-purpose plant upon the total power and water system. Dual-purpose has many economic advantages, but if some of the penalties enumerated above exist in a system, then much of the production cost advantages may be eliminated by those penalties. Only through a detailed study of all the factors can the true economies of dual-purpose be properly evaluated.

Figure I

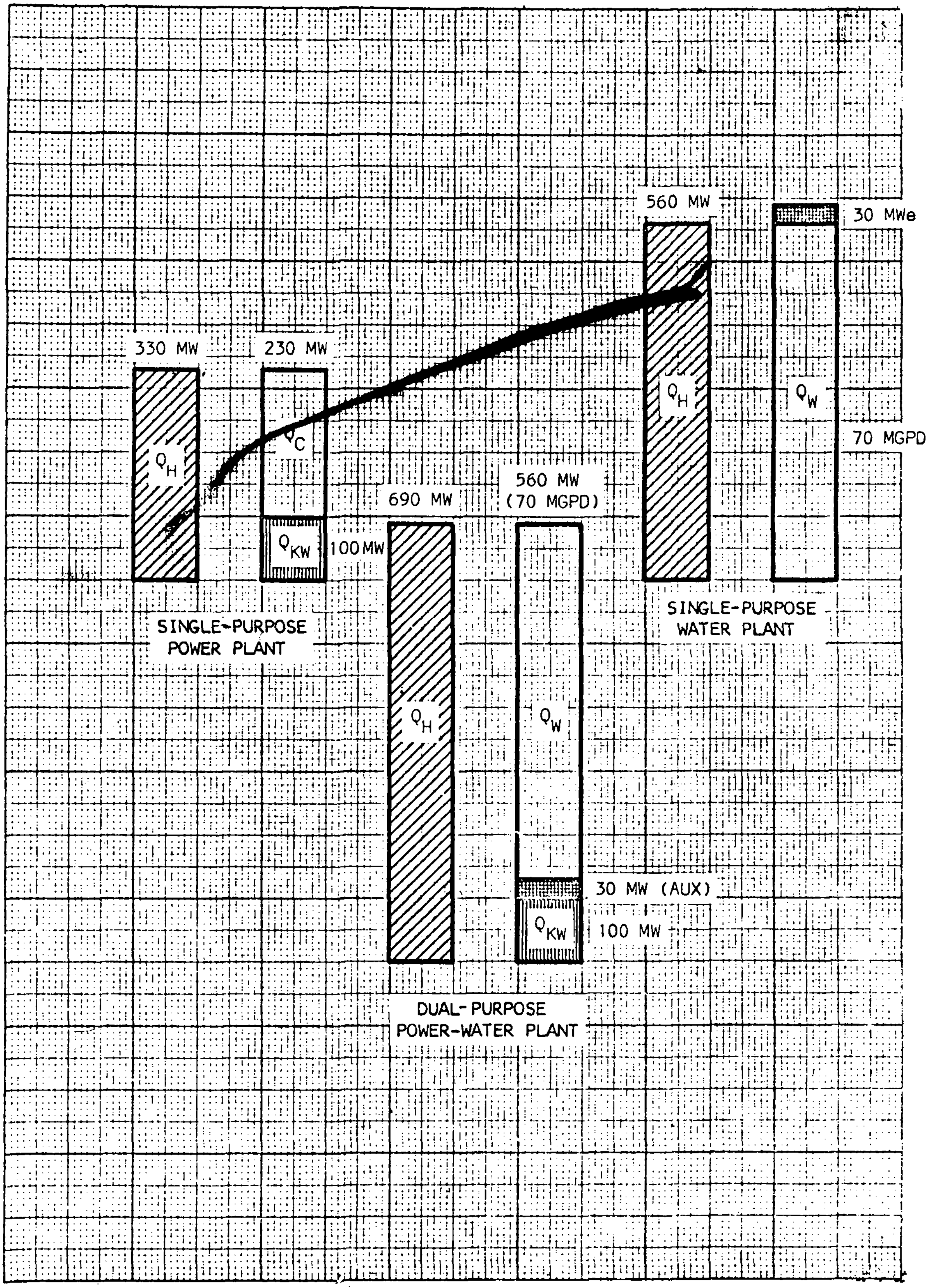

330 MW
230 MW
Q_H
Q_C
Q_{KW}
100 MW
SINGLE-PURPOSE POWER PLANT
690 MW
560 MW (70 MGPD)
Q_H
Q_W
30 MW (AUX)
Q_{KW}
100 MW
DUAL-PURPOSE POWER-WATER PLANT
560 MW
30 MWe
Q_H
Q_W
70 MGPD
SINGLE-PURPOSE WATER PLANT

Figure II

Multi-stage flash evaporation

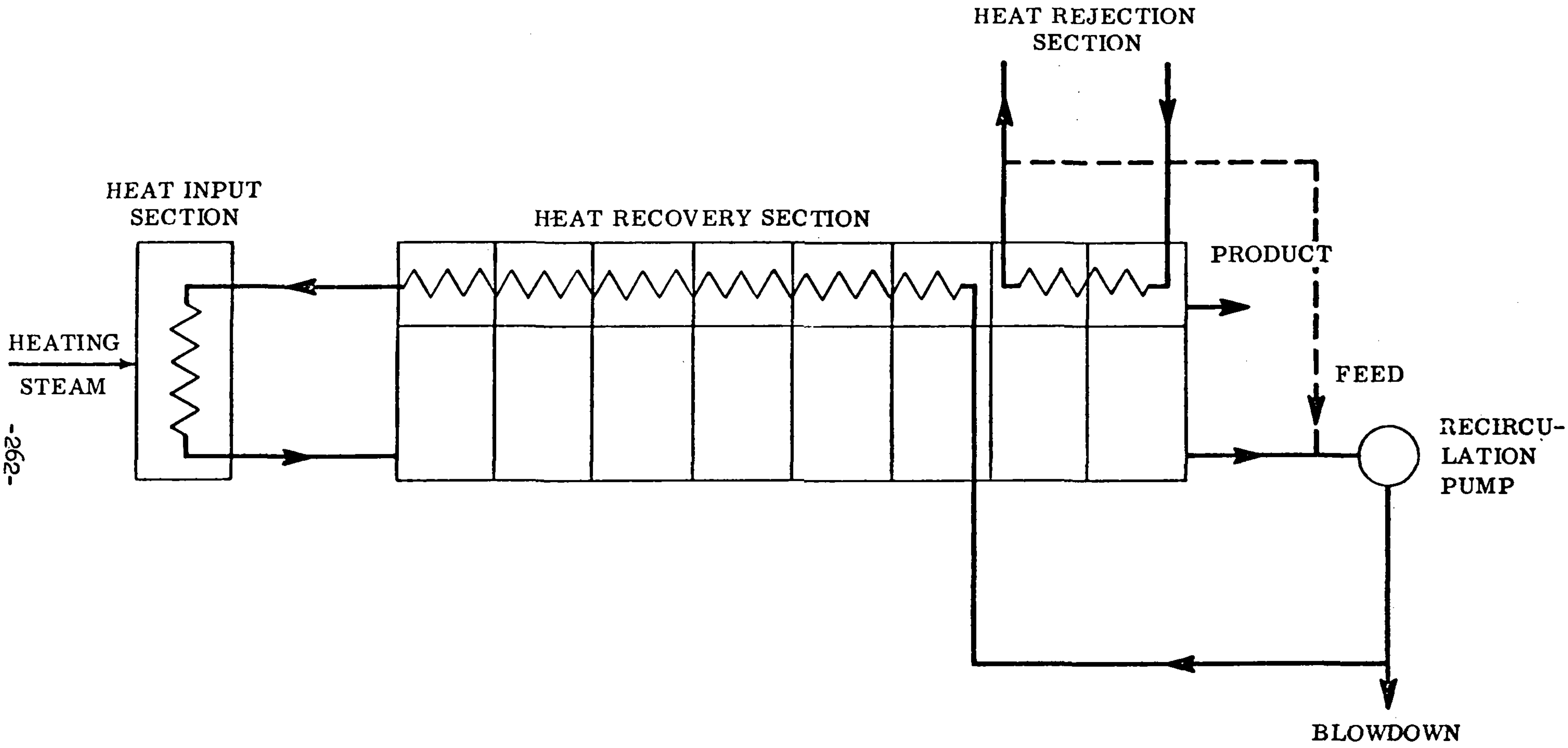


Figure III

Heat balance - backpressure turbines

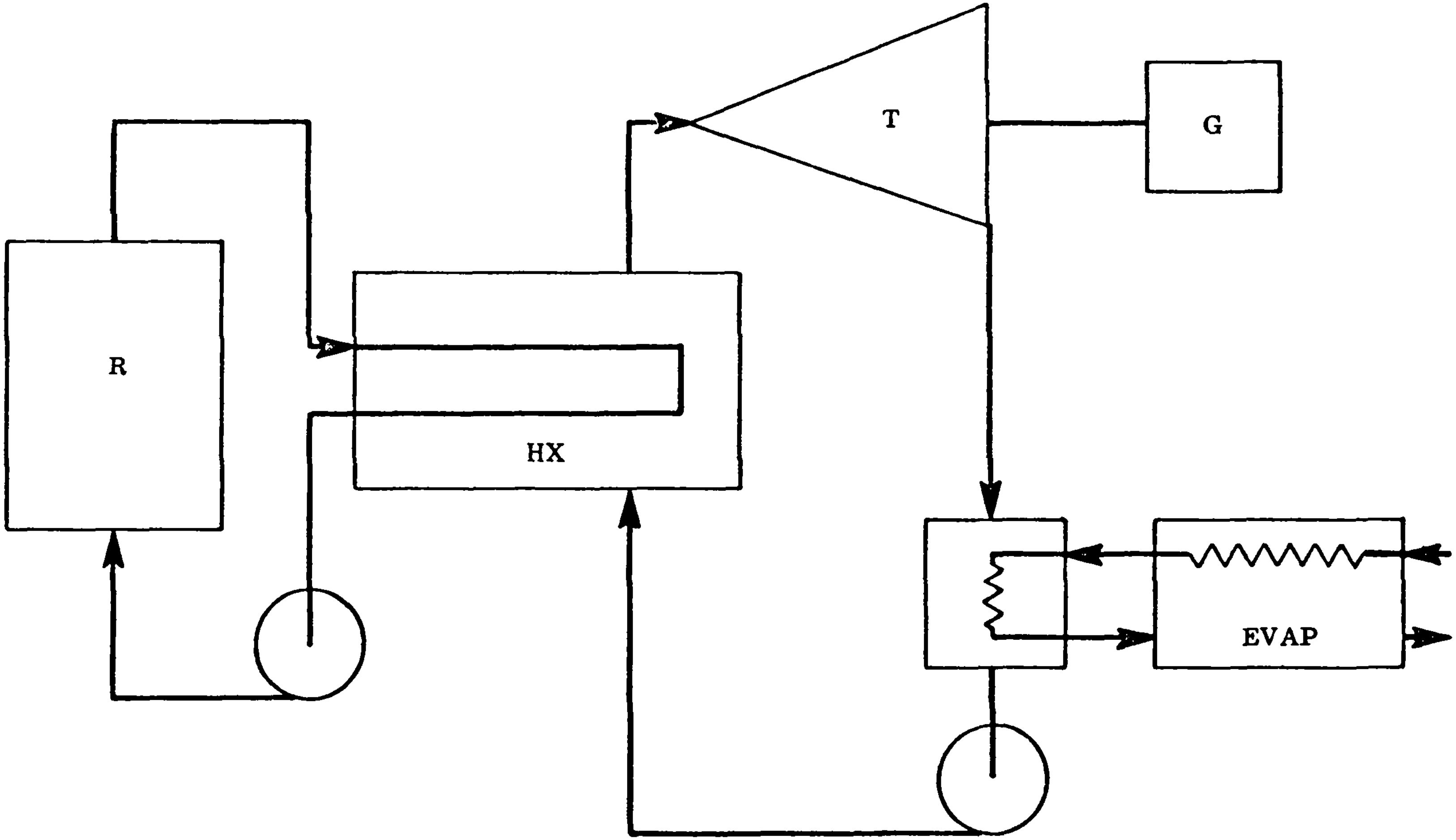


Figure IV

Heat balance - extraction turbines

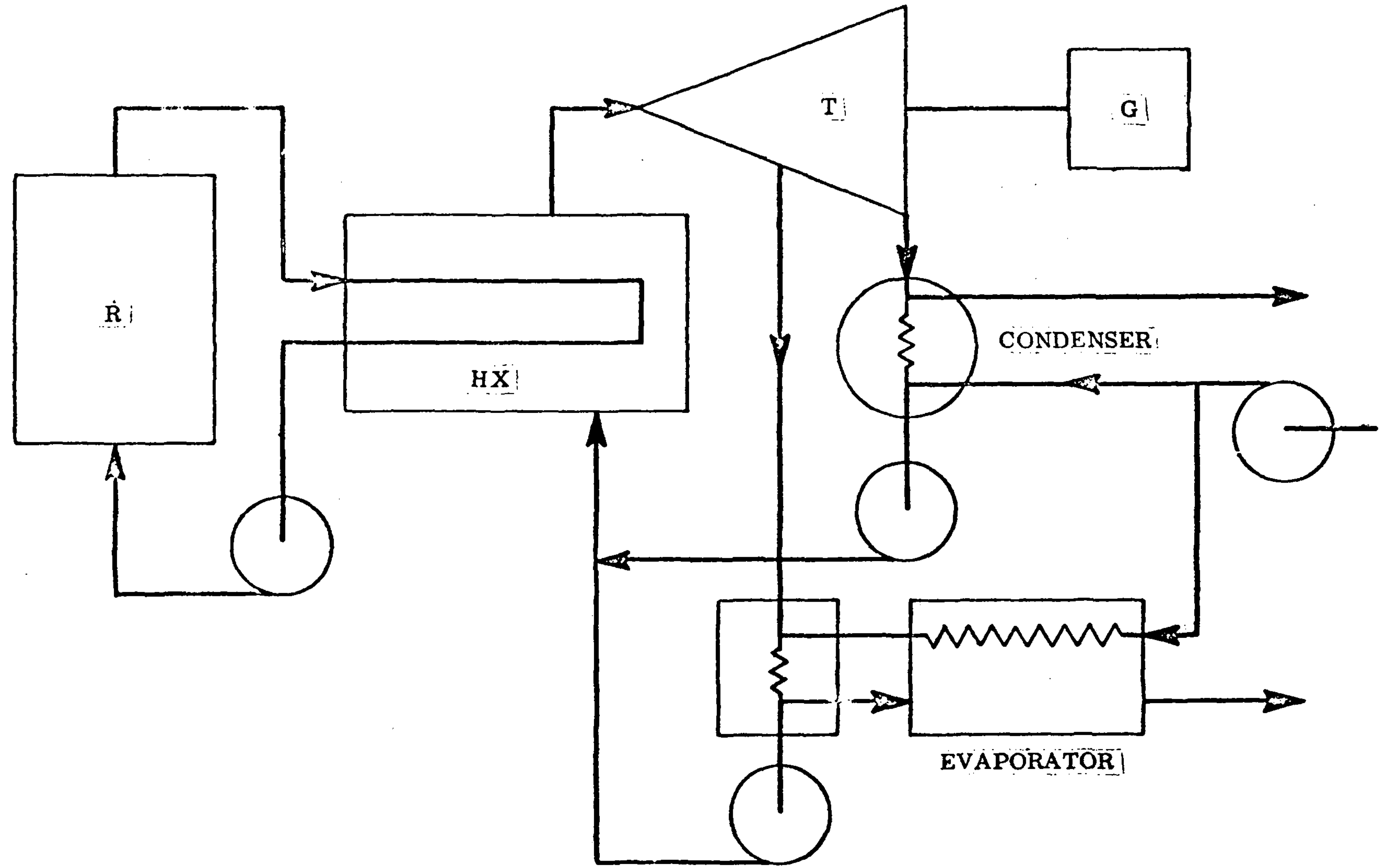


Figure V

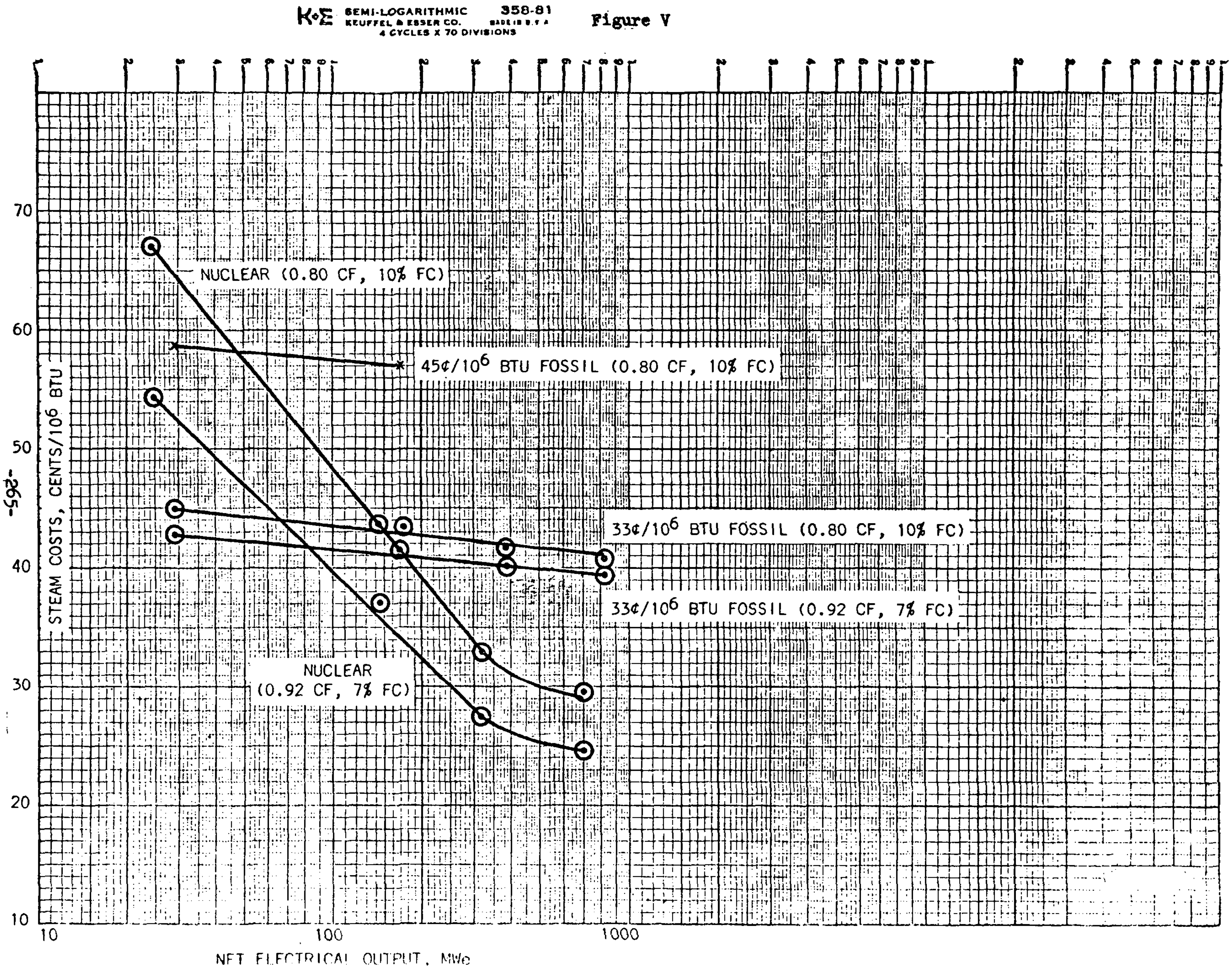
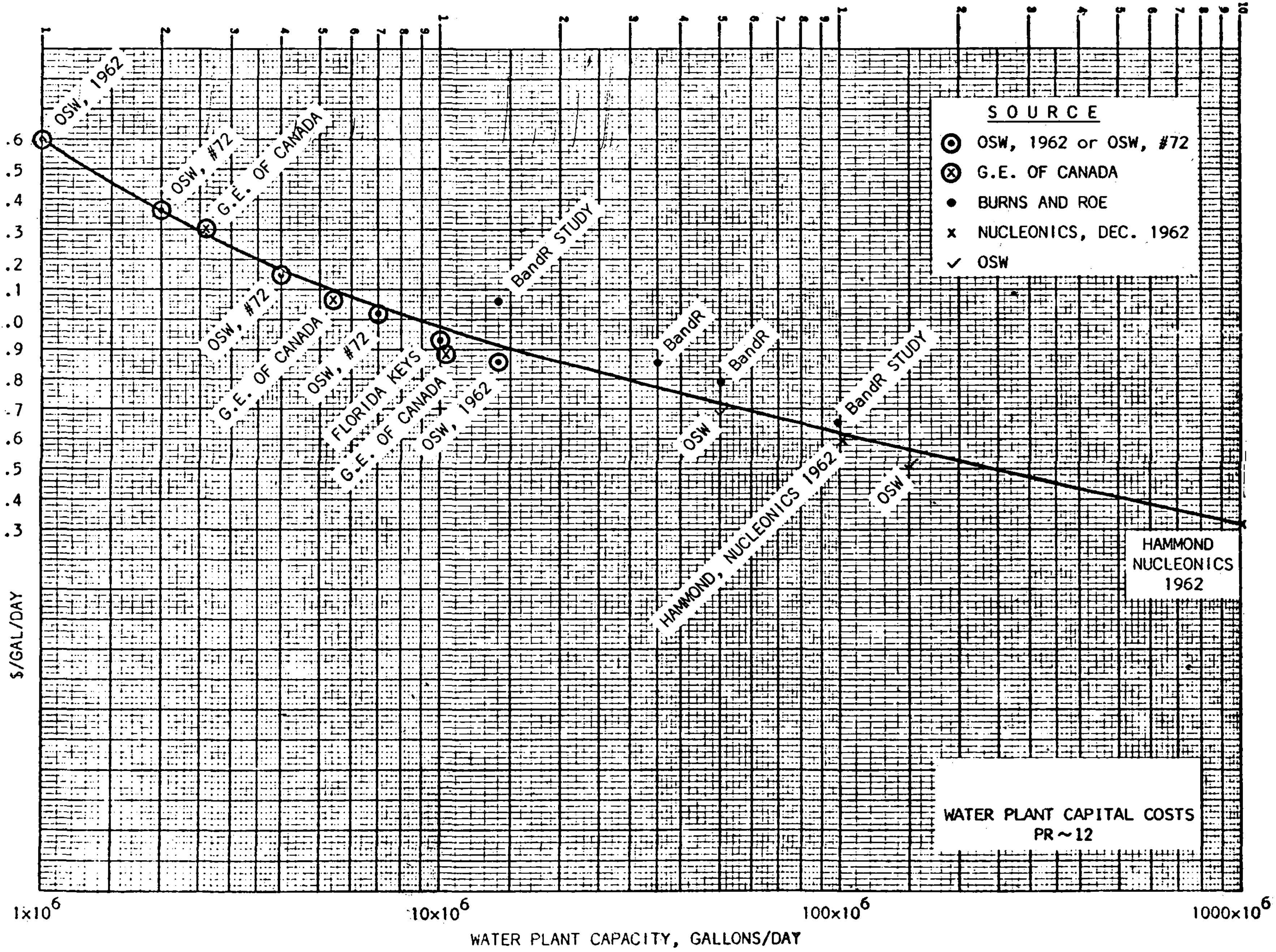

K+E SEMI-LOGARITHMIC 358-81
KEUFFEL & ESSER CO. MADE IN U.S.A.
4 CYCLES X 70 DIVISIONS
STEAM COSTS, CENTS/10^6 BTU
70
60
50
40
30
20
10
NET ELECTRICAL OUTPUT, MWe
10
100
1000
NUCLEAR (0.80 CF, 10% FC)
45¢/10^6 BTU FOSSIL (0.80 CF, 10% FC)
33¢/10^6 BTU FOSSIL (0.80 CF, 10% FC)
33¢/10^6 BTU FOSSIL (0.92 CF, 7% FC)
NUCLEAR
(0.92 CF, 7% FC)

Figure VI



SOURCE
OSW, 1962 or OSW, #72
G.E. OF CANADA
BURNS AND ROE
NUCLEONICS, DEC. 1962
OSW
OSW, 1962
OSW, #72
G.E. OF CANADA
OSW, #72
G.E. OF CANADA
OSW, #72
FLORIDA KEYS
G.E. OF CANADA
OSW, 1962
BandR STUDY
BandR
BandR
OSW
BandR STUDY
HAMMOND, NUCLEONICS 1962
OSW
HAMMOND NUCLEONICS 1962
WATER PLANT CAPITAL COSTS PR ~ 12
$/GAL/DAY
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
1x10^6
10x10^6
100x10^6
1000x10^6
WATER PLANT CAPACITY, GALLONS/DAY

Table 1

Small-size Dual-purpose Plants

Water plant size	2 MGPD	10 MGPD
Power plant size	6,000 kw	50,000 kw
Capital cost (7 per cent FC, 80 per cent CF)	39¢	23¢
Fuel cost (35 cents/10^6 BTU)	19¢	18¢
Maintenance and operating costs	20¢[a/]	11¢
Total water costs	78¢/1,000 gal	52¢/1,000 gal

Source: For 2 MGPD, P. Sporn, Fresh Water from Saline Water, talk, 11 March; Kuhn, Loeb and Co., (report figures corrected 7 per cent FC, 35¢/10^6 BTU fuel).

For 10 MGPD, Burns and Roe, Inc., Florida Keys report for the Atomic Energy Commission and the Office of Saline Water, (report figures corrected, 7 per cent FC, 35¢/10^6 BTU fuel).

[a/] Corrected to 20¢/1,000 gal rather than 10¢/1,000 gal in Sporn report.

Table 2

Medium-size Dual-purpose plants

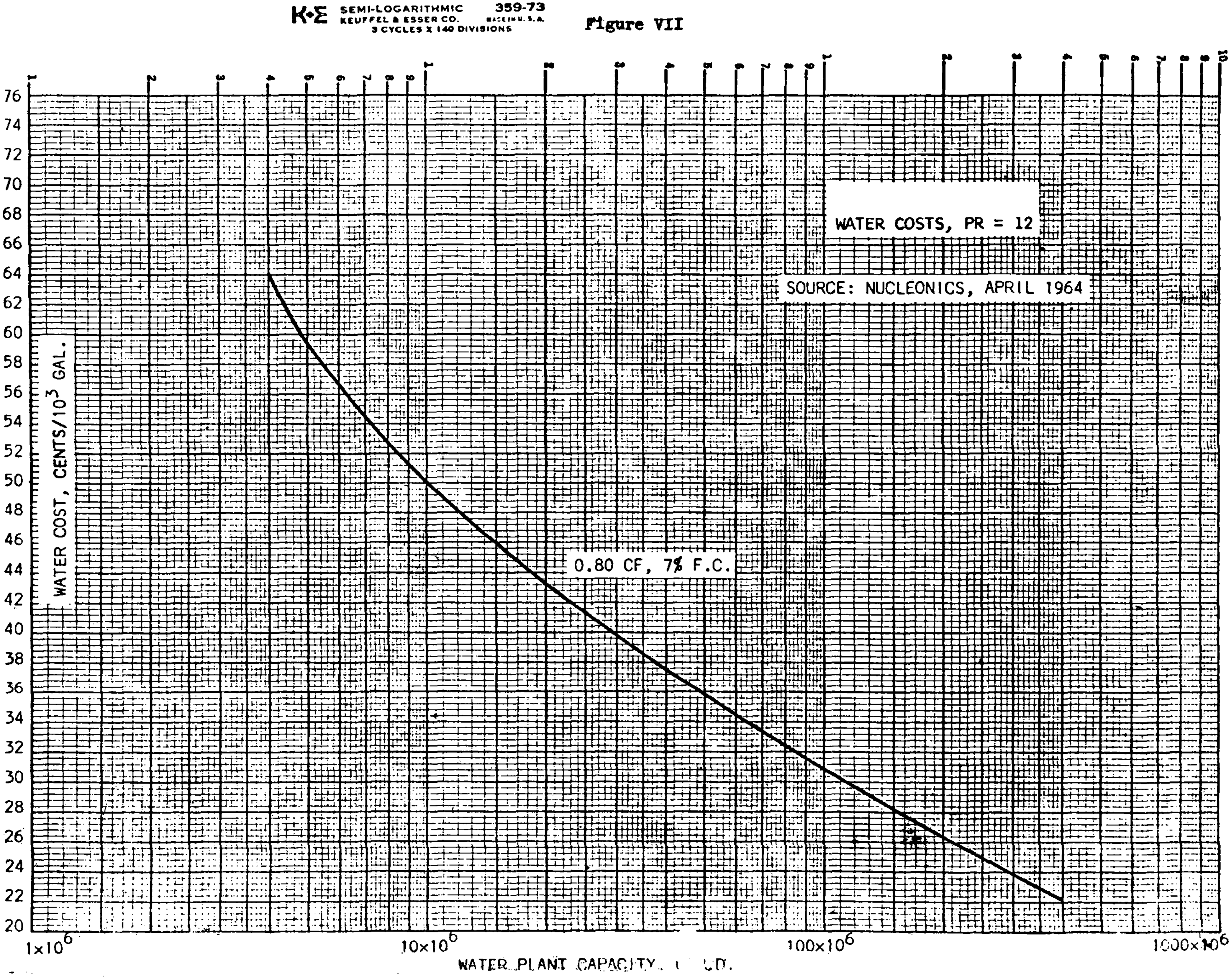
	Fossil Fuel			Nuclear Fuel		
Thermal rating	600 MW	1,000 MW	1,500 MW	600 MW	1,000 MW	1,500 MW
Power plant size, MW	167.5	279	419	100	166	251
Water plant size, 10^6 gal/day	52.5	92.7	156	61.4	91.8	127
Water costs, cents/1,000 gal	34	34.9	36.6	32.7	28.9	26.5

Table 3

Large-size dual-purpose plants

	Fossil		Nuclear	
Thermal rating	1,800 MW	1,500 MW	3,220 MW	8,300 MW (D_2O)
Power plant size, MW	360	180	390	680
Water plant size, 10^6 gal/day	170	170	350	970
Water costs, cents/1,000 gal	38	33	31	26

Figure VII


K·Σ SEMI-LOGARITHMIC 359-73
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 140 DIVISIONS
WATER COSTS, PR = 12
SOURCE: NUCLEONICS, APRIL 1964
0.80 CF, 7% F.C.
WATER COST, CENTS/10^3 GAL.
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
1×10^6
10×10^6
100×10^6
1000×10^6
WATER PLANT CAPACITY, G.P.D.

XVII. COSTS AND COSTING PROCEDURES IN DESALINATION

by J.J.C. Bradbury

It has become apparent during the course of the last few years that a tremendous pressure is being exerted on the water resources of many developing countries, particularly those located in arid or semi-arid regions. In many of these areas further economic progress will not be possible until adequate additional supplies of water become available and, in some instances, failure to provide this additional water may well result in standards of living being reduced below present levels.

This great need to reinforce existing natural water supplies forms the largest problem facing administrators and policy-makers in many developing countries. Fundamentally the solution to this problem is concerned with the basic economic proposition of making the best possible use of scarce resources which have alternative uses. In these circumstances, the chief concern of those responsible for taking the necessary decisions in this field should be that their deliberations are based upon proper economic criteria after careful consideration of the costs associated with various alternatives. The only way in which a realistic choice can be made concerning alternative sources of water supply is to evaluate them by means of a realistic cost appraisal applied to all on a consistent basis.

It will be appreciated, therefore, that any policy-maker charged with deciding between alternative possible water sources should have available to him an adequate costing procedure as a fundamental to his consideration of the problem.

The first advantage accruing from the use of a proper costing procedure is that it will assist in deciding whether desalination itself is a proper solution to the problem of water sources when compared on a consistent basis with other alternatives such as well fields and the long-distance bulk transportation of water which may be available within the particular area.

The second main advantage of proper costing in desalination arises from its use in rate-setting. In many countries of the world it is considered socially desirable for the Government to set water rates at a level which will not penalize the poorer sections of the community and therefore involves a measure of subsidy in so far as the true cost of production is not recovered from consumers. Obviously, it is essential to know the actual cost of water before the proper amount of subsidy can be calculated. There are cases of Governments giving water subsidies which they do not intend because their existing costing procedures are so inadequate that the proper costs of producing water are not brought to light and are not covered adequately by revenue from water sales.

Thirdly, having decided on desalination as the proper source of future increments of water production, it is then necessary to specify which type of desalination system is the most suitable having regard to the conditions peculiar to the proposed location. Physical and technical considerations will have a profound influence in deciding the basic type of plant to be installed. For example, raw water salinity may influence the choice as between evaporation and electrodialysis, since high salinity water, whilst suitable for evaporators, cannot be used economically by electrodialysis plants which require a brackish intake. However, the final design parameters of the chosen system can only be established after considering the estimated costs of production, allowing for all local conditions. Manufacturers of desalination equipment are always prepared to supply estimated operating costs for their plants, but the discerning administrator will be anxious to benefit from others who already possess a similar type of plant and can be expected to know by experience the detailed costs of operation. Unfortunately, the multiplicity of different costing procedures which now exist at various desalination sites throughout the world prevents any useful comparisons being made in many instances. This diversity in costing treatment is one of the most salient points to emerge from the United Nations report on "Water Desalination in Developing Countries", 1/ published in 1964, and was responsible for the formation of the Study Group which was convened at United Nations Headquarters during October 1964 and produced proposals for a costing procedure to apply to water desalination.

A. Factors affecting variations in water costs

Differences in water costs throughout the world do not depend exclusively on different approaches to accounting procedures and the financial principles involved. Other considerations can affect unit costs of production and further extend the difficulties associated with trying to make realistic cost comparisons between different sites. These aspects can be considered under various headings, the most important of which concerns the various technical factors associated with desalination projects.

The basic type of plant installed will have a significant impact upon over-all production costs and plants in operation will need to be segregated into, for example, flash-evaporation, vapour-compression, electrodialysis, freezing and solvent extraction before any useful comparisons can be made. Each of these processes has its own distinctive characteristics which in turn affect the cost of operation. Thus, the total investment for a vapour-compression desalination plant appears to be approximately $260 per cubic metre of daily capacity, whilst multi-flash evaporators have comparable figures in the range of $350 to $500. Of the multi-flash installations detailed in the United Nations report, investment costs in most cases fell broadly within this range with Guernsey and Eilat at the $320 level, Nassau at $420 and Kuwait at $510. The Virgin Islands plant seems to be in a special category in so far as the investment cost of this location is in excess of $1,000 per cubic metre of daily capacity. The freezing system suffers from the disadvantage of having investment costs per unit of output capacity higher than those applicable to the vapour-compression or multi-flash systems. Total investment for an electrodialysis plant is as low as $125 per cubic metre of capacity, but the attraction of this is outweighed by other operational inconveniences.

Apart from the basic principle of operation, costs can be affected by variations in design applicable to individual installations. Thus, the plant installed at the Virgin Islands uses 11 kWh of electricity per cubic metre of output. This is in sharp contrast with the Nassau installation where electricity consumption

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1/ United Nations publication, Sales No.: 64.II.B.5.

is only 1.1 kWH per cubic metre. The reason for this wide divergence is that at the Virgin Islands the yield ratio of sea-water to fresh water is high at 15:1 and this involves a high requirement for water pumping. The figure given for Nassau does not necessarily imply that this plant is particularly economic in water pumping requirements, since for local reasons of power station convenience, it was decided to operate the main sea-water feed pumps by means of steam turbines. This example will illustrate the fallacy of drawing conclusions from installations which are not comparable.

The cost of electricity used for auxiliary power is a significant item in desalination costs, particularly in flash evaporators where considerable quantities of water are pumped by electricity. If the desalination plant is installed in an area having a large inter-connected electricity supply system, then the economies of scale arising from the electricity system will be reflected in the basic price of electricity used for auxiliary power. If, however, the desalination plant is situated in a remote area with only a small electricity supply system, or if the auxiliary power requirements have to be generated at a desalination site, then the cost of electricity will tend to be high.

The method of providing heat to a desalination process can also have a significant effect upon operating costs as between different locations. For example, where separate boilers are installed to provide steam solely for the use of a flash evaporator, the cost of supplying this heat will differ from that applicable to another location where heat is provided from a dual-purpose electricity generation and water production installation. The cost of desalinated water produced in this latter case will be further complicated by the method used for the allocation of joint costs as between electricity and water production.

The question of heat cost illustrates the important effect of geographical influences on the costs of operating desalination plants. Clearly, any plant situated near an abundance of cheap and easily accessible fuel will have a cost advantage when compared with an installation remote from such benefits. Reference has already been made to the way in which the cost of electricity may vary from site to site and this is to a certain extent a reflection of the cost of the available fuel. Thus, it is possible for a desalination project to receive the benefit of cheap fuel through the availability of low-cost electricity for auxiliaries as well as in the form of cheap primary heat. Reference to the United Nations report on water desalination in developing countries shows that fuel cost varies considerably at desalination locations throughout the world. For example, at Eilat in Israel, fuel oil costs $17 per ton, whilst at Kuwait heat for desalination is obtainable free in the form of natural gas. In Malta and Nassau, oil costs $14.00 and $12.80 per ton, respectively, whilst at Qatar the cost is only $2.40 per ton.

Amongst geographical influences must also be included the impact of local geology on the question of foundations with consequent effects on the cost of civil works. Under the heading of geography can also be considered the standard of local workmanship and productivity of labour available to maintain and operate a desalination plant. These may be so bad as to require a considerable expenditure for training or else the maintenance of excess staff.

B. Differences in accounting methods

Quite apart from the various physical and tangible differences in desalination plants which affect costs from area to area throughout the world, variations can also arise due to the differences in accountancy treatment given to the basic information. The most important item under this heading concerns capital charges, particularly depreciation which varies from location to location depending upon what asset life is assumed. As an example of differences which have been found, the evaporating plant in Aruba, Malta and Nassau is depreciated over a twenty-five-year life, the Virgin Islands uses a twenty-year period, whilst at Guernsey and Kuwait depreciation is based on fifteen years. An even shorter life is assumed for the submerged tube evaporators at Kuwait where depreciation is spread over ten years. A further difficulty in assessing the impact of capital charges as between various plants arises from the age of individual installations. Thus, with continued inflation, plants installed ten years ago would have lower investment costs than modern plants and if depreciation is carried on an historical basis, the older plants will tend to have a cost advantage except in so far as this has been nullified by advances in technology.

In view of the considerable investment usually associated with desalination projects the question of interest rates is of great importance in assessing the over-all cost of the resulting product. It is, however, evident from the figures contained in the United Nations survey that at some locations the interest rate used in computing water costs is hypothetical and does not reflect the true local cost of obtaining money. Thus, the Virgin Islands plant is costed on the basis of an assessed 3 1/2 per cent interest, whereas in Nassau the interest rate of 6 1/2 per cent is based upon the actual cost of obtaining a twenty-year loan.

Whilst there are many causes of differences in costs as between desalination plants in different parts of the world, it will be seen that some of these differences arise from the great diversity in approaches which are at present made in the accounting principles involved. In order to obviate the differences arising from this cause, the United Nations has published during 1965 its proposals for a costing procedure for application to water desalination projects. 2/ It is hoped that the application of this procedure will result in a greater measure of uniformity and enable comparisons between water supply sources to be carried out on a much more comparable basis.

C. The United Nations costing procedure

For single purpose plants, the calculations are comparatively simple, the main requirement being to ensure that all proper charges are included in the annual operating costs.

The over-all costs associated with any desalination plant can be considered under the two main headings of fixed and variable costs.

Fixed costs are those expenses which it is necessary to meet regardless of the level of output, whilst variable costs are a function of output and vary

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2/ United Nations, Water Desalination: proposals for a costing procedure and related technical and economic considerations (United Nations publication, Sales No.: 65.II.B.5).

accordingly. The greater part of the fixed costs consists of capital charges arising from interest and depreciation on the total investment involved in the installation. In order to assess capital charges it is necessary to obtain a complete summation of total investment to which is applied the local interest rate and a depreciation rate.

Depreciation is a cost item computed from an assumed plant life to take account in the financial accounts of the wearing out of the asset with the passage of time. Unless adequate provision is made out of revenue to cover depreciation, then capital will be consumed during the operation of the plant and costs will be understated.

There are several different methods of assessing depreciation, each of which accords with good accounting practice. Examples are sinking fund, reducing balance and straight-line methods. Whilst these are all acceptable, it has been suggested in the United Nations costing procedure that in order to achieve some measure of uniformity the sinking fund method should be employed. Under this method a fixed annual amount accumulates at compound interest over the life of the asset to equal the original total investment. There is a proviso that the rate of interest used in the sinking fund should not be higher than the one used in computing the over-all annual cost of capital. In accordance with normal accounting practice no depreciation should be applied to investment in land.

It is also suggested in the costing procedure that to assist comparison, an asset life of twenty-five years should be applied to the whole of the fixed investment in equipment, plus the cost of civil engineering works. Although civil works have a longer life than this period, it is felt that in an installation as specialized as desalination the civil works should be considered as being specific to the plant and, therefore, have no further useful life after the equipment is fully depreciated. It has already been mentioned that interest rates applied vary considerably between desalination sites from 6.8 per cent in Nassau to none at all at Kuwait. A further interesting point arises at Guernsey where $112,000 to meet fixed investment was taken from reserves and not debited with interest charges. The balance of the necessary money was obtained from short-term loans with interest varying between 3-1/2 per cent and 6 per cent.

Energy input into a desalination plant can be derived from heat, electricity or a combination of both. The energy requirements may be obtained from a variety of sources, including coal, gas, oil, nuclear, geothermal and solar energy, and it is essential that any economic comparison between these various sources of energy be made on the basis of heat cost and not upon cost per unit weight where applicable. Electricity cost will vary depending upon whether the requirements are imported from a public supply system or self-generated but regardless of how it is obtained, the cost of electricity should be calculated on a uniform basis.

The following information taken from the United Nations proposals on desalination costing procedures details the items which should be included in the computation of investment and annual operating costs for single-purpose desalination plants.

1. Investment

(1) Preliminary research and project design including feasibility study and initial tests of site and raw water.

(2) Land required to accommodate all the plant and ancillary buildings.

(3) Equipment, storage, supplemental installations and buildings. This will include total erected cost of plant, together with site access roads, drainage, fencing and lighting. All operational buildings and water storage facilities are also included.

(4) Engineering supervision covers the cost of site supervision during the course of the contract.

(5) Interest during construction can be a significant item if construction extends over a lengthy period. The total cost of this item is capitalized using the local cost of money applicable at the time of construction.

(6) Performance testing is normally allowed for by the contractor in his contract price but, where commissioning is carried out using local labour and facilities, this cost of bringing plant to its rated output should be capitalized.

(7) It is usual to include an item for miscellaneous contingencies covering various extra works, unforeseen difficulties and delays which may arise from the late delivery of equipment.

The foregoing items together constitute the total investment associated with the purchase, erection and commissioning of a desalination plant.

2. Annual operating costs

The annual operating costs for a desalination installation can be divided into fixed costs, which are independent of output, and variable costs, which fluctuate as a function of water production.

3. Fixed costs

In view of the large amount of capital usually invested in a sea-water desalination plant, one of the most important fixed costs is that arising from depreciation. Depreciation is calculated on the total value of the fixed investment and, as previously mentioned, this should be based on a sinking fund using the local rate of interest at the plant site. Insurances will be needed to safeguard the capital investment against normal hazards of nature, and also such special hazards as are deemed necessary from the nature of the desalination process.

The continuous operation of a desalination installation will involve expenditure on salaries and wages for supervisory staff, together with certain items of consumable stores. Since these expenses are independent of plant output they are properly allocable to fixed costs.

With regard to direct maintenance costs associated with desalination plants, these will fluctuate according to whether the plants are in normal operation or undergoing overhaul. It is considered, however, that since repair and maintenance staffs must be retained on a continuous basis these expenses should be regarded as fixed in nature. Normally, the most convenient method of dealing with maintenance and repair materials is to regard them as fixed costs, but there are two exceptions in tubing for flash evaporators and membranes used in electrodialysis. It may be necessary with these two items to incur especially heavy expenses for periodic replacements. If these replacements are charged to repairs and maintenance as they occur wide cyclic fluctuations will be caused in water production costs. It is therefore suggested that to obviate these fluctuations a fixed percentage of total investment is set aside to cover these replacements.

Where the plant site has been rented rather than purchased the payments on this account should be shown under the heading of fixed costs.

4. Variable costs

Certain items of expense are proportional to the output of a desalination plant and will vary with production. Of these the most important costs are associated with energy requirements, chemicals and raw materials. The multiplicity of energy sources and variation in costs has already been mentioned. Chemicals are those associated with the pre-treatment of raw water in the evaporative and flashing processes and also chlorination used to control algae growth in raw water.

Having obtained the total annual fixed and variable costs of operation and knowing the effective annual water output, it is comparatively simple to calculate the average cost of product per 1,000 gallons.

D. Dual-purpose desalination plants

In any consideration of the costs associated with dual-purpose desalination plants the main purpose continues to be the inclusion of all the fixed and variable costs. However, in this instance, the greatest problem arises from the need to allocate these costs on an equitable basis between the resulting products of water and electricity. Complications arise from the fact that certain items of expenditure are common to both products and that water production obtains its heat from steam which has already made its contribution to electricity generation.

In a normal conventional power station using steam turbines, the steam after having performed its mechanical work across the turbine blades is exhausted to a condenser at low vacuum and there condensed to water. During this process of condensation, the latent heat in the steam is given up to the condenser cooling water and discharged to waste. Approximately three quarters of the total heat entering the power station as fuel is lost through this wastage.

The availability of such a large quantity of latent heat from a steam turbine has been the main cause of the various dual-purpose electricity and water production schemes which have been put forward up to the present time. However, it should be borne in mind that dual-purpose designs usually require steam to be exhausted from the turbine at a pressure in excess of that found in the condenser of a conventional plant and this places a cost burden upon electricity production.

Several proposals have been advanced for the allocation of total costs between water and electricity based upon the usage of heat by each product. At one extreme, water production can be debited with the whole of the turbine exhaust heat content, thus removing the normal condenser loss from the turbine. This arrangement results in a very high thermal efficiency for the turbine with corresponding low electricity costs. Water production then carries a heavy burden of heat costs and is clearly approaching the same position as a single-purpose plant being debited with its total requirement of latent heat. This system can be adopted to allocate the total joint expenses between water and electricity in the ratio in which they utilize the initial heat in the steam leaving the boiler. The resultant over-all cost position would be heavily biased against water and in favour of electricity.

A further proposal which has been put forward is to split the exhaust heat equally between electricity and water and divide joint costs in the same proportion. So far as heat is concerned, this will give an advantage to electricity production over a conventional system, but there is little justification for assuming that the total fixed variable costs of operation will divide in this proportion.

The method adopted in Nassau for costing water and electricity production from a dual-purpose plant is to compare the dual-purpose costs with those which would have been associated with a conventional electricity generating plant.

To obtain the investment cost applicable to water production an estimate is made of the total investment associated with a conventional power station having the same net electrical output as the dual system. The difference between this estimate and the actual investment required for the complete dual-purpose installation is then taken as the extra investment required to produce water. With regard to operating costs, the same principle is applied of charging water production with the extra cost above that which would have been associated with a conventional power station of the same net electrical output. The heat consumed by water production is calculated by assessing electricity production at the thermal efficiency which would apply to a conventional turbine generator of the same size and using the same steam conditions. Using this efficiency and knowing the electrical output, the heat consumption of the turbine can be calculated, the balance of heat used being debited to water production.

This method of calculation involves the use of only one set of hypothetical figures, these being in respect of the equivalent conventional power station. The disadvantage of having to refer to the costs of a hypothetical station is alleviated to a certain extent by the fact that the technology of the small machines usually involved is so well established that realistic estimates based upon much past experience are comparatively easy to obtain. Under this system water is regarded by a by-product and its cost appears as a residual.

Mr. Joseph Barnea, in a contribution contained in the United Nations costing procedure proposals, has suggested a further method of allocating costs in a dual-purpose electricity and desalination system. This method uses the net annual marketable output of water and electricity associated with the dual-purpose plant to calculate the size and investment required for single-purpose power and water plants of the most economic design operating under the same load factor as the dual plant. Using this basic data, the total annual costs of the separate equivalent single-purpose power and water plants are estimated. The summation of these two figures gives the total annual cost of producing in two single plants the same net marketable quantities of electricity and water as will be derived from the dual-purpose plant. Having obtained the total combined cost of both single-purpose plants it is comparatively simple to calculate the percentage of this total formed by the separate single-purpose water and power installation costs. These percentages are then applied to the annual costs of the dual-purpose plant as a means of allocating these to water and power production. Basically, this system applies the annual cost relationship for two single-purpose plants to the allocation of costs in a dual plant having the same net marketable output of both water and power as do the two single-purpose plants.

The necessary calculations may be repeated at intervals of, say, five years to ensure that the division of costs as between water and electricity production continues to bear the proper relationship to the advances made in the separate technologies of production.

Due to the existing state of technology, it may become necessary to adopt a completely different plant type when estimating the single-purpose costs for comparison purposes. Thus, the most economic single-purpose method of producing electricity may be by means of diesel engines, whereas a dual-purpose desalination plant would require the installation of steam turbines. Similarly, to obtain economies of scale, the size of alternative single-purpose electricity generating equipment may well be much larger than what is technically necessary for a dual-purpose operation.

The main advantages of using the Barnea proposals are:

(1) In the planning stages of a project the method will confirm that in the prevailing circumstances a dual-purpose plant would be more economic than two separate plants.

(2) The allocation of costs between the products is on a basis of alternative costs and not on arbitrary allocations using heat values and other physical data.

(3) Using this method, comparisons can be made at any time between different plants showing the net effects on product costs of any advances made in the technology of water and power production.

(4) The calculation of the base load penalty is facilitated.

In an interconnected power system, the normal method of operation is to operate the generators with the cheapest fuel cost on base load. A more expensive plant is then loaded strictly in merit order of fuel cost, the most expensive being reserved for peaking operation only, at low load factors. If a steam turbine associated with a desalination plant has low incremental fuel costs, it will normally run on base load for electricity production and no extra costs will arise by virtue of its water-producing activities. However, if a conventional generating plant with lower fuel costs is installed on the supply system, then the necessity of giving the electricity base load to a turbine associated with desalination will involve an expense to electricity production arising from fuel cost savings which are forgone by the under-utilization of the cheaper generators.

The main disadvantage of the alternative cost method is that it is based upon hypothetical figures in respect of both single-purpose water and electricity plants. The estimates for a single-purpose water plant may not be very reliable since there are not many of these installations in operation and past experience is limited.

A further point to be considered is that the system will be somewhat inadequate in reflecting variations in costs which occur over short-term periods. Although most of the annual costs tend to be fixed in nature, heat consumption will vary with the thermal efficiency of plant performance. Past experience shows that an evaporating plant even with chemical dosing of raw water is liable to scale accumulation resulting in eventual cleaning. Inevitably, heat consumption will rise as scale accumulates, causing costs to rise over a cleaning cycle, the duration of which will vary with plant design characteristics and location. The point is covered in the Nassau installation by comparing the desalination plant heat consumption each month with the heat which would have been used by a single-purpose generator for the same electricity output.

Whilst the basic principles of desalination technology must apply all over the world, it is possible to vary individual designs to make allowance for the particular economic conditions applying at particular sites. In view of the comparatively large investment usually associated with these installations, the rate of interest assumes great importance in the economics of operation. In a country having a high rate of interest but a relatively low cost of fuel, it might be economically advantageous to save capital by reducing evaporator-gain ratio. This would increase the plant's consumption of heat and lower the thermal efficiency but, with an abundance of cheap fuel, this may be considered an acceptable method of saving scarce capital. It is possible to envisage the opposite set of circumstances where a country having an abundance of cheap capital but high fuel costs builds evaporators with high gain ratios and high fuel economies at the expense of incurring additional capital expenditure.

The prevailing interest rate will also have a profound effect on the amount of pre-building which can be contemplated when a plant is constructed initially. However, in the case of a dual-purpose desalination installation the degree of permissible pre-building will also depend upon other technical factors. The most salient technical consideration arises from the fact that the outputs of water and electricity in a dual-purpose plant are in a fixed proportion. It is, for example, not possible to increase the output of water without there being a demand for electricity available at the right level. Thus, if 5,000 cubic metres of water per day can be obtained from a base electrical load of 6,000 kW, 10,000 cubic metres per day will not be available until the electricity base load has risen to 12,000 kW. It is, therefore, clear that a decision to carry out pre-building cannot rest on economic considerations alone but must be made after a careful analysis of the separate growth rates for water and electricity to ensure that both are compatible with the outputs proposed for the additional installation.

Much attention is being given at present to the possibility of combining desalination plants with nuclear-fired power stations, and economic advantages are being claimed for this combination. In the present state of technology nuclear-fired boilers are limited to comparatively low steam conditions compared with those being attained in advanced designs of conventionally-fired plants. These low steam conditions result in low turbine efficiencies. Consequently, a relatively greater amount of waste heat is dumped to the condenser of a nuclear-powered turbo-generator than to the condenser of a conventional machine of comparable electrical output. This greater availability of waste heat means that, all else being equal, more waste heat per unit of electrical output can be obtained from a distillation plant associated with a nuclear power station than from a fossil-fuel fired generating plant. In these circumstances it may be possible for the addition of a water desalination plant to lower the costs of nuclear power generation sufficiently to make the construction of a nuclear power station economically justified.

The combination of desalination and nuclear power plants is not, however, without its disadvantages. The chief of these disadvantages is that the desalination installation located adjacent to the nuclear station must suffer from the isolation which may be imposed by an exclusion area. This in turn will have an adverse effect on water costs by increasing the transmission expenses associated with the provision of longer pipelines and increased pumping requirements.

The operating and maintenance staff requirements for a dual-purpose nuclear and water installation will be particularly exacting in view of the present specialized nature of nuclear technology. There are probably few countries whose level of technical education would allow a nuclear installation to be staffed by local technicians. These would seem to require the importation of foreign staff, particularly in developing countries, and it can, therefore, be reasonably anticipated that, initially, supervisory costs may be high.

The foregoing has attempted to illustrate the many differences in production costs found at desalination sites throughout the world and to give some reasons as to why these exist at present. There is no doubt that the adoption by all desalination users of a standard costing procedure as recommended by the United Nations would make results somewhat more comparable. Although local costs for the purpose of comparison can be expressed in terms of dollars, differences in the purchasing power of each currency will tend to nullify accurate comparisons. Despite this limitation it is hoped that more attention given to the aspect of desalination costing will result in policy decisions concerning water supply sources being based, in future, on more substantial economic foundations than have been used in some instances in the past.

XVIII. THE PRICING OF WATER, WITH SPECIAL REFERENCE TO DESALINATED WATER

by J. Barnea

A. The characteristics of water

Water is for the economist the most difficult commodity to handle and in many respects a unique commodity - and that perhaps not only for the economist.

Pure water is colourless, odourless and tasteless; in general, water has no uniform shape, since it can assume the form of a solid, liquid or vapour, has no typical cost of production, since it may be free or an expensive commodity, has no typical temperature, and, in its natural occurrences, has a large variety of quality characteristics. The usefulness of water depends on its elevation (for hydropower or gravity flow), its temperature, its quality, its quantity (for example, for navigation), its location, its seasonal availability, its ownership characteristics and its cost. Water may be available as a flow or as a store; water can be derived as meteoric water from the hydrological cycle or it can be juvenile water from the interior of the earth, a source of water of which we know, so far, very little.

In the case of water, which in this respect is like air and unlike most other natural resources, the natural resource and the resource product are identical. 1/ Water is used for far more purposes than any other commodity, even air, whose many purposes include those for human and animal needs, for cooling, for the production of chemicals and for air transport. The amount of water handled, whether measured by volume or weight, is greater, in any economy, than the amount of any other product, and it is also the only commodity in which public organization and public management predominate.

Water conditions vary widely from one part of the globe to another, from one country to another, and even, in many cases, from one region of a country to another. There are areas with too much water where the control of floods is the main problem and there are, of course, areas with insufficient water where the shortage of water is the main obstacle to economic development. We can therefore say that water with its numerous variations in physical, legal, economic and other aspects is a commodity concerning which it is extremely difficult to make generalizations. Detailed knowledge of given conditions in an area is imperative before advice on any aspect of water resources development can be rendered.

B. The cost of water

Before we discuss prices and pricing it is essential to understand the considerable variations in water cost. Water cost in itself may have different meanings, and it may be useful to distinguish between six different main categories of water costs.

1/ In the case of food, for instance, land is the resource and food is the resource product.

The first category is the cost of water at source. We would define this as the cost of water in store or in flow as nature has provided it. This may be rain in the field, spring water, river water or natural storage in a lake. As no investments are or have been involved, such water has not had a cost and should be a free commodity. However, where water rights have been established, these water sources have a price, assuming that the owner of this type of water sells or is willing to sell some of it, and we therefore have a case of water which has no cost but has a price.

The second category of water from the point of view of cost may be called a developed water source. This may include ground water made available through wells, river water stored in large artificial reservoirs, etc. Obviously, this type of water has a cost and, if it is sold, will also have a price. However, where such water is developed by the final consumer for his own use such as, for instance, ground water being developed by an industrial enterprise for its own use or by a farmer for his own use, such water will have a cost but no price.

The above classification of water costs refers basically to one source of water. However, in many municipal systems as well as in other water systems and even in the case of some individual water suppliers, the water is not derived from one source but from several. The water being derived from different sources, each with its own peculiar cost structure, results in a water-mix for which the water cost can be calculated. Therefore, a third category of water cost is the cost of a water-mix.

The fourth category of water cost might be called the delivered cost of water, a term which should include components for transportation and/or distribution. Depending on local conditions, these components for transportation and distribution may be considerable. Such delivered water supplies are usually available to purchasers or free of charge from public fountains. In a few cases, too, private enterprises transport water over long distances for their own use - for example, some mining companies in northern Chile obtain water supplies by pipeline from the Andes.

There is also treated water, and, thus the cost of treated water. However, treated water is not a distinct category since water from a given source may be of such superior quality that it needs no treatment (for example, mountain spring water), or it may be used for a purpose which requires no treatment (such as irrigation, fire fighting, flushing of toilets, cooling in power stations, etc.). However, as a rule, water used for human consumption and for food and pharmaceutical industries must be treated.

For the purpose of this lecture it may be appropriate to add still another category of water cost, namely, the cost of desalinated water. All desalinated water has a cost. Moreover, desalinated water frequently has at least two other distinguishing characteristics, namely, (i) a desalinated source of water is not subject to limitations as regards reserves and seasonal supply and (ii) desalinated water is not subject to historical restraints in respect of water rights.

Corresponding to these six categories of water costs, one should properly distinguish six types of water prices. However, actual water prices as a rule bear little relation to the cost of the water. For this reason no water price statistics are given in this paper.

C. Pricing systems

Before we describe any pricing system, we should have a clear understanding of what we mean by a water price and water pricing. Normally, a price is defined as the amount of money paid for a commodity in a market. Thus, theoretical demand and supply determine price. However, there are many types of prices, such as free market prices, controlled prices, managed prices, administered prices, official prices, etc. Each has its specific meaning and each refers in general to a specific commodity with a given quality standard.

In the case of water the term "price" will have a far less precise meaning because there is normally no market in which demand and supply determine a price. To some extent, water pricing is similar to the pricing of electricity, natural gas, telephone services, and other public services whose nature precludes the existence of numerous, competing suppliers, but instead makes for one monopolistic supplier. These are customarily called "rates" rather than "prices" and the rates are usually a type of tariff which the monopolistic supplier establishes with the concurrence of a public body which controls and supervises the rate-making. But in the case of water, most water-supply systems are municipally and governmentally owned, and not subject to public-utility control. Where "water rates" exist, they usually represent something completely different from electricity or telephone rates. Furthermore, many sources of water are privately owned, and end-use is sometimes determined through water rights. It is thus difficult to apply the term "rates" in the case of water, and, in the absence of a better term, we might retain the expression "price", stressing, however, that the term does not correspond to its meaning as applied to most other commodities.

Water price may be defined as the price paid by the end-users for a certain quantity of water or for a supply of water with the quantity left undetermined within certain limits (unmetred supply). The payment can either be a direct payment or an indirect payment through taxes. Correspondingly, water pricing may be defined as the totality of considerations and policies applied by the supplier in respect of the money to be collected (or not to be collected) from the water consumer.

There exist numerous water-price systems, of which the following are some:

(1) Water supplied to the consumer free of charge, such as that at public fountains, free water for fire fighting, hospitals and other public purposes, and free water supplies for mining camps, company housing schemes, etc.

(2) Unmetred supply of water to households (in some cases the unmetred supply is limited by the size of the water pipe reaching the house). Such unmetred supply is paid for either by general municipal taxes or by specific water taxes.

(3) Water paid for at a uniform price per unit of water.

(4) Water supplied at a price per unit but with price reductions for the purchase of increased quantities of water.

(5) Water supplied at a price per unit with increasing prices for larger quantities used by the same consumer.

(6) Water prices varying according to the type of consumer, such as low-cost water for agriculture and higher-cost water for industry.

(7) Water priced by quality.

(8) Water priced by quality and quantity.

(9) Combinations of the above, such as providing a certain minimum quantity of water free of charge with prices rising for increased quantities, etc.

This paper need not elaborate on the numerous pricing systems which are found all over the world. Many of the systems clearly have shortcomings of which some may be the result of historical or political conditions and some may not be of great economic significance. The economic validity of a pricing system can, of course, be judged only within the context of its local conditions, and that is the reason why we regard the factors and philosophy in pricing as more important than the actual pricing system.

D. Factors determining pricing

There are two basic categories of factors in water pricing which experience has shown to be of significance: (1) the cost and policy factors; and (2) the type of supply organization.

1. The cost and policy factors

Obviously, water prices in potentially water-short areas should fully cover water costs, and comprehensive water pricing is the best means of preventing water waste. 2/ The cost factors to be considered and taken into account in water pricing should include the following: the cost and location of the source of water; the cost of transportation and distribution; the cost of treatment, where necessary; the cost of the water-mix, where applicable; the seasonal characteristics of the water supply; the water demand and its seasonal variations; and, for a long-term water policy, the reserve of fresh or brackish water. Thus, from a long-term point of view it may be advisable to over-price water and allow the water-supply organization a considerable profit, not only because such profits would be available for further investments in water supply but, more importantly, because in most countries low-cost sources of water are exploited first while the steady increase in demand necessitates the development of higher-cost water sources at increasing cost over the long term.

As soon as the price of water begins to rise, it becomes possible for a water-supply system to absorb higher-cost water supplies without giving rise to objections on the part of consumers. A municipality or governmental authority should take into account a number of factors when framing a water-pricing policy, factors of which some are not customarily taken into account by a private water supplier: the ability of the consumer to pay for the water; the effect of the water supply on the potential growth of the economy; and the desirability, from the economic point of view, of discouraging the use of water for the wrong purposes.

2/ Wastage may lead to the necessity for developing additional, higher-cost sources of supply, and this, in turn, would lead to higher water costs for all consumers.

To elaborate further on some of these factors, the policy adopted in the allocation - and reallocation - of water may be based on any one or several considerations: (a) the ability of consumers to pay; (b) the income effect in the use of water for a particular purpose - that is, the return in using a given quantity of water; (c) the employment effect; and (d) the foreign-exchange-earnings effect. The income- and employment-effect bases usually favour industry and tourism at the expense of irrigation, since the two former uses are likely to result in a higher income return and employment effect than does the latter.

In any case, the question of allocation of water arises primarily in areas or countries suffering from inadequate water supplies for actual or potential requirements, and is a very complicated one politically and administratively.

While there have been many advocates of the reallocation of water - particularly on the basis of income return - such reallocation on a substantial scale and as a consistent policy has not, as far as is known, been adopted by any government so far, and remains only a subject of discussion among economists. However, in the case of a few of the countries suffering from water shortages, industrial users have been known to buy out the irrigation rights of individual farmers, and, in such cases, we may say that the market has taken over the reallocation of water.

In formulating its allocation system, a water-supply and water-pricing authority will have to consider the particular situation. In a certain type of situation, a water authority may find it best either to do nothing about allocating low-cost water or to allocate low-cost water to irrigation and other purposes whose consumers are unable to pay a high price and, at the same time, to allocate high-cost water to consumers who can pay a higher tariff. While this system may still permit covering water costs, it may involve far greater investments than a system of allocation based on the economic effectiveness of water use for particular purposes. This will be the case where heavy additional investments in new water-supply facilities are required to implement such allocation. On the other hand, if the irrigation is for the production of food which would otherwise have to be imported, the encouragement of water use for irrigation will result in a saving of foreign exchange. The soundness of this system will depend also on the effect of higher-priced water on the cost and competitive position of the industries consuming the water. If the additional investments referred to do not unduly affect - through the rise in water prices they would necessitate - the position of these industries - this would be the case, for example, of a petroleum industry or some other industry based on good natural resources, such as a tourist industry - this fact combined with some of the other advantages of the allocation system may make the system the best over-all economic solution. 3/

3/ There remains the difficult question of the opportunity cost of the additional investments that might be needed where water is allocated by ability of the consumer to pay. One way of measuring the opportunity costs would be to compare the foreign-exchange earning capacity of such additional investments if invested in fields other than water development with the foreign-exchange earnings of the water used in agriculture. One would also have to consider the cost of dislocation if the low-cost water were to be withdrawn from agriculture.

There exists one particularly difficult situation which does not lend itself to allocation of water on the basis of ability of consumers to pay. This is the situation obtaining in those inland areas which have strictly limited fresh-water sources, no means of obtaining additional high-cost fresh-water supplies, and which lack a saline-water body that could be used as a source of desalinated water. In such areas where there is a given and fixed quantity of water, the allocation of water measured by its economic effectiveness appears to be the only sound basis for a long-term governmental policy.

2. The type of supply organization

The other general factor determining pricing is the type of supply organization that is dealing with the water. Four types of organization may be distinguished: (a) individual systems; (b) commercial systems; (c) municipal systems; and (d) governmental systems.

(a) Individual systems

An individual system is a system wherein a water consumer supplies his own water. This may be a farmer using his own ground water or service, or a hotel possessing its own distillation plant, or a large industrial enterprise producing its own desalinated water either in a separate plant or by using surplus steam from its industrial operation. It is obvious that an individual system is normally the best solution to the water-supply problem from the point of view of the individual consumer and frequently, but not always, from the point of view of the area or country as a whole.

As self-suppliers of water will always try to keep their costs at a minimum and as they normally have to provide themselves for financing, maintenance and operation, self-supply systems in a modern economy are well handled. Numerous cases exist of industrial enterprises supplying their own water and where they do not conflict with the common interest it may be advisable for the water authority to avoid interfering with them. It should be noted that the self-supplying of water exists under all economic systems. Desalination will frequently allow industrial enterprises or mining enterprises, tourist hotels, port administrations, and many other commercial enterprises to develop their own water supply without harming the common interest. It may therefore be advisable in many locations to avoid bureaucratic control of such self-suppliers. In particular, control is not necessary where private interests want to undertake the desalination of sea water, since even in a water-short area one user of the sea water along a country's coastline is scarcely likely to conflict with or restrict the supplies of a second user of sea water. If this statement sounds too obvious, let it be said that government officials in some water-short areas whose water supplies have had to be controlled by government have been known to extend this philosophy to the desalination of sea water. Indeed, a case in point was encountered by the present author in a country with a very long sea coast. 4/

4/ As a matter of analogy, it may be noted that the self-supply of electricity is normally permitted even in countries where the sale of electricity is a government monopoly.

(b) Commercial systems

A commercial water-supply system is one wherein private companies develop and/or sell water supplies. Such companies are relatively rare and tend to be discontinued in water-short areas where the water supply has become a matter for public concern. There are a few countries in which commercial water-supply companies operate very successfully and, in some of them, the pricing of these companies is subject to public control as well as, in some cases, to court review. It is obvious that where commercial enterprises sell water for domestic purposes, a public interest is involved and not only the price of water, but reliability in supply and quality and non-discrimination in supply are matters for public concern.

Since profit in a commercial system is essential (if a company is not to go bankrupt), the pricing of water by a private company must be such as to cover all costs. But it is equally desirable that private companies should not be permitted grossly to overcharge. Instances of gross overcharge of customers by small water companies operating without any governmental control in several less-developed countries have been known to exist. In a few cases private companies marketing desalinated water in areas lacking high-quality water have also been known to overcharge for water.

It is possible that with the advent of desalination and its heavy capital requirements new commercial water-supply organizations may come into being. In some countries it may prove easier for commercial interests rather than municipalities or Governments to raise the heavy capital requirements involved in desalination, to attract technicians, and to operate the plants efficiently. In some cases, it may develop that desalinated water may be used in conjunction with electricity, and that an electricity company will undertake the marketing of desalinated water. Depending on the local circumstances, commercial sale of desalinated water may prove desirable. However, it will then become necessary to develop a public-utility control system as a governmental function in order to ensure that suppliers of water, despite their monopoly position, establish a fair price, reliability in supply, and non-discrimination in their treatment of consumers.

(c) Municipal systems

Municipal water-supply systems are among the oldest water-supply systems in existence, and in many countries water supply is regarded as a municipal function. Unfortunately, the pricing of water in a municipal water system is, as a rule, part of municipal politics, with the result that pricing is handled within a municipal tax system. Consequently, the price of water frequently fails fully to cover costs and in many instances no proper cost data for such a municipal water-supply system are available. The opposite case also exists wherein very cheap water is in fact available, but the municipality sets extremely high water prices so as to use water revenue to finance other municipal services.

As a rule, the operation, efficiency in planning, and maintenance of municipal water-supply systems are not subject to control by any external body but only to political control by the municipality. As a result, comparatively few municipal systems are very efficient, and the pricing of water in a municipal system is more a matter of municipal policy than of ensuring a well-run public or private enterprise.

Municipally-owned electricity-supply systems are now gradually disappearing, and it is to be hoped that municipal water-supply systems will similarly be curtailed, at least in water-short areas, although in many cases municipalities will retain water-distribution facilities.

(d) Governmental systems

In some countries, we see that public authorities are gradually stepping in and taking over the functions of water-resources development at all stages. This is noticeable, for instance, in California and in Israel as well as in a few other places. As a rule, water-resources development and supply on a nation-wide basis is undertaken by Governments only reluctantly and only where these functions cannot any longer be handled on a village, municipal or area basis. Where the Government becomes the supplier of water, the possibility arises of developing a water-grid system similar to an electricity-grid system. A grid system provides economies of scale, increased reliability (a water supply ceases to depend only on one source), and the economies of a water-mix whereby water with different cost characteristics and, to some extent, different quality characteristics can be fitted into the mix. 5/ The pricing of water in governmental systems is entirely bound up with government policy, including the problem of water allocation, which was discussed earlier.

Governments can and frequently do subsidize water so that water prices are below water costs. The degree of subsidization depends on the quantity of water to be subsidized and on the financial ability of a government to bear such subsidy. Obviously, a rich country with a sizable governmental budget can more easily afford to subsidize water than can a poor country. In other words, government finances determine the degree and amount of subsidies which a country can afford.

However, there are two further remarks to be made regarding governmental supply systems. A system which subsidizes water in water-short areas finds it difficult to increase its supply because additional supplies will usually be obtainable only at higher cost and will lead to a sharp increase in water subsidies unless the policy of water subsidization is curtailed in favour of higher prices for water. While a government is and should be free to decide whether or not to subsidize water, the cost of water should be known so that the authorities might determine how much subsidizing of water will cost. It cannot be stressed enough that the proper costing of water in government systems is a pre-condition for efficient government pricing and/or subsidization policy.

E. Desalinated water pricing

Desalinated water possesses a number of characteristics distinguishing it from natural water.

(1) All desalinated water has a cost, usually a high cost.

5/ However, under difficult topographical conditions, a country-wide water grid may not be feasible.

(2) Desalination plants based on an unlimited supply of saline water (such as those on the sea-shore) are capable of producing fresh water in unlimited quantities, subject only to the plant's desalination capacity, whereas all natural sources of water have a limited size.

(3) There is no seasonal or annual variation in the availability of desalinated water, whereas all natural sources of water are subject to variations in supply.

(4) The cost structure of desalinated water involves a high element of equipment cost and energy input, which means that, where a country has to import equipment and energy, desalinated water is foreign-exchange intensive.

(5) Desalinated water supply is not burdened by historical water rights, and the marketing of desalinated water therefore is feasible in every conceivable form.

In view of these characteristics of desalinated water, it may be useful to distinguish two main groups of desalination systems: (i) A system in which desalinated water is the only or main source of supply. This is a system in which the above characteristics would be fully applicable. (ii) A water-supply system in which desalinated water is of minor importance to a system water-mix. In this second case the water pricing will have to follow the principles we discussed earlier.

Let us now consider the water-supply system which exclusively or mainly consists of desalinated water. In such a system it may be appropriate from an economic and financial point of view to apply pricing systems as they are applied in an electricity system, namely, lower prices for a base-load demand and higher prices for a peak demand. Since, by definition, provided all other factors are equal, desalinated water capacity can be expanded, and, since cost will fall as output rises, it is obvious that the large-scale consumer will be a better customer for a desalinated-water supply than the small-scale consumer, and the base-load consumer will be a preferred customer as compared to the peak-load customer. This type of approach would be the pure commercial approach to desalinated water pricing, and from a purely economic point of view it appears to be the best approach available. However, there are, and there will be, in many specific circumstances economic or social restraints which will require a modification of the commercial approach to desalination.

In countries short of foreign exchange and short of energy, an expansion of desalination capacity will lead to higher foreign-exchange requirements, and detailed calculations will be necessary to determine whether the expansion of desalination capacity and the resulting foreign-exchange requiremenns have the same degree of over-all priority in the allocation of foreign exchange as the needs of foreign exchange for other essential purposes in the country concerned. As a rule, it will be found that high-cost pricing of desalinated water will discourage waste and that, if an expansion of demand nevertheless occurs, it may be derived from customers who, because of their successful economic operation, can afford an increased consumption of such water. If such a demand is derived from industries, mines, tourist industries and similar economic entities, it may well be that, in the last analysis, the consumption of desalinated water by such customers may raise the foreign-exchange capacity of the country concerned. However, if the bulk of desalinated water in a country which is short of foreign exchange and is an importer of energy is purchased for domestic purposes, then an expansion of desalinating capacity may lead to further foreign-exchange requirements, and may have to be discouraged. It may therefore be desirable, in such circumstances, since the actual rationing of water is unfeasible, to discourage a growth in demand for desalinated water by residential users by introducing very high prices.

Countries which are exporters of petroleum or other forms of energy can usually disregard foreign-exchange considerations in the pricing of desalinated water.

In countries where there is an absolute shortage of water and the quantity of fresh water available to the population is below the acceptable minimum for health and sanitation, a pricing policy must be so designed as to supply the necessary minimum quantity at prices within the purchasing power of the population. This may require a complicated pricing system with increasing prices for increasing demands until a level is reached where the price covers the cost of desalinated water, or prices will have to be so calculated as to ensure that the total return fully covers costs. Where this is not possible, subsidies by municipalities or governments will become necessary.

It is essential for any pricing policy of a desalination plant to keep careful and proper accounts of all costs, including amortization and interest, so that a desalination system once established can itself generate the necessary funds for the renewal of equipment and for proper maintenance.

The necessity of proper costing and proper accounts is very much greater in the case of desalination than in other forms of water supply. This implies the need, on the part of management, to ensure the employment of properly-trained manpower, so that a desalination system may be able to maintain its technical capability and its reliability of supply, particularly where desalinated water is the community's chief or only source of water supplies.

F. The philosophy of water pricing

In the field of water supply one frequently hears that water supply is a social or community function and that water should be supplied free of charge in unlimited quantities to all consumers. This philosophy, held most frequently by municipalities, both in industrial and less-developed countries, is acceptable on practical grounds only in areas where low-cost water in large quantities is available, but is questionable, both in principle as well as on practical grounds, in areas where low-cost water is limited. It is true that a community has a commitment to see to it that the minimum requirements for potable water are available to all consumers, just as a community nowadays feels it is its duty to prevent starvation among its citizens. It cannot, however, be said that everyone should get food or, by analogy, water free of charge or that everyone should consume the same amount of food or water. In other words, a social need may be a justification for a limited action in respect of the supply of a minimum quantity, but it cannot be the over-all guideline for a commodity supply system. Water supply has frequently been compared to road construction, implying that, as roads are open to all users, water should be freely available to all consumers. This comparison is wrong because in the case of water we deal with a commodity whose increased quantitative use leads to increased consumption and additional costs, possibly including wastage, whereas a road is a service facility where wastage of its capital investment can only be brought about by its non-use.

It is essential, therefore, to distinguish between the economics of a water-supply system and the communal function of guaranteeing to the poorest section of the population a minimum potable water supply at prices they can afford to pay.

With the advent of desalination, which means high-cost water, the social function in water supply should not be eliminated, but it should be defined and limited as regards its proper social aspects. For this, two conditions should be laid down where desalinated water is used: (1) all water supplies should be metered; and (2) the quantities supplied at a reduced price should be limited to the minimum required by health considerations and by the poorest section of the population.

If this approach is followed, it will normally be found that social considerations apply only to a limited share of a desalination supply while normal commercial considerations are applicable for the major bulk of the water supply.

The philosophy of water pricing, however, does not relate only to social aspects. The more important element it must embrace is the recognition that water and electricity are the two basic factors for the growth of a modern economy and for industrialization. We know today that electrification very often needs government support through priorities in the allocation of finance where private capital is not available or where it is the government's policy to supply electricity as a governmental function. However, the view is now well established that, whoever is the owner of an electricity system, the system as a whole has to be operated on commercial lines and must be thoroughly forward-looking to ensure that economic growth is not impeded by shortages of electricity. By analogy, it should be the government's task to see to it that water-resources development and water supply, whether operated by private companies or governmental companies, should be operated efficiently and with energetic foresight, in order that water-supply shortages should not become an obstacle to economic growth.

The analogy between electricity development and water-resources development can be carried a little further. It is inadvisable for an energy-importing country to underprice electricity, since so doing might lead to the introduction of too many electricity-intensive industries, while correct electricity pricing coupled with an intensive electrification drive is the way to develop the kind of electricity system which will contribute to the economic growth of an area without encouraging the growth of industries unsuitable for the energy conditions of the country. Similarly, intensive water-resources development, coupled with realistic water pricing, will prevent the possibility of water shortages as an obstacle to economic development, and will at the same time discourage the development of water-intensive industries in areas where low-cost water resources are limited and water costs are high. Every area undergoing economic development needs a reliable water supply but not every area can afford low-cost water. An appropriate water-pricing policy is essential if an economy is to adjust itself to its own water-cost conditions.

XIX. THE UTILIZATION OF BY-PRODUCTS AND RELATED EFFECTS ON THE COST OF DESALINATED WATER

by W.F. McIlhenny and P.E. Muehlberg

The water distributed on and under the earth's surface is preponderantly saline. Usually its content of dissolved minerals is too great to permit it to be used for drinking or for irrigation purposes, and too low to enable the minerals to be recovered economically. The relatively small amount of fresh water on the earth is very unevenly distributed and any region is fortunate to be supplied with sufficient fresh water to sustain the agricultural, industrial and domestic needs of a growing population. An area is often equally fortunate to have a source of dissolved minerals in sufficiently high concentration in water to permit their economic recovery as raw materials or as chemical commodities.

The operation of a desalination plant, particularly one using a distillation process at the present level of technology, may create an economic source of chemical raw materials by producing a concentrated brine, in addition to producing fresh water.

A. Chemical composition of saline waters

Naturally-occurring saline waters and brines differ widely from one another, both in total concentration and in chemical make-up. The total dissolved solids content varies from an arbitrarily-defined minimum of 2,500 parts per million, up to more than 350,000 parts per million. The brine present in the greatest abundance on the earth, sea water, normally contains approximately 35,000 parts per million of dissolved solids. There is probably no orderly distribution pattern for the total dissolved solids content of terrestrial brines. The chemical composition, and the ratio of the abundance of one dissolved element to that of another, also vary greatly among different brines and saline waters. The relative chemical composition of sea water, which is shown in table 1, however, varies only slightly with geographic location. 1/

When the respective chemical compositions of a very large number of brines obtained from all parts of the world are compared, a general characteristic of the brines becomes evident: that the dissolved solids content of each brine is composed almost entirely of some combination of the same seven ions. These are the four cations: sodium, potassium, magnesium, and calcium, and the three anions: chloride, sulphate, and bicarbonate. These seven ions are also those present in sea water in the greatest abundance.

The only chemical requirements restricting the possible number of variations of this group of ions are that the cation equivalents should be equal to the anion equivalents, and that the solubility-product constant of any possible

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1/ H.V. Sverdrup, M.W. Johnson and R.H. Fleming, The Oceans (Prentice-Hall, Inc., 1963).

compound should not be exceeded. Several of the four cations may be present in extremely low concentrations in a particular brine, or one or two of the three anions may be almost entirely absent. Of the cations, sodium is usually present in the greatest concentration, and chloride is most frequently the anion of highest concentration. Potassium is usually the least concentrated cation.

Various combinations of other, "minor", ions at differing concentration levels make up the balance of the dissolved solids content. In sea water these are the bromide, strontium, borate, silicate and fluoride ions. In brines of either non-marine origin or of altered marine composition, other minor ions may be encountered. Lithium, barium, aluminium, cesium, iodide, rubidium, sulphide, and the ions of the heavy metals are frequently encountered in concentrations greater than one part per million.

Infrequently, one of the usually minor ions will be present at a moderate concentration level, or even at a higher concentration level than one of the so-called major ions, as in the alkali lakes of western North America, where borates occur at high concentrations in surface brines.

Of the various desalination processes proven to be economically feasible to date, multiple-effect, falling film distillation is capable of producing an effluent brine with the highest concentration of dissolved materials, and therefore the most potentially valuable brine for the recovery of the dissolved minerals.

The dissolved materials in the feed water regardless of the source will be some combination of the seven major elements. The concentration of the bicarbonate ion in the feed water must be essentially zero to prevent soft-scale formation, corrosion, and accumulation of non-condensibles in the desalination process. This is best accomplished by choosing as a feed a saline water of low initial bicarbonate content and then further reducing this by acidification and decarbonation. The product of the sulphate and calcium contents of the feed brine must not exceed the solubility product of calcium sulphate to prevent the formation of "hard-scale", or anhydrite, on heat-exchange surfaces. An ion-exchange process can remove most of the calcium from the feed brine and can use the effluent brine to regenerate the resin.

From the standpoint of heat economy, and to minimize the capital invested in the saline water conversion plant, it is advantageous to concentrate the feed brine to as high a value as can be permitted by calcium sulphate scale formation. At the present levels of technology, this value lies at a sea water concentration factor of slightly greater than five corresponding to a total dissolved solids content of approximately 18 per cent.

The temperature of the effluent brine will depend upon the temperature of the cooling water available for use in the final-stage condenser in the process. At a cooling water temperature of about 85°F, the temperature of the effluent brine would be about 120°F.

The effluent brine from a saline conversion plant will probably have these characteristics: 2/

2/ Dow Chemical Company, A Brine Feasibility Study on the Utilization of Waste Brines from Desalination Plants (Office of Saline Water Progress Report, to be issued).

(1) Its dissolved solids content will be about 18 per cent, and will be largely composed of sodium, magnesium, potassium, chlorine, and sulphur, with sodium and chlorine present in greatest abundance, and a fairly low calcium content.

(2) The bicarbonate content and the oxygen content will both be essentially zero.

(3) The total alkalinity will be close to zero.

(4) The brine will be available at approximately 120°F, with a specific gravity of about 1.12.

B. Potential chemical and mineral products

From the four major cations and two major anions present in the effluent brine approximately twenty minerals can be recovered, if only the processes of evaporation and fractional crystallization are considered. In general, these minerals are complex salts of eight simpler chemical compounds. The number of chemical compounds recoverable is, of course, increased if other materials are added to the brine. Thus, by adding hydroxyl ion from calcium hydroxide, magnesium hydroxide can be precipitated.

If the desalination plant is desalting sea water, the bromine will be present in the effluent brine at a concentration of about 300 parts per million, and can be recovered by adding sulphuric acid and chlorine to the brine, blowing with air and absorbing the bromine in a sulphur dioxide solution.

These "first-generation" products, so called because they are the ones obtainable directly from the brine without further processing, are shown in table 2. Also shown are some "second-generation" products, fundamentally important to a chemical industry, which can be obtained by further processing of several of the "first-generation" materials. Important are chlorine and caustic soda, produced by the electrolysis of sodium chloride, hydrochloric acid and magnesium oxide, formed by the calcination of magnesium chloride, and sulphuric acid, which can be produced by high temperature decomposition of magnesium sulphate.

Most of the products just mentioned are produced and consumed in tremendous tonnages in heavily industrialized parts of the world, where they are converted into other chemicals basic to the region's economy. The heavy chemicals basic to a chemical industry are shown in table 3 with the industrial uses of each shown. It can be seen that all of these except nitric and phosphoric acids can be produced directly or indirectly from brine chemicals. 3/ Other brine-based chemicals, such as potassium chloride, potassium sulphate and to a lesser extent magnesium oxide, and magnesium sulphate require little or no further processing to be used as commercial fertilizers.

3/ W.F. McIlhenny and D.A. Ballard, The Sea as a Source of Raw Materials, paper presented at Symposium on Economic Importance of Chemicals from the Sea, 144th National American Chemical Society Meeting, Los Angeles, 3 April 1963.

C. Current production of minerals from sea water and brines

Although the total world production of the most of the basic chemicals we have considered is based on mined ores, a substantial fraction is now produced from sea water and from terrestrial brines. A partial listing of the present production is shown in table 4. Approximately 30 per cent of the total world production of 105 million tons of sodium chloride (common salt) is obtained through the solar evaporation of sea water and a considerable portion is produced from land-based brines. About two-thirds of the total world production of bromine originates from sea water and the remaining third is derived from subterranean brines. Natural brines, such as those occurring on the eastern shore of the Caspian Sea and in the western part of North America, account for a major fraction of the total world production of sodium sulphate.

Magnesium compounds, including the oxide, carbonate, chloride and sulphate, are produced in large volume from both sea water and land-based brines. In North America, the quantity of magnesium oxide produced from sea water and brines is three times that obtained from solid ores. Almost all of the more than 154,000 short tons of magnesium metal produced annually in the world comes from sea water.

Although the greater part by far of the world supply of potassium compounds is mined from bedded deposits, significant quantities of this element are recovered from both subterranean and surface brines, of which the waters of the Dead Sea are a classic example. Recovery of potassium compounds from sea water itself has not quite become a commercial reality, not because the technology is lacking, but because of the economic competition from other sources.

Three of the minor elements found in sea water are produced commercially from brines. Approximately one-quarter of the total world consumption of boron compounds is recovered from lake brines in California. This brine is also a significant source of lithium chemicals. Underground brines occurring in the North American States of California and Michigan and in Japan, are the source of perhaps 40 per cent of the total world production of the element iodine.

D. Economic state of brine processing technology

The present large-scale recovery of basic minerals from brines is convincing evidence that brine-processing technology is widespread and quite well advanced on commercial levels. In a recently completed research contract with the Office of Saline Water, the Dow Chemical Company has examined intensively each of the known commercial brine-processing operations in the world and then compared the technology involved in each case. We could find very few instances of the application of newly discovered or more advanced technology. Each of the commercial or suggested recovery processes found in the literature, regardless of the substances being recovered, fits very neatly into a number of unit chemical engineering operations whose parameters are well known.

For example, the age-old process for the recovery of common salt from sea water by solar evaporation depends upon crystallization of salt when water is evaporated as solar energy is absorbed. The unit operation involved here is evaporation. The direct unit operation involved for recovery of magnesium values from sea water is precipitation, which is then followed in sequence by the unit operations of settling, filtration and calcination.

The most important of the unit operations is that in which the material desired is separated from the brine and also from other materials which make it impure and usually unsaleable.

This unit operation or series of unit operations constitute what we term a unit cell. Other materials may be added (such as solvent makeup, or a precipitating ion), and energy is almost always required. The physical state of the product is often changed. This concept is shown in figure I.

The product from the unit cell is usually either sufficiently impure or of an improper physical form, so that further purification and product treatment is required.

In our recently conducted survey for the Office of Saline Water of all the available literature on brine-processing, information was gathered on 160 different existing and proposed processes for recovering fifty-one different direct products. Only ten different types of unit cell were employed in the total number of processes. These are listed in table 5.

The portions of the recovery processes subsequent to the initial unit cell, required for converting the initially obtained material into marketable form, can also be reduced to a relatively small number of different unit cells. For each type of unit cell, the fundamental engineering relationships (physical size, influent and effluent conditions, throughput, etc.) will be similar. Reliable engineering data, including estimated equipment costs, are available in the literature for the same or very similar operations. By employing these relationships, it is possible to obtain fairly close approximations of the required plant equipment sizes, the necessary capital investment, and the operating costs for each unit cell, and therefore for the entire process of a complete chemical recovery operation.

E. Value of dissolved chemicals

A vexing question, and one which is particularly important when the effect of chemical recovery on water costs is considered, is the value of the chemicals in the desalination plant effluent brine. Since the dissolved materials in brines are present chiefly as ions, they can associate in more than one way to produce different sets of chemical compounds. It is quite incorrect to speak of compounds in solution in a multi-component brine. Any particular brine, then, can be the source of at least several different possible combinations of minerals, and, conversely any particular brine can be synthesized by dissolving several different combinations of the finished products. The weight of each product in any particular combination required to synthesize, say, 1,000 gallons of the brine, is easily computed from the brine analysis. Each of the products, in its finished marketable form, will have a unit economic value, or market price per ton, at the particular geographic location of the brine source. If this competitive market value has not been already established at the location under consideration, it can be calculated by using the unit price quoted at existing production points and the cost of transportation between the brine site and the existing production point. Of the several combinations, the value representing the lowest delivered unit cost is the proper one to use. This minimum cost will represent the maximum possible worth of the brine under any conditions. Because the calculation of a large number of cases is tedious, a computer programme has been developed to allow the calculation of the minimum cost, maximum worth. The maximum worth of sea water is shown in table 6.

The maximum worth, will usually be many times the actual value of the effluent desalination brine chargeable to a plant for recovering one or more of the contained minerals. The selling prices of products recovered from brines are those of the marketable forms of the products which usually are solids of relatively low water content. In the brine the potential products are present as ions in a comparatively dilute aqueous solution. To convert the ions from the dissolved state to saleable product requires considerable processing, the amount and cost of which depend upon the nature of the products to be recovered, and upon the identity and concentration of the ions in solution.

In table 7 is shown the small amount of information that eixsts for the costs of chemicals in the dissolved state and as solid products. A material in a diluted dissolved state is very roughly worth one tenth of its value as a marketable product.

Whatever the nature of the substance to be recovered in saleable form from a brine, the initial concentration of its component ions in solution is the largest single factor influencing its recovery cost. This is a fairly evident relationship in the recovery of materials like common salt, where many pounds of water must be removed by evaporation. Throughout a wide concentration range, both the physical size of the evaporation equipment and the total heat to be supplied to the process bear an inverse linear relationship to the initial concentration of the sodium and chloride ions in solution. If the source of the heat is purchased fuel or steam, the impact of the cost of heat energy on the operating expense is obvious. In the case of solar evaporation, the effect of initial concentration upon total operating expense is not quite so evident, although it is just as real. The greater the concentration, the less land area is required and less residence time is necessary before salt can be harvested. The capital charges and maintenance costs of the solar ponds are a relatively greater cost item in the operating expense of a solar salt recovery operation. 4/

In other cases, of which the recovery of magnesium hydroxide from sea water is an example, it is only the size of the primary equipment, and hence only the capital charges, which are appreciably affected by initial concentration. Such situations are characteristic of products which are removed from solution by the addition of stoichiometric quantities of chemicals or energy, as is typical of both the precipitation and electrolysis unit cells.

In processes such as solvent extraction, absorption or ion exchange, the cost of process chemicals is important and is affected by the initial concentration. In the proposed recovery of potassium from sea water by the dipicrylamine process, substantially all of the dipicrylamine is recycled in the process after it has performed its function of precipitating potassium from the sea water. The cost of the dipicrylamine is high enough to cause its residual solubility of two parts

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4/ Dale W. Kaufman, "Sodium Chloride", American Chemical Society Mimeograph Series No. 145 (Reinhold Publishing Corporation, 1960).

per million in the effluent sea water to be economically prohibitive. 5/ This process, however, does show promise with brines having an appreciably higher concentration of potassium than sea water.

Most of the processes proposed for the recovery of the trace elements from sea water and other brines, although truly ingenious from the standpoint of the chemistry involved, have little or no chance of economic success. 6/ The extremely low initial concentration of these elements would necessitate the handling of enormous volumes of brine per unit weight of the element sought. It can usually be demonstrated in these cases that some one of the items of cost: capital charges, pumping cost, or cost of process chemicals, will be greater than the total value of the product recovered. 7/

F. Chemical recovery plant capital and operating cost

It is a general characteristic of the chemical industry, and in particular of those plants producing basic chemicals by continuous processes, that the total plant investment required is relatively high in relation to the total value of the materials produced. The parameter defined by this statement is the ratio of the total market value of the materials produced to the total cost of the plant plus working capital, or the number of dollars of gross sales generated by one dollar of capital invested in the plant, and is called the "turnover ratio". It is useful in comparing the economics of production of one chemical with those of another, and in making very preliminary estimates of the capital requirements of proposed processes. 8/

The turnover ratios for a large number of chemical products have been calculated and found to lie generally between the values of 0.1 and 8.0 for a wide variety of products. Some turnover ratios are shown in table 8. This range of values can be narrowed, and the accuracy of estimation increased, by being further selective in both the type of chemical product considered and its rate of production. As the total plant size increases, the plant cost per unit of product will decrease. Also, processes producing basic inorganic chemicals have certain general characteristics in common which distinguish them from plants producing organic chemicals. If we limit our consideration to plants producing between 10,000 and 100,000 tons per year of "heavy" inorganic chemicals, the corresponding turnover ratios will now vary between approximately 0.6 and 1.8, with the average being very nearly 1.0. Since the products recovered from brine are basic inorganic chemicals, it will require the investment of approximately one dollar of capital to produce saleable material having a market value of one dollar per year.

5/ J.A. Tallmage, J.B. Butt and Herman J. Solomon, "Minerals from Sea Salt", Industrial and Engineering Chemistry, vol. 56, No. 7 (July 1964), pp. 44-69.

6/ A.J. Weinberger and D.F. Declapp, By-products from Saline Water Conversion Plants (Office of Saline Water Research and Development Progress Report No. 110, September 1964); W.R. Grace and Company, Mineral By-products from the Sea (Office of Saline Water Research and Development Progress Report No. 91, March 1964).

7/ W.F. McIlhenny and D.A. Ballard, op. cit.

8/ Gordon Kiddoo, "Turnover ratios analyzed", Chemical Engineering, vol. 58 (October, 1951), pp. 145-148.

The published and tabulated turnover ratios are for chemical plants built in the United States and selling competitively in the United States market as well as in the world market.

In table 9 is listed the battery limit construction costs for similar plants constructed in the United States and abroad. It can be seen that although costs vary, the United States turnover ratio can be used to estimate foreign capital investment in a chemical recovery plant.

A comparison of the cost of chemical plant components abroad as compared with a typical United States plant is shown in table 10.

A more accurate estimate of the capital cost can be made when the chemicals to be produced are chosen, the plant size picked, and the process selected. A complete plant can be designed and the costs of the individual pieces of equipment estimated, with considerable accuracy.

The cost of energy is usually a relatively large item in the total operating expense of a chemical plant compared with a non-chemical plant. This energy is usually in the form of heat, as required for evaporation and drying, or in the form of electrical energy for the operation of pumps and other equipment, or for electrolysis. A change in the unit cost of fuel or of electrical power would therefore have a relatively large impact on the total operating cost.

Since the operations performed on the brine and intermediate materials would probably be conducted inside process equipment which is usually both mechanized and automated, a relatively low total labour requirement per unit of capital investment is to be expected compared with other types of industry. Further, the total personnel required to operate a chemical plant varies considerably less with change in plant size or with operating rate than in the case of non-chemical plants. The labour cost of a chemical plant is thus not likely to be the major fraction of total operating expense if the plant is operating close to designed capacity. An increase in hourly wages would have a relatively small effect on the total operating expense.

The operating costs of a chemical plant are quite like the costs to be expected from an advanced desalination plant (which is really a chemical production plant). In table 11 are listed the various costs which must be considered when the cost of operation is estimated.

The cost of raw materials is what the chemical plant must pay the desalination plant for the brine, and is the amount of money available to lessen the cost of water.

G. Integrated water and chemical costs

A combination of a water plant and a chemical plant is shown in figure II. Each plant can be considered as a unit, or the combination of the two can be considered as a unit.

Each plant can be optimized separately, to arrive at a cost of water in the desalination plant and a cost for chemical production in the chemical recovery plant with a value assigned to the effluent brine, which would in general be low enough to allow the chemical plant a reasonable return on investment.

Or, the combination of the two plants can be optimized to arrive at the cost of water. The value assigned to the brine would be immaterial. Only the values of the entering energy and raw materials, and of the effluent water and chemicals are important.

Care should be taken that the production of chemicals is both economic and competitive and that it is not subsidized by a higher cost of water.

The consideration of the optimum combination of plants may have an effect on the design of the desalination plant, and indeed even of the process chosen for the plant.

It can be expected that the water plant and the chemical plant would share facilities. A single steam and electrical source would serve both plants and shops and offices would be shared. Some sharing of operating and maintenance personnel and of supervisory labour is to be expected. All of these would lower the dual facility capital and operating costs.

Since a desalination plant will always discharge a brine containing dissolved minerals at an appreciably greater concentration than that at which they were originally present in the feed water, the desalination process has upgraded the form of these minerals as potential raw materials for finished products. The value added by the desalination process can be measured directly by the decrease in the cost of their recovery from the effluent brine compared with their recovery cost from the feed water.

The decrease in recovery costs can be considerable. As pointed out earlier, present technology permits the effluent brine from distillation processes to be discharged at sea-water concentration factors of approximately five. If we assume a feed water containing 20,000 parts per million of dissolved solids and a fuel cost of $0.20 per million BTU in a process for recovering common salt by quadruple-effect evaporation, then the savings in fuel cost alone will be about $1.00 per ton of salt produced, in addition to the other benefits resulting from increased concentration such as decreased capital costs.

The increased temperature, and lack of bicarbonate and oxygen in the effluent brine from a distillation desalination process also represent value added by the process. The recovery efficiency of bromine, for example, increases considerably with an increase in temperature. The virtual absence of dissolved oxygen and bicarbonate ion in the effluent would reduce both its corrosiveness and tendency toward scale formation.

The immediate and constant availability of the effluent brine from a desalination plant is also important. Brines, including sea water, are free only as long as they remain a part of nature. To deliver sea water continuously from an arm of the ocean to a plant site requires capital investment in the form of an intake structure, a system of flumes or pipelines, and equipment for pumping, screening and chlorinating the water. These capital charges, together with the pumping and maintenance costs, are not negligible. Likewise, the cost of supplying a plant with a continuous flow of brine from a subterranean source is substantial. The effluent brine from a desalination plant would be physically available to an adjacent mineral-recovery plant at a small fraction of this cost.

The decreased cost of recovering the minerals from the desalination plant effluent brine can therefore be credited to the desalination process, and can be expressed on the basis of a unit of fresh water produced.

Whether a desalination plant is desalting sea water at a coastal location or whether it is operating inland using a subterranean brine, the disposal of the brine it discharges is troublesome. At an inland location, the disposal methods generally available will either be to impound the brine in a large, natural closed basin, or to reinject the brine into an underground geological formation having the proper characteristics. Impounding requires the availability of a large area of cheap land and is usually adaptable only to regions where the natural evaporation rate greatly exceeds the rainfall. For reinjection, wells must be drilled and high-pressure pumping is necessary. The risk exists of the pollution of adjacent fresh water in an adjoining stratum by the reinjected brine.

On the sea coast, an improperly designed brine disposal system can be harmful to fisheries. The high temperature, high salinity and lack of oxygen content can adversely affect the local marine ecological cycle and cause the disappearance of oysters, clams, and other economically important marine life. A multi-discharge outfall is usually constructed at considerable distance from the shore, and the effluent brine is diluted with sea water prior to its ultimate discharge.

The costs associated with the effluent brine disposal can be reduced to some extent by recovering the contained minerals. The major benefits to the disposal problem to be derived from the recovery are the reduction in the volume of the effluent as well as a decrease in the absolute quantity of the solids.

H. Chemical market considerations

The need for chemical recovery from saline waters must of necessity be considered only as part of the total resource requirements of a region. The relative needs, the local short and long-range requirements and the effects of by-product recovery on the local economy must all be considered. 9/

For many locations, moderate to small saline water plants will be sufficient to supply or augment the community water needs. It is the chemical production from these plants that will affect the water costs rather than the few very large plants projected for the immediate future.

The potential chemicals from a 5 million gallon per day saline water conversion plant are shown in table 12. Both first and second generation chemicals are shown, and it should be understood that although the production given is for this size plant, not all of the tabulated chemicals can be produced at the same time from the same amount of feed sea water.

As a potential economic source of the saleable forms of the minerals it contains, the brine discharged from a desalination plant must compete with all naturally occurring sources of these same minerals. The occurrence of other natural sources of the same minerals in the area must be considered. For example, the proposed site for a desalination plant may lie relatively close to subterranean bedded salt or to extensive magnesite deposits. It is not an unlikely situation that a known aquifer carrying a natural brine saturated with sodium chloride and containing 3 or 4 per cent of magnesium chloride may underlie the geological formation carrying the saline water of the same composition proposed as the feed

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9/ Dean F. Frasche, Mineral Resources (National Academy of Sciences - National Research Council, Publication 1000-C, 1962); Paul Weiss, Renewable Resources (National Academy of Sciences - National Research Council, Publication 1000-A, 1962); Gilbert F. White, Social and Economic Aspects of Natural Resources (National Academy of Sciences - National Research Council, Publication 1000-G, 1962).

to a desalination plant. In these cases, saleable forms of both sodium chloride and magnesia could be produced from the more concentrated natural source at a lower cost than from the brine discharged from the desalination plant.

The pertinent cost comparison to make is between the costs of the mineral recovery processes using the desalination plant effluent and competing sources, rather than between the desalination plant effluent and the saline water fed to the desalination process. It is perfectly valid to say that the desalination process has increased the value of its feed brine as a source of the contained minerals, but its value may not have been upgraded sufficiently to economically justify its use in comparison with other sources. It would be extremely unwise to base an industrial venture on the use of any save the most economically attractive source of raw materials available.

The fresh water production from a desalination plant can justifiably be credited, then, only with the lowering in mineral recovery costs which would result from the use of its effluent as a raw material instead of the most economically attractive of the other sources.

Although a lower recovery cost is a necessary criterion, it alone is still not a sufficient condition to warrant applying a credit to the fresh water production. The other necessary condition is that all the recovered products should be sold at prices higher than their respective production costs. If these two conditions are both realized, then the fresh water cost can justifiably be reduced by the difference between the cost of recovering the by-products from the desalination plant effluent and the estimated cost of their recovery from the next most economically attractive source.

It is probably the best policy to keep fresh-water production costs sharply separated from the estimated mineral-production economics during the preliminary planning stage of an integrated plant, until it has been determined which products are economically recoverable. During the physical design stage, in which the plan layout is determined, the concept should be that of a multi-product plant using weak brine as a raw material.

The determination of whether or not it is economically feasible to recover the by-products from the effluent brine of a proposed desalination plant is best based on the results of comprehensive market surveys and critical appraisals of the known sources of raw materials of a region with regard to the possible products. Consideration should be given to world markets and supply sources as well as to local and regional demands for the products. This information will assist in determining the impact of the proposed volume of production on existing price levels, in addition to indicating the over-all effect on the regional economy.

If sodium chloride were recovered from the effluent brine of a large desalination plant proposed for a region having some existing solar salt production, the existing solar salt production could be expanded immediately by substituting the effluent brine for the sea water fed to the solar ponds. However, if the existing solar salt production were located at some distance from the site of the desalination plant, it could be economically forced from existence.

A further example is the large desalination plant, now in the conceptual design stage, for the Pacific coast of the United States of North America. If totally recovered, the amount of sodium chloride contained in its effluent brine would be equal to the existing consumption of this material in the entire western region of this country.

The creation of new local and regional markets for many of the potential by-products recoverable from the effluent brine will be a very likely consequence of the operation of a desalination plant in many regions. The consumption of salt in nations having industrial economies has increased at a rate that lies somewhere between the rate of population growth and the rate of increase of the gross national product. 10/ The availability of both fresh water and low-cost salt, and the prior availability of the energy on which the desalination process is already premised, are all basic to a chemical industry.

Table 1

Elements in solution in sea water

(Incomplete list of 44 elements determined)

Element	After Sverdrup (19.0 per cent chlorinity) ppm	"Normal" Sea Water (19.381 per cent chlorinity) ppm
Chlorine	18,980	19,360.5
Sodium	10,561	10,767.8
Magnesium	1,272	1,297.5
Sulphur	884	900.2
Calcium	400	408.1
Potassium	380	387.6
Bromine	65	65.9
Carbon	28	28
Strontium	13	13.6
Boron	4.6	4.6
Fluorine	1.4	1.3
Aluminium	0.5	
Silicon	0.2 - 4.0	0.2 - 4.0
Nitrogen	0.01 - 0.7	
Rubidium	0.2	
Lithium	0.1	
Phosphorus	0.001 - 0.10	
Iodine	0.05	0.05

Note: As prepared by the Hydrographic Laboratories, Copenhagen, Denmark.

10/ Phillip F. Lewis, ed., Stanford Research Institute Newsletter, Stanford Research Institute.

Table 2

First and second generation chemicals and uses

First Gen. Chemical	Second Gen. Chemical	Principal uses
NaCl	Cl_2	Plastics, organic solvents
	H_2	Ammonia, plastics, fertilizers
	NaOH	Paper, rayon, soap
$MgCl_2$	HCl	Metal industries, other chemicals
	MgO	Refractories, steel production
$Mg(OH)_2$	MgO	Refractories
Na_2SO_4		Paper, synthetic detergents
Br_2	$C_2H_4Br_2$	Gasoline additives
	CH_3Br	Grain fumigant disinfectant
K_2SO_4		Fertilizers
KCl		Fertilizers
$MgSO_4$	H_2SO_4	Rayon, metal industries, chemicals
	MgO	
$CaSO_4$		Plaster, construction materials
$CaCO_3$	CaO	Chemicals, construction material
	CO_2	Dry ice

Table 3

Basic heavy chemicals

	Chemicals, Plastics	Pharmaceuticals	Food	Agriculture	Textiles	Rubber	Paints, Pigments	Petroleum	Pulp, Paper	Glass, Ceramics	Metallurgy	Water, Sewage	Cleaning, Refrig'n	Explosives
Sulphuric acid	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Salt-derived:														
Soda ash	X	X	X		X	X		X	X	X	X	X	X	
Caustic soda	X	X	X		X	X	X	X	X	X	X		X	
Chlorine	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ammonia	X	X	X	X	X	X	X	X	X		X	X	X	X
Nitric acid	X	X		X	X		X				X			X
Phosphoric acid	X	X	X	X	X			X	X		X	X	X	
Hydrochloric acid	X	X	X	X	X	X	X	X	X	X	X	X	X	

Source: Manufacturing Chemists Association, Inc., The Chemical Industry Facts Book, 5th ed., (Manufacturing Chemists Association, Inc., 1962).

Table 4

Chemicals currently recovered commercially from natural brines

Bromine, Br_2
Calcium carbonate, $CaCO_3$
Calcium chloride, $CaCl_2$
Calcium sulphate, $CaSO_4 \cdot 2H_2O$ (Gypsum)
Chlorine, Cl_2
Hydrogen, H_2
Iodine, I_2
Lithium sodium phosphate, Li_2NaPO_4
Magnesium chloride, $MgCl_2 \cdot 6H_2O$
Magnesium hydroxide, $Mg(OH)_2$
Magnesium sulphate $MgSO_4 \cdot 7H_2O$ (Epsom salt)
Potassium chloride, KCl
Potassium magnesium chloride, $KMgCl_3 \cdot 6H_2O$ (Carnallite)
Potassium sulphate, K_2SO_4 (Potash)
Sodium bicarbonate, $NaHCO_3$ (Baking soda)
Sodium borate, $Na_2B_4O_7 \cdot 10H_2O$ (Borax)
Sodium carbonate, Na_2CO_3 (Soda ash)
Sodium chloride, NaCl (Common salt)
Sodium hydroxide, NaOH (Caustic soda)
Sodium sulphate, $Na_2SO_4 \cdot 10H_2O$ (Glauber's salt)

Source: Dow Chemical Company, A Brine Feasibility Study on the Utilization of Waste Brines from Desalination Plants (Office of Saline Water Progress Report, to be issued).

Figure I

CONCEPT OF UNIT CELL

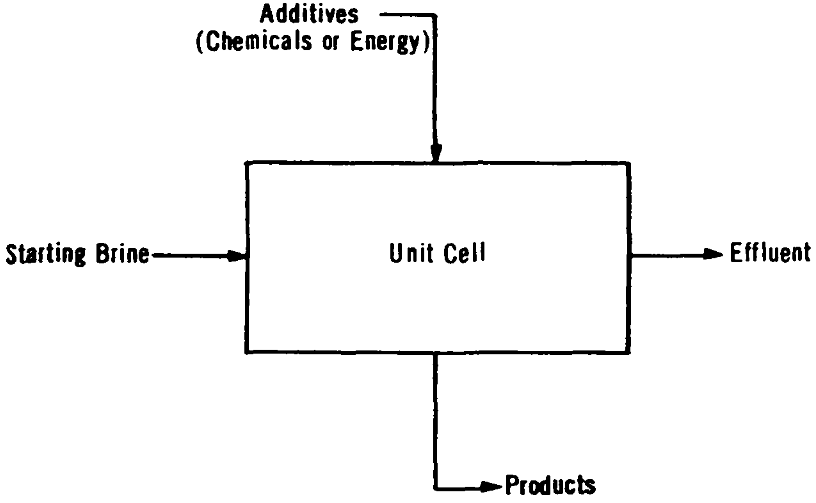

Table 5

Unit processes employed in commercial and proposed recovery of chemicals from brines

- Absorption
- Adsorption
- Distillation
- Electrolysis
- Evaporation
- Flotation
- Freezing
- Ion exchange
- Oxidation-reduction
- Precipitation

Source: Dow Chemical Company, A Brine Feasibility Study on the Utilization of Waste Brines from Desalination Plants (Office of Saline Water Progress Report, to be issued).

Table 6

Calculated maximum worth of sea water

Cost of synthesizing one million pounds of sea water from lowest-cost combination of sources of dissolved ions available.

Compound Used	Weight Need lbs	Cost per MM lbs dollars
H_3BO_3	26.3	1.39
$Mg(OH)_2$	3,110	44.20
NaBr	85	34.00
$NaHCO_3$	195	4.97
$SrSO_4$	28.5	0.92
$CaSO_4 \cdot 2H_2O$	1,760	3.70
KCl	737	8.85
NaCl	27,200	136.00
H_2SO_4	1,739	20.95
HCl	2,575.6	125.00
Total cost of compounds used		379.98

Maximum possible worth of 1,000 gallons of sea water = $3.24

Table 7

Comparison of market prices of chemicals in solid form and in solution

Compound	Form	Sales Price $/Ton	Price Ratio
NaCl	Brine	3.22	0.60
	Salt (solar)	5.40	
NaOH	50%	58	0.58
	Flake	100	
KOH	45%	165	0.78
	Flake	212	
$CaCl_2$	30%	19.1	0.43
	Solid (78%)	44.0	
Ammonium thiocyanate	50%	340	0.85
	Crystalline	400	
$FeCl_3$	Sewage Grade	80	0.47
	Crystals	170	
Sodium silicate	44%	55.0	0.81
	Solid 1:3.2	67.5	
Sodium sulphhydrate	42%	130	0.635
	Flake (71%)	205	
Al_2Cl_6	32%	240	0.57
	Solid Anhydrous	420	

Source: Dow Chemical Company, A Brine Feasibility Study on the Utilization of Waste Brines from Desalination Plants (Office of Saline Water Progress Report, to be issued).

Table 8

Turnover ratios

Product	Capacity T/Yr	Turnover Ratio $/T/$/Ann T
Aluminium sulphate	8,700	1.05
Ammonia	105,000	0.89
Ammonia	35,000	0.81
Calcium phosphate		
Super phosphate	20,000	0.70
Triple super phosphate	50,000	0.54
Calcium oxide (lime)	150,000	1.73
Caustic soda	4,000	0.38
Chlorine	5,000	0.45
Phosphoric acid	40,000	1.21
Portland cement		1.00
Potassium chloride	187,000	0.42
Sodium carbonate	280,000	0.32
Sodium sulphate	52,000	1.13
Sulphur	12,000	0.67
Sulphur	55,000	1.42
Sulphuric acid	84,000	0.76
	280,000	1.31
	Industry medians	
Chemicals		1.47
Mining		1.03
Glass, cement, gypsum		1.29
Aircraft and parts		4.38
Food and beverages		3.22
Metal products		2.28
All industry		1.92

Sources: H.C. Baumna, Fundamentals of Cost Engineering in the Chemical Industry (Reinhold Publishing Corporation, 1964); Dow Chemical Company, A Brine Feasibility Study on the Utilization of Waste Brines from Desalination Plants (Office of Saline Water Progress Report, to be issued); Gordon Kiddoo, "Turnover ratios analyzed", Chemical Engineering, vol. 58 (October 1951), pp. 145-148.

Table 9

Comparison of United States and foreign chemical plant construction costs

Country	Equipment	Labour	Material	Engineering	Total
United States	0.28	0.26	0.38	0.08	1.00
United Kingdom	0.21	0.18	0.41	0.05	0.85
Italy	0.22	0.35	0.29	0.04	0.90
Mexico	0.25	0.40	0.32	0.03	1.00
Brazil	0.24	0.32	0.46	0.03	1.05
Australia	0.24	0.17	0.38	0.06	0.85
Canada	0.27	0.28	0.38	0.07	0.98
France	0.27	0.21	0.47	0.05	1.00
Federal Republic of Germany	0.22	0.28	0.30	0.04	0.84
Japan	0.27	0.26	0.35	0.04	0.92

Source: H.C. Baumna, Fundamentals of Cost Engineering in the Chemical Industry (Reinhold Publishing Corporation, 1964).

Table 10

Cost of chemical plant components as compared with United States cost (% of installed cost)

Component	United States	Italy	India	Mexico	Brazil	Canada	United Kingdom
Process equipment	26.4	20.2	20.0	27.8	27.0	26.8	21.5
Site development	2.5	8.9	0.8	2.1	0.4		2.7
Buildings	18.1	17.8	14.0	9.6	11.6	18.0	24.6
Non-process equipment	0.6	5.4	4.4	6.0	4.3	3.0	2.5
Piping	11.3	7.8	10.0	11.0	8.0	12.4	7.8
Insulation	1.8	1.1	1.0	0.7	0.4	4.0	1.6
Instrumentation	5.0	2.1	2.0	2.3	2.1	3.5	3.1
Electrical	6.3	3.3	4.7	5.6	2.8	6.3	7.6
Steam plant	3.1	2.8	2.6	3.5	4.6		3.0
Refrigeration	1.2	2.0	2.3	2.4	4.7	2.0	1.9
Compressed air	0.6	1.7	1.6	2.4	4.3	1.8	1.9
Water supply	2.5	0.8	2.4	4.7	1.6		0.6
Distribution piping	3.1	3.4	2.1	3.0	4.0	2.2	2.5
Fire protection	0.6	1.7	3.0	2.4	2.0	0.1	0.4
Electrical service	3.2	5.4	5.5	6.0	10.5	2.4	1.1
Painting	1.2	0.4	0.7	0.4	0.5	1.6	0.4
Spare parts	1.2	2.0	3.3	1.1	0.5	1.0	1.1
Engineering, A.E. and Const. supervision	11.3	13.2	12.7	4.8	10.7	14.9	15.7
Duties, special taxes			6.9	4.2			

Source: H.C. Baumna, *Fundamentals of Cost Engineering in the Chemical Industry* (Reinhold Publishing Corporation, 1964).

Table 11

Chemical manufacturing cost estimate

	Cost per (steam day)(month)(year)(unit)
A. Materials	
1. Raw materials	
2. Utilities	
steam	
electricity	
water	
fuel	
B. Labour	
1. Direct operating labour	
2. Maintenance labour	
3. Supervision	
4. Payroll burden	
C. Overhead	
1. Laboratory	
2. Purchasing,rreceiving, warehousing	
3. Personnel relations	
4. Fire protection	
5. Accounting	
6. Plant protection	
7. Safety, first aid	
D. Capital	
1. Depreciation	
2. Maintenance materials	
3. Insurance	
4. Taxes	
E. Marketing and Distribution	
1. Packaging	
2. Shipping	
3. Sales costs	
F. Research	
G. General and Administrative	
H. Return on Investment	

Source: H.C. Baumna, Fundamentals of Cost Engineering in the Chemical Industry (Reinhold Publishing Corporation, 1964).

Table 12

Chemicals potentially recoverable from a 5 MGPD sea-water conversion plant

Basis: Normal sea water
5:1 concentration factor

Chemical Compound	Tons per 330-day year at 90% recovery
Brome	509
Calcium carbonate	7,900
Calcium sulphate (Gypsum)	13,600
Chlorine[a]	128,500
Hydrochloric acid[a][b]	30,200
Magnesium chloride (as hexahydrate)	84,000
Magnesium oxide (Magnesia)[a]	16,550
Magnesium sulphate (Epsom salt)	53,500
Potassium chloride (Potash)	5,730
Sodium borate (Borax)	316
Sodium chloride (Common salt)	212,000
Sodium hydroxide (Caustic soda)[a]	146,000
Sodium sulphate (Glauber's salt)	70,500

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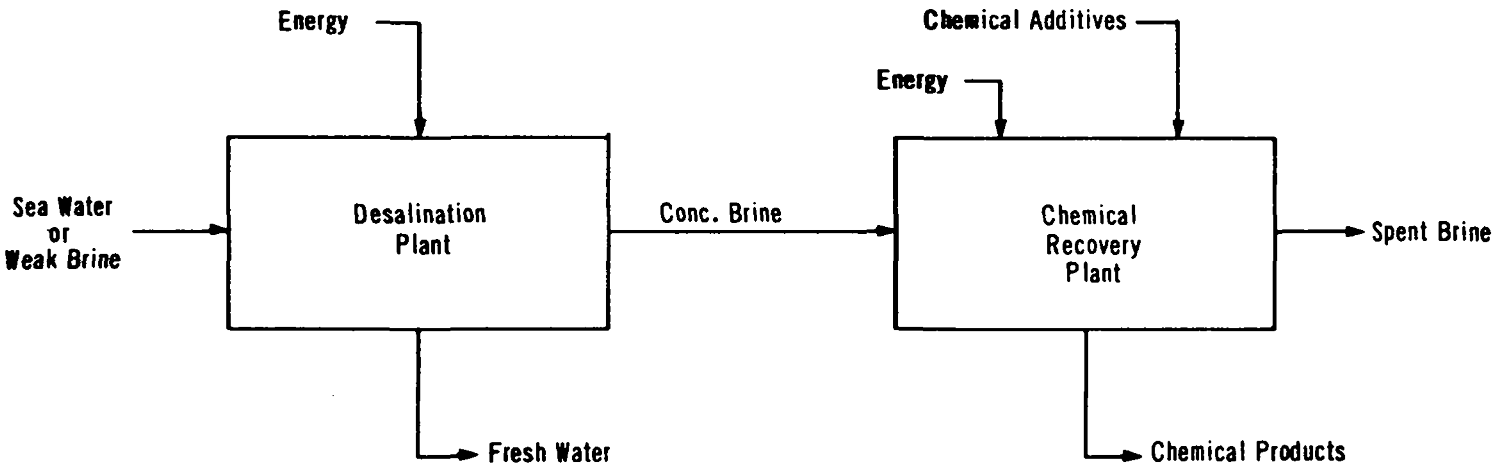
[a] Second-generation chemical.

[b] Equivalent to magnesium chloride.

Figure II

INTEGRATED DESALINATION–CHEMICAL PLANT



PART THREE

REPORTS ON OPERATIONAL EXPERIENCE OF DESALINATION PLANTS

(Round-Table Discussion)

I. OPERATING EXPERIENCE WITH A FLASH EVAPORATION DESALINATION PLANT AT NASSAU (BAHAMAS)

by J.J.C. Bradbury

The Government of the Bahamas has installed two sea water evaporating plants, each of 2,720 cubic metres daily capacity, at the Clifton Pier Power Station of the Bahamas Electricity Corporation. These distilling units were designed to give full output when using all the exhaust steam available at 12 p.s.i.a. from a 6,100 kW back pressure turbo-alternator. To provide flexibility of operation and allow water production to proceed when the back pressure machine is out of service, a second turbine at the power station has been provided with steam pass-out facilities. Under normal operating conditions, steam for the desalination process is supplied from the exhaust of the back pressure turbine, whilst the pass-out machine operates as a conventional turbine exhausting all its steam to a condenser.

High pressure steam at 625 p.s.i.g. and 850°F is obtained from two water tube boilers, each rates at 100,000 lbs of steam per hour and burning Bunker 'C' residual fuel.

The plants are basically of a once-through design, each taking in 3,479,000 lbs of sea water per hour at 92°F and discharging 3,057,000 lbs per hour at 105°F. Twenty flash chambers are provided where hot brine is evaporated over an 85°F flash range from 190°F to 105°F. In order to maintain a constant inlet temperature of 92°F provision is made for mixing some of the outgoing brine with the colder incoming sea water. This small measure of recirculation varies with the time of the year and is dependent upon the sea temperature. The main sea water feed pumps supplying the evaporators are driven by steam turbines consuming approximately 10,500 lbs per hour of high pressure steam. Following its expansion in the turbine, this steam is discharged to the exhaust steam heater where its latent heat can be used in the evaporative process.

From the feed pump discharge, raw sea water passes through the tubes of twenty heat exchangers arranged in series, one located above each flash chamber. These heat ecchangers perform a dual function in so far as they condense the steam being produced in the flash chambers whilst the resultant latent heat made available in this process is used to preheat the raw sea water. The temperature of the raw water feed rises by approximately 4-1/4°F across each heat exchanger and is consequently discharged from the last preheater tube nest at a temperature of 177°F.

At this stage, the raw feed water is passed to a large condenser known as the exhaust steam heater where it is used to condense 35,500 lbs per hour of exhaust steam from a 6,100 kW turbine, plus 10,000 lbs of steam from the feed pump turbine. As a result of this condensation process, the feed water is elevated to a final temperature of 190°F.

The hot brine is then passed through the various flash chambers where it boils under reduced pressure. As temperature falls through succeeding flash chambers, boiling is maintained by a progressive reduction in pressure. This process is repeated until, in the twentieth flash chamber, pressure conditions are such that boiling takes place at 105°F. From this last effect the residual concentrated brine is discharged to waste at 105°F by means of a 170 h.p. pump.

Vacuum is maintained in the various sections of the plant by using standard power-station type air ejectors, operated by high pressure steam.

In order to reduce the incidence of scale formation on the heat exchanger tubes in the hot sections of the plant, chemical injection facilities have been provided to use a sodium polyphosphate compound known as Hagevap.

When the evaporating plants were first commissioned, it was observed that output fell progressively. It was noticed that this steady fall in output was accompanied by an equally progressive rise in the temperature difference between the steam entering the exhaust steam heater and the hot brine flowing through the exhaust steam heater tubes. This rise in the exhaust steam heater temperature differential indicated that some heat insulating barrier was present on the heater tube surfaces which adversely affected the heat transfer coefficient. The plant manufacturers closed down the evaporators and carried out an investigation of the inside surfaces of the tubes contained in the exhaust steam heater and the preheaters at the hot end of the plant. The result of this investigation was the discovery of a soft sludge adhering to the inside surfaces of the heat exchanger tubes. Since this sludge is loosely formed and not as compact as hard magnesium hydroxide and calcium carbonate scales it has a very poor heat transfer coefficient. Following the discovery of this sludge the plant manufacturer proceeded to carry out a series of tests using varying dosing rates of Hagevap and Calgon, coupled with the addition of extra antifoam and sequestering agents. However, the basic trends of falling output and rising temperature differential across the exhaust steam heater continued to prevail.

An analysis of the sludge showed it to be composed of small particles of magnesium hydroxide and calcium carbonate which were bonded to ferric hydroxide. It is felt that the presence of ferric hydroxide is the most important factor in this problem since this chemical is of a glutinous nature and readily forms an adhesive base on the tube surfaces to which the harder scale compounds can stick. Since the evaporator preheater water boxes and connecting pipe-work are made of iron, the ferric hydroxide may arise from the contact of aerated sea water with these iron surfaces.

For one period the chemical dosing regime was changed to Swasp (sea water anti-scaling preparation). This product is a cornstarch preparation and results seemed to indicate that, since output was not falling, no sludge was being produced. At the end of the test period, however, it was found that, whilst no sludge was present, the formation of hard scale in the exhaust steam heater necessitated such a large use of acid for its removal that this system could not be considered economically feasible. Having decided that very little could be done by varying the chemical dosing regimes to obviate sludge formation, the manufacturer then turned his attention to trying to install some means of removing this scale by mechanical methods.

As a result of investigations in Europe, it was decided to install a variation of the Taprogge system which had been used with great success for cleaning slime from condenser tubes in river-based power stations. Under this system, sponge rubber balls are injected into the circulating water and are swept through the condenser tubes. Since they are somewhat oversize, their passage through these tubes has the effect of removing deposits.

The evaporators in Nassau were modified by the connexion of a Taprogge ball injection pipe intended to feed approximately 500 sponge rubber balls at a time through the eight hottest heat exchangers and the exhaust steam heater. Having passed through these sections, the balls are then caught by a collector and diverted back to a sump ready to recommence the cleaning cycle. Each complete cleaning operation takes approximately four minutes and is controlled by the automatic opening and closing of the Taprogge injection and return valves.

Present experience with this system seems to indicate that it has a beneficial effect upon the plant operation and it is possible to see a definite improvement in both output and thermal performance.

During the course of a one-month reliability test carried out on these evaporators, the average daily output obtained was 139,000 cubic metres, representing 98.3 per cent of the nominal rating. Experiments have been carried out using balls having a carborundum coating strip and it is possible that various different materials and ball designs will be available for this application in the future.

Fresh water quality from the Clifton Pier evaporators has been good, the total dissolved solids averaging about 3 ppm. The mixing of this high quality water with the existing well water supply in Nassau has resulted in a considerable improvement in over-all quality.

Acid cleaning of the desalination plants has been carried out from time to time, using inhibited sulphamic acid supplied in a granular form which can be easily handled. Following earlier difficulties, the acid cleaning system pipework was replaced with plastic pipe and appears to be functioning in a satisfactory manner.

II. HISTORY, EXPERIENCE AND ECONOMICS OF WATER PRODUCTION IN KUWAIT

by M.H. Ali El-Saie

Kuwait used to have practically no potable water and between 1925 and 1950, it relied on a very limited supply of water imported by boat from Shat Al-Arab, Iraq. In 1950 the Kuwait Oil Company supplied the city with 80,000 igpd. [1] In 1953, water was produced from the first one million igpd submerged tube distillation plant ordered by H.H. the Amir of Kuwait, and in 1955 this was followed by a similar plant of one million gallon capacity. In 1957, the first 4 x 1/2 million igpd flash-type evaporator was commissioned. In 1960, the 'E' distillation plant was commissioned which has a capacity of 2 x 1 million igpd. Five 1 million igpd plants are now under construction and will be commissioned soon.

Brackish water 4,500 ppm T.D.S. is available at Sulibiyah and 18 million igpd are produced. Also, in 1961 ground water was discovered at Rawdatain, and Umm Al Aish, which produces about 5 million igpd at 1,000 ppm T.D.S. An electrodialysis plant of 200,000 igpd, commissioned recently, is still under investigation.

The distillation plants are installed at the Shuwaikh (160 mW) and Shuaiba (210mW) steam power stations. Cn both sites sea water intakes are common. Pass-out steam is obtained from turbo-alternators and/or direct from boiler food distillation plants. Fuel for the boilers is natural gas from oilfields obtained at no charge, and gas oil is a standby only.

A. Submerged tube type evaporators

1. Shuwaikh 'A' and 'B' plants

The plants are supplied by the Westinghouse (United States) and Weir (United Kingdom) companies respectively. Each consists of ten-triple-effect evaporators of 100,000 igpd, commissioned in 1953 and 1955 respectively. Each evaporator consists of three horizontal (steel in case of Shuwaikh 'A' and cast iron for Shuwaikh 'B') cylindrical shells each with horizontal tube bundle of cupro-nickel 70/30 and horizontal shell tube condenser. All pumps are motor-driven, with cast iron casing, phospher-bronze impellers and stainless steel shafts.

At the beginning, on Shuwaikh 'A' plant, scale formation was prohibitive and required mechanical cleaning.

Laboratory and extensive site research into different treatments, acids, inhibiters and running conditions, has led to the following:

---

[1] Imperial gallons per day.

Hagevap, continuous dosing, to sea water feed of 2.5 ppm.

For Plant 'B', additional food of ferric chloride, of 150 ppm, each alternate week.

Top temperature of brine and steam, respectively, 180°F. and 225°F.

Brine concentration (ratio of chlorides): less than 3.

Scale cracking every seven to ten days was found necessary. The scale cracking routine, in brief, is to stop the evaporator and admit live steam to the steam tube bundles in each effect, and then admit cold sea water rapidly to the shell to give the scale a sudden shock or contraction. Thus, the scale outside the tubes cracks, flakes and drops inside the shell, and is then blown down and washed through a drain valve in each shell. HC acid boost, two to three times per year has been very effective. Acid is used in cleaning at each annual overhaul.

The plants have been running very satisfactorily and require overhaul every ten thousand running hours.

Recirculation of brine to first and second effects in plant 'A' to increase brine velocity has proved inefficient because it increases power consumption.

It has been found that calcium sulphate forms in the evaporator at lower temperature and concentration of brine is greater than in laboratory tests. In the author's opinion, this is due to local boiling and low mass transfer at the heating surface which means high temperature and concentration as the brine bubbles.

2. The Cepi-Comav apparatus

This was offered free by the manufacturer. It is, briefly described, a permanent magnet supposed to change the properties of sea water ions and molecules and hence prevent scale formation without any chemical treatment. Tests proved a complete failure.

B. Flash type sea water evaporators

1. Shuwaikh 'C' and 'D' plant

As this plant is the first flash type to produce distillate from sea water at such a rate of production, it has proved a turning point in the history of sea water distillation and its success has encouraged companies all over the world to carry out a great deal of work on flash distillation.

Four flash type evaporators, each with four stages, one stage over the other, with the main heat input section over the top of the four stages, and each unit of 525,000 igpd production, were supplied by the Westinghouse Company. The first unit was commissioned in 1957. Many modifications were introduced into the original offer as a result of our site experience and results from prototype tests at the factory mainly on brine control, purity of distillate and scale formation. The plant ran very satisfactorily, except for the distillate purity which was high; this was cured by introducing a suitable Monel demister in the stage at lower vacuum.

Because of choking in the heater water box, scale formation increased. Strainers were introduced into the sea water feed make-up which stopped this trouble and water strainers will be used in all future plants. Fixed speed electrically-driven pumps resulted in difficult start-up and control.

The plant is running with top brine temperature of $194^{\circ}F$. Five ppm Hagevap is administered to the sea water feed and 150 gallens of HCl at 33 per cent concentration are used to loosen scale in tubes once a year; the brine blow-down concentration ratio is 2. Acid cleaning of the heater is needed only every 8,000-10,000 hours. The shell and all interiers are of mild steel; the tubes are Cu Ni 70/30 and the pumps of stainless steel.

2. Shuwaikh 'E' plant

Two x three tiers of 19-stage units, each producing 1 million igpd, were first commissioned in 1960. The materials are similar to those used in plant 'C'. Before writing up specifications, a survey was carried out to obtain all available information from all interested companies and design specifications were then issued. The best commercial offer was submitted by the G. and J. Weir Company, but a large number of alterations were introduced into it before signing the contract.

The original offer was for 26 stages, 3 for heat rejection and 23 for heat gain. The new feature in this design was the presence of two separate heating coils in the heat gain section, one for recirculating brine, the other for sea water feed. The sea water feed from the outlet of the heat gain section is admitted to a separate deaerating heater then mixed with the recirculating brine from the heat input heater outlet. There is a clear advantage in this design from the points of view of heat transfer and corrosion in the flash chamber.

The feature was rejected, however, because of our previous experience with the very aggressive corrosion properties of Kuwait Bay sea water at the water boxes, while we usually have little or no trouble with concentrated brine in the water boxes. The plants were redesigned to have only recirculating brine in the heat gain section.

Also, the control weirs for inter-stage brine control were questioned and a series of tests on a prototype were carried out in the presence of the author. The type of weirs selected was agreed upon after changing the height of the flash chambers and adding baffle plates. The heat exchange surface in the heater is practically double the surface offered; again, we insisted on this increase from previous experience at the site.

Laboratory tests at the Weir factory were carried out before final design approval and major modifications were introduced to avoid corrosion of sea water in the boxes. A sensitive steam centrol of the heater provided very smooth operation. The plant is running very well with top brine temperature of $194^{\circ}F$. Hagevap dosing of the sea water feed is at 5 ppm. The brine concentration ratio is 2. Acid cleaning is undertaken every 10,000 hours.

3. Shuwaikh 'F' and Shuaiba 'A' plants

These plants are five units of 1 million igpd, with two tiers of thirty stages, and similar in principles and running condition to plant 'E', but with less specific heat consumption. (Specific heat consumption in BTU per lb of distillate for 'C' and 'D' is 345; for 'E' 184.75; for 'F' 143.7.) Also, the whole plant has remote automatic control from a central control room at each site.

In view of long experience at the site, and the little sign of erosion and corrosion on the heat exchange surfaces on most of the effects, we decided to use cupro-nickel 70/30 only in the stages where the heat transfer surfaces were exposed to heavy corrosion (in top stages where CO_2 release is maximum and in the bottom stage where there is O_2 liberation due to presence of feed make-up) and also in the main heater. In the rest of the evaporator, aluminium brass has been used.

Laboratory tests of brine control, purity of distillate and dimension of stages were carried out on a prototype before final design. Also, sea water supply to plants will be of a constant temperature all year. The first unit was just in the course of being commissioned when this paper was dispatched.

C. Corrosion problems

1. Sulphate reducing bacteria

The presence of sulphate reducing bacteria in Kuwait sea water results in heavy corrosion of steel components in contact with sea water, specially C.I.

2. CO_2 attack

CO_2 attacks the interior of the flash chambers, the ejector condenser and distillate pipes.

3. Preventive methods

(a) Continuous chlorination of sea water to kill bacteria and marine growth.

(b) Cathodic protection.

(c) Application of paint and coatings:

  (i) Pipes and pumps for sea water, hot applied bitumastic enamel.

  (ii) Rubber lining of sea water boxes.

  (iii) For other places, zinc-rich primer and chlorinated rubber paint.

(d) Careful choice of materials for the different components.

(e) Separate venting of first and last flash stages.

(f) Elevating of ejector condenser temperature.

(g) Injection of $Ca(HO)_2$ and $NaHCO_3$ to distillate mains.

D. Water production cost

All calculations in the table below are for 1 million igpd plants of each type on full production all year, except for outages other than stand-by.

Overhead charges of 75 per cent on wages and salaries included.

Fuel is free, except for depreciation and maintenance of the gas line and accessories.

Plant:	Shuwaikh 'A'	Shuwaikh 'B'	Shuwaikh 'C' and 'D'	Shuwaikh 'E'	Shuwaikh 'F' and Shuaiba 'A'
	K.D.	K.D.	K.D.	K.D.	K.D.
Maintenance wages:	10,335/075	10,409/470	2,616/073	2,616/073	2,616/073
Material cost for maintenance:	12,284/431	13,731/784	1,216/087	1,200/000	1,200/000
Maintenance cost (workshops):	7,429/198	1,649/439	331/528	331/528	331/528
Operating wages:	22,523/700	20,971/239	11,250/000	6,000/000	6,000/000
Cost of PD8	2,168/775	1,945/516	4,375/872	4,375/872	4,375/872
Cost of ferric chloride:	-	1,380/000	-	-	-
Cost of acid for cleaning:	1,125/000	1,125/000	375/000	375/000	375/000
Cost of chlorine:	8,175/000	8,175/000	5,017/500	3,190/000	2,100/000
Cost of electricity consumed:	11,500/000	10,420/000	13,900/000	1,300/000	340/800
Cost of steam consumed:	43,800/000	42,600/000	36,250/000	17,600/000	12,800/000
Depreciation of unit (15 yrs):	118,000/000	86,000/000	46,200/000	23,300/000	27,000/000
Depreciation of unit (20 yrs):	-	-	34,500/000	17,500/000	20,250/000
Total cost based on 15 yrs. depreciation:	237,341/179	197,407/209	121,532/060	60,293/473	56,003/569
Total cost based on 20 yrs. depreciation:	-	-	109,822/405	48,693/047	49,253/569
Production in million gals/year:	300	290	330	330	330
Cost of 1,000 Imp. gals in Fils: on depreciation of 15 years:	790	650	368	173	169
20 years:	-	-	336	144	149

Note: One K.D = 1,000 fils = $2.8 = £1.

E. Summary, conclusions and recommendations

(1) The multi-stage sea water flash type evaporator is the most reliable equipment for producing distillate from sea water at reasonable cost, and the submerged tube type should be limited to very small plants where a lot of outage is possible.

(2) The mechanics of scale formation is a complicated subject, and local conditions are of major importance (nature of sea water, design conditions, chemical treatment, etc.). The writer therefore advises that any authority which decides to install a sea water distillation plant of large capacity should first build a unit of reasonable size and carry out tests on scale formation and chemical treatment before committing itself to the full-scale installation required. Kuwait is lucky in that no iron content is present in the sea-water; in other places, the presence of iron has caused a good deal of trouble with respect to the appropriate dosing of Hagevap and has formed very complicated sludge and scale. Again, acid treatment is, in the writer's opinion, the best treatment for large units, especially in countries paying for fuel, provided that reliable pH and dosing controls are applied.

(3) The importance of clear-cut specifications when ordering a plant cannot be overestimated; these should be prepared under the guidance of experts who have site experience and who appreciate the difference in effort required between receiving the offers and placing the order. Prototype tests in the laboratory, or on site, are sometimes of great importance and can save a lot of time and money.

(4) Much work still needs to be carried out in order to reach a practical, definite correlation between size of flash stages and their duties, especially for units of large capacity (1 mgpd and over), and also for brine control.

(5) Choice of materials, chemicals and coating is, in the writer's opinion, a factor which leads to savings in capital as well as on maintenance charges.

(6) The steam water ration is given for different plants in the heat flow diagram, but in Kuwait this is not an important factor because fuel is free and hence the ratios were chosen for availability of power installation and economy.

(7) Flash type evaporators are sensitive to variation in sea water temperature, brine temperature and feed inputs, and the writer advises that changes should be reduced to a minimum and be automatically controlled and not left to manual operation. Also, equipment should be suitable for easy start-up and shut-down.

(8) The cost of production from sea water distillation has fallen rapidly between 1953 and the present.

APPENDIX A

Table 1 - Sea Water Analysis

	Shuwaikh site	Shuaiba site
	From Kuwait Bay	From the Arabian Gulf
Total dissolved solids in ppm	48,200	42,000
Total alkalinity, $CaCO_3$ in ppm	150	135
Chlorides, Cl, in ppm	24,800	23,100
Sulphates, SO_4, in ppm	3,500	3,100
Permanent hardness, $CaCO_3$ in ppm	7,950	8,400
Temporary hardness, $CaCO_3$ in ppm	100	100
Total hardness, $CaCO_3$, in ppm	8,050	8,500
Calcium, Ca", in ppm	400	500
Magnesium, Mg", in ppm	1,690	1,665
Bromine, Br", in ppm	80	80
Silica, SlO_2, in ppm	5	5.0
pH	8.8	8.3
Neutral electrical conductivity, as micromhos at 20°C.	76,800	70,500
Maximum sea water temperature	90°F	90°F
Minimum sea water temperature	58°F	58°F

Table 2 - Analyses of Scale Deposits

In percentages

(a) Submerged tube type evaporators:

Shuwaikh A with 2.5 ppm PD8 treatment and
Shuwaikh B with 150 ppm ferric chloride and 2.5 ppm PD8 treatment

	1st effect		2nd effect		3rd effect	
	"A"	"B"	"A"	"B"	"A"	"B"
$Mg(OH)_2$	40.0	65.0	4.5	75.0	44.5	72.0
$Ca\ CO_3$	49.6	15.0	90.0	10.5	48.2	4.0
$Ca\ SO_4$	7.5	1.5	1.5	1.8	1.0	3.5
$Si\ O_2$	1.3	5.6	3.5	6.8	5.2	4.5
Fe_2O_3	-	12.5	-	4.2	-	15.2

(b) Flash type evaporators:

Shuwaikh C and D with 5 ppm PD8 and Shuwaikh E with 4 ppm PD8 treatment

	"C" and "D"	"E"
Organic matter	10.5	8.5
$Si\ O_2$	6.1	6.5
Soluble Phosphates Ha_3PO_4	2.5	3.6
$Mg_3\ (PO_4)_2$	23.4	22.8
$Mg\ (OH)_2$	40.5	42.3
$Ca\ SO_4$	4.8	1.5
$Ca\ CO_3$	6.5	4.2
Na Cl	5.1	8.0
$Fe_2\ O_3$	Trace	1.2

Table 3 - Evaporator Brine Analysis

	Shuwaikh 'A'	Shuwaikh 'B'	Shuwaikh 'C' and 'D'	Shuwaikh 'E'
Conductivity	160,000	143,000	149,000	180,000
T.D.S. in ppm	101,490	90,705	94,510	114,175
pH ...	9.6	9.4	9.4	9.5
Total caustic as NaOH in ppm	80	85	70	80
Total alkalinity as $CaCO_3$ in ppm	285	275	310	385
Chlorides as Cl' in ppm	50,000	47,900	48,000	58,500
Sulphates as SO_4'' in ppm	6,890	6,315	6,300	8,150
Total hardness as $CaCO_3$ in ppm	16,875	15,000	15,625	19,125
Calcium as Ca^{++} in ppm	1,000	940	940	1,200
Magnesium as Mg^{++} in ppm	3,495	3,320	3,320	3,920

APPENDIX B

Table 1

Submerged Tube Type Evaporator: Shuwaikh 'A' Plant

	Shell dia:	Area of heating surface ft^2	Evaporator Tubes			
			No. off	O.D.	Gauge	Length
1st Effect	6'1"	2,150	728	1"	18	2 x 11'8 1/4"
2nd Effect	6'1"	2,150	728	1"	18	2 x 11'8 1/4"
3rd Effect	6'1"	2,220	540	1"	18	2 x 16'1 1/4"
Condenser	6'1"	1,600	388	7/8"	18	18'1 7/8"

Electric load without recirculation 47 kVA

Electric load with recirculation 66.5 kVA

Table 2

Submerged Tube Type Evaporator: Shuwaikh 'B' Plant:

	Shell dia:	Area of heating surface ft^2	Evaporator Tubes			
			No. off	O.D.	Gauge	Length
1st Effect	9'	2,200	818	3/4"	16	14'1 3/4"
2nd Effect	9'	2,200	818	3/4"	16	14'1 3/4"
3rd Effect	9'	2,200	818	3/4"	16	14'1 3/4"
No. 2 Preheater	2'2"	200	88	1"	16	8'3 1/2"
No. 3 Preheater	2'2"	200	88	1"	16	8'3 1/2"
Condenser and	3'8"	1,700	750	3/4"	18	11'10 1/2"
No. 1 Preheater		300	132	3/4"	18	

Electric load: 46 kVA

Table 3

Flash Type Evaporator: Shuwaikh 'C' and 'D' Plant

	No. of stages	Area of heating surface ft^2	Evaporator Tubes				Water velocity inside tubes ft/Sec
			No. off	O.D.	Gauge	Length	
Heat Rejection Section	1	8,800	1,288	7/8"	18	30'	6.5
Heat Gain Section	3	26,400	3,864	7/8"	18	30'	6.5
Heat Input Section	1	7,000	1,200	7/8"	18	28'6"	6.5
Make Up Evap.	1	2,000	588	7/8"	18		

Electric load 340 kVA

Table 4

Flash Type Evaporator: Shuwaikh 'E' Plant

	No. of stages	Area of heating surface ft^2	Evaporator Tubes				Water velocity inside tubes ft/Sec
			No. off	O.D.	I.D.	Length	
Heat Rejection Section	3)	77,400	14,644	1"	0.904"	20'6"	6.5
Heat Gain Section	16)						
Heat Input Section	1	6,000	1,530	1"	0.904"	14'8"	6.5

Electric load 78 kVA

Table 5

Flash Type Evaporator: Shuwaikh 'F' Plant

	No. of stages	Area of heating surface ft^2	Evaporator Tubes				Water velocity inside tubes ft/Sec
			No. off	O.D.	I.D.	Length	
Heat Rejection Section	3	12,570	4,286	1"	0.904"	20'7 7/8"	6.5
Heat Gain Section	27	138,780	24,100	1"	0.904"	20'7 7/8"	6
Heat Input Section	1	5,455	1,676	1"	0.904"	12'8 7/8"	7

Electric load 60 kVA

APPENDIX C

Photographs and sketches

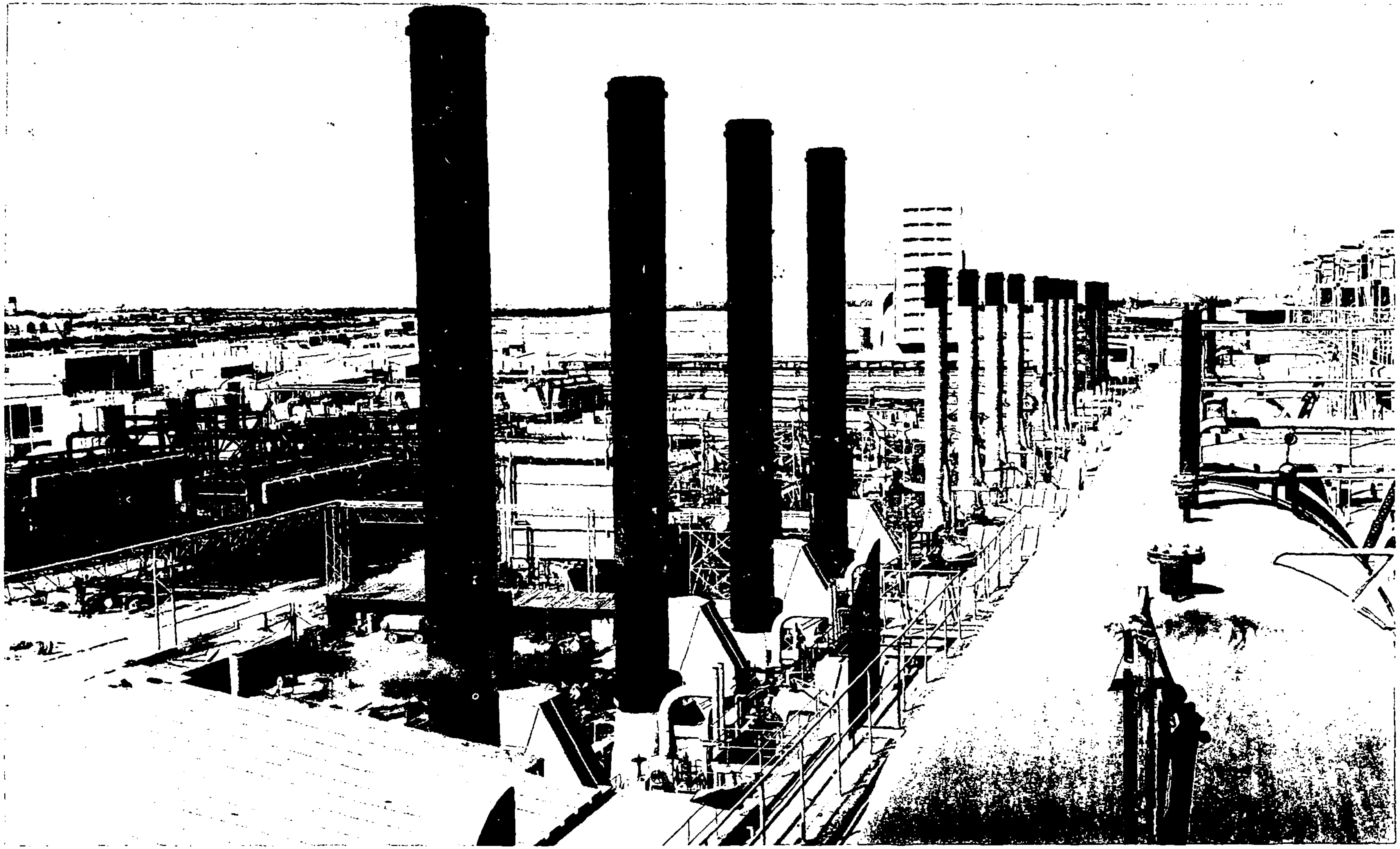


Figure 1. Shuwaikh Power Station and Distillation Plant

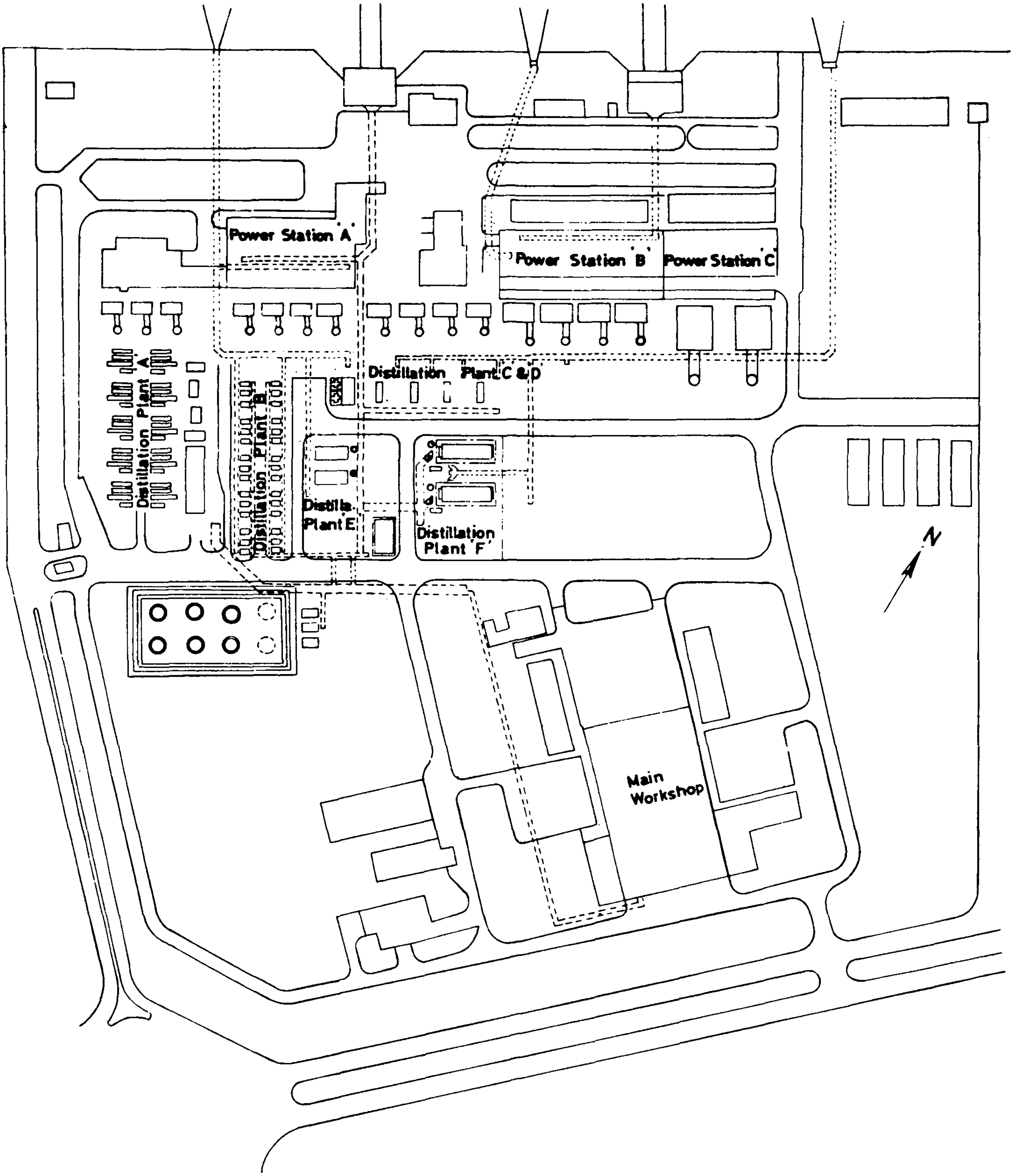


Figure 2. Site layout for Shuwaikh Power and Distillation Plant

Figure 3. Shuwaikh 'A' Distillation Plant

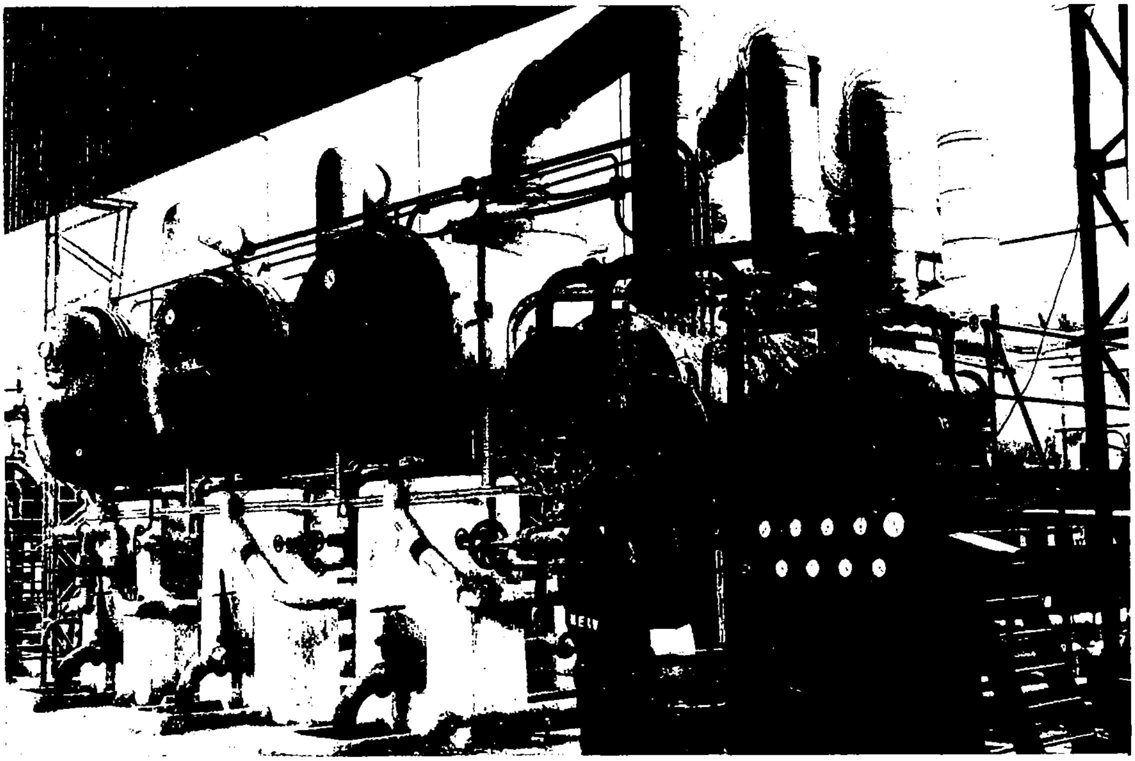


Figure 4. One Evaporator, Shuwaikh 'A' Distillation Plant

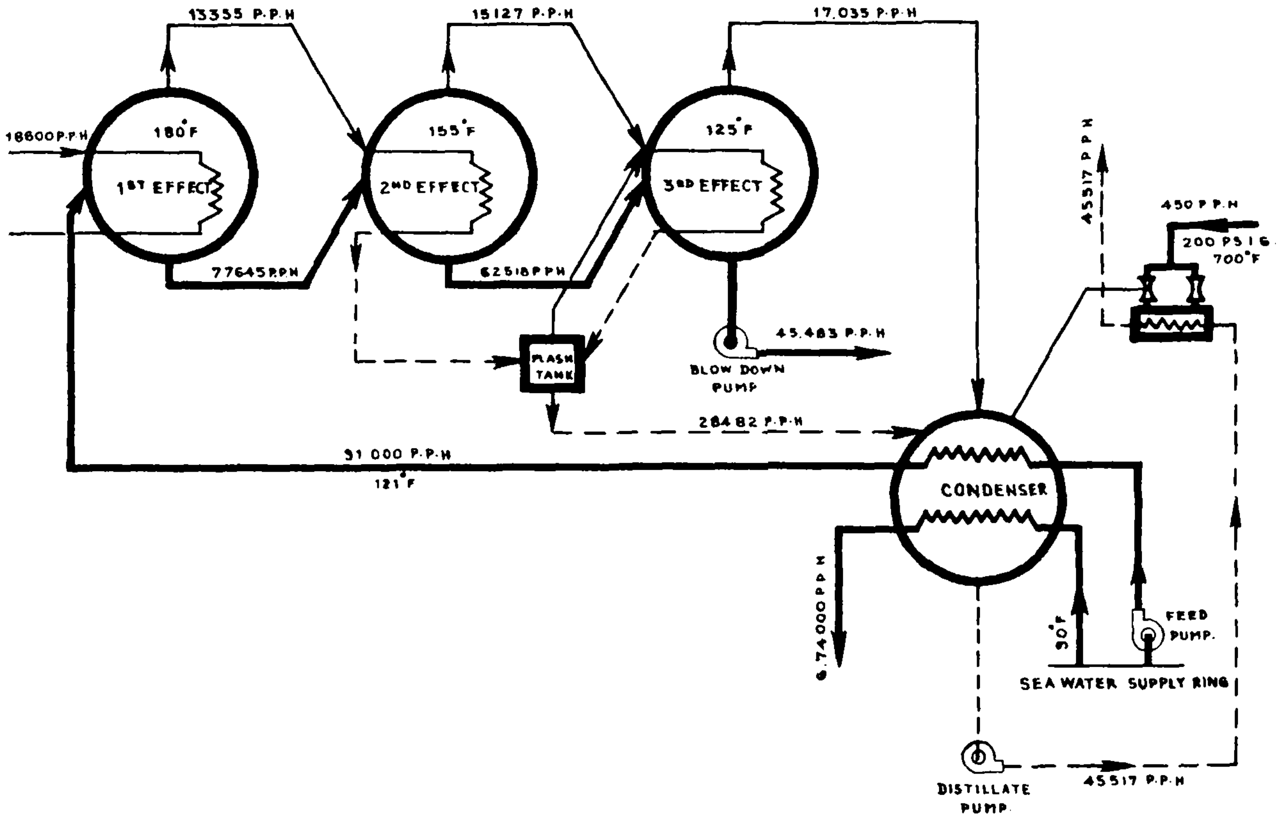


Figure 5. Heat Flow Diagram, Submerged Tube Type Sea Water Evaporator, Shuwaikh 'A' Plant

Specific Heat Consumption 520 Btu/lb of Distillate.

━━ Sea Water And Brine —— Steam And Condensate ----Distillate.

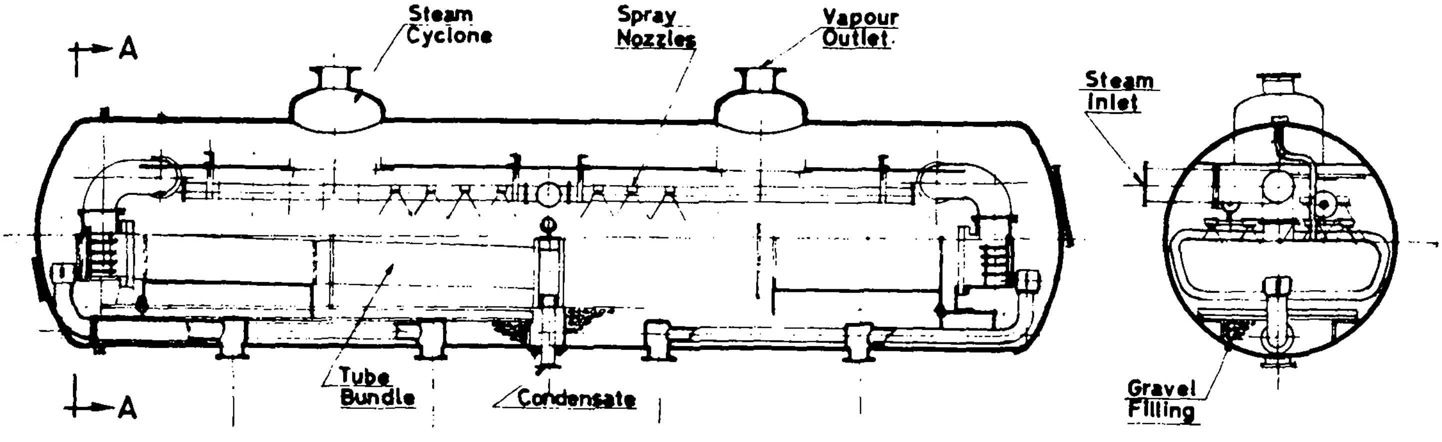


Figure 6. Submerged Tube Type Sea Water Evaporator Shuwaik 'A'

Section-AA

Section In A Stage With Re-circulation.

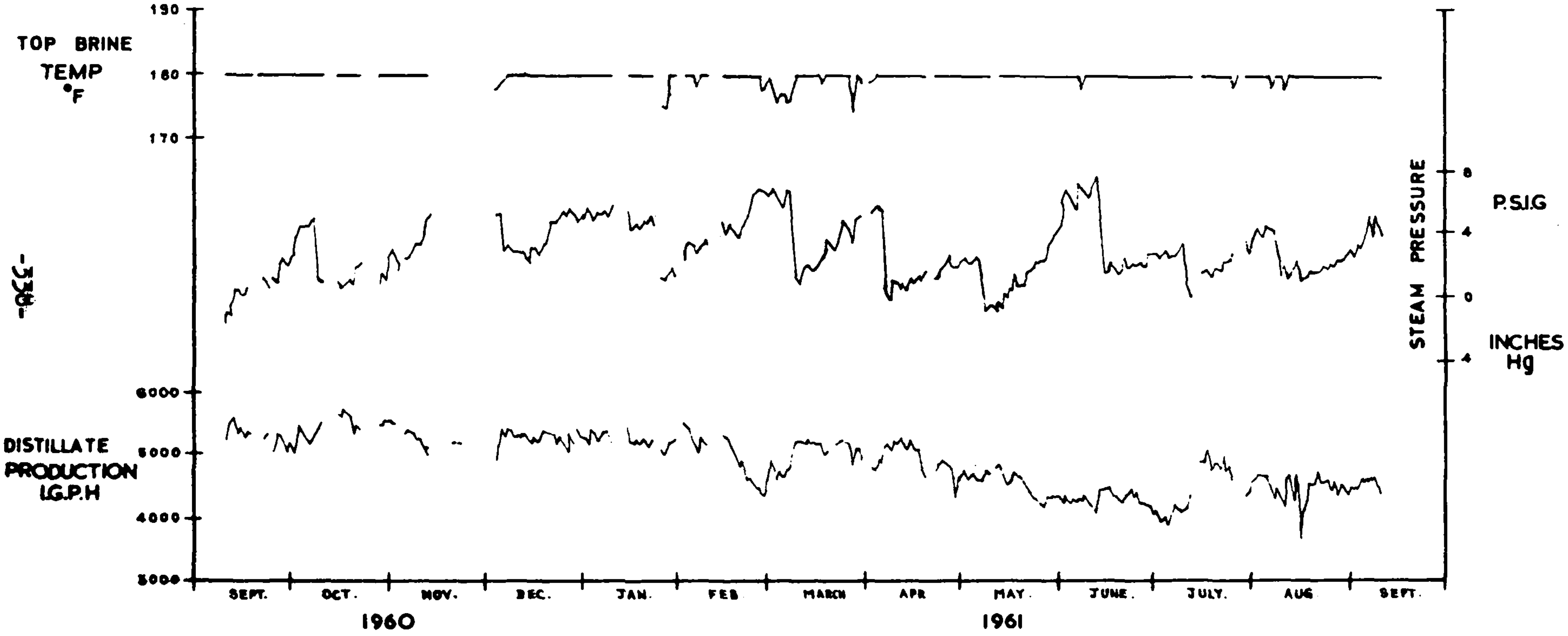


Figure 7. Submerged Tube Type Evaporator, Shuwaikh 'A' Plant (Without Recirculation)

Density As Nacl. Ratio 2-P.D8 Injection 2.5 PPM

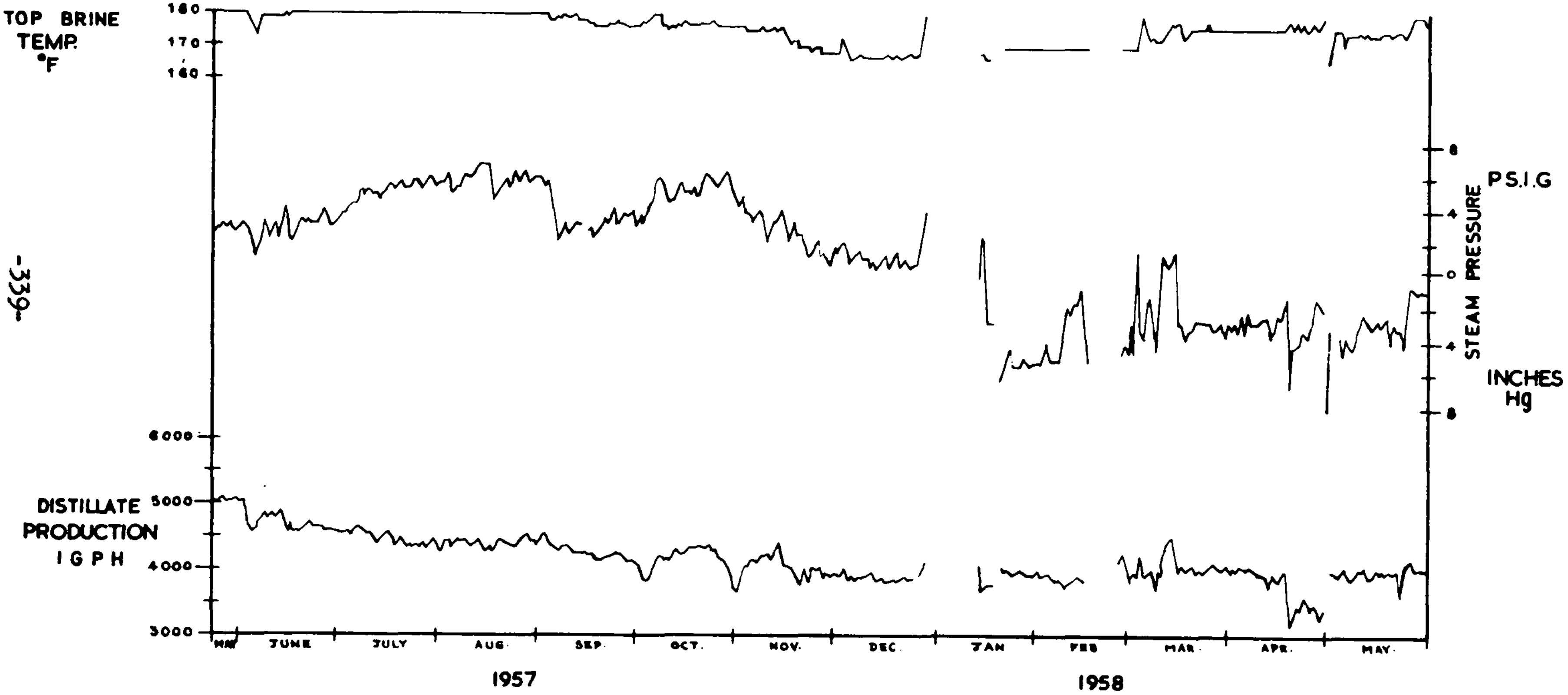


Figure 8. Submerged Tube Type Evaporator, Shuwaikh 'A' Plant (With Recirculation)

Density As Nacl Ratio 2 - PD8 Injection 2.5 PPM.

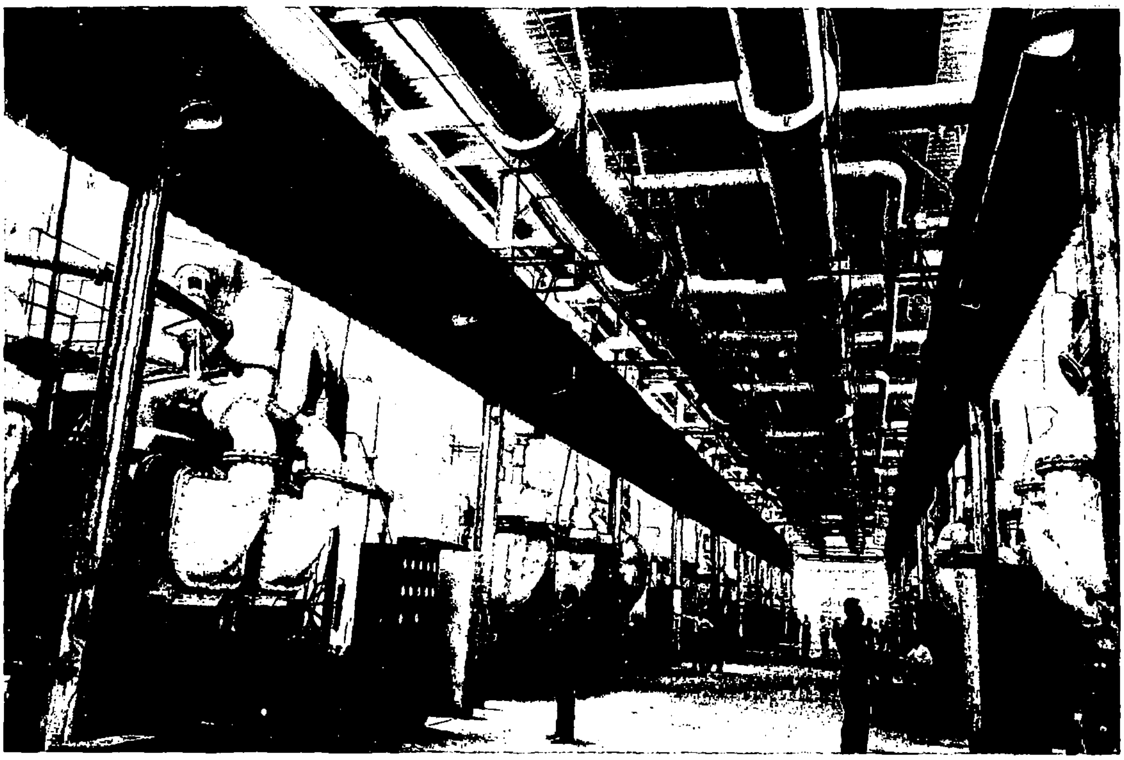


Figure 9. Shuwaikh'B' Distillation Plant

Figure 10. One Evaporator, Shuwaikh'B' Distillation Plant

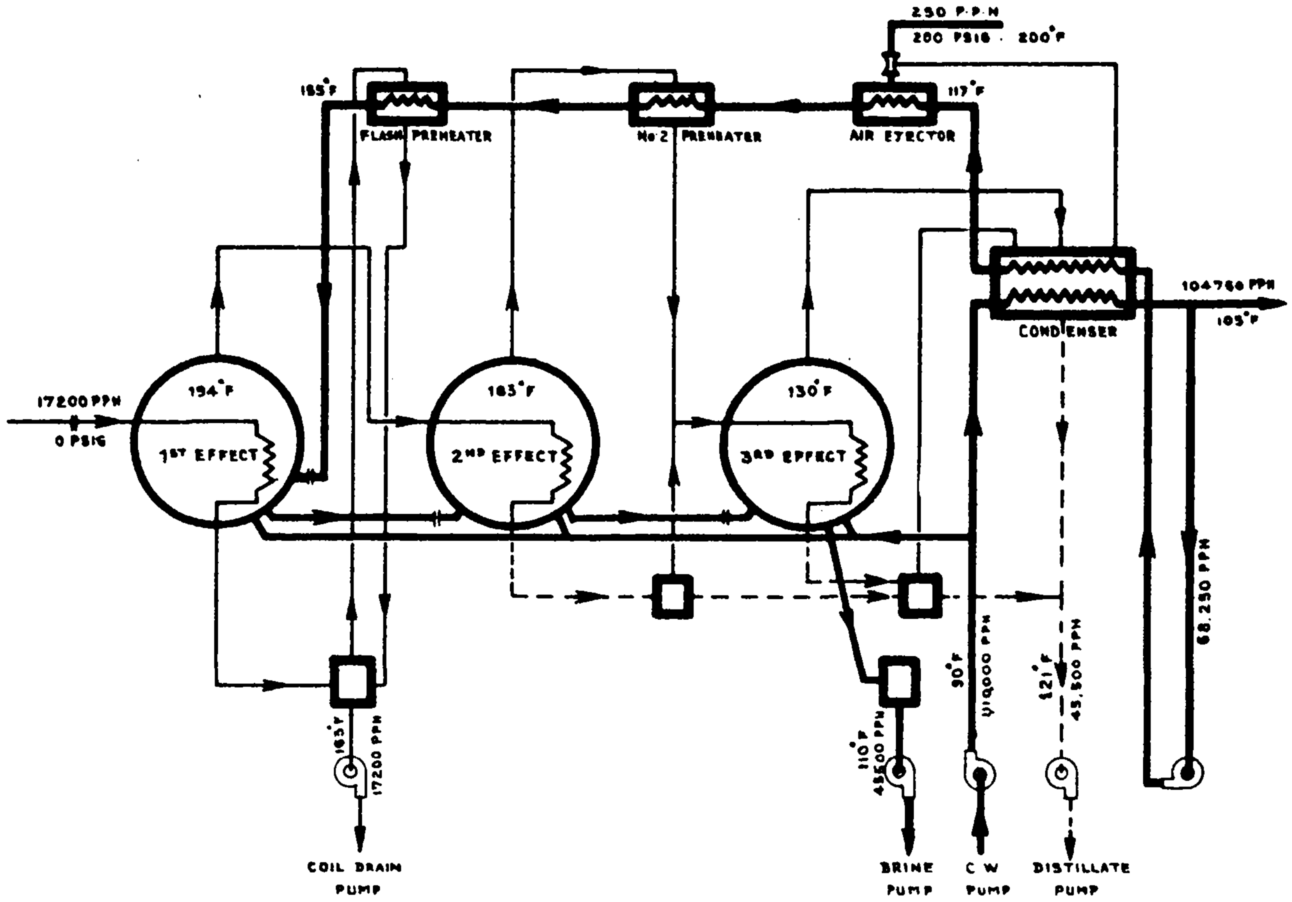


Figure 11. Heat Flow Diagram, Submerged Tube Type Sea Water Evaporator, Shuwaikh 'B' Plant.

Specific Heat Consumption 420 Btu/lb of Distillate.

▬▬ Sea Water And Brine —— Steam And Condensate ---- Distillate.

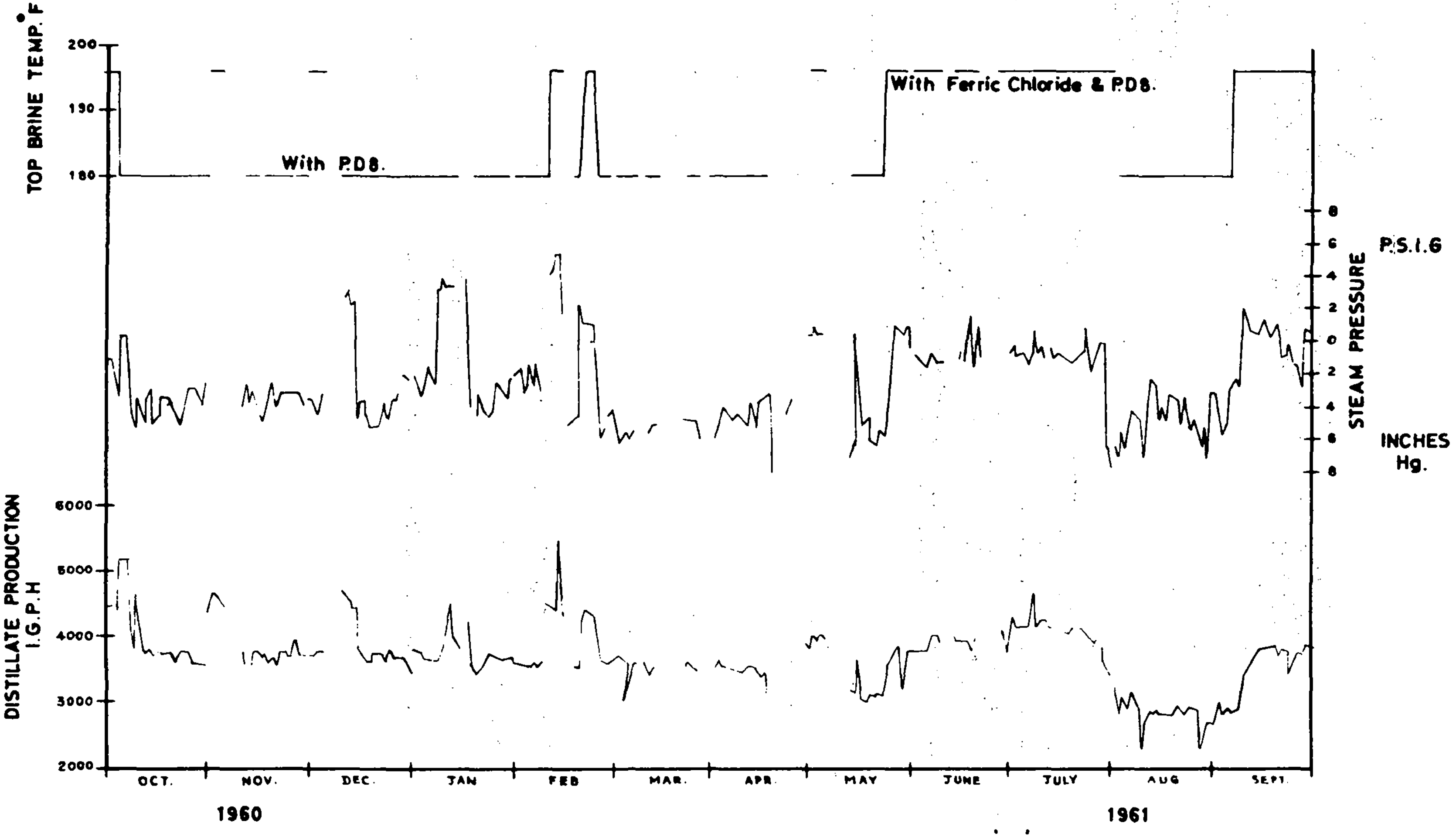


Figure 12. Submerged Tube Type Evaporator Shuwaikh B Plant

Density As Nacl. Ratio 2 - P.D8 Injection 2.5 P.P.M Ferric Chloride 150 P.P.M.

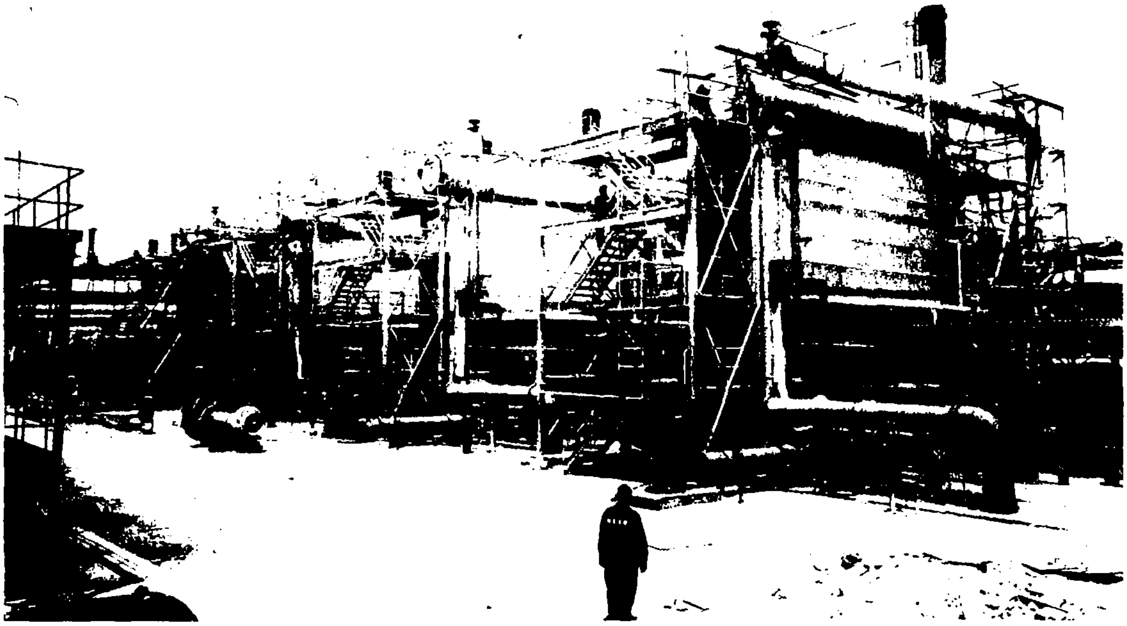


Figure 13. Shuwaikh 'C'&'D' Distillation Plant

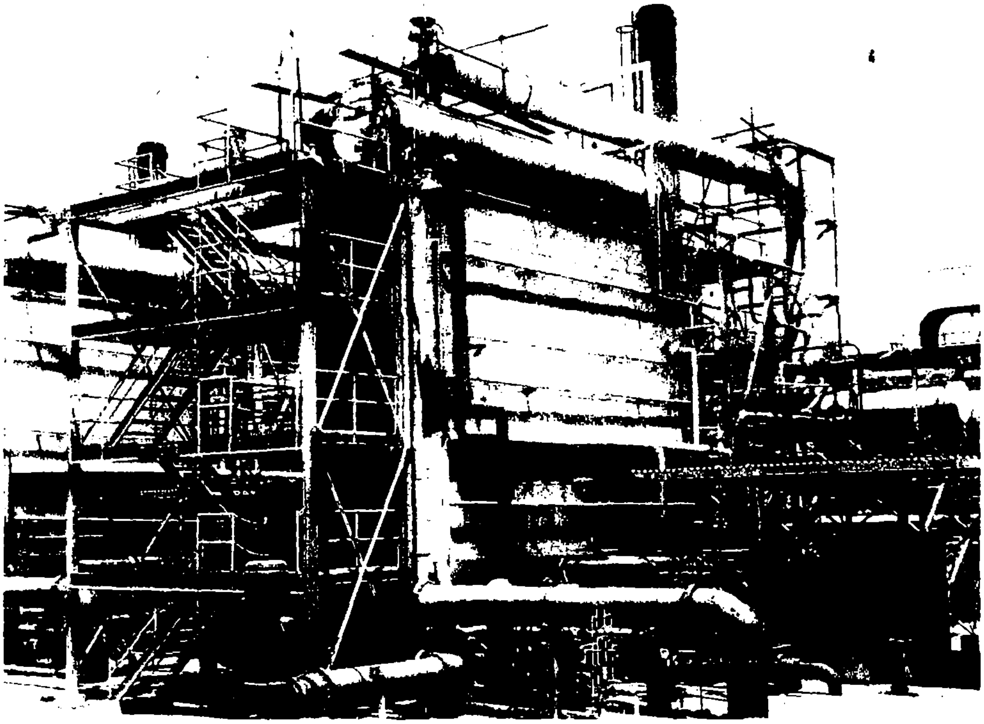


Figure 14. One Evaporator, Shuwaikh 'C'&'D' Distillation Plant

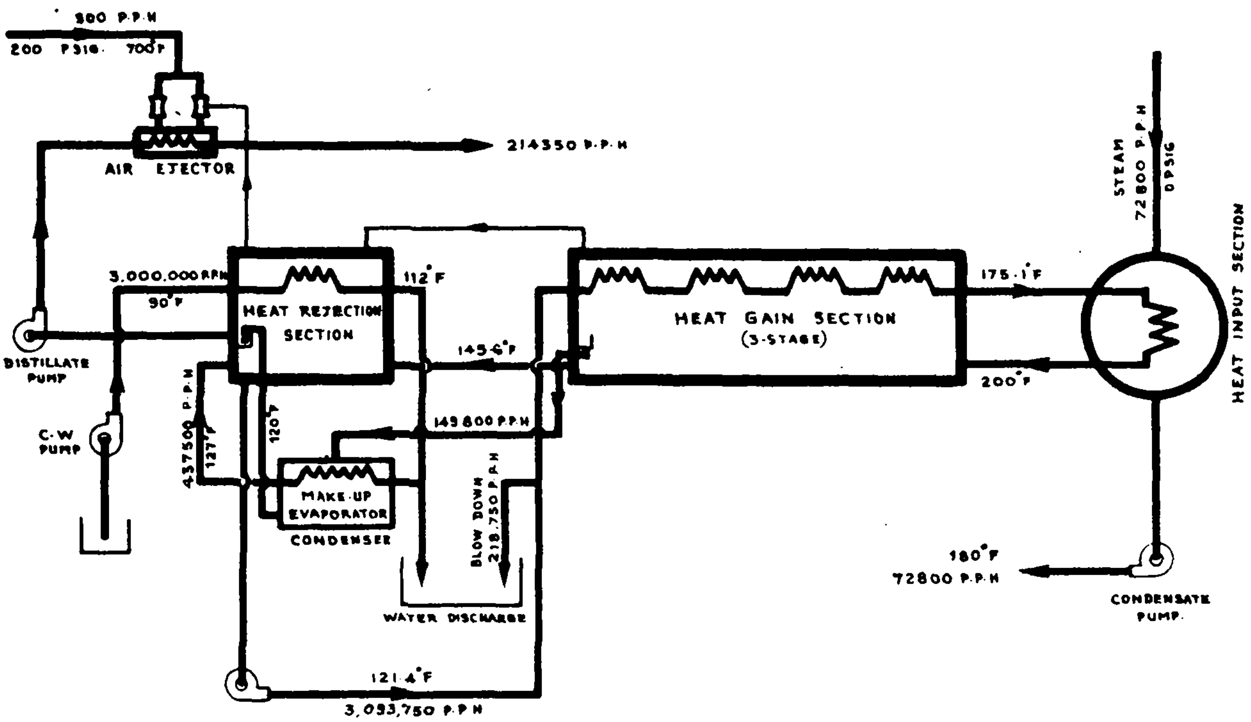


Figure 15. Heat Flow Diagram, Flash Type Sea Water Evaporator, Shuwaikh 'C' & 'D' Plants.

Circulation Ratio 13.4 – Specific Heat Consumption 345 Btu/lb of Distillate.

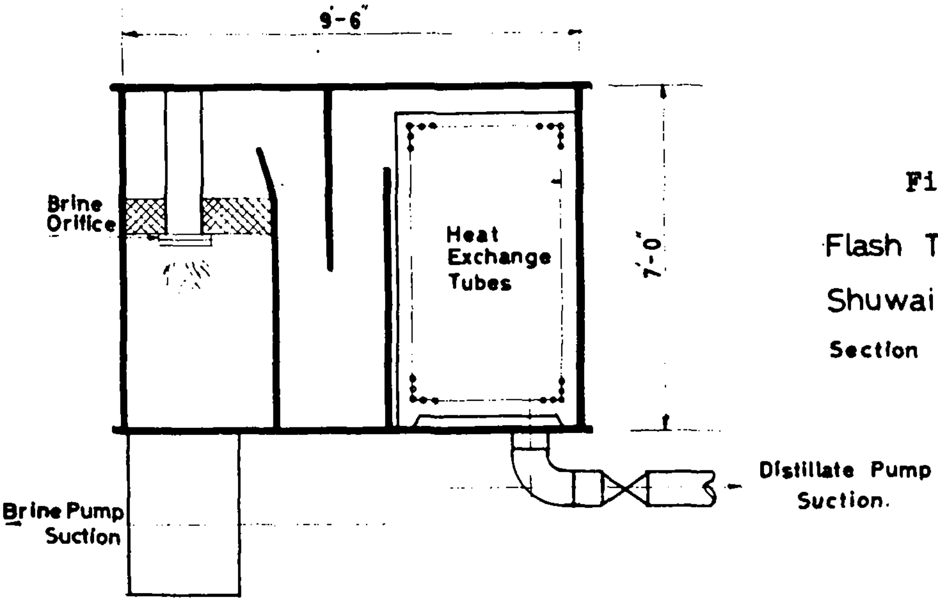


Figure 16

Flash Type Sea Water Evaporator

Shuwaikh 'C' & 'D'

Section In A Stage.

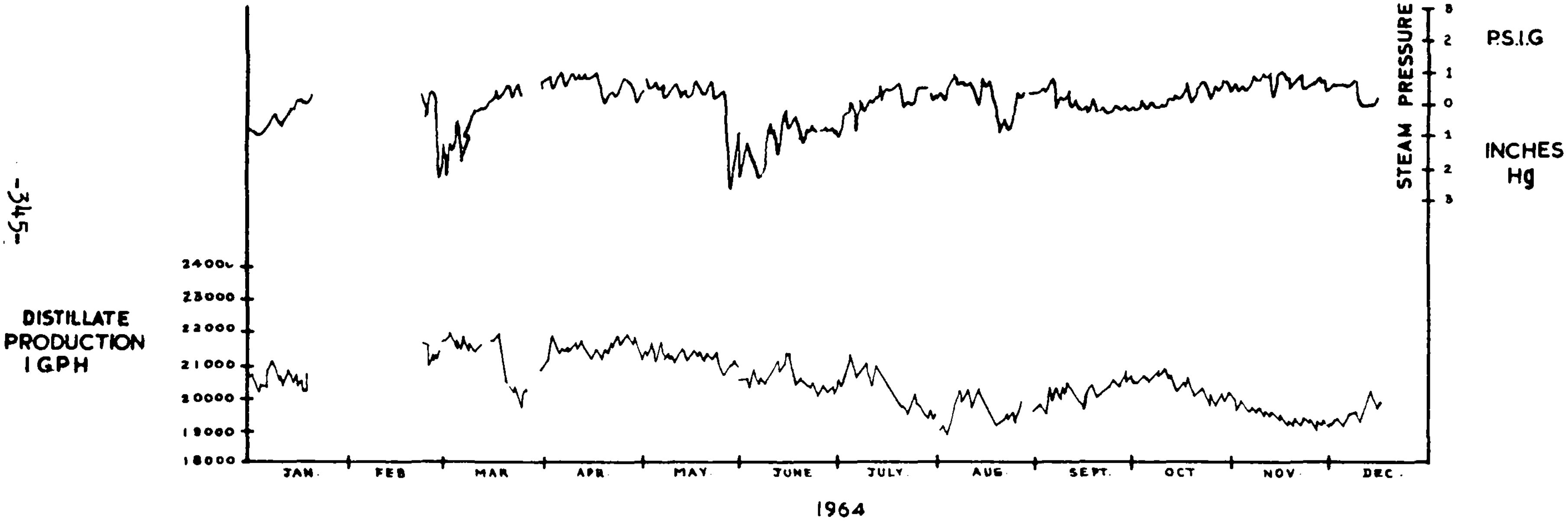


Figure 17. Flash Type Evaporator, Shuwaikh 'C' Plant.

Top Brine Temp. 194°F - Density As Nacl Ratio 1.8 - P.D 8 Injection 5 PPM.

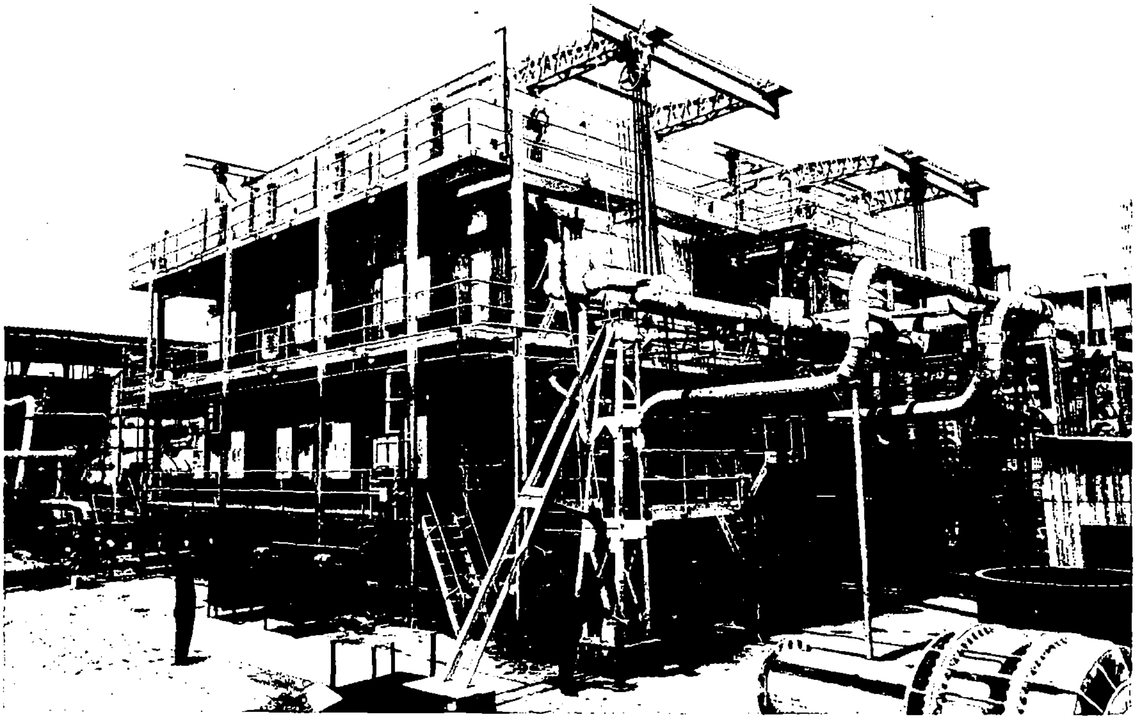


Figure 18. Shuwaikh 'E' Distillation Plant·

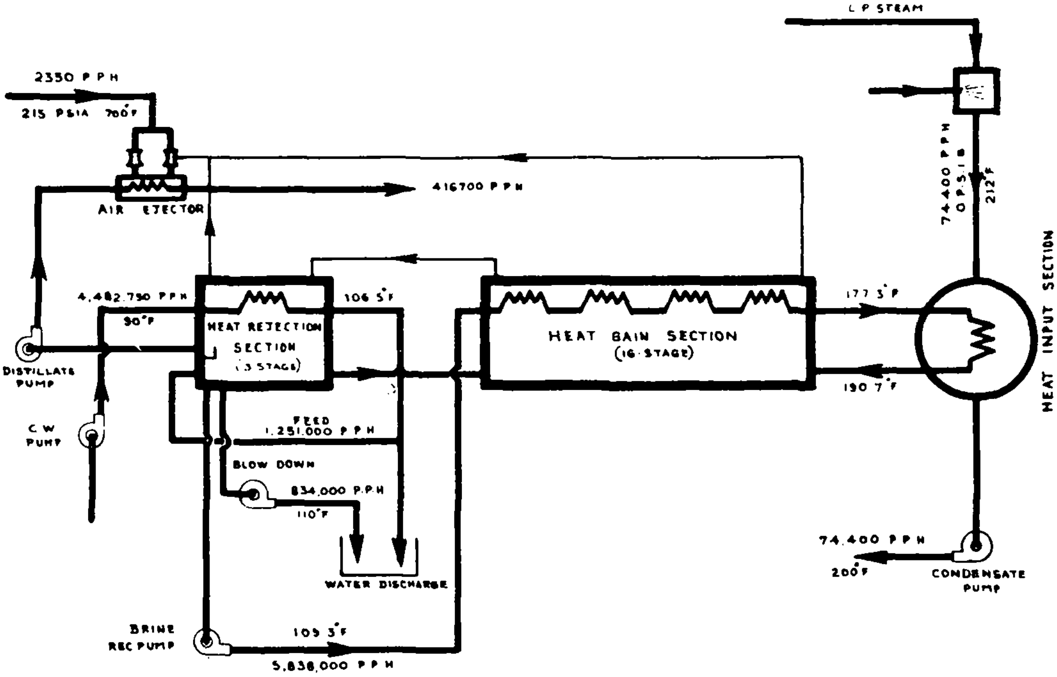


Figure 19. Heat Flow Diagram, Flash Type Sea Water Evaporator, Shuwaikh 'E' Plant.

Circulation Ratio 14 – Specific Heat Consumption 184.75 Btu/lb of Distillate.

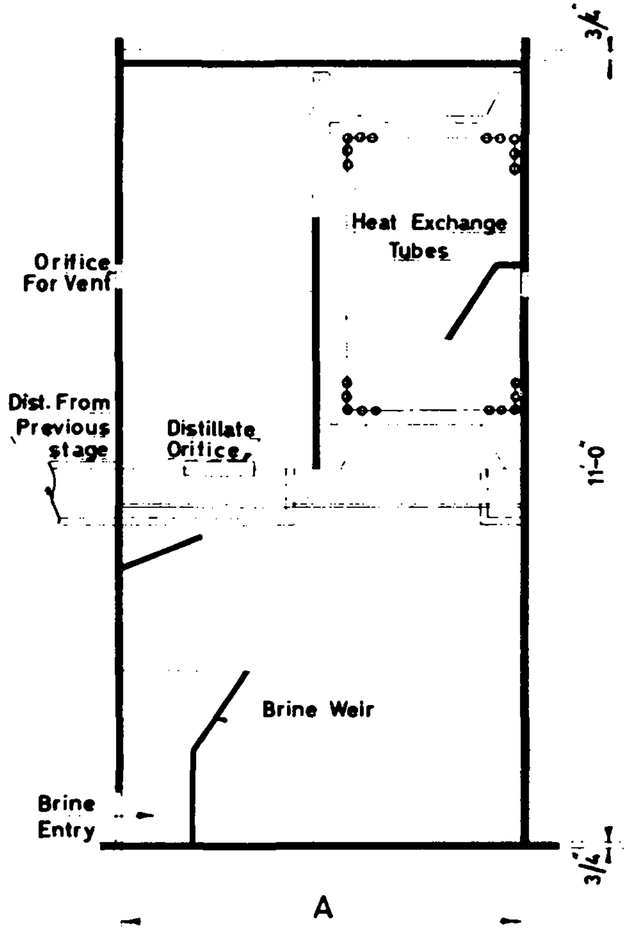


Figure 20. Flash Type Sea Water Evaporator Shuwaikh 'E'

Section In A Stage

A. Varies From 4'-2 3/4" to 10'-4 3/4".

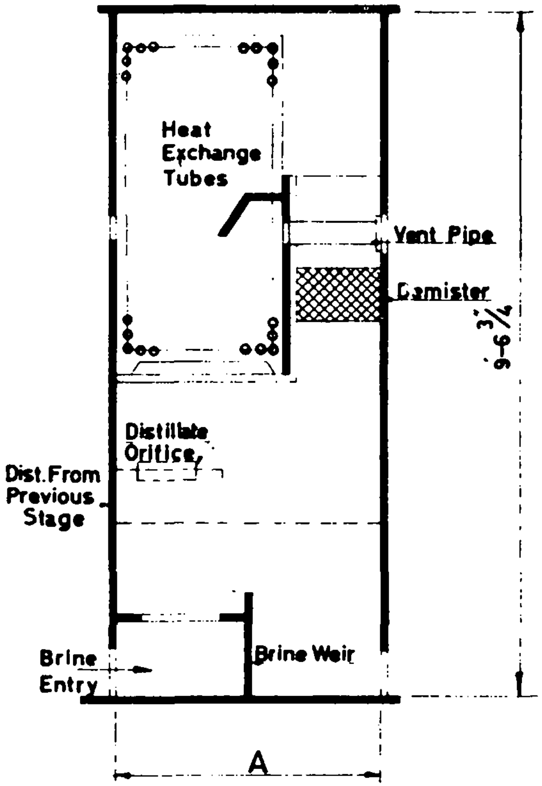


Figure 25. Flash Type Sea Water Evaporator Shuwaikh 'F'

Section In A Stage

A. Varies From 3'-8" to 9'-6"

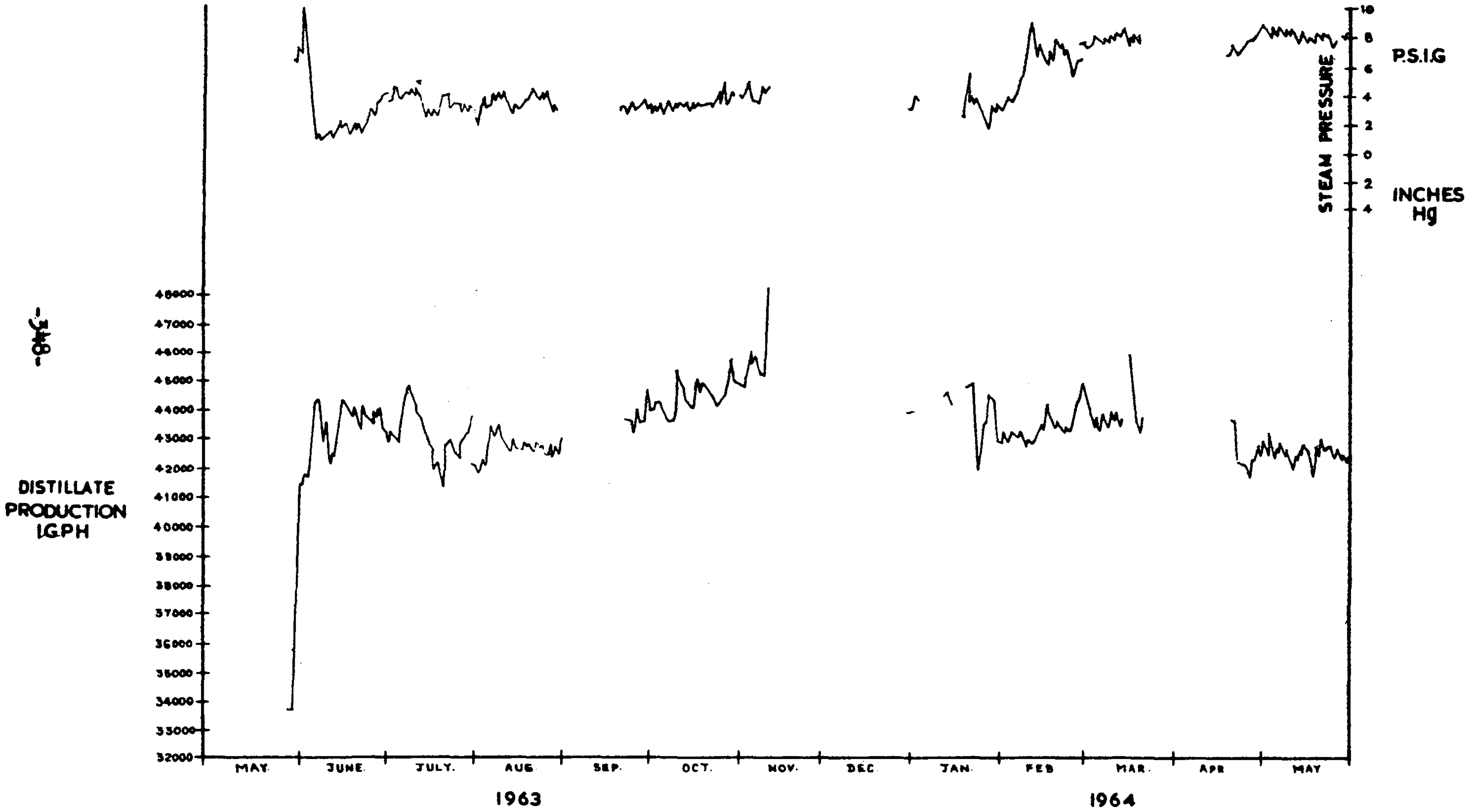


Figure 21. Flash Type Evaporator, Shuwaikh 'E' Plant

Top Brine Temp. 194°F - Condenser C.W. Outlet 110°-112°F

NaCl. Ratio 1·8 – P.D 8 Injection 5 PPM.

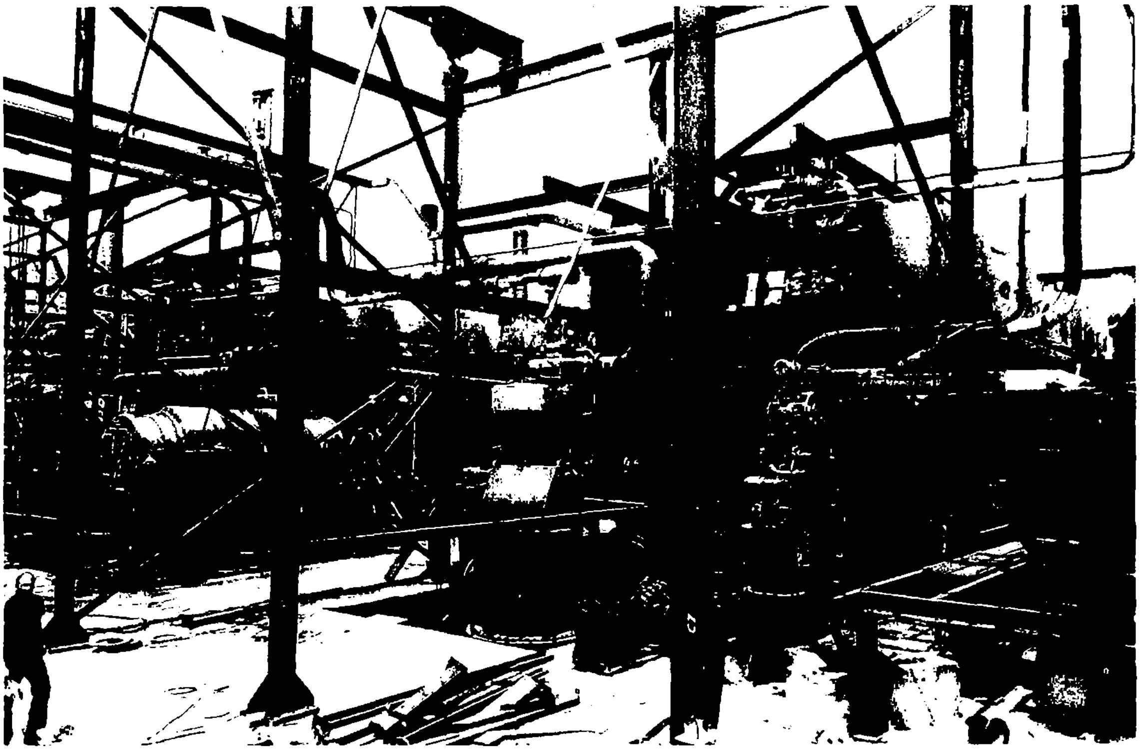


Figure 22. Shuwaikh 'F' Distillation Plant

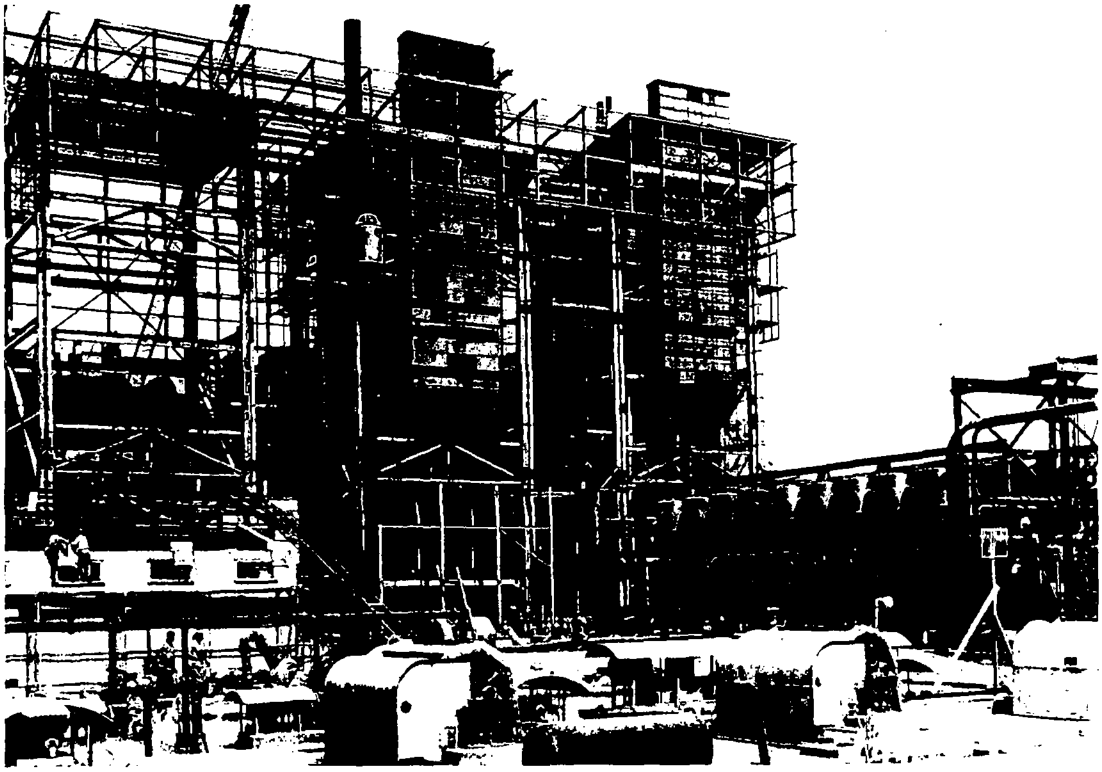


Figure 23. Shuaiba Power Station and Distillation Plant

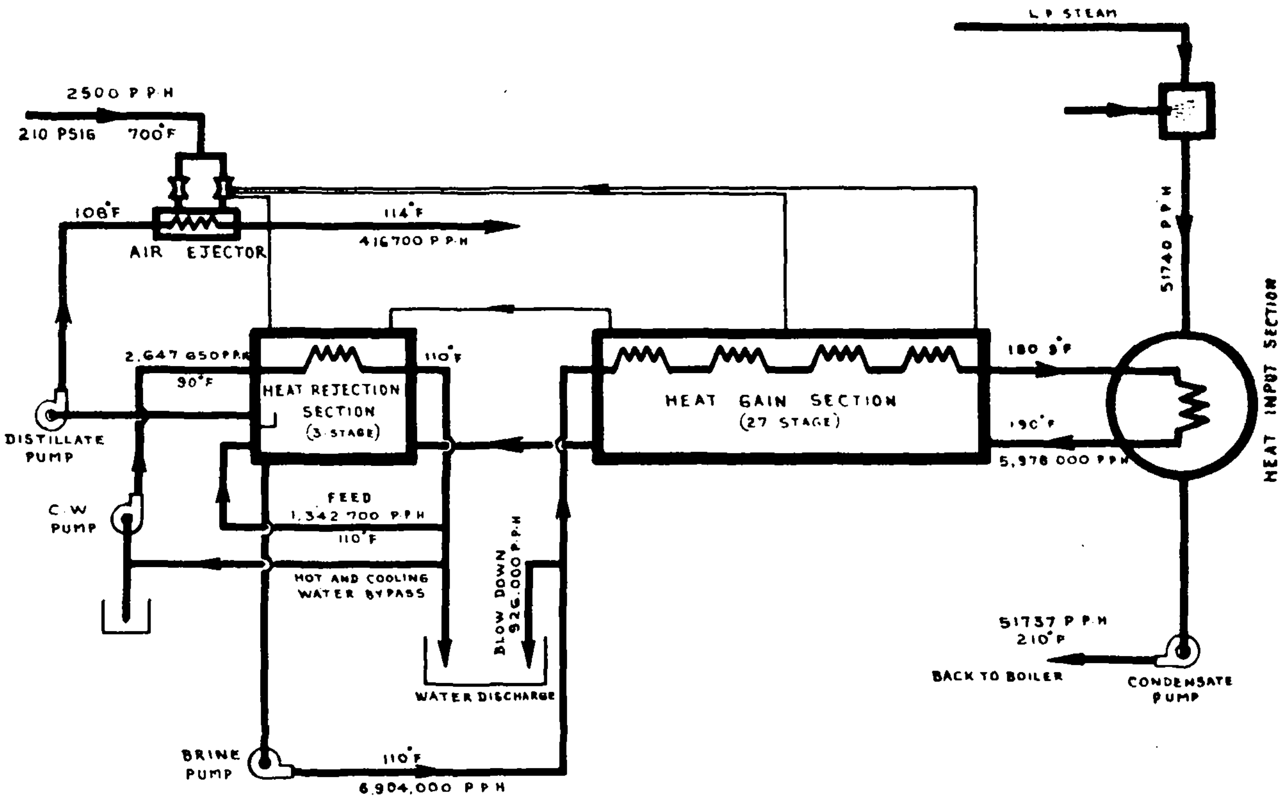


Figure 24. Heat Flow Diagram, Flash Type Sea Water Evaporator, Shuwaikh 'F' Plant.

Circulation Ratio 14·3 – Specific Heat Consumption 134·7 Btu/lb of Distillate.

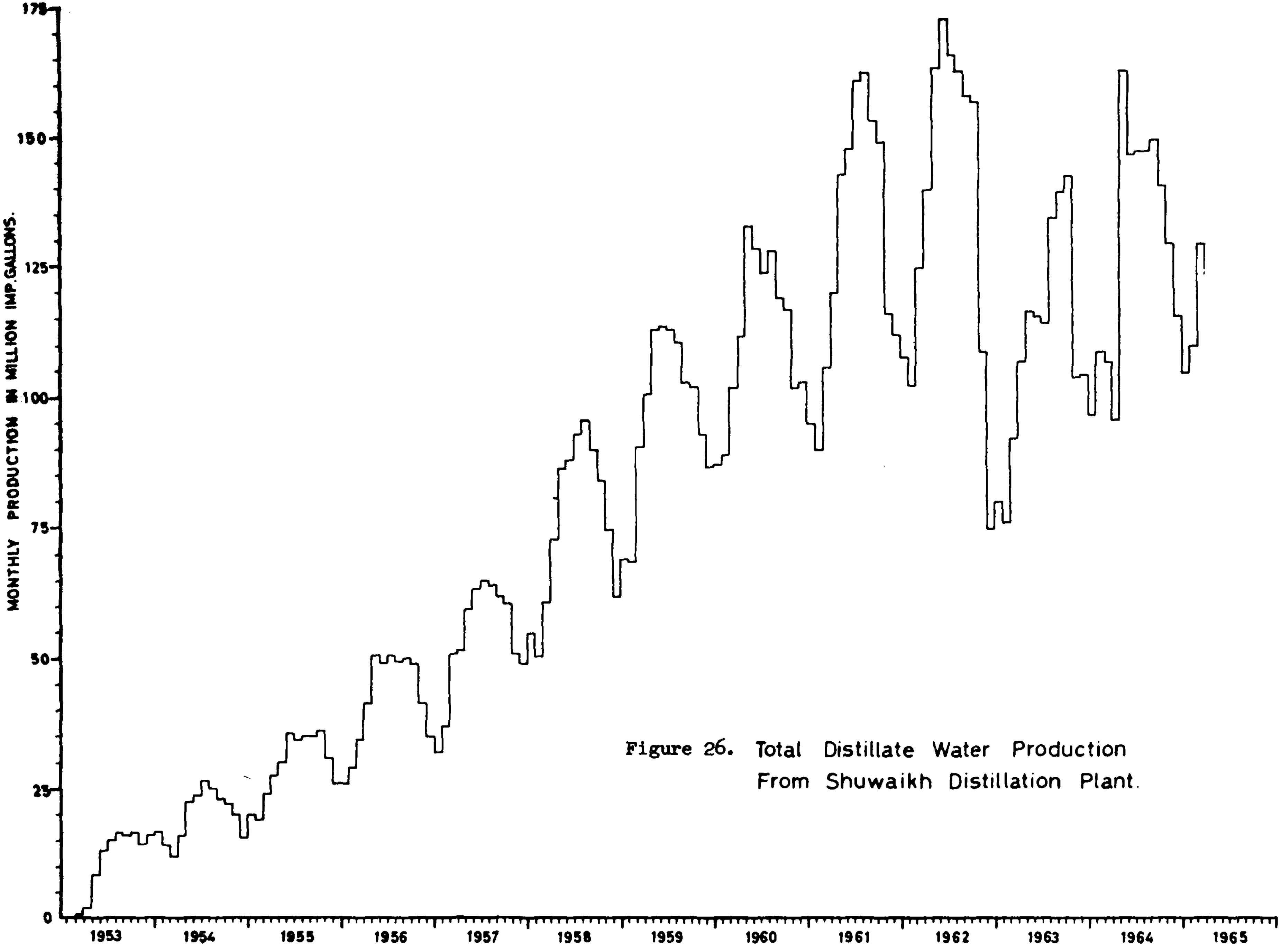


Figure 26. Total Distillate Water Production From Shuwaikh Distillation Plant.

III. OPERATION OF A DESALINATION PLANT IN THE UNITED STATES VIRGIN ISLANDS

by R. V. Knapp

A. History of facility

The Island of St. Thomas has throughout its history been plagued by a deficiency of potable water. It has relied largely upon rain water falling into catchment basins constructed on the hillsides around its principal city, Charlotte Amalie, and in recent years on the airport runway. This has been supplemented also by water brought in by barges from Puerto Rico. The cost of the barged water varied greatly depending on the carrier, which has sometimes been a commercial carrier, sometimes vessels owned by the local Government and sometimes the United States Navy.

Because of this situation, the Secretary of the Interior of the United States recommended to the Congress in early 1958 the enactment of legislation to authorize the construction and operation by the Virgin Islands Corporation of salt water distillation facilities. The request for legislative authorization was accompanied by a contractual agreement between the Virgin Islands Corporation and the Virgin Islands Government, by which the latter agreed to purchase the water produced at a price covering all production costs plus a reasonable rate of return. As a result, the Congress, on 2 September 1958, approved a bill authorizing the Virgin Islands Corporation to "construct, operate and maintain salt water distillation facilities in St. Thomas, Virgin Islands".

B. Design

The present plant, costing $2,100,000.00 in round figures was completed in January 1962. It consists of a 28-stage flash evaporator combined with a steam power plant. The evaporator was designed for 275,000 gpd of water having a salinity of not more than 5 parts per million. Sea water is supplied to the plant through about 800 feet of 16 inch cast iron cement lined pipe, by three 1800 gpm pumps, installed in an intake structure equipped with a trash rack and a travelling screen. The screen is manually operated.

The steam power plant consists of two 30,000 lb per hour, 600 psig 750°F water tube boilers supplying an extraction-condensing turbine driving a 3750 KVA, 80 per cent power factor, 13,200 volt generator. Extraction steam at 5 psig from the turbine is the heat source for the distillation process.

1. Design features of plant

Item	Rating
Rated capacity - gpd	275,000
Thermal economy - lb of water/1,000 BTU	7
Max. brine temp. - ^{o}F	195
Design sea water temp. - ^{o}F	85
Distillate impurities - ppm	5

2. Equipment troubles

Many operating problems have been encountered, caused by improper choice of construction materials, engineering errors and lack of operating knowledge.

3. Pump intake structure

The pump intake structure is supplied with a travelling screen. The screen is Monel and the structural parts are carbon steel. The unit is rotated and washed twice a day. After start-up of the evaporator it was found necessary to seal the sides and bottom with angle iron and install polyethylene strips between screen sections to eliminate entry of floating solids into pump suctions. The intake was also poorly located so a 48-inch tar coated steel pipe suction line, 40 feet long, was installed to eliminate troubles with floating solids. Operation has been satisfactory since the changes were made. The steel housing structure is in poor condition, but it will live until a new unit in a new location is completed.

4. Sea water pumps

The heat balance requirements for the plant are 1,980 gpm of sea water for the distillation plant and 2,480 gpm for the turbine condenser. This makes a total of 4,460 gpm, which means that all three of the 1,800 gpm pumps must be operated to get full distribution and generating capacity. Such a situation was impossible. Accordingly, supply piping was revised so that the water would flow through the turbine condenser and distillation plant in series rather than in parallel. So, only two pumps are required for operation, with one spare. The pumps of the vertical type, as supplied, had Ni-resist cast iron casings, wrought iron columns, Ni-resist impeller bowls, 316 stainless steel impellers and 416 stainless shafts and couplings. Because of electrolysis, pump shafts, columns and couplings began to fail about two months after start-up. The shafts and couplings being of 416 stainless, which is magnetic, were replaced by non-magnetic 316 stainless steel units and the pump columns were made of 316 stainless steel. Initially the pump suctions were installed about 6 inches below normal low-tide water level. Their level had to be dropped 3 feet to improve their submergence since wave action would cause the pumps to lose suction.

5. Pipeline

The 16-inch cast iron cement lined pipe has been quite satisfactory. However, the pipe is of bell and spigot construction installed on piers above ground without adequate anchoring. It has been necessary to provide added anchors to keep the line in place.

6. Evaporators

The evaporators are of the horizontal flash type with 28 stages in four bodies. All bodies have 894 5/8 inch O.D., 0.049 inch wall tubes. Three bodies have tubes 58 ft 10 inches long and the fourth 30 ft 8 inches of aluminium brass.

Water boxes were cast iron and the cross-over lines were rubber-lined carbon steel.

On the evaporators and piping we have had some troubles and many problems. Our main problem has been trying to keep the tubes clean.

Aqua-Chem chemicals and Haveg have been used in the feed water to the unit and with both it was necessary to shut the unit down for acid cleaning. The time employed for such cleaning has varied from 18 hours to 36 hours using hydrochloric or sulphamic acid. The sulphamic acid was used finally as it was a safer material for our workmen.

Some months ago we started feeding hydrochloric acid and later sulphuric acid into the system with the make-up feed water to maintain pH at the water heater outlet on an experimental basis. As this seemed to be a successful method of controlling scale we installed manual pH control and a deaerator. The use of this equipment seems to keep scaling under control when maintaining the pH at about 7.1 to 7.2 but our efficiency is lower than it should be.

However, as long as we can make an adequate amount of water, we will keep the plant in operation until a new 1 mgd unit now under construction goes into operation in November this year.

A large amount of trouble was caused by the rubber lining in the cross-over piping tearing loose and blocking the tube sheets. Also, graphitization of the cast iron water boxes was experienced. Eventually, it was necessary to replace the water boxes and piping with copper-nickel units.

Shortly after starting up the unit, it was found necessary to revamp the gauge glass installations. The glasses had been installed with two elbows at the top and bottom of each glass. Trouble was experienced with leakage in the joints and many glasses were broken due to changes in alignment. Longer glasses were installed without the extra fittings to correct this defect. It was also necessary to remove the drain valves at the bottoms of the various stages to eliminate leakage. When the valves were used, any sediment which did not wash out would prevent proper closure and leakage resulted. The valves were replaced with pipe caps. All of the demisters have been replaced because of scaling and deterioration. Future demisters should be made of Monel or 3.6 stainless steel. This equipment may also be partly responsible for our lowered thermal efficiency.

Many minor troubles have been experienced with vent dampers, distillate dampers, gauge valves, steam jet ejectors and other items, as air leakage and removal are important to operation and have a definite effect on operating results.

7. Salt water heater

This unit is a 4 pass heater with 2,509 square feet of heating surface in 1,400 3/4 inch O.D., 0.049 inch wall 9 ft 6 inch long aluminium brass tubes.

No trouble has been experienced with the heater except that of cleanliness.

8. Pumps

The pumps as supplied have been reasonably satisfactory and were built as follows:

Distillate pumps - all bronze.
Condensate pumps - cast iron casings with bronze impellers and stainless steel shafts.
Brine pumps - all bronze with Monel shafts.

It was necessary to rebuild the condensed pump piping in order to get adequate capacity.

The net positive suction head on the brine pumps is on the short side, so any drop in brine level in the evaporator body on the section side creates a leakage problem and a subsequent loss of vacuum. Maintaining proper shaft sealing on the horizontal pumps is a constant chore.

9. Boilers

A high sulphur No. 6 fuel oil is being burned and the boiler inner casings were not properly sealed. Consequently, furnace gases passed around the edges of the inner casing, causing corrosion of the outer casings to the point where the entire casings on boilers and economizers had to be replaced. The inner casings as rebuilt were sealed to prevent recurrence of this.

An additional difficulty on our steam generating units was failure of economizer tube return bands. Operation of the boilers without the economizers caused a definite increase in steam costs.

10. Operating Results

It is quite easy to see that operation of this plant has not been very economical because of the many mechanical faults and the nature of those faults. If the trouble was not with the evaporator system, it was with the boilers, with attendant increase in steam cost. However, even though the plant was designed for a production rate of 275,000 gpd, it has been possible to easily maintain a production rate of around 300,000 gpd.

Design production cost was estimated at $1.75 per thousand gallons. During the first eleven months of operation, costs were $2.37 per thousand gallons. This was a result of writing-off the cost of changing the sea water piping and the low production rates of the first four months.

Following this, costs have risen until on 30 June 1964 they had reached $3.21 per thousand gallons. Costs for the fiscal year closing 30 June 1965 are not available at the time of writing this paper.

While costs are interesting they do not present a figure which can be readily or honestly compared. It is felt that pounds of water produced per 1,000 BTU is a figure which can be compared with all types of units.

Following are such figures for this plant:

1962	(11 months)	6.13	lb	of water	per	1,000	BTU
1963		6.64	"	"		"	"
1964		5.64	"	"		"	"
1965	(5 months)	5.11	"	"		"	"

The above values show a steady decrease in plant efficiency since 1963 which is attributed to the excessive number of shut downs required for repairs and by the local government purchaser, although it is felt that fouling conditions in the unit also contribute.

What has been written in the foregoing report on the experiences in this plant may seem somewhat derogatory. It is hoped that this is not the impression that has been created. The art or science of water distillation is new and many lessons still remain to be learned. There is no doubt that many of the problems encountered in this plant belong to, or were created by, the operators and the aim of this paper has merely been to point out our problems for the benefit of any interested parties. It is felt that this plant has been of benefit to all and that it has served St. Thomas very well.

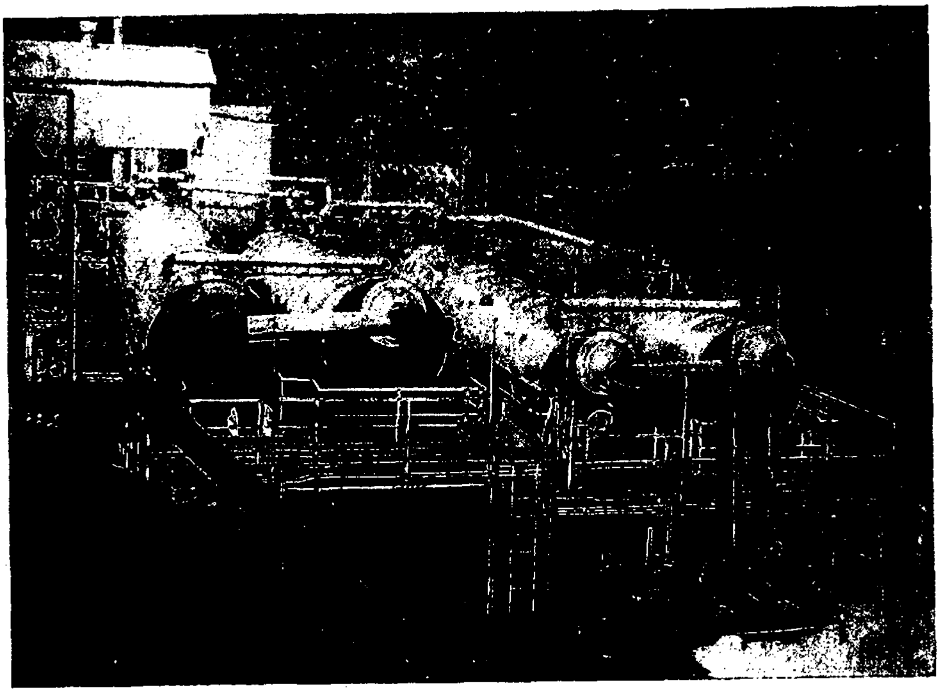


Figure I. **Sea Water Distillation Plant**

The plant, located in St. Thomas, produces 275,000 gpd.

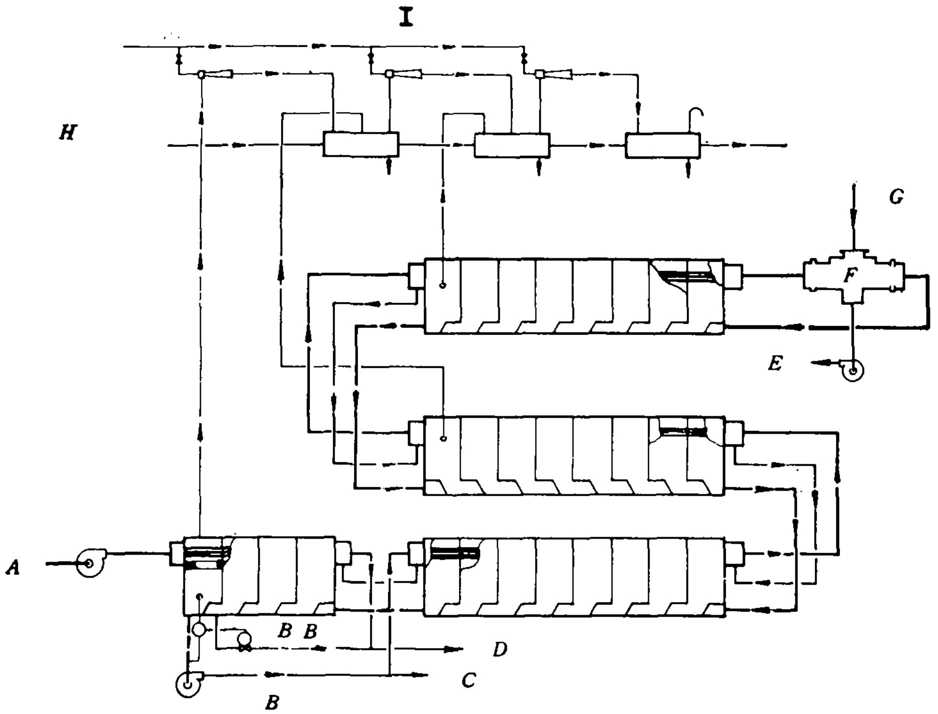


Figure II. **Flow Chart of Distillation Plant**

In the diagram, A *represents sea water feed;* B, *brine recirculation;* BB, *makeup;* C, *blowdown;* D, *cooling-water discharge;* E, *condensate;* F, *the sea water heater;* G, *the low-pressure steam;* H, *the sea water used for cooling; and* I, *the air ejector system.*

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ANNEX I

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