Nuclear Energy for Water Desalination
NUCLEAR ENERGY FOR WATER DESALINATION
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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world”.

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NUCLEAR ENERGY
FOR WATER DESALINATION

REPORT OF A PANEL ON THE USE OF
NUCLEAR ENERGY FOR WATER DESALINATION
HELD IN VIENNA
5-9 APRIL 1965

INTERNATIONAL ATOMIC ENERGY AGENCY
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NUCLEAR ENERGY FOR WATER DESALINATION
IAEA, VIENNA, 1966
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Nuclear energy can play an important part in the production of fresh water from saline water to meet the growing water shortages in many parts of the world. During the sixth General Conference of the International Atomic Energy Agency in 1962, the Tunisian delegate emphasized the potential application of atomic energy to desalination, especially for the developing countries. While such possibilities appeared rather distant at that time, significant progress has since been made. In his address summarizing the results of the Third International Conference on the Peaceful Uses of Atomic Energy, Dr. Glenn T. Seaborg observed:

"The studies that have been undertaken to date indicate that combination nuclear installations in the next few decades will be able to produce fresh water and electric power at costs which may be attractive for many municipal and industrial needs throughout the world. The water from these combination plants may even find economic potential for selected agricultural use when compared with other alternatives in specific situations."

To reach these goals, much effort and time will be required. Extensive research and development programmes, covering both desalting and reactor technology, have been started in different countries to reduce the cost of desalted water. In view of the complexity and magnitude of the problems encountered in finding the best solution to meet the water requirements in a given area, there is a great need for close co-operation among the national and international organizations involved. The Agency is aware of its responsibilities in nuclear desalination and is anxious to play its role in furthering international collaboration.

As part of its programme for nuclear desalination, the Agency has already held a series of five panels to cover various aspects. This publication deals mainly with the fifth panel, which was held in April 1965 under the chairmanship of Mr. J. Gaussens and attended by 37 participants and observers from 17 countries and international organizations. It includes a summary of the points emerging from the discussions, the papers prepared for the Panel, abstracts of the reference material submitted to the Panel, and the recommendations of the Panel on the Agency's future activities. For convenience, it was thought desirable to include in the annexes a brief account of the two immediately previous panels held in April 1964 and September 1963.

The Agency is grateful to various Member States for their support and to the participants in the panels for their valuable contributions.
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SUMMARY REPORT AND RECOMMENDATIONS

1. INTRODUCTION

The Fifth Panel on the Use of Nuclear Energy for Water Desalination, held from 5 to 9 April 1965, had two main objectives.

Firstly the Panel reviewed the latest developments pertaining to nuclear desalination and related topics, thereby continuing with the work of the earlier Panels. A number of valuable papers and studies were presented and discussed. A summary of the highlights of the proceedings is given. No attempt is made to make this summary comprehensive and appropriate references are provided wherever necessary.

Secondly, the Panel - at the request of the Agency - made recommendations regarding a possible programme of future activities by the Agency in the field of nuclear desalination. For this purpose, a working group of experts and members of the Secretariat met earlier and drafted a report for the consideration of the Panel. The final recommendations of the Panel are included in the summary report and have been accepted by the Director General to form the basis of the future programme of the Agency in this area.

2. WATER QUALITY

The quality of water is an important consideration in determining its potential use. A wide range of use values can be assigned to water of a given quality depending upon the consumer's requirements. It would not be appropriate to assign systematically a high value to water of high quality. This value can only be determined after having estimated the economic benefits resulting from its use in a specific situation.

From the point of view of the consumer, the quality of the water can be of prime importance. As far as salinity is concerned, this quality is expressed both by the total amount of dissolved salts and the nature and quantity of each one of them. For a desalination plant, the choice of process depends on the quality of the water both upstream and downstream of the plants: upstream the quality is determined by the source of the water, while downstream it is fixed by the consumer.

3. DESALINATION PROCESSES

3.1. Cost components [1, 2]

The energy consumption is one of the important parameters of a water plant. The various desalination processes offer a fairly wide range of possi-

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1 In this summary only numbers between square brackets refer to the numbers in the Contents List allotted to the reference documents published below.
bilities in this respect but one has to be rather careful when comparing their energy consumption per unit product.

The minimum energy theoretically required in any reversible process to desalt 1 m$^3$ of sea water (35 000 ppm) at ambient temperature is 0.7 kWh (2.8 kWh/10$^3$ gal). However, the present practical values are far above this figure because of irreversibilities of actual processes (frictions, temperature differences, etc.). It should also be mentioned that the above figure implies that the brine should be kept at the same concentration as the incoming sea water, which practically means that no finite quantity of water has been desalted.

When comparing the energy consumption per unit product (kWh/m$^3$) for different desalination processes, the form of energy used (thermal or electrical) should be stated clearly as it requires about 3 kWh thermal to produce 1 kWh electrical. This comparison should also include the power used by the auxiliaries of the desalination plant, e.g. pumping power. Energy consumption, even so adjusted, is only one of the parameters for determining the total energy cost to the desalination plant. For instance the cost of electrical energy includes in addition to the heat source other components such as turbogenerator, condenser, switchyard, etc.

A breakdown of the cost of desalted water shows the important part played by capital investment. Its share in the cost varies considerably from one process to another, and any comparison between two processes must take it into account. The capital investment varies for a given process according to the quality of both salted and desalted water and the cost of the energy available. The respective shares of capital investment and energy cost are obtained as a result of an optimization study carried out according to a set of assumed ground rules. In this respect several approaches are possible.

3.2. Technical characteristics

A large-scale effort is being launched by the Office of Saline Water (OSW) in the United States of America for the development of desalting technology [18]. Recent progress regarding various processes being demonstrated in the USA was reported to the Panel [1].

A novel arrangement of a flash process (multieffect - multistage) is under test by the OSW. This unit is an 8-effect, 64-stage flash pilot plant having a capacity of 40 m$^3$/d (10 000 gal/d). The advantages of this new concept are connected in part with the possibility of raising the maximum permissible brine temperature.

Certain doubts remain as regards the size effect by scaling up flash evaporators. In their present design, it appears that this effect must decrease considerably above a capacity of 40 000 m$^3$/d (10 Mgd$^2$). The United States programme, which also includes other distillation processes, provides for stepwise development in this connection. After design studies, full-scale blocks or "modules" of a 200 000 m$^3$/d (50-Mgd) unit will be constructed. This will make it possible to study simultaneously flash evaporation operation and problems associated with high-capacity installations.

$^2$ Mgd = million US gallons per day.
For high-capacity plants having an output in the range of 40,000 m\(^3\)/d (10-Mgd), the so-called "long-tube vertical" process seems to constitute a competitor to the flash evaporation process.

A desalination plant may be designed in order to increase its output in a later stage if required. For instance, a plant of the flash evaporation type could be designed with a relatively low temperature in the brine heater and high temperature sections added subsequently if desired, thus increasing the performance ratio.

While a major share of efforts is being devoted to distillation, other promising processes, especially reverse osmosis, are receiving attention. A first prototype using reverse osmosis producing 100 m\(^3\)/d (25 Mgd) of fresh water from brackish water is expected to start operation in 1967.

4. SINGLE-PURPOSE DESALINATION PLANTS

To avoid the formation of scale, the temperature of the brine in plants using distillation processes should at no point exceed a certain maximum value depending upon content and nature of salts, prior chemical treatment, materials used and other factors.

Considerable research work is being carried out to increase the maximum permissible brine temperature. The San Diego demonstration plant using the pH method of scale control has been satisfactorily operated at 120°C (250°F) over a considerable period of time. Means of scale control are under investigation in order to reach temperatures of 150°C (300°F) [1].

Existing types of power reactors generate steam at much higher temperatures. At present it seems that no substantial savings in capital and operating cost could be obtained by developing new types of reactors supplying steam at low temperatures in the range of those mentioned above.

The use of several desalting processes arranged in series in the steam circuit could provide an attractive scheme. For example, the high-pressure steam could be used first to perform mechanical work in a desalination plant using the vapour compression process, and thereafter to heat the brine of a flash evaporation plant [6].

5. DUAL-PURPOSE PLANTS

5.1. General

Most of the actual design studies consider expanding the high-pressure steam from the reactor plant in a turbine and thus generating electric power. The low-pressure steam is used as the heat source of a distillation plant.

It was pointed out that under certain conditions the cost of prime steam can be allocated to power and water production in such a way that the cost of neither product is affected by varying over a reasonable range the temperature of the exhaust steam from a back pressure turbine. If the costs are independent of the product ratio in this way, one can assume that neither product is subsidizing the other [6].
5.2. Flexibility and reliability

The flexibility of a dual-purpose plant can be defined as its ability to vary its output of water and power according to the demand for each. Two main components of a nuclear dual-purpose plant, the reactor and turbo-generator can be operated at varying load without much difficulty. Such an operation, however, could give rise to inconvenient transients in large distillation units. The flexibility of the entire plant depends, in addition, on the combined response of its components. To obtain maximum benefit from a dual-purpose arrangement, both power and water plant should be operated at rated capacity and with a high utilization factor. Those conditions are easily met when the plant is part of a large system.

In some developing countries where the demand for power is at present small, but is growing at a rapid rate, it might appear economically attractive to install power units which would be operated at full load only after a certain time. In such cases flexibility becomes an important factor.

Some of the means leading to a more flexible operation of the plant, e.g. dump condenser, by-pass line, pass-out condensing turbine, could also improve the reliability of the system. Looser coupling of the different components will thus be achieved with an additional investment cost.

Further development studies on flexibility should, therefore, be desirable for the benefit of the prospective users of dual-purpose plants.

5.3. Dual-purpose projects under consideration

A joint US-Israel feasibility study of a dual-purpose plant for meeting Israel's needs is under way [16]. A plant producing 400 000 to 500 000 m$^3$/d (100 - 125 Mgd) and 175 to 200 MW(e) of salable electric power is being considered. Preliminary analysis indicates that a nuclear heat source of 1000 to 1500 MW(th) feeding a back-pressure turbine could be the most economic alternative. Base load operation of water and power plants has been assumed.

Bids have already been received for installing a nuclear dual-purpose plant producing 150 MW(e) and 20 000 m$^3$ of water/d (5 Mgd) near Alexandria (UAR) [14]. Dual-purpose plants might also be considered for solving water shortage problems in regions such as Mexico City [15], North East of Brazil [17] and Athens [13].

6. ECONOMIC CONSIDERATIONS

6.1. Plant sizing and optimization

It has been pointed out that when investigating the means of meeting power and water demands in a given area, a market survey should be undertaken and the shape of the demand curves established as a function of the selling prices and their variation with time [4]. This will serve as a guide to determine whether a dual-purpose plant should be considered and the range of possible water and power outputs. Such an approach is quite im-
important for large sized plants as in the case of nuclear ones. However, a plant of low output which is marginal in a given system, will not change the economic picture of the system as a whole.

Several approaches have been used for optimizing dual-purpose plants. If water and power productions of the plant are precisely fixed, all possible schemes giving the same outputs should be investigated. The optimum one will yield the lowest total annual cost (fixed charges, fuel operation and maintenance). This method, therefore, does not require the evaluation of the steam cost to the water plant and the establishment of separated water and power costs.

In most cases the required quantities of water and power are not stated so rigidly. An approach which is frequently used consists in giving a value to the annual power production and to deduce it from the total annual cost of the dual-purpose plant to determine a unit water cost [8]. This method involves the calculation of the cost of the steam to the brine heater and subsequent optimization of the water plant, the criteria being the lowest water cost. The main difficulty of this "power credit" method lies in the choice of the value to be given to the electric power generated.

6.2. Costing procedures

Several procedures are used for establishing water and power costs in a dual-purpose plant. The "power credit" approach already mentioned is one of them. Another approach consists in allocating to each product a share of the total cost according to a set of ground rules. In this connection it should be mentioned that one cost allocation method has recently been developed in the United Nations [7]. Since any costing procedure for determining the costs of each one of the combined products is necessarily arbitrary, it should be defined in each case. It could, therefore, be worthwhile proceeding to a review of the different costing procedures.

7. NUCLEAR REACTORS FOR DESALINATION

The incentive for considering the use of nuclear reactors for desalination lies in their potential for providing low cost energy for desalination, especially in large sizes. As a result of recent further improvements in nuclear reactor economics, both in fuel cycle and capital costs, this incentive has increased.

Several studies have been made to investigate the technical and economic feasibility of different types and sizes of reactors in conjunction with desalination plants. The results of some of the recent studies were reported to the Panel in review papers. A summary of these is given here.

In the USA a study of single- and dual-purpose plants using nuclear and conventional power has been made by the Catalytic Co., under contract of the US Department of the Interior and the USAEC [8]. The thermal capacity of the plants investigated ranges from 200 to 1500 MW. Two categories of reactor plants have been considered. One is representative of low-temperature water reactors, namely the boiling-water reactor, pressurized water re-
actor and spectral shift controlled reactor, and the other is representative of high-temperature reactors such as the sodium-graphite reactor and the high-temperature gas-cooled reactor. Comparisons have been made with conventional heat sources in which the fuel is natural gas at 9 cents per million kcal (35 cents per million Btu). Brine heater temperature has been assumed at 120°C (250°F). Computations have been made for several fixed-charge rates and power credits.

Tables I and II from this study summarize the main results. Table I shows water costs at the plant outlet without storage and conveyance costs and using variable power credit in the case of dual-purpose plants. This factor is defined as the production cost of a power only plant of the most efficient type operating under the same fixed charge structure equal in size to the net salable power output of the dual plant being considered. Table II summarizes the results of the optimization of dual-purpose plants with 14% fixed charge rate and variable power credit factors.

The USAEC is supplementing its reactor programme to develop appropriate reactor types for anticipated desalination applications [18]. While assessments are being made on a number of reactor systems, special attention is being given to the Heavy Water Organic Cooled Reactor concept which is being pursued as a reference system for large scale desalination programmes.

Studies are also being undertaken regarding reactor coupling parameters in dual-purpose operation, analyses of operating flexibility and of varying product ratios and reactors for single-purpose application.

It is proposed to construct a first prototype reactor of 1000 MW(th) capacity which could be operated in 1970. It would not be coupled to desalination plants to minimize any possible interference between them. If these separated plants prove to be successful, the next step would be a combination of a 3500 MW(th) reactor and large size desalination plant with several units of 200 000 m³/d (50 Mgd) capacity.

In the Soviet Union [5], the cost of heating steam for desalination has been determined for three types of reactors which are being developed there at present, i.e. graphite moderated-water cooled-nuclear superheated, PWR, fast breeder. Several sizes from 250 to 2000 MW(th) have been investigated. The influence of the temperature of the heating steam and of the number of stages of the desalination plant on the cost of fresh water has been studied.

The main results are given in Table III, and the assumptions made are referred to in [5]. The cost of the heating steam to the desalination plant has been taken as equal to the value of the additional electric energy which could have been produced by the same reactor operating with a condensing turbine. It was pointed out that the economic data which appear in Table III reflect the level of reactor technology as of 1964, and must, therefore, be considered as conservative.

It should be mentioned that a nuclear dual-purpose plant using a fast breeder reactor is at present under construction in the Soviet Union on the Caspian Sea. This plant will generate 150 MW of electricity and produce 120 000 m³ of fresh water per day (30 Mgd). It is scheduled to be commissioned by 1968/1969.
<table>
<thead>
<tr>
<th></th>
<th>Fossil fuelled</th>
<th>Nuclear reactor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low temperature</td>
<td>High temperature</td>
<td>Low temperature</td>
</tr>
<tr>
<td>Fixed charge rate</td>
<td>(MW(\text{th}))</td>
<td>(MW(\text{th}))</td>
<td>(MW(\text{th}))</td>
</tr>
<tr>
<td>200 600 1000 1500</td>
<td>200 600 1000 1500</td>
<td>200 600 1000 1500</td>
<td>200 600 1000 1500</td>
</tr>
<tr>
<td>Dual-purpose plants&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4%</td>
<td>0.365 0.307 0.319 0.320</td>
<td>0.349 0.275 0.320 0.318</td>
<td>0.392 0.227 0.202 0.197</td>
</tr>
<tr>
<td>7%</td>
<td>0.455 0.374 0.391 0.373</td>
<td>0.454 0.349 0.349 0.366</td>
<td>0.553 0.327 0.289 0.265</td>
</tr>
<tr>
<td>14%</td>
<td>0.605 0.503 0.506 0.517</td>
<td>0.613 0.480 0.455 0.463</td>
<td>0.964 0.589 0.521 0.478</td>
</tr>
<tr>
<td>Water only plants&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4%</td>
<td>0.482 0.425 0.402 0.398</td>
<td>0.491 0.430 0.407 0.402</td>
<td>0.499 0.362 0.308 0.294</td>
</tr>
<tr>
<td>7%</td>
<td>0.582 0.505 0.481 0.476</td>
<td>0.598 0.516 0.490 0.484</td>
<td>0.656 0.458 0.408 0.383</td>
</tr>
<tr>
<td>14%</td>
<td>0.797 0.674 0.647 0.641</td>
<td>0.831 0.699 0.667 0.660</td>
<td>(-)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Variable power credit.
<sup>b</sup> Power purchased at 6 mills/kWh.
## TABLE II
**SUMMARIZED RESULTS - DUAL PLANT OPTIMIZATION**  
*Basis: 14% fixed charge rate, variable power credit factor*

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Fossil fuelled</th>
<th>Nuclear reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steam conditions</strong></td>
<td><strong>Low temperature</strong></td>
<td><strong>High temperature</strong></td>
</tr>
<tr>
<td><strong>Input to dual plant (MW(th))</strong></td>
<td><strong>200</strong></td>
<td><strong>600</strong></td>
</tr>
<tr>
<td><strong>Investments (million $)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water intake and canal</td>
<td>0.246</td>
<td>0.727</td>
</tr>
<tr>
<td>Interest on construction money</td>
<td>0.205</td>
<td>0.518</td>
</tr>
<tr>
<td>Non-depreciating items</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>TOTAL</td>
<td>15.720</td>
<td>37.600</td>
</tr>
<tr>
<td>Fuel cost (million $ per year)</td>
<td>5.897</td>
<td>9.829</td>
</tr>
<tr>
<td>Operating cost, steam and power plant (million $ per year)</td>
<td>0.576</td>
<td>0.709</td>
</tr>
<tr>
<td><strong>Steam</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Million $ per hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from steam plant</td>
<td>682.55</td>
<td>2047.65</td>
</tr>
<tr>
<td>to water plant</td>
<td>566.00</td>
<td>1640.00</td>
</tr>
<tr>
<td>to brine heater</td>
<td>531.49</td>
<td>1589.65</td>
</tr>
<tr>
<td>Dollar per million $/hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from steam plant</td>
<td>0.8247</td>
<td>0.5212</td>
</tr>
<tr>
<td>to brine heater</td>
<td>0.1847</td>
<td>0.2879</td>
</tr>
<tr>
<td>Steam conditions</td>
<td>Fossil fuelled</td>
<td>Nuclear reactor</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>----------------</td>
</tr>
<tr>
<td></td>
<td>Low temperature</td>
<td>High temperature</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>600</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost (mills per kWh)</td>
<td>10.290</td>
<td>7.194</td>
</tr>
<tr>
<td>Gross power generated (MW)</td>
<td>212.69</td>
<td>187.50</td>
</tr>
<tr>
<td>Gross power generated (MW)</td>
<td>212.69</td>
<td>187.50</td>
</tr>
<tr>
<td>Power to water plant (MW)</td>
<td>3.16</td>
<td>11.82</td>
</tr>
<tr>
<td>Power to water plant (MW)</td>
<td>3.16</td>
<td>11.82</td>
</tr>
<tr>
<td>Net available power (MW)</td>
<td>34.34</td>
<td>100.68</td>
</tr>
<tr>
<td>Net available power (MW)</td>
<td>34.34</td>
<td>100.68</td>
</tr>
<tr>
<td>Operating cost, water plant (million $ per year)</td>
<td>1.046</td>
<td>1.504</td>
</tr>
<tr>
<td>Operating cost, water plant (million $ per year)</td>
<td>1.046</td>
<td>1.504</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant performance factor (lb water per lb steam)</td>
<td>8.98</td>
<td>10.43</td>
</tr>
<tr>
<td>Plant performance factor (lb water per lb steam)</td>
<td>8.98</td>
<td>10.43</td>
</tr>
<tr>
<td>Plant production (million gallons per day)</td>
<td>14.69</td>
<td>51.63</td>
</tr>
<tr>
<td>Plant production (million gallons per day)</td>
<td>14.69</td>
<td>51.63</td>
</tr>
<tr>
<td>Cost (dollars per thousand gallons)</td>
<td>0.605</td>
<td>0.569</td>
</tr>
<tr>
<td>Cost (dollars per thousand gallons)</td>
<td>0.605</td>
<td>0.569</td>
</tr>
</tbody>
</table>
The possibility of using existing Canadian heavy-water reactor designs in a dual-purpose plant has been studied and the cost of water calculated [9]. Two cases have been considered, one with a high water-to-power ratio (back pressure turbine) and one with a low product ratio (extraction steam). Water costs are ranging from 6.6 to 13.7 US $/m³ (24.9 to 51.7 $/10³ gal) according to the adopted fixed charge rate (5 to 10%). These costs correspond to a net power output of 200 MW and two different water productions: 500 000 and 580 000 m³/d (125 and 144.3 Mgd). A power credit of 5.3 mill/kWh has been assumed. It is worth mentioning that a new Canadian price of 13.55 US $/lb for heavy water has been used in the study.

While no formal reports were submitted to this Panel on the studies of reactor applications for desalination in other countries, it is understood that further such investigations are being made.

In the United Kingdom a detailed design and construction study of a desalination plant is being carried out jointly by the United Kingdom Atomic Energy Authority and an experienced manufacturer. The plant has a capacity of 135 000 m³/d (30 million (Imp) gal/d) and would operate in conjunction with a large advanced gas-cooled reactor based on a coastal site in the United Kingdom. The study is aimed at the establishment of realistic costing for water production plant of this scale. The results of the study will be published.

The detailed design study is coupled with a development programme on desalination plant occupying the next two to three years, which has now been formulated by the U.K.A.E.A. and which will be mainly concerned with the flash distillation process. The authorities in the United Kingdom believe that with the wide practical experience of its industry in this field and the accumulated "know how" it is not necessary to allocate any of this budget to the construction and operation of pilot plants, but to be free to concentrate on those basic parameters of the system where the greatest opportunities for economic improvements will lie. The recently formed Water Resources Board has set up a co-ordinating study group which will investigate the place of desalination in the United Kingdom from the year 1970 onwards.

Complementary to the work on the actual desalination plant, a considerable effort is being employed within the U.K.A.E.A. on optimization studies on various reactor systems suitable for use in conjunction with desalination plants.

In Italy, CNEN is developing organic-cooled reactors for desalination purposes. In France studies are continuing about the possible application of gas-cooled reactors for desalination.

8. RECOMMENDATIONS OF THE PANEL ON THE AGENCY'S ROLE AND FUTURE ACTIVITIES IN NUCLEAR DESALINATION

8.1. Introducton

This report sets forth the proposed role of the Agency in international desalting activities and recommends a programme to be undertaken by the Agency to meet the needs of its Member States. In the preparation of this report, consideration was given to the resources available to the Agency,
### SUMMARY REPORT

#### TABLE III

**TECHNICAL AND ECONOMIC DATA ON NUCLEAR DUAL-PURPOSE PLANTS USING DIFFERENT TYPES OF REACTOR**

<table>
<thead>
<tr>
<th>Thermal capacity of reactor (MW)</th>
<th>Electric capacity (MW)</th>
<th>Fresh-water production (m³/h)</th>
<th>Cost of electric power (kopecks*/kWh)</th>
<th>Cost of fresh water (kopecks/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beloyarsk atomic power station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Graphite - light water - nuclear superheat)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>75</td>
<td>2,320</td>
<td>1.64</td>
<td>29.6</td>
</tr>
<tr>
<td>500</td>
<td>150</td>
<td>4,170</td>
<td>0.92</td>
<td>19.8</td>
</tr>
<tr>
<td>1000</td>
<td>300</td>
<td>7,310</td>
<td>0.51</td>
<td>14.4</td>
</tr>
<tr>
<td>2000</td>
<td>600</td>
<td>14,620</td>
<td>0.45</td>
<td>14.1</td>
</tr>
<tr>
<td>Novovoronezh atomic power station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(PWR)</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>250</td>
<td>40</td>
<td>2,810</td>
<td>2.5</td>
<td>42.2</td>
</tr>
<tr>
<td>500</td>
<td>80</td>
<td>5,620</td>
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<td>28.9</td>
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<tr>
<td>1000</td>
<td>160</td>
<td>8,850</td>
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<tr>
<td>2000</td>
<td>320</td>
<td>17,700</td>
<td>0.48</td>
<td>15.4</td>
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<tr>
<td>Shevchenko atomic power station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Fast reactor)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>250</td>
<td>75</td>
<td>2,320</td>
<td>2.1</td>
<td>47.0</td>
</tr>
<tr>
<td>500</td>
<td>150</td>
<td>4,640</td>
<td>1.09</td>
<td>26.4</td>
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<tr>
<td>1000</td>
<td>300</td>
<td>7,310</td>
<td>0.45</td>
<td>16.4</td>
</tr>
<tr>
<td>2000</td>
<td>600</td>
<td>12,600</td>
<td>0.30</td>
<td>11.0</td>
</tr>
</tbody>
</table>

* 1 kopeck = 1.11 US cent.

The programme and needs of its Member States, and the relationship of the Agency to the United Nations and other national and international organizations.

The recent interest in desalting and the assessment of the role of nuclear power in this application is such as to warrant at this time the establishment by the Agency of a continuing programme in this field of technological application. Under such a programme, the Agency would work in close accord with its Member States and national and other international...
organizations to further the practical application of nuclear energy for the benefit of all people.

While this report sets forth a recommended programme and suggests means whereby such a programme could be implemented, it is believed that the Agency should determine the most appropriate approach to be adopted for specific tasks as they evolve. The Agency should also take maximum advantage of the developments of its Member States and seek their cooperation and participation in furtherance of its programme.

8.2. Review of previous Agency activities

The continuous effort of the Agency in the field of desalting was initiated in September 1962 when the Tunisian Representative made a request for Agency assistance to study the potentialities of a dual-purpose plant for the industrialization of the southern part of the country. Previous activities may be classified according to three categories:

8.2.1. Activities not related to a specific project

These activities include the four meetings of experts held on the use of nuclear energy in saline water conversion and study and research work. The first Panel was held in March, 1963, and assessed the possibility of using nuclear reactors for desalination. The second met in September 1963 and dealt with desalination processes which could be used in nuclear installations. It also studied the respective advantages and disadvantages of single-purpose and dual-purpose systems. The third Panel, held in April 1964, was devoted mainly to the technical and economic aspects of dual-purpose installations. The fourth was a one-afternoon meeting in Geneva, and gave each country an opportunity to present its needs and interest in desalination.

A research contract is under way with Israel on the "Feasibility of Nuclear Reactors for Sea Water Distillation". Some study was made within the Agency mainly related to different possible schemes for dual-purpose systems.

8.2.2. Activities related to specific projects

The mission for studying the potential of a dual-purpose nuclear reactor for the industrialization of southern Tunisia was carried out in 1963. At a later date an Agency observer participated in a US desalination mission in Tunisia.

An Agency observer is participating in the US-Israel desalination programme.

An Agency observer also participated in a US desalination mission in UAR.

Different consultant services were made available to Tunisia, Mexico, India and Greece. Turkey, Peru and Chile have recently requested similar assistance.

The USSR-US Agreement provides for a certain measure of Agency participation in some activities.
8.2.3. Information

The following technical reports have been published in the Agency's Technical Reports Series: No. 24 "Desalination of Water Using Conventional and Nuclear Energy", and No. 35 "Study on the Potentialities of the Use of Nuclear Reactors for the Industrialization of Southern Tunisia". A certain number of technical reports, such as Panel reports, have not been published but are available upon request.

8.3. Role of the Agency

It is proposed that the role of the Agency be to:

(1) Serve as the international focal point for matters relating to the use of nuclear energy for desalination.
(2) Provide assistance and advice to its Member States in this field.
(3) Provide co-ordination services for Member States in this field.
(4) Stimulate the practical consideration of nuclear energy in desalination.

In this proposed role, the Agency would rely heavily on the support of its Member States. From time to time members of the Agency staff and/or specialists from its Member States would act as advisors, observers and consultants for specific undertakings and periodic working groups, panels, and symposia would be convened to assist the Agency and/or its Member States in areas of need.

The Agency will have a direct interest in those desalination processes which appear to have favourable potential for the near-term application of nuclear energy. It should devote special attention to those desalination processes which can be made integral with nuclear reactors. The Agency should also keep under review other desalination processes which may have future potential for nuclear energy application or which might affect the overall economic consideration of nuclear energy (e.g. desalination processes using primarily electrical energy). With regard to water resources evaluation, the Agency should rely upon the information and experience available in other international as well as national organizations.

8.4. Proposed Agency activities

8.4.1. Collection, analysis and dissemination of information

It is recommended that the Agency should carry out the following functions in relation to information on the technical and economic aspects of nuclear desalting:

(1) The Agency should make as much use as possible of the work done under the national programmes and of the information gained by Agency participation in various projects and special missions.
(2) The Agency should approach the national organizations for any further clarification and detailed information not included in the published reports and encourage them to extend their studies to provide general benefit to the Member States.
(3) In certain circumstances the Agency should initiate or undertake studies relating to specific problems in its competence and not otherwise covered.

(4) The Agency should digest and evaluate the information obtained and disseminate it to the Member States in an appropriate form.

(5) In disseminating information to Member States the Agency should draw attention to the elements entering into and the procedures used in the determination of the costs of desalting water by any particular nuclear desalination scheme.

(6) From time to time, the Agency should prepare reports on the status of nuclear desalination. In addition, the Agency should consider the possibility of disseminating highlights of the progress and developments in this field among Member States containing references to relevant literature, sources of data, etc.

8.4.2. Special studies

To assist its Member States in evaluating nuclear desalination schemes the Agency should prepare a report on different procedures for costing and evaluating nuclear desalination. Taking into account established procedures and those currently being developed by the United Nations and others, both for the nuclear power reactor and desalination plants, the report should include a review of various methods of assessing total capital and annual costs of schemes for providing electric power and water supplies, and the effects of using various procedures of allocating costs between water and power. It would not, however, be desirable to build numbers into the costing procedures since the values to be used must be established for each individual case.

The Agency should review the methods of optimizing the design of dual-purpose power and water plants, with particular reference to application of nuclear energy.

On the basis of data collected by the Agency through the means described in section 8.3.1 above, the following appear to be the most useful areas for other special studies in the near future:

(1) The Agency should make a continuing study of reactor types and their applicability to various desalination situations in single and dual-purpose applications. Special attention should be paid to the problems relating to coupling of such reactors with desalting units, including the flexibility and reliability.

(2) The Agency should pay special regard to the problem of siting of nuclear desalting plants.

(3) The Agency should devote special attention to distillation processes, mainly to obtain those data which are needed for its technical and economic studies.

8.4.3. Assistance to Member States in specific projects

The Agency should be prepared to undertake specific nuclear desalination studies for given locations in requesting countries, based on the special conditions prevailing at the location. These specific studies are useful not
only for the requesting countries, but also because the information developed through these studies may be of great value in relation to other situations.

9. FUTURE PROGRAMME OF MEETINGS

The Panel, at the request of the Deputy Director General for Technical Operations, has considered the future role of the Desalination Panel in the Agency's desalination programme. As originally conceived, the Desalination Panel was a rather small expert group to advise the Agency in its direct activities in the field. It was noted that the Panel subsequently acquired other functions which diminished its effectiveness in its original role. The other functions, however, are recognized to be valuable adjuncts to the Agency's programme.

It is suggested that the functions, which under the aegis of the Agency can be appropriately fulfilled by international gatherings, are:

1. To advise the Agency regarding technical and economic questions which the Agency has a need to answer,

2. To provide a forum for free discussion between experts and other interested parties in specific topics and the status of matters of nuclear desalination, and

3. To provide a means by which the Agency's programme in the field can be reviewed and commented on by representatives of its Member States.

It is felt that these three functions can be separated. The first might appropriately be achieved by the Agency convening small working groups from time to time to assist and advise it on particular topics identified by the Agency. The second could be met by open meetings, such as technical seminars, in which there would be maximum opportunity for the exchange of views on technical and economic topics. The frequency of such meetings would depend on the rate of advancement in the art and the occurrence of relevant gatherings elsewhere. The last function, while not necessarily of a technical nature, is one which needs to be met occasionally and would not have to be of an extended duration. It is believed that a one or two day meeting could be held immediately before or after a scheduled meeting of the Agency which attracts general representation and thus impose a minimum burden both on the Agency and the participants.
INTRODUCTION

The water problem

The annual precipitation which falls in the land areas of the earth is much more than sufficient to supply the needs of the earth's population. Similarly, the average annual precipitation of 30 inches over the 48 states of continental United States of America would supply an adequate amount of fresh water for all purposes. Yet there are regions both in the United States and the world at large in which the amounts of available water are insufficient. Conversely there are areas in which an overabundance of fresh water exists. The relatively high cost of transporting water appears to limit redistribution to moderate distances. Consequently, in some areas of the world and the United States, economic growth has been restricted because of a limited water supply.

The ever increasing use of water is due to the combination of increasing population, rising living standards, progressive industrialization, and expansion of agricultural irrigation. In the United States the problem is further aggravated since an increasing fraction of the population lives in the arid or semi-arid parts of the country. It has been estimated that within the next two decades the full development of conventional water sources will be required in such areas as the South Pacific basin, Colorado River, upper Rio-Grande-Pecos River, Great Basin and upper Missouri River.

Of the approximately one fourth of the earth's surface which is land, about 60% is arid. Much of the water in such areas is mineralized in varying degrees of severity, and the average distance to potable water supplies in a given area is usually great. Further, this 60% of the earth's land surface supports only about 5% of the earth's three thousand million people. In the coming years, the world's increased population will make it imperative to increase the productivity of this dry land. In the majority of these areas the only unlimited source of water is salt water.

Thus the problem of availability of water in sufficient quantity, and of adequate quality, available when and where needed and at reasonable cost
is one of world-wide importance. The great diversity of this problem and its relationship to social, technological and economic factors is not yet fully understood.

Solutions to the problem

Water problems are so numerous and diversified that no single plan or course of action appears capable of alleviating or solving them. Certain remedial approaches to the problem, such as more efficient use of available water, are self-evident. For example, in a region having a limited supply of water or a foreseeable limit of available fresh water, steps might be taken to reduce per capita consumption, reduce the local population drawing on the supply, reduce losses in storage, transit and use, develop more efficient industrial practices as they relate to water use, grow crops that consume less water and develop others that are more tolerant to brackish water. Multiple use of water also will assist in extending the water supply.

However, the re-use of water has certain inherent problems. The best practical treatment of municipal and industrial water effluents may return to streams substances detrimental to aquatic life and to direct re-use of stream waters. Even a so-called complete treatment, if it does not also remove dissolved nutrients in the form of phosphorus and nitrogen compounds, will provide a good medium for algal growth in river water. Such a situation could upset the natural balance of plant and animal life and limit direct re-use of this water. Stream dilution is a partial solution to this problem, but will limit any saving attributable to re-use because more storage reservoirs will be needed to supply the water to dilute the wastes during periods of low stream flow.

Another obvious attack on the problem is to increase the available supply of water by desalting local saline water, by transporting fresh water from a water-rich region or from a remote desalination plant.

Even though well over 25 million gallons of fresh water are being produced daily from saline sources, saline water conversion is still in its infancy. The cost of desalination has been drastically reduced over the past ten years, but is still relatively high. Nevertheless, in some areas desalination is even now competitive with other means of obtaining potable water. The cost of desalination is being reduced continuously and in an increasing number of situations it will provide the cheapest or only means of obtaining new water. It should be noted that the cost of desalinated water must be compared with the true cost of the incremental supply of conventional water obtained by the construction of new reservoirs, aqueducts, etc. To both must be added the cost of distribution. In considering a specific water supply problem in any part of the world it is necessary to consider the overall problem of water sources, use, re-use and distribution.

It is apparent that desalination will first contribute to the solution or alleviation of water supply problems in fairly isolated areas requiring relatively small amounts of potable water where alternatives are either non-existent or expensive. Distillation and electrodialysis desalination units are already supplying potable water in many such locations throughout the world. It would appear that the greatest demand in the immediate future
will be for conversion plants having capacities ranging from a few thousand gallons per day up to 10 or 20 million US gal/d (Mgd). For this size plant fossil fuel appears to have a cost advantage over nuclear fuel for most applications.

On the other hand, if one considers the production of very large quantities of desalinated water (e.g. 150 Mgd to $2 \times 10^6$ gal/d) nuclear-powered plants appear to be the only answer. Dual-purpose power-water plants offer special advantages in economics for those areas which can utilize the power as well as the water produced. In the immediate future the most likely candidates for such large dual-purpose plants are regions having a large population, a well-developed technical culture, and no readily available source of additional natural fresh water. Such a region may be typified by our southern California region. In such a region the incremental additions in both power and water will be large and the existing power networks and water distribution systems present great flexibility in the use of the output of such a large plant.

It must be recognized, however, that the economy of operation of the large dual-purpose plant can be realized only under limited conditions. It is almost mandatory that these plants operate under base load conditions - that is at full design power continuously. One way to achieve this is to tie into a power grid which is capable of absorbing full plant output at all times.

Another approach which offers interesting possibilities is to tie a dual-purpose plant to a number of discrete inland or remote saline water conversion plants which operate on electricity. Thus the dual-purpose plant would generate electricity and distill sea water; during off-peak load periods the surplus electric power would drive reverse-osmosis, vapour compression, freezing or electrodialysis plants. This system would achieve the desired "base load" condition for the main plant.

It must also be recognized that, where there is not a requirement for large quantities of power, large single-purpose water plants may be justified solely on the value of the water produced.

CURRENT TECHNOLOGY OF DESALINATION

Background

The second law of thermodynamics provides a basis for the calculation of the absolute minimum energy required for desalination regardless of the process. For sea water this energy amounts to about 2.8 kWh per 1000 gal of product water. Somewhat less energy would be required for conversion of brackish waters. This is the minimum energy required for an infinitely slow operation and with no losses or inefficiencies of any kind. Every real or practical process will require more than the minimum figure and it appears that about four times this thermodynamic minimum is the best that one could hope to attain.

The energy requirements for six current conversion processes are listed in Table I. It is estimated that by the year 1980, research and development will have reduced the energy requirement of certain processes to around 10 kWh of high-quality energy per 1000 gal of product water.
### ENERGY REQUIREMENTS FOR SIX DESALINATION PROCESSES

<table>
<thead>
<tr>
<th>Processes using heat</th>
<th>Energy required per 1000 gal product water</th>
<th>1964 Technology (Btu x 10^3)</th>
<th>Estimate for 1980 Technology (Btu x 10^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multistage flash distillation</td>
<td>1020, 300</td>
<td>610(^a), 180</td>
<td></td>
</tr>
<tr>
<td>Long tube vertical distillation (LTV)</td>
<td>1020, 300</td>
<td>610(^a), 180</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processes using electricity(^b)</th>
<th>1964 Technology (Btu x 10^3)</th>
<th>Estimate for 1980 Technology (Btu x 10^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrodialysis (brackish water only)</td>
<td>83, 25</td>
<td>50, 15</td>
</tr>
<tr>
<td>Vapour compression distillation</td>
<td>610, 180</td>
<td>360, 105</td>
</tr>
<tr>
<td>Freezing</td>
<td>610, 180</td>
<td>360, 105</td>
</tr>
<tr>
<td>Reverse osmosis</td>
<td>170, 50</td>
<td>102, 30</td>
</tr>
</tbody>
</table>

\(^a\) The estimated 1980 energy requirements are for high efficiency processes and are not applicable to processes using low cost energy.

\(^b\) The energy values given for the "electrical" processes are the thermal energies for the appropriate electrical power generation at 33\% plant efficiency.

If a saline solution is separated from pure water by a semi-permeable membrane (one which rejects salt), pure water will flow spontaneously into the saline solution. However, if sufficient pressure is applied to the saline solution the flow of water will be reversed, permitting pure water to be forced out of the salt solution.

This process is one which holds promise of outstanding economy in the conversion of saline water to fresh water. Such a prediction is based upon the premises that no phase change is involved, such as is essential in many of the better-known processes (e.g. distillation), with the result that energy costs may be held to an extremely low value and because of the inherent simplicity of the system. It is apparent that progress in the development of the reverse-osmosis process is highly dependent upon the availability of suitable membranes and that the economy of the process is closely related to the flux (flow) of potable water which passes through such a membrane under a given applied pressure.

In the preparation of membranes, the processing conditions control the permeability with respect to both salt and water. This makes it possible to prepare specific membranes for use with given feed streams so that the salt in the product is maintained near 500 ppm, regardless of feed concen-
tration. Such control of membrane permeability has been achieved and has resulted in maximization of the productivity of membranes for each feed composition tested while maintaining the required quality. Certain feed additives such as polyvinylmethyl ether, for example, have also been shown to reduce preferentially salt permeation, further maximizing membrane productivity.

Pilot plants (500 and 1000 gal/d) have been operated successfully for considerable periods of time by the University of California, an Office of Saline Water contractor. Excellent results have been obtained; one of paramount importance was the demonstration of membrane life under field conditions. This is a major achievement in the development of reverse-osmosis processes. The first membranes had very short useful lives. At present a membrane life of well over six months has been demonstrated and there is every reason to believe that membrane life measured in years will be achieved. A design study has been made with respect to the construction of a large reverse-osmosis production plant and design criteria have been established.

A continuing programme of basic and applied research has been carried out to assure further advances in technology and even more efficient reverse-osmosis plants in the future. As a result of these studies considerable progress has been made in understanding the fundamental principles of reverse osmosis. Equations of flow have been developed, boundary layer limitations are better understood, membrane casting techniques have been improved, and theories have been advanced to explain the role of special salts in membrane fabrication. Theories have been advanced to explain the mechanism of water transport and salt rejection, and some of the physical and chemical characteristics which impart unique properties to cellulose acetate membranes have been elucidated. Whereas the early membranes had a water flux of 0.2 gal/ft$^2$ per day, membranes have been developed under the current programme which have water fluxes as high as 22 gal/ft$^2$ per day, an increase of more than a hundredfold. Preliminary cost estimates of reverse-osmosis systems show that the largest cost item in the system is the capital investment and that the major contributor to capital costs is the membrane-separator unit. The practicality of more sophisticated designs requires extensive study. At present four design configurations for membrane-separator units are under consideration. The flat plate and frame design was used in both pilot plants which were just mentioned. Still to be constructed and tested are the shell and tube configuration (Havens), the vertical spiral configuration, and the narrow channel configuration. The latter configuration, which, incidentally, has been successfully perfected by nature in life processes through millions of years of evolution, involves utilization of thin channels having dimensions smaller than the boundary layer which ordinarily would be built-up. The design problems of successfully applying this solution are extremely formidable, but this and other innovations (turbulence promotion, pulsing, etc.) are being tested, evaluated, and brought to fruition.

It must be recognized that reverse-osmosis desalination is a new technology. Technical and engineering problems will develop. However, progress to date encourages optimism. The success of the plate and frame
1000 gal/d pilot plant and dramatic improvements in membrane lifetime have put us in a position to design and construct an experimental plant capable of producing 50,000 to 200,000 gal/d of converted water on the basis of existing technology. We fully expect, in the next five years, to see reverse-osmosis desalination plants supplying pure, potable water to satisfy municipal and industrial needs.

Processes

Electrodialytic processes

While the Office of Saline Water is very optimistic about the potential of reverse-osmosis processes, the most important membrane process today in terms of operational units is undoubtedly electrodialysis. We are, accordingly, actively engaged in the development of advanced concepts of electrodialysis which generally may be described as advanced transport depletion. Conventional electrodialysis uses both cation and anion-selective membranes. The Deming transport depletion process uses a cation-selective membrane and a neutral membrane to separate the depleted and concentrated streams. The electrogravitation transport depletion process uses only a cation-selective membrane and utilizes differences in solution density to separate the concentrated and demineralized streams rather than an intermediate membrane. The advantage of the advanced transport depletion process over conventional electrodialysis may be summarized as follows:

(a) They avoid the use of expensive and historically troublesome anion-selective membranes
(b) They eliminate the deleterious polarization effects associated with anion-selective membranes, and thus permit the use of high current densities
(c) They provide an advantageous polarization effect at the cation-selective membrane that automatically acidifies the concentrate stream
(d) They permit radically simpler designs of demineralizers that will be much lower in cost, and permit greater utilization of membrane area
(e) The electrogravitation transport depletion process offers a high degree of demineralization per length of solution passage and freedom from problems with membrane damage
(f) As a result of the above factors, they are more adaptable to low-cost household and small industrial water demineralization requirements.

The technical feasibility of the electrogravitation transport depletion process and the effects of some of the operating variables have been evaluated in a small experimental unit. This work showed that a high degree of demineralization could be obtained in a short path length at satisfactory current efficiencies and at production rates per unit area of membrane comparable to those used in electrodialysis. The process permits simpler designs of demineralizers that have low maintenance cost and freedom from operating problems, and it can tolerate water containing suspended solids as well as a high concentration of scale-formers.

It is thus apparent that substantial economies can yet be realized in electrodialytic processes, and that improved demineralizer designs and membranes will assure an increasingly important role for electromembrane processes in the desalting of brackish waters.
Electrochemical desalination

Looking beyond reverse-osmosis and advanced electrodialytic processes, we are seeking new methods and new concepts of separation which do not require a phase change, which do not involve membranes and boundary layer phenomena, and which separate salt from water, rather than water from salt. One such method which is under development is electrochemical desalination based on pairs of specially prepared carbon electrodes, one of which specifically removes cations and the other anions upon application of an appropriate low voltage. This method is unlike most desalting processes which require expenditure of work (thermal cycling in distillation and freezing, mechanical work in reverse osmosis) on the total liquid volume in order to recover only a fraction of the total water. The new process has inherent cost and cycling advantages which are particularly pronounced with respect to brackish waters. A 3234 ppm brackish water has one salt molecule for each one thousand water molecules. The inherent advantage of removing the salt from the water rather than vice versa is obvious. Thus far work has centred on the use of carbon electrodes for reasons of (1) economy, (2) ease of chemical modifications, (3) total available surface area, and (4) the fact that it is electrically conductive. Recent research has increased the faradaic efficiency of these electrodes from 25 to over 90% and the ion-adsorptive capacity of the carbons has also been increased substantially. These two developments make the economic potential of the process much more attractive, and bench-scale evaluation is currently being undertaken. A small laboratory unit has been operating for over a year without significant decrease in the capacity of these electrodes to absorb and desorb ions from saline solutions. As a result of recent encouraging laboratory developments, it is planned to construct and operate a somewhat larger bench-scale unit from which meaningful economic data can be obtained.

Pilot plants

The Office of Saline Water recently constructed a Research and Development Test Station at Wrightsville Beach, North Carolina, and currently has five pilot plants in operation. Three are distillation processes, one is a freezing process and one is concerned with chemical pre-treatment of sea water. The plants range in capacity from 5000 to 35 000 gal/d. A sixth pilot plant to investigate the hydrate process is nearing completion. Briefly the pilot plants are as follows:

(1) Distillation (vertical tube type)

(a) Development work is under way on a 37 000 gal/d plant equipped with vertical double-fluted (evaporative and condensing surfaces) tubes. Investigation is concerned mainly with heat transfer. Recent pilot plant runs have demonstrated that coefficients can be maintained at 2000 to 2500 Btu ft⁻² degF⁻¹h⁻¹ - as you know, this compares very favourably with the customary 400-800 values. The results appear promising and the double-fluted tube concept is being considered for incorporation in the Freeport Demonstration Plant.
(b) Flash. Additional work on heat transfer and scale control is being conducted on a 10,000 gal/d six-stage flash unit. Means of scale control up to temperatures of 300°F by means of pH control, additives, and sludges are under investigation.

Another pilot plant, involving a novel arrangement of a flash process (multieffect-multistage) is also under test. This unit is an eight-effect, 64-stage flash pilot plant having a capacity of 10,000 gal/d.

(2) Freezing. Freezing may be appropriately characterized as a crystallization process in which ice crystals are formed by use of a primary or secondary refrigerant, washed free of brine and melted to form potable water. Two systems are being developed; one system employing a refrigerant such as butane in direct contact with pre-cooled sea water, and the other using flash evaporation of pre-cooled sea water at a pressure of about 3 mm Hg absolute to effect freezing.

(a) Secondary refrigerant method. Two plants, of 15,000 and 200,000 gal/d, are under construction. The smaller unit is just beginning operations and the larger is not yet complete.

(b) Flash type. Two units have been built, of 15,000 and 60,000 gal/d, by US companies. The latter has been moved to Wrightsville Beach where it will operate at about 100,000 gal/d.

(3) Hydrate system. Following laboratory scale operations, two plants are being built. One of these is just beginning to operate but data are not yet available.

(4) Pre-treatment of saline water. Four methods of pre-treatment are being investigated as a means of preventing or reducing scaling, especially for distillation systems.

(a) Acid treatment. H₂SO₄ is added to the sea water which reduces scaling by CaCO₃ and MgOH₂. Acid treatment is not effective for CaSO₄ but has permitted raising distillation temperatures from 190 to 250°F.

(b) Sludge systems. This method consists of circulating a "seed" sludge and is effective for removal of CaSO₄. It may be used in conjunction with acid treatment.

(c) Ion exchange is used in the Roswell vapour compression plant as an integral part of the system. The plant would not operate properly without it.

(d) Chemical. MgNH₃PO₄ is precipitated. This system has thus far only operated on a pilot plant scale. It has worked well and shows economic promise.

Demonstration plants

The Demonstration Plants Program had as its primary objectives: (1) the determination of the economic potentials of processes; and (2) the demonstration of their operational reliability. Each plant design incorporated experimental features for the purpose of establishing design data that can be applied directly to second generation plants. In addition, every effort is made to maintain production in order to develop costs consistent with the size of the plant.
Freeport Plant (LTV)

The Freeport plant has operated since May 1961 under a variety of conditions and has produced for use of customers more than 900 million gal of water. This plant was the first distillation plant to operate successfully under the pH method of scale control at temperatures up to 235°F. With the higher operating temperature, it has been possible to produce the 1 million rated capacity with one third of the equipment out of service.

The vacuum de-aerator was completely changed in order to eliminate the alkaline scale-forming ingredient of the sea water. The brine distribution in the evaporators was brought under more precise control and, lastly, some of the condensate type pumps were replaced with special design pumps capable of handling the boiling brine solutions without undue corrosion and erosion of the pumps.

The result of this experience will be reflected in future plants of this design achieving smaller plant size for the same production rate as the Freeport plant.

San Diego (MSG)

The San Diego plant has operated for 23 months, during which time the plant produced 517 million gal of product water. Modifications to this plant resulted in net output increase of 40% beyond design. This plant also used the pH method of scale control which permitted the operation of the evaporator at temperatures as high as 250°F compared to the more conventional 190°F used in commercial plants employing proprietary agents to prevent scale formation. This plant demonstrated reliable operation over a considerable period of time.

Recently the design of an advanced version of this process has been performed. This design is based on pilot plant work performed over the past three years and will incorporate the best features of both multistage and multieffect distillation. This design forms the basis for a replacement plant for the previous San Diego plant.

The replacement plant is expected to produce at the same rate as the first plant — 1 million gal/d. This unit will (1) have two thirds the heat transfer surface of the original plant; (2) require half as much steam; (3) use 70% as much acid for pre-treatment as the original plant; and (4) produce half as much blowdown or concentrated sea water.

Webster (electrodialysis)

The electrodialysis plant at Webster has operated as the sole source of water for the City of Webster, South Dakota, since March 1962. This plant, using the sheet flow type of membrane, has demonstrated the practicality of processing high hardness water by this process. While considerable advance has been made in this direction, revisions to the process are currently under way which will make the process more reliable. Over the past three years, it has been observed that small amounts of organic materials tend to plug up the membranes.
The vapour compression distillation process was installed at Roswell for the purpose of developing a process which could be used in areas not having large heat sinks for the disposal of energy in the waste streams. This is accomplished by recompressing low-pressure steam to a higher usable pressure. This plant operates under a delicate chemical balance in which the hardness constituent calcium is removed from the incoming brackish water stream by means of ion exchange. It was intended originally that the regeneration of the ion exchange be accomplished by the highly saline waters of the blowdown. To date, this has not been completely achieved, but by a series of equipment changes this goal is being approached.

The vapour compression plant as installed is expected to use only 70% as much energy as the first San Diego plant. This, of course, is based upon successful development of a scale-prevention technique.

Should the ion exchange process for scale prevention be too costly, a second technique of scale prevention, the seed slurry technique, is provided in the equipment on hand and is part of the next development programme to be conducted in this plant. The compressor used in this plant is of high efficiency, but the efficiency is very sensitive to scaling in the system. This appears as a marked decrease in capacity with only a slight increase in pressure drop across the system. Thus it is easy to starve the compressor or cause it to surge, which requires shut-down of the plant. As with the development of any distillation process in which we expect better than 90% performance on-stream, this handicap is of concern to us now because it gives relatively few operating hours. When and if the process can be developed to operate with no scale formation on the heat exchanger surfaces, the compressor should perform very well.

Large plant design and construction programme

The Office of Saline Water has embarked on a programme of design that will lead to the construction of plants many times the size of those now in existence. The primary objective of the "large plant programme" is to develop the technology of desalting water and the capabilities of industry to take advantage of the reduction in unit cost associated with large-scale operation. The achievement of economic desalination in large plants will pave the way for economic smaller units by sustaining an industrial base for desalination.

This programme is paced by the requirements under study by the Metropolitan Water District of Southern California and Israel. These studies are for plants in the size range of 100 to 150 Mgd and the time period of 1970-71. While plants in this size range could undoubtedly be built with today's technology, they would be unnecessarily costly and would incorporate features which would be doubtful from a technological viewpoint.

To bring the industry to a state of readiness to build such plants within the time period of interest, an intensive development programme has been initiated. This consists of the following concurrent sub-programmes:
(1) Conceptual design studies: 16 contracts have been executed with manufacturers and engineering firms both "experienced" and "inexperienced" with respect to desalting for the purpose of eliciting new ideas in distillation technology and stimulating competition.

(2) Supporting studies: Contracts will be issued for studies of specific plant components with the same basic objectives as the conceptual design studies.

(3) Module and component test programme: One or more "modules" or "building blocks" of full-sized plants will be erected and tested at West Coast test sites. These modules might take the form of eight stages of a 60-stage plant with the stages having one third the brine flow of a 50 Mgd plant (on the assumption that the scale-up to a full plant would not involve a large risk). Also, such components as a full-sized recycle pump will be tested.

(4) Advanced technology flash distillation plant: To test the entire flow system, and to have a test vehicle suitable for working on hydraulic heat transfer, thermodynamics, and materials problems, it is planned to replace the multistage flash plant (Point Loma I) with a completely new plant (Point Loma II) incorporating many experimental features, as well as operational improvements based on experience with the original plant. With this plant we expect to advance the art of flash distillation by working with manufacturers to develop improved flashing devices, demisters, reduced width of brine flow passages, obtain more accurate data on heat transfer in condensers, and run some tests on concrete exposed to actual evaporator conditions. This plant is planned to incorporate a multiple-recirculation cycle which is expected to facilitate operation of the plant at temperatures up to 300°F or higher, for testing improved scale control methods. There will be cross-feed of test results between this plant and the large plant modules being tested concurrently.

(5) Large plant feasibility studies: Concurrently with the foregoing there are now under way the two feasibility studies for large plants that I have already mentioned, the Metropolitan Water District of Southern California study which is jointly supported by MWD, Office of Saline Water-USDI, and USAEC, and the study for Israel. These studies represent real situations and accordingly will provide valuable guidance for the large plant programme.

SUMMARY

In summary I would like to offer the following suggestions and tentative conclusions:

(1) In considering the water problem of any municipality, area, region, or country, it is imperative that one look at the entire water supply question, including potential alternative solutions. Such solutions involve social, technological and economic factors. No single plan is capable of solving every water problem and no single approach such as desalination or re-use is always superior.

(2) Up to the present time, practical desalination plants have necessarily been limited to distillation. It must be kept in mind, however, that other
processes will soon be available having lower energy requirements than distillation. Consequently the selection of the desalination process and energy source becomes more involved but with a corresponding potential for a better solution.

(3) It would appear that in the immediate future, the greatest demand, and thus the largest market, will be for conversion plants having capacities ranging from a few thousand gallons per day to 10 or 20 Mgd.

(4) Nuclear power must be considered as an energy source in competition with other forms of energy. Except where some unusual problem exists, such as logistics, the least expensive energy source is the best source.

(5) Nuclear-fired large capacity dual-purpose plants can supply relatively low cost power and water. Their application in the development of large integrated regions appears to be natural. Such applications may be limited at the present time since relatively few areas can simultaneously assimilate such large blocks of power and volumes of water.

(6) If the primary need is low cost desalinated water, dual-purpose plants may not necessarily be more advantageous than single-purpose plants.

(7) We have suggested the concept of "Base Load Power Generation through Multi-Process Systems" as a possible means of supplying regional water needs by huge dual-purpose installations.

(8) Finally, I earnestly recommend that more effort be made to develop realistic water costing procedures.
THE GENERAL SITUATION OF WATER SUPPLY

It was said classically that man's basic requirements are food, shelter, and clothing. As a constituent part of food, and a primary necessity, we must include water. But what do we mean by water? It is said that one enthusiastic salesman of bottled water in the American West stuck on labels claiming 'Our water is 99 per cent pure', and this sounds superficially quite a claim - until you reflect that 1 per cent is 10 000 parts per million (ppm). Neither human beings nor food-stock animals nor the normal land crops can tolerate water with such a concentration of salts. About 2000 ppm is the maximum tolerance of humans and food-stock animals and crops, and in fact for healthy humans it is about 500 ppm. Thus, since men and animals have lived over many thousands of years, they must have been able to obtain quite easily water of purity greater than 99.9%, i.e. less than 0.1% of salts. As we know, this has been possible only because of the low 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 produce only a concentration of the order 3.5% in the main reservoir, the sea, and usually much less than 0.1% in the reflux streams which we call rivers and the hold-up areas which we call lochs or lakes.

But for modern man we must surely add to food, shelter and clothing a fourth basic requirement, power. In fact civilized man has never been able to exist without harnessing energy beyond his own, whether by wind, water, animal power or, as now, by thermal conversion. Without power he could not have made the jump from the nomadic hunter to the pastoral and farming settler on which civilization depends. Without power he could neither grow his food nor elaborate his shelter into dwellings and temples. And certainly without the increase in power which the advent of thermal conversion brought in the 18th century the world of man as we know it could not exist. There seems therefore some reason to regard water and power as the ultimate basic physical needs of man on which food, shelter and clothing, as well as all civilized elaborations, depend.

Now the massive thermal capacity of the sea and its vapour pressure and latent heat are the main things which determine the average temperature of our environment under the action of the sun. Hence the engineer will easily recognize that it is primarily the sea which determines the thermodynamic availability of any energy which he wants to use as power on this earth, since it fixes the general level of ambient conditions of temperature.

* The text of this paper originates from a Nominated Lecture delivered by Professor Silver on 5 November 1964 at a meeting of the Institution of Mechanical Engineers. This Institution has kindly authorized the publication of the full text in these Proceedings.
It is his ultimate sink of heat rejection, and thermodynamically a sink is just as much a 'source' of power potentiality as what we call technically a source. Thus we can properly regard the sea as the basic essential for our two fundamental needs, power and water. Life evolved first in the sea and then emerged from it, but it is interesting to realize that in what we choose to call life's highest form, ourselves, we have never shaken off a dependence on it.

Historically, so far as water and food supplies are concerned, we have relied on the condensation part of the distillation cycle, depending on the rain for our crops, and tapping off the reflux streams and hold-up areas, i.e. the rivers and lakes, for our water requirements. In some areas where the distribution of rain was not suitable for agriculture we have irrigated from the rivers and lakes. As civilization developed and city sizes increased, the natural hold-up areas became inadequate. Artificial reservoirs were made making as much use as possible of local contours, but inevitably being sited further and further away from the centres of water consumption. Thus the traditional engineering associated with water supply is that of the civil engineer rather than the mechanical engineer, although the latter has, of course, been involved in the pumps and the distribution system. However, the point I want to make is that in all this tremendous and complex system development of water supply we have chosen to use reservoirs of fresh water which are minute in comparison with the giant reservoir of 96.5% water which we have in the sea. Not only are such reservoirs small compared with the sea, but for some important population centres they are much further away than the sea. But we have had to use them – all because of this 3\(\frac{1}{2}\)% of salt. Ultimately of course the reason was economic. It cost us much less, in most of the centres of the world which developed with the industrial revolution, to tap off the natural solar distillation-cycle reflux than to separate this salt. That this economic fact was the basic reason can be realized from the reverse situation on board ship. With the coming of steam power it became cheaper to use the sea as the reservoir and distil fresh-water supplies on ships. And when in this century the development of arid zones began, it was cheaper to distil fresh water from the sea than to transfer it from less arid territories.

Thus we see that if we want to make a rational engineering approach to the problem of water supply, and ultimately also agricultural development, in any area, we ought now to begin by assessing comparatively the two alternative processes: (1) cost of catchment, storage and transport of rain water; (2) cost of conversion of sea water and transport of the product. It is presumed in (2) that the conversion plant can be designed to meet the main load so that storage is minimal, the real store being in the sea. In any area already well developed, such as most of Britain and Western Europe, we have the complication that substantial catchment, storage and transport networks for rainwater already exist. While these are continually being extended, it is difficult to know precisely the true cost of such extensions since they undoubtedly benefit from the existence of facilities constructed in times of cheaper labour and of capital long since written off or paid for. But for any newly developing territory this investigation should certainly be made. I would urge that it should be done also in Britain and other territories al-
ready developed and that we should try more accurately to assess the cost of extensions to conventional supply systems. The value of land and amenities should clearly be included in assessing the cost of catchment and storage. It was gratifying to note the announcement earlier this year that DSIR has given a grant to the Water Research Association which will inter alia be used to investigate the true incremental costs of additions to conventional water supplies. Only when these are available can we properly make comparison with the alternative of supply by sea-water conversion.

RELATION BETWEEN WATER AND POWER CONSUMPTIONS

Now I have already mentioned water and power as the basic requirements of modern life. You will not therefore be surprised when I go on to argue that when considering water supply to a new area or extensions in an existing scheme we should not regard this separately from the developing power requirements in the same areas. Nothing is so characteristic of modern life as the rate of increase of power capacity in civilized countries and the corresponding power installations in developing territories. For thermodynamic reasons there is an inherent link between the cost of sea-water conversion and power and this I shall discuss fully later. Meanwhile, however, let me give some interesting statistics. About 40 years ago in both Britain and America, the average consumption of water and electricity, although individually very different in the two countries, was such that the ratio of water consumption to power consumption was of the order of 100 gal/kWh. At the present day the rates, while again very different, both show a ratio of the order of 10 gal/kWh. The huge increase in electricity consumption in both countries is the chief cause. Water consumption is clearly pressing on diminishing resources. Now this trend poses to us a very interesting question. As civilization develops is it possible that the ratio of water consumption to power consumption can continually decrease? Or is there perhaps some lower limit which is technically necessary for the standards of cleanliness and health which we want to maintain? I think that in principle we must accept that such a limit must exist and we should try to get some pointers to its value. If we consider that microcosm of human society, a tourist ship, it is interesting to note that there has been pressure for increased water facilities, and one of the latest of such vessels has installed fresh-water supply facilities — excluding those required for the boiler and turbine plant — of 134,000 gal/d while the electricity supplies are 3000 kW. Thus we have 72,000 kWh per day, so that the water/power consumption ratio here is 1.86 gal/kWh. In Kuwait, which may be regarded as a typical developing territory, the ratio of water consumption to electricity consumption was approximately 3 gal/kWh in 1960. These figures can, I think, be taken to point to a figure of the order 2-5 gal/kWh as the lower limits of water/power consumption which we can expect to apply in modern civilization. Note that this excludes all agricultural water, i.e. water for food supplies. If we assume this sociological statistic, some very interesting consequences follow in respect of any possible reliance on sea-water conversion for water supplies.
SEA-WATER CONVERSION AND POWER

The maximum performance ratio yet achieved in distillation plants is about 12, i.e. 12 lb fresh water produced per 1000 Btu of heat input, i.e. 1.2 gal per 1000 Btu heat, which we can express as 4.1 gal/kWh(th). Where a distillation plant takes its heat input entirely from the reject heat from electricity generation at temperatures in the range 200-250°F, with steam supply conditions representative of modern practice the efficiency of electrical power production will be of the order of $\frac{1}{3}$, i.e. 1 kWh of power will be produced along with every 2 kWh(th) reject. Hence such a system can give a basic water/power ratio of the order 8 gal/kWh. This can clearly meet our sociological requirement for, if the ratio is lower, i.e. if the electrical power demand is greater, the remainder of the power can be produced more efficiently in turbines condensing at much lower temperatures. But equally obviously a distillation plant performance ratio of only 3 can give only about 2 gal/kWh and cannot therefore meet the water/power needs.

Let us now consider the position of conversion processes which consume energy in the form of power instead of heat. Two obvious examples are vapour compression distillation and freezing. Both of these are essentially heat-pump processes, the former pumping about 1000 Btu/lb of water produced and the latter pumping about 140 Btu/lb of water produced. If we assume that both processes are designed with regenerative heat exchange so that the effective heat-pump action is through a minimal temperature difference of 10 degF, we can construct Table I.

**Table I**

<table>
<thead>
<tr>
<th>Calculation of order of magnitude of power requirements for vapour compression distillation and freezing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour compression</td>
</tr>
<tr>
<td>Minimum order of temperature difference (degR)</td>
</tr>
<tr>
<td>Order base temperature (degR)</td>
</tr>
<tr>
<td>Thus order of Carnot refrigeration factor</td>
</tr>
<tr>
<td>Thus order of practical refrigeration factor</td>
</tr>
<tr>
<td>Thus order of power required (Btu/lb)</td>
</tr>
<tr>
<td>Thus order of power required (kWh/gal)</td>
</tr>
<tr>
<td>Thus gallons produced per kWh consumed</td>
</tr>
</tbody>
</table>

With the figures derived in Table I we can now do the following simple calculation:

Community normal requirements of power in kWh = 0.5 W where W is the water requirement in gallons. Additional power requirement if all water
is produced by vapour compression conversion of sea water $= 0.132$ W. Thus increase in power consumption compared with normal $= 26\%$. Similarly, for freezing, the increase in power consumption compared with normal requirements comes to be $5\%$.

To complete the picture we should note that all processes, including distillation, also consume power for auxiliaries such as pumps. The multi-stage flash process has its major power load in the recirculation pump, to which nothing in other processes corresponds. Hence we may ignore feed and brine reject pump power for all processes which will be small and comparable, but for flash distillation should take note of the recirculation power. For a performance ratio of 12 this will be about 0.012 kWh/gal, i.e. about one-half that of the freezing process.

If the social structure requires a greater water/power consumption ratio than the amount of 2 gal/kWh assumed here, then the additional power consumptions needed for water conversion mean greater additions to normal consumptions. Table II shows this effect.

**TABLE II**

PERCENTAGE ADDITIONS TO NORMAL POWER CONSUMPTION TO PROVIDE ALL WATER BY CONVERSION PROCESS

<table>
<thead>
<tr>
<th>Water/power consumption ratio</th>
<th>Percentage addition due to flash distillation</th>
<th>Percentage addition due to vapour compression distillation</th>
<th>Percentage addition due to freezing</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.5</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>6.5</td>
<td>66</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>13</td>
<td>132</td>
<td>26</td>
</tr>
</tbody>
</table>

The figures in Table II seem to me to be worth serious consideration. Everyone knows that one of the besetting problems of power generation is the problem of load factor. Is it possible that combination with water conversion would ease this situation, and benefit the economics of both processes? As distinct from electricity, product water can be stored — and provided the storage amount is small compared with conventional water-supply reservoirs we are still within the proper philosophy of sea-water conversion, i.e. storage in the sea. Storage of one day's product is quite an acceptable concept and hence this could be used to flatten out diurnal load variations on the station. The most striking example from Table II is obviously vapour compression in the situation of a 10 gal/kWh consumption ratio. A generating station with a normal diurnal load factor of 43% could be run at 100% electricity load the whole day provided the vapour compression plant can be smoothly operated at any water production rate between zero and full load, with rapid variations in opposite phase to the external electricity demand. Assuming that any of the conversion plants can be de-
TABLE III

STATION ELECTRIC POWER LOAD FACTORS IMPROVED TO 100% BY COMBINATION WITH CONVERSION PROCESSES

<table>
<thead>
<tr>
<th>Water/power production ratio</th>
<th>Load factor per cent before combination with:</th>
<th>Flash distillation</th>
<th>Vapour compression distillation</th>
<th>Freezing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>97.5</td>
<td>79.5</td>
<td>85.2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>93.8</td>
<td>60.2</td>
<td>88.5</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>88.5</td>
<td>43.1</td>
<td>79.5</td>
</tr>
</tbody>
</table>

Signed to give that type of variation — which is by no means certain as the design problems involved are difficult — we can construct Table III, showing the electricity load factors which could be improved to 100% by the adoption of combined power and water conversion. Note that the characteristic ratio in the first column is now the actual supply ratio from the station. Hence it need no longer be thought of as a consumption ratio characteristic of a community, but as the designed contribution ratio of the particular station. Thus, for example, in a country like present-day Britain a combined station might be designed to give only 1 gal/kWh or less, as a contribution to the water supply which would remain mainly conventional, to match the community ratio of the order 10 gal/kWh.

It will be realized that vapour compression and freezing, as processes consuming power, have this advantage over the thermal consuming process of flash distillation, that if they existed as viable processes they could be installed to use the peak capacity of existing power stations to the extent shown by Table III. Flash distillation, although of course it can be operated by primary thermal consumption, is obviously most economic when it takes its heat as reject heat from power generation, and hence its inclusion in a station does mean specific combination and appropriate design modifications. Moreover, it must be sited along with the generating station.

In making these comparisons we are up against the difficulty that flash distillation already exists, in quite a few sizeable commercial installations by different manufacturers, while the other processes have not yet gone beyond the pilot plant or demonstration plant stage. Reliable energy consumptions and costs are known for flash, but are unknown for the others. Thus, for example, the figures for freezing in Table I are only on a theoretical basis. Nevertheless we have there a total energy consumption of the order 9 Btu power per lb whereas with flash distillation at performance ratio 12 we need 83 Btu thermal per lb. There is therefore an apparent factor of the order 9 to 1 in favour of freezing from the point of view of energy consumption. Before discussing the matter of capital costs to realize these consumptions we have, however, to consider the relative costs of the forms of energy required for these two different processes.
ENERGY COSTS IN SEA-WATER CONVERSION

The power consumption of 9 Btu/lb for freezing implies a thermal consumption in the power-producing device of about 27 Btu/lb. Hence if we were to compare freezing with a flash distillation plant using direct thermal supply for the same fuel, the energy cost ratio would be about 3 to 1 in favour of freezing. However, in most cases, as already discussed, flash distillation will be operated by reject heat from a power installation, which must obviously be assessed at some cost lower than the original fuel cost. It is now commonly accepted that the proper way to assess this cost is in terms of the fuel consumption required to produce power when the heat is rejected at the temperature required for distillation as compared with rejecting the heat at the most efficient vacuum possible at the same site. For representative modern steam conditions the factor is of the order of about 0.4, i.e. the additional thermal consumption at the boiler needed to provide 1 Btu of reject heat at temperatures in the range required for distillation (200-250°F) as compared with rejection at vacuum of about 85°F is 0.4 Btu. Hence 83 Btu thermal consumption per pound of product water by a distillation plant using reject heat requires only about 33 Btu of equivalent fuel consumption. Thus the difference between distillation and freezing is narrowed down to the order of 33 Btu as compared with 27 Btu. We must, however, include the appreciable pumping power associated with distillation. We have already seen that this is of the order 4.5 Btu power per pound, and therefore equivalent to about 13 Btu fuel. The true order of relative energy costs is therefore 46 to 27, i.e. distillation energy costs will be of the order 1.7 times freezing energy costs. While this is much less than the 9 times energy consumption which has sometimes mistakenly been quoted as representative of relative energy costs, it is nevertheless substantial.

Table I shows that the energy requirements of vapour compression are about 5 times those of freezing. The energy is in the same form, hence the costs per unit energy are the same. Thus flash distillation energy costs, on the assumed performance ratio 12, will be 1.7/5, i.e. about one-third of the energy costs of vapour compression.

Hence for these three processes we have the comparative energy costs shown in Table IV, using flash distillation as base.

Table IV has been produced to show the point, which is sometimes not realized, that despite the apparent thermodynamic attractiveness of the vapour compression process, flash distillation has already achieved lower energy costs.

However, to compare the economics of the processes properly we require to know the capital cost. In principle it has always been possible to get low energy costs by distillation - the problem has been that all methods of achieving lower energy cost tended to increase capital cost. The breakthrough which occurred in the late 1950's, when sea-water conversion costs by distillation were practically halved, was because the new multi-stage flash process could give the same energy costs as the previous multiple-effect pool boiling process at less than half the comparable capital cost - and much lower energy costs for still acceptable capital cost.

Other new processes besides vapour compression and freezing are of course under investigation. Electrodialysis, at present proved satisfactory
TABLE IV
COMPARATIVE ENERGY COSTS (FLASH AS UNITY)

<table>
<thead>
<tr>
<th>Flash distillation performance ratio 12 (already achieved)</th>
<th>Vapour compression (theoretical on minimal temperature differences) and full regenerative exchange</th>
<th>Freezing (theoretical on minimal temperature difference) and full regenerative exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0.59</td>
</tr>
<tr>
<td>1</td>
<td>2 or 3</td>
<td>0.55 - 0.59</td>
</tr>
</tbody>
</table>

The second row of figures includes an allowance based on Table III for the load factor effect discussed earlier. It is difficult in this paper to give more detail on this because it clearly depends so much on the relevant product ratio, but the range indicated seems probable.

for brackish water, is being developed in the hope of tackling sea-water. Reverse osmosis is also under active research but is still at the laboratory stage. Too little is yet known on these and other ideas for inclusion in this paper. My own specialist experience has been with distillation. It seems to me appropriate therefore that I should now give some discussion of technical aspects which govern this process.

MULTI-STAGE FLASH DISTILLATION PROCESS

In the earlier discussion in this paper I have spoken of distillation as giving performance ratios of the order 12 lb per 1000 Btu heat input, i.e. about 12 lb of vapour can be produced and condensed from brine by the latent heat of about 1 lb of steam at atmospheric range. I have assumed therefore that you know roughly how this multiplication effect is obtained. In essence it is done by using the condensation heat release of part of the vapour produced to provide part of the heat input necessary for the total evaporation. In the initial history of distillation this was done by what was called the multiple effect principle. Vapour was produced literally by boiling brine in a vessel, and condensed by being used to boil brine in another vessel at lower pressure. This multiple-effect pool boiling system was standard for many years and is still valuable in particular cases, including marine distillation. In its maximum development it was embodied in the plants at Aruba and Curaçao, with six effects giving a performance ratio of 4.9, and a maximum unit capacity of 450 000 gal/d. To achieve higher performance ratios with this principle was not only very difficult technically, but also exceedingly expensive, so that in fact this particular plant represented simultaneously the maximum achievement and the end of that system. The reasons for its being superseded have been given in detail elsewhere [1]. The multi-stage flash process was introduced in 1956 and since 1958 has completely transformed the situation. It is now possible to get performance ratios of the
order of 10 more cheaply than was possible for 5 with the multiple-effect system. More important, it is also known that the same type of practical limitations to performance ratio and to unit size do not exist for this process. Hence there is no doubt we are in for a period of extensive expansion of multi-flash plant capacities and performances with a consequent reduction in product water cost. I propose therefore to limit my lecture to this process and not to include any further discussion of multiple effect distillation.

The essential features of the multi-stage flash distillation process can be seen from Fig. 1. Suppose we have a given temperature range, say $t_x - t_y$. Then the order of magnitude of vapour which can be flashed off a stream of saturated brine falling down this range is a fraction $s(t_x - t_y)/L$.

Hence the order of magnitude of flash vapour obtainable is

$$\frac{s(t_x - t_y)Q}{L}$$

With $t_x - t_y$ of order 100 degF, where $Q$ is the rate of flow of saturated brine down the stages, a basic requirement of the multi-flash system is that we must circulate through the system a brine rate of order 10 times the desired product rate.

This can be done in either of two main ways. One obvious method is to use a feed rate of order 10 times the distillate product rate. This means that the associated brine reject rate is of order nine times the distillate rate. Hence a high rate of enthalpy rejection in this brine is implied and such a system is not suitable for high performance ratio plant — unless the additional complication of liquid-liquid heat exchangers is used to recover heat from the brine into the incoming feed. Moreover, in cases where, as is usual, some chemical treatment is employed for prevention of scale formation, such treatment has to be proportional to the feed rate, and becomes very high for high feed rates. Hence I shall do no more than mention the existence of this method.

Figure 1 shows the better method. The required brine flow rate is obtained by recirculation. In the diagram the feed to the plant is $M_f$, which is usually about $2M_d$. The recirculated quantity is $M_r$ which flows through the main banks of heaters, from that in the $(n-j)$th stage to the first stage. On emerging from the heater in the first stage it has reached a temperature indicated by $t_f$. It then passes through the heat input heater where its temperature rises to $t_0$. In all this flow it is at a pressure greater than the saturation pressure $p_0$ corresponding to $t_0$, so that no boiling or flash occurs. It then enters the flash chamber of the first stage where the pressure is reduced below $p_0$. A fraction flashes, becomes vapour at temperature $T_1$ corresponding to the pure water saturation pressure $p_1$ at which the chamber is maintained, while all the brine falls in temperature ideally to $t_1$, which is the saturation temperature of the brine corresponding to $p_1$, that is $t_1 = T_1 + \Delta t_x$. The flashed vapour is condensed by rejecting its latent heat to $M_t$ as shown.

This action continues all the way down the decreasing pressure stages to the $(n-j)$th stage. These first $(n-j)$ stages constitute what is called the heat

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1 Notation is given in the Annex.
FIG. 1. Diagram of multi-stage flash process
recovery section. This term is precise in that all heat given out by condensation in this section is in fact recovered.

The remaining j stages shown in the diagram are usually referred to collectively as constituting the heat rejection section.

A notable paper on this type of plant was presented to the Institution in 1959 by Frankel [2] and while I have previously mentioned the following circumstance in public, I think it would be nevertheless appropriate that in a Nominated Lecture I should do so again. The possible thermodynamic and economic advantages of the multi-stage flash distillation system were first realized and put into practice both by Dr. Frankel and myself simultaneously and working quite independently. It was one of those peculiar coincidences which must happen from time to time in technical development. Neither of us knew of the other's work, and since the arguments which seem elementary now were then quite novel, when we did learn of the other's developments we were, I am sure, both encouraged and stimulated, despite the competitive situation. There were of course some differences in the actual embodiments in design and these are commented on in the discussion of Frankel's paper. It should also be recorded here that the first installation using flash distillation for the production of substantial quantities of fresh water from the sea (units of 500,000 gal/d) was due to neither of us but to the American company, Westinghouse. This was, however, on the design basis previously associated with marine flash distillation in which the number of stages was just slightly higher than the performance ratio, just as in multiple-effect boiling distillation the number of effects is necessarily slightly higher than the performance ratio. The new point which was realized and applied by Frankel and by myself can be expressed most simply by saying that for flash distillation there is no such necessary relationship. You can make the number of stages as large as you like, quite independently of the performance ratio. The result is that for a given performance ratio you can continually, although asymptotically, improve your mean temperature difference for heat exchange, by continually increasing the number of stages. I have given the theory of this in detail in a book which is in course of publication [3]. It is shown that the heat transfer surface required is of order

\[
\frac{S}{M_d} \approx \frac{nL}{U(t_0 - t_b)} \ln \frac{n}{n - R} \tag{1}
\]

It can also be shown that to a good approximation the amount of constructional material required in a plant containing n stages is of the form \(a' + b'\sqrt{n/M_d}\).

Hence when we include capital cost factors per unit of constructional material and heat transfer area, we find that the capital cost of a plant is of the form

\[
\frac{C}{M_d} = a_c + b_c \sqrt{\frac{n}{M_d}} + C_c n \ln \frac{n}{n - R} \tag{2}
\]

Since the energy consumption cost (neglecting pump power) is inversely proportional to \(R\), it is clear that the major operating cost of water produced
by distillation, including interest and amortization charges on capital and energy consumption costs, is of the form

\[ \frac{K}{M_d} = A + \frac{B}{\sqrt{M_d}} \sqrt{n} + Cn \ln \frac{n}{n - R} + \frac{E}{R} \]  \hspace{1cm} (3)

This is minimized for a fixed \( n \) and \( M_d \) at an optimum value of \( R = R_0 \) given by

\[ R_0 = \frac{E}{2nC} \left[ \sqrt{1 + \frac{4n^2C}{E}} - 1 \right] = \frac{E}{C} - \frac{E}{2nC} \text{ where } \frac{4n^2C}{E} \text{ is large} \]  \hspace{1cm} (4)

Hence in designing a distillation plant for a certain area it is not necessarily correct to design for the highest technically possible performance ratio, as this may give expensive water product. The interest and financing procedures for the proposal must be examined and an optimum performance ratio chosen from Eq. (4).

We have still to make a choice of \( n \). For a given \( R \) and \( M_d \) the second term in Eq. (2) increases as \( n \) increases while the third term diminishes. Differentiation to find a minimum is not permissible here since \( n \) is by definition necessarily an integer and therefore discontinuous. But by computation a best value \( n_0 \) along with a best value \( R_0 \) can be found.

We may investigate orders of magnitude, however, on the assumption that \( n \) is a continuous function and noting that while \( R_0 \) according to Eq. (4) increases with \( n \), the function \( R_0/n \) has a maximum value at \( n = \sqrt{E/C} \), where \( R_0 = \frac{1}{2} \sqrt{E/C} = n/2 \). Thus the order of magnitude of water cost when optimized for a given \( M_d \) must be

\[ \frac{K}{M_d} = A + \frac{B}{\sqrt{M_d}} \left( \frac{E}{C} \right)^{1/4} + (EC)^{1/4} \ln 2 + 2(EC)^{1/4} \]

\[ = A + \frac{B}{\sqrt{M_d}} \left( \frac{E}{C} \right)^{1/4} + 2.69(EC)^{1/4} \]  \hspace{1cm} (5)

(N. B. The assumption of \( n = 2R \) contained herein is for order of magnitude purposes. In most cases optimum design for specific conditions requires \( n > 2R \) and the costs are slightly less than those discussed herein.)

I have led up to Eq. (5) because it is fundamental in understanding the possibilities of economic water desalination by distillation. This is the order of magnitude of the unit cost of the water product, and we see clearly that it is governed by only five characteristics, namely \( A, B, C, E \) and \( M_d \). All possible ways of reducing unit product cost must depend on modifying some or all of these factors appropriately. Hence the most useful technological study which we can give is to show or discuss what engineering features determine these parameters. We can therefore discuss them in turn.
PRODUCT RATE $M_d$

Many hopes of lowering water desalination costs depend on the idea that larger unit size will reduce costs. On this assumption the American Office of Saline Water and Atomic Energy Commission have considered instituting detailed engineering design studies for plants of unit capacity as large as 500 million gal/d. Since the maximum unit size yet achieved does not exceed 5 million gal/d, there is a long way to go. Equation (5) reveals the true basis of these hopes. Only the second term is a diminishing function of $M_d$, the others are unaffected. Even for a plant of infinite capacity, we should have

$$\left( \frac{K}{M_d} \right)_x = A + 2.69(EC)^\frac{1}{2}$$  \hspace{1cm} (6)$$

The relative utility of the large plant concept in reducing costs depends, therefore, on the relative contributions of the three terms in Eq. (5) in existing plants of feasible size. Before considering this it is as well to have a look at Eq. (6) which gives the absolute minimum water cost. It depends on $A$, $E$, and $C$ only and we may therefore continue our discussion of the parameters leaving $B$ to the last.

VOLUME OR TIME PARAMETER $A$

The technological origin of $A$ is in the basic requirement that the brine and the vapour ascending from it and the heat transfer surface must be enclosed in an envelope of such material and dimensions as to (a) allow adequate residence time for equilibration to take place; (b) allow vapour flow to occur without excessive carry-over entrainment of brine to contaminate the product; (c) withstand the loads arising from the different pressure relative to the atmosphere; and (d) resist adequately corrosive and erosive action. The designer has to consider all these factors together and his decisions will determine the amount and kind of material envelope required. The residence time is the volume of brine in the vessel divided by the rate of circulation. However, the depth of brine is fixed practically constant by hydrostatic and thermodynamic requirements, and hence only the plan area $A_p$ of the vessel is a valid variable together with rate of circulation. The rate of circulation per unit product is approximately $L/(t_0 - t_b)$, so that the residence time is proportional to $A_p(t_0 - t_b)$. Not much is yet known about residence time requirements and much research is needed. For the present we have to assume that since the fraction of flash is also proportional to $t_0 - t_b$ we need a specific plan area $A_p$ per unit of product water. The need for location of heating surface and of avoidance of carry-over are the ultimate determinants of the height. Carry-over limitations also determine the order of magnitude of permissible rising vapour velocity and hence also determine a plan area in association with a height. The designer must adopt whichever plan area is larger, of the two requirements so far as he can assess them. Having done so he still has some choice in how he disposes
his plan area whether nearly square or very elongated, but he has somehow to match with his heating surface tube length. He has then to choose a material and its thickness to meet conditions (c) and (d). Up to now steel has been used and it has worked out that, on an interest plus amortization rate of 10% per annum, i.e. $1.14 \times 10^{-6}$ per hour, we obtain for A a value of order $3 \times 10^{-6} \ £/lb$ product, i.e. $3 \times 10^{-5} \ £/gal$ or approximately 7d./1000 gal.

SURFACE PARAMETER C

From the previous theory it will be realized that the parameter C, which represents the heat transfer surface, will be mainly inversely proportional to $U(t_0 - t_b)$. Hence it can be reduced by improved heat transfer rate or extended temperature range. This is the origin of all the relevant research on scale formation, not only for improved heat transfer but also to permit extension of the temperature range. Multi-flash plants were originally limited to about the range 200-100°F. Extension of the top temperature to 250°F has now proved possible and this reduces C in the ratio 2/3. Further reduction may yet prove worthwhile. However, such extensions introduce pressure design and corrosion problems which are absent in the lower ranges, and hence increase the value of A and of B. The value of C is also influenced by the heat exchanger design, the tube-plates, and the way in which the designer disposes his surfaces reacts on A and B also. However, in present practice the order of magnitude of C, again on interest and amortization rate of 10%, is about $2.5 \times 10^{-7} \ £/lb$, i.e. $6 \times 10^{-5} \ pence/lb$.

ENERGY PARAMETER E

E is the cost of 1000 Btu of heat supply, or approximately 1 lb of supply steam. Its value is therefore affected by the prime fuel cost at the site and also by the question of whether the distillation plant is combined with a power system in the manner discussed earlier. For present purposes we may regard it as a variable in the range 0.02 - 0.06 pence/lb steam or per 1000 Btu.

DEDUCTIONS FROM THE VALUES OF E AND C

Thus we have values of EC of order in the range $12 \times 10^{-7}$ to $36 \times 10^{-7} \ pence^2/lb^2$ and $(EC)^{1/2}$ of order $1.1 \times 10^{-5}$ to $1.9 \times 10^{-3} \ pence/lb$. Thus the second term of Eq. (6) is of order $3 \times 10^{-3}$ to $5 \times 10^{-3} \ pence/lb$, i.e. 30 to 50d. per 1000 gal. Including A we have a water cost in the range 37 to 57d. per 1000 gal, corresponding to the energy cost range of 0.02 to 0.06d. per 1000 Btu. The number of stages to be expected is greater than $(E/C)^{1/2}$, i.e. greater than 17 to 30, and the order of magnitude of optimized performance ratio is 8 to 15 (see note after Eq. (5)).

STAGING PARAMETER B

We now come to the final parameter B, which permits the consideration of finite plant size. The technology underlying this parameter is perhaps
the most difficult to describe in general terms, precisely since it relates to finite plant size. It is therefore particularly subject to the designer's ingenuity in arranging heating surface, tube-plates, stages and their inter-flow passages, etc. It depends on, and is affected by, practically all the phenomena of equilibration, flashing flow, carry-over, etc., and the limitation to ingenuity in design is the extent of our ignorance of many of these features. I can therefore give only a typical value for the order of magnitude of $B$, with the caveat that it may vary very widely. In designs with which I have been concerned it has worked out that, again on an interest and amortization rate of 10%, $B$ has a value of order $3 \times 10^{-4}$ £/lbh.

For a plant of 1 million gal/d $M_d = 417,000$ lb/h thus

$$\frac{B}{\sqrt{M_d}} = 4.65 \times 10^{-7} \text{ £/lb}$$

Taking $E/C$ at the top value given previously we have $(E/C)^{1/4} = 5.6$, and hence the second term in Eq. (5) becomes $2.6 \times 10^{-6}$ £/lb, or 6.2d./1000 gal. The product water cost is therefore from 43 to 63d./1000 gal according to the range of $E$.

The point to note here is that already at the size of only 1 million gal/d this portion of the water product cost is only of the order of 10% of the total.

Now since the energy consumption part of the cost is $E/R$, it is approximately $2E/(E/C)^{1/2} = 2(E/C)^{1/2}$, that is $2.2 \times 10^{-3}$ to $3.8 \times 10^{-3}$ pence/lb, or 22-38 d./1000 gal. Hence in the optimized infinite plant, the capital charges portion of the water cost from the formula is about 15-19 d./1000 gal, and in the optimized plant for 1 million gal/d the capital charges portion is 21-25 d./1000 gal. Thus the proportion of the capital cost which can vary with size in the formula is about 28 to 24% of the capital cost of a unit for 1 million gal/d, in the performance ratio range from about 8 to 15. It is therefore important to note that this large proportion of capital cost, at that size, becomes less important as size increases, and the actual savings in optimized water cost in going beyond that size cannot be more than about 10%. I do not want to argue from this that we should not seek the savings to be obtained from very large unit plant design, but I do think it is important to show that these savings may not be preponderant. In particular, places which are now needing water supply by desalination should not feel that they must wait until technology is competent to supply very large unit plants. The extra cost of obtaining a large installation by multiple units of size within present assured competence may not be excessive.

ANCILLARY PLANT AND ADDITIONAL COSTS

It will be appreciated that in Eq. (2), and in the subsequent material, I have been aiming at presenting a rough general philosophy of design of the main desalination plant structure, and hence have omitted important ancillary items like pumps, valves, control gear, etc. There is considerable intrinsic interest in the technology of these, particularly the pumps, but from the cost point of view it may be said that they add something of the order of 15%
to the capital costs. Hence for an infinite-size plant this rough analysis predicts optimized water costs in the range

\[ 22 + 1.15(15) = 39 \text{d.}/1000 \text{ gal} \]

for thermal energy costs 0.02 pence to 0.06 pence per 1000 Btu respectively.

For a unit size of 1 million gal/d the corresponding figures are 46 to 67d./1000 gal.

It will be understood that in this general analysis, which has been done to reveal the underlying technical features and problems in a basic way, I make no claim nor have any commitment to commercial accuracy. Also before closing this section I should remind you that specific design will give better figures with n>2R, and that a 10% per annum rate of combined interest and amortization has been used on the capital.

POSSIBLE IMPROVEMENTS IN DISTILLATION

With these provisos I believe, however, that the figures given are a valid guide as to what is reasonably possible with distillation today. They reveal that while research and development on those phenomena which determine A and B will be useful, the preponderating term is that in \((EC)^{1/2}\). Research and development to reduce C will be the most effective, and system design along with power to give low E is of major importance.

The concentration of effort on improvement of heat transfer coefficients by prevention of scale and by better understanding of condensation heat transfer is therefore well worth while, since these coefficients primarily determine C. It will also be understood that proposals to remove tubular heat-exchange surface altogether have the same objective. Some attempts have been made to use an immiscible fluid as heat transfer medium. In one particular process, referred to as the vapour-reheat system for no reason other than that this name was used by its originators, we have essentially a multi-flash system in which recycled fresh water is used to condense the flashed vapour by direct contact. This recycled water flows counter-currently, i.e. upwards from stage to stage in respect of temperature, and on exit from the top stage goes through a heat exchanger to preheat the incoming seawater feed, which is subsequently further heated in a heat input section. No such plant has yet been built. The recycle fresh-water stream, since it must flow unconfined up the pressure gradient, requires as many pumps as it has stages. It seems to me unnecessarily complicated and I doubt whether it will prove worthwhile.

The question of raising the top temperature to reduce C has been mentioned earlier in the paper. It is worth considering whether we can get any indication as to how high we should go. A full answer to this requires consideration of stress and corrosion requirements which raise the values of A and B as we reduce C by raising the top temperature - and there is also the question of increased risk of scale formation. But there is one deduction
I should like to show which is independent of these. Suppose we are working on a reject heat system. The cost of energy $E$ will increase as we raise the temperature of extraction, and as we have seen, it is the product $(EC)^{1/2}$ which is important. Now the replacement cost factor for bled steam is approximately $(H_b - H_c)/(H_0 - H_c)$, where $H_b$, $H_c$, $H_0$ are the enthalpies at bleed, turbine exhaust, and boiler exit respectively. Thus EC for given boiler and condenser conditions is proportional to $(H_b - H_c)/(t_b - t_0)$. Now even for transition from superheated to wet steam and subsequent wet expansion, the enthalpy drop along an adiabatic - and even when not isentropic - is practically proportional to the saturation temperature drop. Hence, in fact, on a reject heat system the product EC is quite insensitive to extraction pressure and temperature. For this reason it is my view that whenever we are working on an extraction system, as we should normally be for best economy, there is little advantage in seeking for advanced temperatures and meeting all the problems which then arise. These are only worth meeting, or trying to meet, when dealing with a direct heating system, i.e. a single-purpose plant producing water only and not power also.

As soon as I state this principle you may ask whether it is perhaps worthwhile coming lower in top temperature and pressure. The answer lies not in the effect on C but in A and B. Low pressures mean large volumes and considerable plant dimensions. High pressures mean lower volumes and dimensions but higher stresses and more expensive scantlings. It is my own view that there is likely to be little advantage in going much above atmospheric pressure, i.e. that we are already at about the optimum. This may seem a very timid and unadventurous conclusion, but the arguments are obvious in the negligible effect of changing pressure on the chief parameter EC, in extraction systems. Moreover, many other matters have to be considered, and I like to think of larger plants in cheaper constructional materials than steel and hence prefer to think along lines which will steer clear of increased temperature problems.

Before leaving this point I should just add that increasing the temperature does not even help the recirculation pumping costs appreciably. True the recirculation quantity falls, but the head goes up, and the power consumption is hardly affected. The capital cost of the pump may be reduced but the effect is slight.

COST POSSIBILITIES OF OTHER PROCESSES

Now what I should like to have done - and you would no doubt have wished it - is to give a similar cost analysis and discussion for other processes such as freezing. Unfortunately this is impossible, because the experience and working data that permit the foregoing analysis to be offered with reasonable confidence do not exist for any process other than distillation. Hence I have tried to deal with the matter by a more devious route, as follows, and I hope you will find it of interest and use.

We have used a basic prime thermal energy cost of 0.06d./1000 Btu. On this, power energy will cost about three times, i.e. 0.18d./1000 Btu
(0.615d./kWh). Taking the energy requirements from Table 1 we therefore have the energy costs as follows:

<table>
<thead>
<tr>
<th></th>
<th>Vapour compression distillation</th>
<th>Freezing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy portion of product water cost, d./lb</td>
<td>0.008</td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td>d./1000 gal</td>
<td>80</td>
</tr>
</tbody>
</table>

Comparing these with the water costs by flash distillation discussed earlier we see that vapour compression distillation is out immediately. For freezing, however, comparing with the very large size flash-plant total costs, we have a balance of from 23d./1000 gal, which can be allowed for the capital costs of freezing to compete with distillation under very good extraction conditions, and 46d./1000 gal to compete with distillation unhelped by extraction. Recalling the assumed interest rate of 10% per annum ($1.15 \times 10^{-5}$ per hour), this means that freezing will be cheaper than the cheapest flash distillation provided the capital cost of the equipment is less than 0.0023/$1.15 \times 10^{-5}$d. per lb/h, i.e. 200d. per lb/h. For a freezing process we are entitled to consider a product of 1 lb/h as being a heat-pump load of order 140 Btu/h. Hence to be competitive we need refrigeration plant costing less than 1.4d. per Btu/h capacity, i.e. less than £6 per 1000 Btu/h or £6000 per million Btu/h.

While crude, I believe this calculation is sufficient to show that freezing techniques are potentially applicable. Modern air-conditioning plant with centrifugal compressors can be obtained for prices in the range £8000-10000 per million Btu/h. Admittedly any proposed freezing process has additional costs for separation and washing of ice crystals, but clearly the costs must be regarded as capable of being brought within the same range by research and development. But of course distillation has a long start, with much accumulated experience, and will progressively reduce its costs also. There is clearly an interesting time ahead.

As for other processes, little is known, but we can sum up the situation like this: No process can possibly use less energy than the heat of solution, which is about 1.2 Btu/lb. Assuming a maximum efficiency of the order of 50%, it seems probable therefore that we shall never get a process using less than about 2.5 Btu/lb, giving an energy cost of order 5d./1000 gal. Doing a similar sum to that for freezing, we see that an ambitious inventor will have to realize this with a plant of capital cost less than £1.25 per lb/h capacity if his process is to be competitive with flash distillation. The inventor who did the impossible and produced a plant with no energy consumption would similarly have to do it for a capital cost of £1.42 per lb/h capacity to be competitive. But, did I say the inventor who did the impossible? Surely in this context this is the conventional water engineer constructing a catchment area and reservoir. Can he do it today for £1.42 per lb/h, that is 12s. per gal/d capacity? And not for a 30-d or a six-month supply, but for an inexhaustible assured store?
That question is clearly the basic one to determine future policy in water supply. All other costs, maintenance, distribution, etc., are additional to all systems, including conventional supply.

STABILITY AND CONTROL PROBLEM IN FLASH DISTILLATION

Now I hope I have, as required for this kind of paper, given an acceptable presentation of the general engineering of the subject. Such general engineering and cost studies are of great importance because they interest everyone. But I am now going to yield to a temptation which has been with me throughout the preparation of the paper, and include an account of one detailed matter of engineering design in flash distillation. I have chosen the question of stability and control for two reasons: (a) discussion of most of the other main design features is already given in my paper at Athens and in other references, but this matter has not to my knowledge previously been presented analytically; (b) as a reminder to our economist friends that however cheap or expensive a device may be it is useless if those working it find it unstable, unreliable, or very difficult to control reliably.

In a multi-flash distillation plant we have 20 or more stages. In each there is of necessity a free level of brine. The attainment of the designed performance ratio depends critically upon reaching and maintaining the correct temperatures individually in each stage, and therefore the correct pressures above each level. The flow of brine from stage to stage is influenced by the pressure and temperature difference, and by the levels. If a level rises too high, or if splashing is too violent, the purity of the distillate can be lost by carry-over. If a level falls too low vapour can escape and efficiency suffer disastrously. How are we going to control so many temperatures and levels all simultaneously, without undue complexity and cost?

Consider Fig. 2 which shows saturated water at rate $Q_s$ at temperature $T_1$ entering a chamber in which it may be allowed to flash. In the upper region of this chamber cooling water flows through a bank of tubes at rate $Q_c$ with entering temperature $t_1$. The problem is to determine the saturation temperature $T$, and therefore corresponding pressure, at which the chamber will operate. In this simplified treatment we assume pure water in both circuits and hence avoid complications of varying specific heat and boiling point elevation. We have the following relations:

$$Q_s c(T_1 - T) = ML = Q_c c(t_2 - t_1) = US\theta$$  \hspace{1cm} (7)

Using the condenser parameter $\alpha = US/Q_c c = \ln[(T_1 - t_1)/(T_1 - t_2)]$, we have $T - t_1 = Te^\alpha - t_2 e^\alpha$. Thus $T_1 - T = T_1 - t_1 - Te^\alpha + t_2 e^\alpha$. Also $t_2 - t_1 = (Q_s/Q_c)(T_1 - T)$. Define $q = Q_s/Q_c$, thus $t_2 = t_1 + q(T_1 - T)$.

By substitution and manipulation we find eventually that

$$T_1 - T = \frac{(T_1 - t_1)(1 - e^{-\alpha})}{1 - e^{-\alpha} + q}$$  \hspace{1cm} (8)
Equation (8) determines the temperature drop, and therefore pressure drop in terms of the temperature difference between the two entering streams. It shows that the result is a fraction of that difference, the value of the fraction being

\[
\frac{1-e^{-\alpha}}{1-e^{-\alpha} + q}
\]

From Fig. 1 we see that in the heat recovery stages at least, and assuming steady operation, the value of \(q\) will be 1. Hence an infinite surface \((\alpha = \infty)\) would give a drop just half of the initial difference in such sections.

I think that the presentation of this equation will help you to realize fully the complexity of realizing flash distillation design objectives successfully in practice. For a given \(q\) the fraction is completely dependent on the performance of the heat-exchange surface, as indicated by the presence of \(\alpha\). Any surging or variation of cooling flow quantity \(Q_c\), any fouling which upsetts \(U\), will alter this fraction. Even more important, any surging in \(q\) — and this is easily possible since \(Q_s\) is flowing between free levels in two chambers — will affect the fraction. Further, the actual value of the available difference \(T_i - t_i\) depends on the operation of the stages above and below the one under consideration, since the upper determines \(T_i\) and the lower determines \(t_i\). The whole functioning of the plant, the amount of vapour produced, and the thermodynamic efficiency, depends on getting the pressure and temperature drops between stages operating stably at their designed values. Hence the control problem is revealed as that of maintaining steady values of \(\alpha\) and of \(q\), and of course, because of the free levels, the most difficult is \(q\). It is for this reason that the success or failure of a multi-stage flash distillation plant depends critically upon the design of the brine flow passages between stages.

At this point, a personal reminiscence may not be out of place. The problem of designing brine flow passages is difficult because the flow takes place under flashing conditions, i.e. it is a problem in two-phase flow. Having already done some theoretical work on this about 15 years before [4], I thought I knew something about this — at least enough to know what I was up against and to appreciate the risks of instability. In planning the first large multi-stage flash distillation plant I worked out a certain design philosophy on this basis and tested it out on a pilot plant which had a capacity.
of 1000 gal/d. The theory showed the possibility of instability above certain loads. With what I thought to be reasonable extrapolation we went straight from this to our first order for a unit capacity of 1 million gal/d — a factor of 1000 from the pilot plant. During the construction period, as you may imagine, I had some nightmare thoughts of the stability problem, and when the plant was first commissioned it seemed that these nightmares were coming true. Up to about a recorded 85% load the plant behaved well and stably, but above that it went quite suddenly completely unstable, so that distillate purity shot up from below the guarantee of 100 to about 10 000 ppm. We took some hasty action to put in baffles and the like to meet the full load requirements, and it looked as if my extrapolation ideas had been unreliable. However, it was soon found that a completely unexpected instrumentation defect existed and that we had in fact been stable up to 110% load. The customer's chief engineer became so interested in this matter that at a later date on his own initiative he took out the extra baffles which we had installed in our emergency action and ran the plant as originally designed, and proved that this was in fact completely satisfactory up to 110% load.

The point about this reminiscence is that despite much work which is now being done on the theory of two-phase flow, and despite much accumulated experience now on the behaviour of several multi-stage flash distillation plants, this is still a key problem in designing for a size beyond that already known. My own view is that to attempt to design any kind of automatically variable passages would be tremendously costly, and probably unsatisfactory. Fixed passages have been designed with great satisfaction for existing sizes of plant (up to unit size 2 million gal/d) on approximate theoretical understanding of the flashing process. I believe we shall be able to continue this design procedure to larger sizes as we learn more about the thermo- and hydro-dynamics of two-phase flow. The passages themselves add little to the capital cost, but the dimensions required to locate them affect profoundly the size and disposition of stages and heating surface, and hence affect all the parameters A, B and C discussed earlier.

Long-term variations in α due to fouling upset efficiency but do not present a control problem as such. However, fluctuations in α are unfortunately possible and do enter the control problem if the behaviour of the recirculation pump is not stable. Now the recirculating pump in large multi-flash distillation has quite a new kind of duty, unprecedented in previous engineering. The capacity it has to handle is of the order of condenser circulating pumps, the head is greater but, most important, its suction conditions are even worse than those of a condenser extraction pump. In the latter the water is usually just slightly below saturation temperature. In the flash recirculation pump it is at or — if full equilibrium is not reached — above saturation temperature. It must be designed and installed with adequate net positive suction head to prevent even the onset of cavitation, because of the instability created throughout the plant if the recirculation quantity surges. Moreover, since the load is appreciable the efficiency must be high, otherwise energy costs will be adversely affected.
CONCLUSION

I return now to general matters for my conclusion. The following figures were given by Colas at Athens in 1962 [5].

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present world population</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>Expected world population in A.D. 2000</td>
<td>$6 \times 10^9$</td>
</tr>
<tr>
<td>Total current fresh water requirements per head in developed countries</td>
<td></td>
</tr>
<tr>
<td>(including industrial and agricultural use)</td>
<td>$220,000$ gal/yr</td>
</tr>
<tr>
<td>Thus expected world total fresh water needs for all countries by A.D. 2000</td>
<td>$1.3 \times 10^{15}$ gal/yr</td>
</tr>
<tr>
<td>Maximum amount of utilisable fresh water flow from all sources in the world</td>
<td>$1.4 \times 10^{16}$ gal/yr</td>
</tr>
</tbody>
</table>

Much of this fresh water flow is inaccessible. All food, and civilization, depends on the accessible portions of this water at present. The total installed capacity of major desalination plant in the world today is less than 100 million gal/d and no unit is yet larger than 2 million gal/d (a unit of 8.34 million gal/d is at present projected for Florida). The water consumption of Glasgow alone is about 100 million gal/d and is rapidly increasing. The water consumption of Edinburgh is about 36 million gal/d and, despite our rainfall, restrictions have sometimes been necessary. The Lake District is threatened with further exploitation of its resources, with probable damage to its amenities. Similar agitations are relevant to Wales. The South of England development is definitely short of water. In areas of the world where well water is exploited, excessive use is lowering the water table and introducing salinity. In Curaçao such action led to withering of the island's fruit groves and palms, and hence desalination of sea-water has been developed there very substantially and to very good effect on the island economy. All the indications are that the expected population expansion cannot take place with any civilized standard of living unless we begin to take our fresh water from the sea, where it is needed.

As an engineering venture desalination is technically interesting and challenging. It is also, for obvious reasons, intensely competitive, and undeniably concerned at present mainly with export. Up to the present British industry has been foremost in this field. The current US research effort, particularly in regard to the newer processes, is formidable, and we must see to it that we work to maintain our position. The interest which the DSIR is now showing is most gratifying. Moreover, like the USAEC, the U.K.A.E.A. has begun to study actively the ways in which nuclear energy and desalination can combine.

To conclude, therefore, I think there is no doubt that the production of fresh water from the sea is one of the growing points of mechanical engineering, that we shall see it much more in action in the future.
REFERENCES

[1] SILVER, R. S., 'British activities in desalination development and research', Int. Conf. on Desalination, Milan, April 1964.

ANNEX

NOTATION

A Volume or time parameter
A_p Plan area of vessel
B Staging parameter
C Surface parameter
c Specific heat of cooling water
E Energy parameter
H_b Enthalpy at bleed
H_c Enthalpy at turbine exhaust
H_0 Enthalpy at boiler exit
K Major operating cost
L Latent heat of vapour
M Rate of condensate
M_d Rate of distillate product
M_f Rate of feed
M_r Recirculation rate
n Number of stages
n_0 Optimum number of stages
P_0 Saturation pressure corresponding to t_0
P_1 Pure water saturation pressure
Q Rate of flow of saturated brine
Q_c Rate of cooling water flow through a bank of tubes
Q_s Rate of flow of saturated water entering chamber
R Performance ratio of plant
R_0 Optimum performance ratio of plant
s Specific heat of brine
S Heat transfer surface
T Vapour saturation temperature
T_1 Temperature of saturated water entering chamber
T_1 Vapour temperature
t_x Brine inlet temperature
t_y Brine outlet temperature
t_1 Cooling water inlet temperature
t_2 Cooling water outlet temperature
t_r Temperature of brine leaving first stage
t_1 Brine temperature in first stage
t_0 Temperature of brine leaving input heater
t_b Lowest stage brine temperature
\Delta_{r x} Boiling point elevation
U Overall heat transfer coefficient
W Weight of water required in gallons
\alpha Condenser parameter
\theta Logarithmic mean temperature difference
EXPERIENCE WITH ELECTRODIALYSIS

J.W. MINKEN*

INTRODUCTION

Before 1952 electrodialysis was only known as a laboratory technique. At present, large electrodialysis units for industrial purposes are commercially available. Although electrodialysis has been discussed in a number of papers, too little has been said about the factors which influence the performance of an electrodialyser.

PRINCIPLE OF THE METHOD

Electrodialysis using ion-exchange materials in membrane form is well known today. As is shown in Fig. 1, a series of compartments separated by alternate cationic and anionic membranes is placed between a set of electrodes. Cationic membranes are permeable for cations but are practically impermeable for anions. The reverse holds for anionic membranes. An impressed current causes salt to be transferred. One stream becomes enriched and the other is depleted.

The performance of an electrodialysis apparatus is determined almost entirely by the properties and dimensions of two adjacent compartments or basic cell pair.

![Schematic electrodialysis stack](image)

CELL PAIR

A cell pair comprises an anionic membrane, a cationic membrane, a layer of depleted liquid, a layer of concentrated liquid, spacers and inlets and outlets for the liquid streams.

The spacers which may be corrugated and perforated plastic sheets support the membranes and ensure an even liquid flow in the compartments. They also obstruct the path of the impressed current, which is reflected in an increase in cell-pair resistance. A hindrance factor of 1.2 to 1.3 is applicable for most separators.

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The inlets and outlets of alternate compartments are connected to one common feed conduit and one common discharge conduit. Equal amounts of liquid must flow through each compartment. Sizing of the conduits and inlet and outlet can be done by common engineering practice.

A part of the total current will by-pass the membranes via the inlets and outlets. The current leakage increases when the ratio of the resistance of the depleted stream to the resistance of the enriched stream increases. However, the electrical resistance of the small openings of the inlets and outlets of a compartment is great in comparison with the resistance of a cell. Therefore in most cases the current leakage is small.

Cationic membranes are never completely impermeable for anions. The reverse is true for anionic membranes. Therefore a small fraction of salts from the enriched stream enters the depleted stream and is then transferred again to the enriched stream. Consequently a part of the impressed current is wasted.

The effectiveness of the impressed current is called "the Coulomb efficiency". The overall current efficiency reflects the Coulomb efficiencies and current leakages. Typical values for current efficiencies are: 0.7 (for seawater conversion), 0.8 (for high saline and moderate brackish water) and 0.85 (for the slightly brackish waters).

The membranes must have a low electrical resistance under actual operation conditions and a good chemical stability to any corrosive agent which the process and waste liquors contain.

In electrodialysis there is a tendency to polarization which may limit the maximum current density and reduce the overall efficiency. To avoid polarization phenomena, the selection of the operating conditions must be based on the following equation:

\[ \frac{i}{c} = yV^x \]  

(1)

where \( i \) is the current density, \( c \) is salinity, \( V \) is the superficial liquid velocity in diluate compartment, and \( x \) and \( y \) are empirical constants, depending on the properties of the membranes and the composition of the liquids. This equation indicates that the current density should not exceed a certain value for a given \( c \) and \( V \) or that for a given \( c \) and \( i \) the liquid velocity must have a certain minimum value. This value should not be exceeded too much since this only results in unnecessary pump-energy.

The composition of the water may impose limitations on the maximum tolerable concentrations in the concentrated compartments to avoid precipitation of salts. In most cases scale prevention methods are necessary.

OPERATING CONDITIONS

The optimum operating conditions, on which an electrodialysis plant is designed, are almost entirely determined by economic factors. The optimum current density can be calculated by expressing the separate cost items which make up the total cost, in terms of the current density, differentiating and setting the derivative at zero.
The cost of an electrodialysis plant, as well as the membrane replacement cost, can be expressed in terms of cost per unit cell pair area; a figure depending on the size of the plant. For a small plant the costs of the auxiliary equipment (instrumentation, wiring, piping; pump, etc.) will be relatively greater than for a large plant; it may, in fact, exceed the costs of the actual dialyser.

At present the costs for a large plant can be as low as $200 per m$^2$ and for small plants, $300$ to $500$ per m$^2$. Only mass production of membranes and equipment can reduce those costs.

The net cell pair area can be calculated as follows:

$$\text{Net cell pair area in m}^2 = \frac{(M)(C_1 - C_2)(F)}{(Q)(3600)(i)(10^{-3})(10^4)}$$

where $M =$ volume of liquid to be processed (m$^3$/h), $C_1 =$ salinity of influent (g equiv/m$^3$), $C_2 =$ salinity of effluent, $F = 96500$ C, $i =$ current density (mA/cm$^2$), and $Q =$ current efficiency (fraction of total impressed current).

An electrodialysis plant should be depreciated over a period of 15 years. The lifetime of the membranes is considerably shorter, especially when more aggressive waters are electrodialysed. Properly manufactured membranes, when used for desalination of non-aggressive waters, may last for more than three years before replacement is needed. When during such a replacement a stack is opened, it will be found that many items, such as gaskets, flow-distributors, end plates, spacers etc., can be used again. It is more economic for larger plants to have their own replacement facilities, such as facilities for cutting membranes and mounting the stacks. A membrane replacement may then amount to $60$ per m$^2$. As an operator can only check a limited number of units, the cost of labour will decrease with an increasing current density and increase when more salt has to be removed. The same applies to the cost of maintenance. Three per cent of the investment would cover the total annual costs of labour, maintenance and insurance.

The power consumption increases with increasing current density. A recent study on the performance of a number of efficient plants showed that the power consumption for the conversion of saline water into potable water of a salinity 5 e.p.m. could be correlated (within 20%) as follows:

$$\text{kWh/m}^3 = \frac{(i)(\text{influent concentration in e.p.m.})^{0.7}}{(66)}$$

The scale prevention costs depend on the composition of the saline water and is a fixed amount per cubic metre of water. If the individual items are worked out with the appropriate values for depreciation, interest and kWh cost, the total cost equation becomes eventually:

$$\text{Cost per m}^3 \text{ of water} = \frac{K_1}{i} + (i)(K_2) + K_3$$
Ki reflects amortization of investment and membrane replacement cost per m$^3$, K$^2$ reflects the power cost and power consumption per m$^3$, and K$^3$ reflects the rectifier and scale prevention cost. Hence the optimum current density is:

$$i = \frac{\sqrt{K_1}}{K_2}$$

DISCUSSION

The main problems in electrodialysis are associated with the use of permselective membranes. A manual, describing laboratory techniques for testing membranes, has been prepared by the Office of Saline Water [1]. Each of these laboratory, or "static", tests gives valuable information about the properties of the membranes. However, understanding of the behaviour of the membranes under actual operating conditions has not yet reached the stage of maturity. Therefore a prediction of the performance of an electrodialyser, based solely on the results of static analysis, should be regarded with reservation.

More reliable engineering data can be obtained if the properties of a cell pair are determined under actual operating or dynamic conditions. For dynamic testing of the impressed current, the voltage drop across a number of cell pairs and the conductivity of the depleted liquid are measured.

The calculated cell pair resistance and the specific resistance of the depleted liquid can be plotted as is shown, schematically, in Fig. 2. The slope of the line indicates the thickness of the depleted cell. The calculated cell pair resistance is not the true resistance but an apparent resistance.

![FIG. 2. Performance of electrodialysis apparatus](image)

It reflects the influence of the spacer and current leakage. Hence, the slope of the line does not indicate the true cell thickness but an apparent cell thickness. The dynamic cell-pair resistance can be expressed as follows:

$$R = K_1 + (K_2) (D)$$

where R is the cell-pair resistance (Ωcm$^2$), D is the specific resistance of depleted liquid (Ω cm), K$^1$ is the intersection of curve and cell-pair resistance co-ordinate, and K$^2$ is the apparent cell-pair thickness (cm). Under favourable conditions K$^1$ and K$^2$ may amount to 25 and 0.2. For most saline water conversion purposes a K$^1$ of 50 and a K$^2$ of 0.5 is acceptable.
If pure sodium chloride solutions are electrodialysed, the dynamic cell-pair resistances are almost always low and remain the same for practically all types of membranes that are now on the market. This is not always the case if other salt solutions are electrodialysed. It has been observed that the dynamic cell-pair resistances may increase very rapidly when, for example, a sodium sulphate solution is used. Membranes of unknown properties should, therefore, be dynamically tested.

It is well known that anion exchange resins readily absorb organic matter. It is only to be expected that anionic membranes are susceptible to absorption of organic matter too. In this connection, the following interesting field experience has been reported [2].

An electrodialysis plant has been designed to reduce the salinity of clarified river water by 36%. The river water was bound to contain minor amounts of a great variety of industrial and municipal waste products. The permanganate value of the clarified water is normally well below 15 but increased due to seasonal variations to 40. Two different types of anionic membranes were used, but the cationic membranes were both of the same type. The active groups of both types of anionic groups were the same but the physical structures were different: one was homogeneous, the other heterogeneous.

During the period of high permanganate values, the salt removing capacity of the units with heterogeneous membranes was 50% below the rated capacity, for the units with homogeneous membranes the capacity was 75% below the rated value. It was also observed that performance tended to improve when the quality of the water improved. Apparently a limiting current density was encountered far below values that were known from other desalination cases. The difference between the two types of anionic membranes is very marked. It shows that the physical structure is important.

It has been stated by Matz [3] that if the water has a permanganate value of approximately 2, no difficulties may be expected.

Anion exchange materials readily absorb degradation products of cationic ion exchange materials. Cationic membranes should therefore be tight and not contain any leachable materials. Ion exchange resins expand and shrink when they are transferred from one ion form to another. This property is used to remove organic compounds. The anion exchange resins are then brought into the hydroxyl form and afterwards in the chloride form. This could be compared to the manual cleaning of a sponge.

Membranes can be cleaned in the same way. The difficulty here, however, is that an expansion of 2% on a cell length of 1.5 m already means an increase in length of 3 cm. Since the compartments are only 0.1 to 0.15 cm thick and are filled with a spacer, the increase in length results in a wrinkling and folding of the membranes. Needless to say, the membranes may easily tear at the folds. In view of possible dimension changes, the membranes should first be equilibrated in the natural water or in a solution containing ions which give the same expansion or shrinkage as the natural water, before cutting. Membranes are sometimes reinforced to hinder increase in length and width. The dimensional change will then mainly occur as a change in thickness and may cause pieces of membrane to break off at the reinforcement. Reinforcement also introduces a hindrance
The solution must be sought by making the actual membrane material dimensionally as stable as possible.

The operating capacities of ion exchange resins diminish owing to fouling and chemical demolition. The manufacturers of water conditioning equipment usually guarantee an operating capacity reduction of <0.8% per 1000 m³ treated water for cation exchange resins (5-8% divinyl benzene) and <6% for anion exchange resins, providing the waters used are non-aggressive. The lifetime of the commercially available membranes has not been firmly established yet. There is, however, fair evidence that a lifetime of three years can be achieved if non-aggressive waters are used.

The sometimes unexpected behaviour of the membranes under actual operating conditions are, in effect, polarization phenomena. Polarization is defined as phenomena, other than ohmic resistances, which in a cell under actual operating conditions cause the potential drop across a membrane stack to depart from the theoretical value [4].

In electrodialysis, the limiting current is often determined by keeping the superficial liquid velocities in the depleted compartments constant using once-through operation and impressing a current. The voltage drop across the cell pairs and the impressed current are measured. At the point where the ohmic resistance increases, the limiting current value for the particular salinity is obtained.

G. Solt has drawn attention to the fact that such an increase may not be observed if pure sodium chloride solutions are used (private communication). He had also observed that, if for given membranes and waters the apparent cell thickness is determined at a certain voltage per cell pair, an increase in voltage may only result in an increase in apparent cell thickness. Apparently a counter-potential occurs across the membranes, which destroys the influence of the potential applied and which increases proportionally with the increase in applied voltage. Thus it seems that both the properties of the membranes and the composition of the water determine the limiting current density.

More information can be obtained from the limiting current density trials if the pH values of the depleted and enriched streams are measured and the difference in salinity between the influent and effluent of the depleted stream is measured. If no polarization occurs, the pH values remain fairly constant and the amount of salt removed is proportional to the increase in current. When polarization occurs, the pH values change and the decrease in salinity is no longer proportional with the impressed current. A change in ohmic resistance may occur if ions are present which create conditions for a counter potential to occur. Also the composition of the rinse water affects the limiting current. It has been found that the hardness-forming ions and anions like sulphate and phosphate may have a pronounced effect on the limiting current. This apparently also applies to organic matter. In most cases the economic conditions are such that the optimum current density is low. However, if the economics dictate that the plant must operate at its maximum possible desalting capacity, precautions must be taken to avoid the occurrence of limiting currents.

Cooke [5] has designed a unique method for testing permeselective membranes. A membrane is placed in an environment of "poisoning" substances
and is exposed to impressed currents. The over-potentials are determined. This method enables him to select the most suitable membrane.

In electrodialysis scale formation occurs particularly on the anionic membranes in the enriched compartment. Scale prevention methods are acidifying the concentrated liquid, application of turbulent flow conditions and threshold treatment with glassy phosphates. Also polarity reversal, pulsation, or superimposing an alternate current over the direct current eases the scale problem.

Most membranes are made from the same materials as ion exchange resins. The South African Council for Scientific and Industrial Research has made parchment permselective membranes. It seems that they are cheaper to manufacture but have a shorter lifetime.

CONCLUSIONS

Electrodialysis using permselective membranes can be used for de-mineralization or concentration. The main problems are associated with the use of permselective membranes. The impressed current cannot exceed a certain value which entirely depends on the properties of the membranes and the composition of the water and waste liquors. Minor amounts of organic matter may drastically influence the performance of an electrodialyser. These substances must be removed. Laboratory techniques have been developed to establish the sensitivity of a membrane against "poisoning" substances.

Electrodialysis has proven to be an excellent saline water conversion method and if the necessary precautions are taken against poisoning substances, little difficulty need be expected.

REFERENCES

OPTIMUM SIZE DETERMINATION OF NUCLEAR DUAL-PURPOSE DESALINATION PLANTS

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ABSTRACT

The economics of dual-purpose desalination plants is presented from a general standpoint. The concept of demand curves for water and electricity is introduced, which leads to a rational sharing of production costs between both commodities within the framework of a market.

The purpose of the study, which is based upon the principles of classical economics, is to develop objective criteria for the design of desalination plants and to derive from these a normative method for pricing both joint products, water and electricity, following as much as possible the structure of the demand.

Such criteria are in particular either the maximization of benefit for the operator or the maximum welfare for the community. They involve either equality between marginal costs and revenues, or equality between marginal costs and marginal satisfactions (theory of surplus).

As the size of the plant is often the predominant factor in selecting the process to be used, it follows from the above considerations that this selection is closely related to:

(a) The shape of the demand curve for water
(b) The economic criterion selected and the relevant constraints (public or private ownership, limitation of the investments, etc.).

This makes market surveys and a rather refined economic analysis indispensable before any decision is taken on the desalination technique to be adopted.
TECHNICAL AND ECONOMIC ASPECTS OF THE USE OF NUCLEAR REACTORS FOR DESALINATION OF WATER AND ELECTRIC POWER GENERATION

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INTRODUCTION

An assessment of the potential supplies of fresh water and the rapid increase in its consumption show that the problem of providing water for domestic and industrial use is of primary importance in a number of countries.

Although, from the point of view of power resources and fresh-water supplies, the natural conditions in the Soviet Union are, on the whole, more favourable than in a number of other countries, the problem of water supplies is nevertheless acute in certain regions. The absence of adequate fresh-water sources hampers industrial and agricultural development and the exploitation of natural resources in these regions. The regions mainly concerned are the areas west and east of the Caspian Sea, Central Asia and Kazakhstan. Estimates show that the supply of fresh water in these regions from sources hundreds of kilometres away would require very heavy capital investment.

In Soviet territory there are also industrial regions, e.g. the Donets basin, in which forced pumping of salt water from mines has led to the salination of rivers and reservoirs, which are, in any case, not very abundant. The industrial development of these regions also requires a large amount of electric power. Thus the provision of water must not be considered without reference to power supplies and, consequently, in the conditions obtaining in the Soviet Union, equal importance must be attached to fresh-water and to electric-power production in considering nuclear desalination plants.

The research carried out (see e.g., Refs. [1-4]) shows that at present fresh water can best be supplied by evaporating salt water. However, the technological problems involved in the production of fresh water and the choice of electric power sources have not yet been adequately studied.

Preliminary technical and economic studies show that the employment of nuclear reactors for water desalination and electric-power production represents one of the more promising developments in their use. From the technological point of view there is no doubt that nuclear reactors can be used as a heat source for simultaneously producing fresh water and electric power. The question of whether their application for this purpose would be economic is much more complicated since the possibility of using them on a large scale will depend on their economic competitiveness with conventional heat sources. Thus the study of the economic aspect of dual-purpose nuclear facilities is of particular interest at the present time.
GENERAL ASSESSMENT OF THE CHARACTERISTICS OF THE REACTOR TYPES IN QUESTION

It is known that, with the increase in the capacity of nuclear plants, their economic characteristics improve more rapidly than those of facilities using organic fuel. There is, generally speaking, reason to believe that, other things being equal, high-capacity nuclear facilities simultaneously producing electric power and fresh water will be more economic than facilities using fossil fuel.

The competitiveness of dual-purpose nuclear plants will depend, to a great extent, on the particular area in which they are located, the fresh-water and electric-power requirements and the minimum level of economy which has to be observed.

It is, however, very important to determine the general requirements which, irrespective of the factors mentioned, must be met by nuclear desalination plants. The evaporators in such plants in which fresh water is produced by distillation may be regarded as a stable consumer of heat of a certain potential. It is obvious in this case, as with a conventional heating plant, that the simultaneous generation of electric power and heat is more economic than their production in separate operations.

The thermodynamic cycle of a power plant with a high heat output essentially depends on its potential and also on the initial parameters of the steam generated.

In nuclear plants, as in conventional ones, the generation of high-temperature high-pressure steam entails a specific increase in capital cost. This increase is justified, however, since the resultant thermodynamic cycle in the facility is more advantageous, permitting the high-potential energy to be used for electric power generation, and the low-potential heat of the exhaust steam in the back-pressure turbines for meeting the requirements of consumers of heat.

Dual-purpose facilities also eliminate the need for certain equipment which is required when two separate plants are used, e.g. turbine condensers, low-pressure regenerative heaters and components of the cooling water system.

It should be noted, in particular, that high capacity is necessary in a nuclear facility not only to ensure economic operation but also because of the nature and magnitude of the task involved, since low-potential heat must be available in very large amounts to meet power requirements and make good the present and prospective shortage of fresh water. The urgency of the problem clearly requires that use should be made of materials and equipment which are already available and which have been tried out in practice, and of well-established steam parameters and operationally-developed assemblies and units. It is also clear that the most promising type of nuclear reactor for the purpose in view is one in which the cost of the energy produced includes a low fuel component and whose unit capital cost decreases most sharply with increasing unit thermal capacity. For such reactors an increase in the installed capacity utilization factor is particularly important, of course, since the fuel component is not dependent on the utilization factor and the capital component is inversely proportional to it. The possibility of use of a nuclear desalination plant with a very high installed capacity utili-
zation factor fundamentally depends on the ability to store the fresh water produced, and this also enhances the competitiveness of nuclear plants with conventional plants.

Among the most highly-developed types of reactor in the Soviet Union are those of the Beloyarsk [5, 6], the Novo-Voronezh [7], and the Shevchenko atomic power stations [8].

The only feature common to all desalination plants with these reactors is the combined production of electric power and heat with an identical heating-steam potential for desalting water. This potential is determined by the operating conditions of the heat-transfer surface of the distillation facility.

The relationship between the two types of production, i.e. electric power and fresh water, is an important factor in considering dual-purpose plants. At a given temperature level of heating steam used for water desalination, this relationship depends on the initial steam parameters - the higher the parameters, the greater the relative output of electric power. Thus plants using reactors of the Beloyarsk and Shevchenko atomic power station types will show a considerably higher electricity generating factor than plants using reactors of the Novo-Voronezh type [8]. This should be borne in mind when choosing plants for a specific region, since the electric-power and fresh-water requirements as well as their cost may vary considerably for different regions.

The unit capacity of the reactor is also important. The problem involved in increasing the unit output can be more easily solved in the case of channel reactors, e.g. those of the Beloyarsk atomic power station type.

The extent and urgency of the need for fresh water and electric power also have a very important bearing on the choice of reactor type for dual-purpose nuclear plants. These factors in effect predetermine the way in which the nuclear fuel is used. A closed fuel cycle is essential for fast-breeder reactors, i.e. a substantial additional capital investment is required for a plant to regenerate irradiated fuel, for fabricating fuel elements from regenerated fuel, etc., not to mention the fact that less technological experience is available regarding fast reactors than thermal facilities. However, when the need for water and power is relatively small but when at the same time the need is an urgent one, it is better to use thermal reactors, not only because of their greater familiarity but because such a high fuel burn-up can be achieved that the fuel need not be regenerated after unloading from the reactor. These considerations are obviously very important for the developing countries.

METHODS OF DETERMINING THE COST OF FRESH WATER AND ELECTRIC POWER

The fact that two types of production take place in the dual-purpose plant gives rise to a number of difficulties and uncertainties in assessing their economic indices. In different countries a number of methods are used for calculating the cost of electric power and fresh water. The most widely used method, for example, consists of designating (fixing) the price of electric power considered as a by-product of the nuclear desalination
plant [2]. If a dual-purpose plant is integrated in a high-capacity power
system, the cost of electric power generated as a by-product of the fresh-
water output is based on the minimum cost of the power produced from the
other sources integrated in the power system. This gives the minimum
arbitrarily adopted figure for the cost of electric power. If on the other hand
the dual-purpose nuclear plant is erected in a region where there is no power
system or no power stations at all, the cost of electric power produced by the
dual-purpose plant may be based on factors inherent in the economic situation.
This gives the maximum arbitrarily adopted figure for the cost of electric power.

When such a method of calculation is used, the cost of fresh water is
based on the annual cost of operating a dual-purpose plant minus the income
derived from the sale of electric power at the arbitrarily fixed price.

However, in the conditions obtaining in the Soviet Union, the fact that
the two types of product yielded by dual-purpose nuclear plants are equally
important from the national economic point of view calls for the adoption
of a method of calculating the economic indices of such plants which will
make it possible to determine separately, and with sufficient accuracy, the
cost of producing electric power and of producing fresh water, and thereby
to determine their prime cost. To meet this requirement, the method used
is as follows.

In general, the annual production costs at a dual-purpose nuclear plant
consist of the cost of producing fresh water ($S_{f.w.}$) and electric power ($S_{el.}$)

$$S = S_{f.w.} + S_{el.} \ (roub. /yr) \ (1)$$

With a given thermal capacity (and parameters) of a nuclear reactor
operating at a dual-purpose plant, the electric capacity will always be less
than when the reactor operates at an atomic power station employing con-
densers. This is due to the fact that the production of fresh water requires
heating steam of a potential which could have been used in a condensing tur-
bine. Thus the cost of producing fresh water can be defined as the total
cost of providing the actual evaporating component of the facility ($S_{e.c.}$) and
the heating steam ($S_{h.s.}$):

$$S_{f.w.} = S_{h.s.} + S_{e.c.} \ (2)$$

The cost of producing the evaporating component of the plant ($S_{e.c.}$) is
determined by amortization payments on capital investments for installing
this component, maintenance costs, wages, etc.

The annual cost of producing heating steam can be defined as the dif-
ference between the cost of producing electric power alone at a condensing
atomic power station and its cost (with the same prime cost level) when it
is produced in dual-purpose plants.

$$S_{h.s.} = PC_e (W_k - W_p); \ (3)$$

where $PC_e$ = prime cost, in kopecks/kWh, of electric power when the reac-
tor concerned is operating at a condensing atomic power station; $W_k$ = output,
in kWh/yr, of electric power at a condensing atomic power station; and $W_p$ =
production, in kWh/yr, of electric power when the reactor concerned is operating at a dual-purpose plant.

Thus the annual production costs at a dual-purpose nuclear plant are expressed as follows:

\[ S = S_{c.c.} + S_{h.s.} + PC_e W_p \] (4)

The aim is to calculate the annual production cost (and, consequently, the prime cost) of fresh water - excluding the cost of heat - and of heating steam at a given prime cost of electric power, which is the same both for a condensing atomic power station and a dual-purpose plant. Strictly speaking, the latter is true provided the transition from the condensing atomic power station to the dual-purpose plant does not involve the exclusion of certain equipment which forms a part of the condensing station only. Thus, when calculating the prime cost of electric power produced in a dual-purpose plant, some correction must be made to take account of the reduction in the cost of generating power resulting from the exclusion of certain equipment (turbine condensers, regenerative heaters, condenser cooling system, etc.). Estimates show that a small correction (3-5%) is sufficient.

ANALYSIS OF THE PRIME COST OF FRESH WATER AND ELECTRIC POWER

Cost of fresh water, excluding cost of heating steam

Of the many existing methods of desalination it was decided to take the distillation method as the object of a technical and economic analysis, since it is the one on which most technical data are now available and it satisfies fresh-water requirements most effectively.

Both from the point of view of operating temperatures and an increase in output, it is advisable to use multiple-effect evaporators with forced circulation in dual-purpose nuclear plants. The heat-transfer coefficient can then be increased three to four times over the natural level and the heat-transfer surface of the evaporators can therefore be reduced; if, on the other hand, the heat-transfer surface is kept constant, the output of each evaporator unit can be increased.

The question of whether an evaporator plant is economic or not also depends to a great extent on the salt conditions of its operation. At present the permissible degree of salinity of water for evaporation must not exceed 120 kg/t. In the Caspian Sea, for example, the average salinity of the water out at sea is 13 kg/t (near the shore it is somewhat less), the main component being NaCl.

The salt content of steam and, hence, of the condensate of desalted water is determined only by the mechanical removal of moisture, since the removal of salts through their solubility in steam begins to have a marked effect only at high pressures [9].

Thus the maximum moisture level in steam from desalted water can be determined from the standard specifications for dry residues in drinking water (under Soviet standards - GOST 2761-44 - drinking water may not have a dry residue exceeding 1000 mg/kg).
When feed water is supplied to the evaporator the maximum moisture content of the steam is 0.8% in accordance with the specification for the permissible concentration of brine, i.e. 120 kg/t. The maximum moisture content may be increased when the steam is washed by the feed water, and in this case it amounts to about 8%. Special steam drying agents may then be dispensed with, the void content may be reduced, and the size and cost of the evaporator may therefore also be reduced.

The unit cost of heat required to produce 1 kg of fresh water can be reduced by regenerative heating of the water fed into the evaporators. The amount of equipment required is then increased by the number of regenerative heaters involved, but the unit cost of heat is considerably reduced. In this paper we have therefore analysed the effect of the basic factors connected with a desalination plant as such on the prime cost of the fresh water. To ascertain the developments and conditions required to obtain the minimum prime cost of fresh water, we assumed a considerably greater range of variation in some of these factors than is obtainable at present.

In general the unit cost of fresh water, excluding the cost of heating steam, is based on the sum of the following components:

$$C_{f.w.}^0 = \frac{S_{e.w.}}{M} = C_{a+m} + C_e + C_{s.w.} + C_w + C_{o.e.}$$

(5)

where $M$ = annual production of fresh water, in t/yr; $C_{a+m}$ = component representing amortization and maintenance; $C_e$ = cost of the electric power required to operate the desalination component of the plant; $C_{s.w.}$ = cost of preparing salt water for desalination; $C_w$ = wages of staff; and $C_{o.e.}$ = other expenditure.

The unit cost of fresh water ($C_{f.w.}^0$) depends, of course, on the assumed and permissible characteristics of the plant: heating steam temperature ($T_{so}$), temperature drop per stage ($\Delta T_{st}$) and the number of stages of evaporation ($n_{st}$). Thus, calculation of the $C_{f.w.}^0$ component taking account of the variation in the basic factors affecting its value

$$C_{f.w.} = f(T_{so}, \Delta T_{st}, n_{st})$$

(6)

was carried out for variations in $T_{so}$ ranging from 40 to 250°C, variations in $\Delta T_{st}$ ranging from 10 to 35°C and variations in $n_{st}$ ranging from 1 to 15, and was based on the assumption that the $C_{a+m}$ value was directly proportional to the heat-exchange surface throughout the desalination plant (evaporators, regenerators, condensers, etc) and that the remaining categories of expenditure per ton of fresh water produced remained constant for a desalination plant with a given fresh-water output.

Figure 1 shows the dependence of the cost of fresh water (excluding the cost of heat) on the saturation temperature of the heating steam ($T_{so}$) for various numbers of stages ($n_{st}$) in the desalination facility and for various values of temperature drop per stage ($\Delta T_{st}$).

The graphs show that, as the $n_{st}$ and $\Delta T_{st}$ values increase, the $C_{f.w.}^0$ values tend toward saturation.
In accordance with formula (3) the cost of producing heating steam was determined on the basis of the cost of electric power for three types of reactor (those used in the Beloyarsk, Novo-Voronezh and Shevchenko atomic power stations) with an installed capacity utilization factor of 0.8.

Using the data given in Ref. [10], the cost (kopecks/kWh) of electric power for condensing atomic power stations with capacities in the range 100-1000 MW can be approximated by the expression:

\[ C_e = 0.457 + 3.8 \exp (-0.916 \times 10^{-2} N_e) \]  

(7)

for the Beloyarsk and Novo-Voronezh atomic power stations; and

\[ C_e = 1073 N_e^{-1.272} \]  

(8)

for the Shevchenko atomic power station, where \( N_e \) = electric power, in MW.
An analysis of the cost of heating steam:

\[ C_{h.s.} = \frac{S_{h.s.}}{Q_h}; \left[ \frac{roub.}{cal} \right] \]  

(9)

where \( Q_h \) = quantity of heat used for desalination, was carried out as a function of the thermal capacity of a reactor of the type in question at various heating-steam saturation temperatures, namely, 80-200°C for the Beloyarsk and Shevchenko reactors and 80-140°C for the Novo-Voronezh reactors, with initial steam parameters of 240 atm abs and 535°C in the first case, and 20 atm abs and 230°C in the second.

However, bearing in mind that at present the permissible temperatures of desalinated water (from the point of view of salt deposition) are in the range of about 110-120°C, the results of calculations for heating-steam temperatures of 130°C are given here. For these conditions Fig. 2 gives the cost of heating steam \((C_{h.s.})\) as a function of the thermal capacity of the reactors in question used in dual-purpose plants, and Fig. 3 shows the electric capacity \((N_e)\) and the output of heat \((Q_h)\) for desalination as a function of the thermal capacity of the same types of reactor.

![Graph showing cost of heating steam vs. reactor thermal capacity]

**Total cost of fresh water**

The total cost of fresh water produced in a dual-purpose plant is determined by the expression:

\[ C_{f.w.} = C^0_{f.w.} + C_{h.s.} \times q; \left[ \frac{kipceks}{t} \right] \]  

(10)

where \( q \) = the specific heat rate required to produce one ton of fresh water:
FIG. 3. Electric capacity of plant and output of heat to produce fresh water with varying thermal capacity of the reactor
1. Output of heat for reactor of type used at Novo-Voronezh atomic power station
2. Output of heat for reactors of type used at Shevchenko and Beloyarsk atomic power stations
3. Electric capacity of plant for reactors of type used at Shevchenko and Beloyarsk atomic power stations
4. Electric capacity of plant for reactor of type used at Novo-Voronezh atomic power station

Figure 4 shows the dependence of the value of $q$ on the heating-steam saturation temperature ($T_{so}$) for various numbers of desalination plant stages and various values of the temperature drop per stage.

Thus we can plot, for the conditions postulated, the dependence of the total cost of fresh water on the number of stages in the evaporating plant for the types of reactor in question at various values of the unit thermal capacity of the reactor ($Q_p$). This dependence is shown in Fig. 5-7.

The figures show that, when the thermal capacity of a reactor is constant, there is a minimum fresh-water cost dependent on the number of stages and that, for larger thermal capacity values, this corresponds to a
FIG. 4. Unit cost of heat for producing fresh water as a function of heating-steam temperature.

FIG. 5. Effect of number of stages on cost of fresh water at various thermal capacities of reactor of type used at Novo-Voronezh atomic power station.
lower number of stages. This is explained by the fact that in Eq. (10), when the thermal capacity is fixed, an increase in the number of stages leads to an increase in the value of $C_{f,w}$ and a reduction in the value of $q$. In the descending part of the curve ($Q_p = \text{const}$, ) the decrease in the value of $q$ is more rapid than the decrease in that of $C_{f,w}$, while in the ascending part the reverse is the case. In addition, there is a specific $\Delta T_{st}$ value corresponding to each $n_{st}$ value (see Fig. 4).

**Technical and economic characteristics of plants**

Using the procedure described in this paper, we have calculated the technical and economic characteristics of dual-purpose plants at various
### TABLE I

TECHNICAL AND ECONOMIC DATA ON NUCLEAR DUAL-PURPOSE PLANTS USING DIFFERENT TYPES OF REACTOR

<table>
<thead>
<tr>
<th>Type of reactor</th>
<th>Thermal capacity of reactor (MW)</th>
<th>Electric capacity (MW)</th>
<th>Fresh-water production (t/h) (t/d)</th>
<th>Cost of electric power (kopecks/kWh)</th>
<th>Cost of fresh, water (kopecks/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beloyarsk atomic power station</td>
<td>250</td>
<td>75</td>
<td>2,220</td>
<td>55,600</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>150</td>
<td>4,170</td>
<td>100,000</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>300</td>
<td>7,310</td>
<td>175,500</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>2,000</td>
<td>600</td>
<td>14,620</td>
<td>382,000</td>
<td>0.45</td>
</tr>
<tr>
<td>Novo-Voronezh atomic power station</td>
<td>250</td>
<td>40</td>
<td>2,810</td>
<td>67,500</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>80</td>
<td>5,620</td>
<td>135,000</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>160</td>
<td>8,850</td>
<td>212,000</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>2,000</td>
<td>320</td>
<td>17,700</td>
<td>425,000</td>
<td>0.48</td>
</tr>
<tr>
<td>Shevchenko atomic power station</td>
<td>250</td>
<td>75</td>
<td>2,320</td>
<td>55,600</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>150</td>
<td>4,840</td>
<td>111,000</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>300</td>
<td>7,310</td>
<td>175,500</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>2,000</td>
<td>600</td>
<td>12,600</td>
<td>302,000</td>
<td>0.30</td>
</tr>
</tbody>
</table>

thermal capacities of the reactor types in question. The results of the calculations are given in Table I. It should be borne in mind that these data are valid only for the initial conditions postulated and on the assumptions mentioned above.

The cost of electric power from condensing atomic power stations has a substantial influence on the technical and economic characteristics of nuclear desalination plants. The data on the cost of electric power generated by the reactors considered in this paper, given in Ref. [10] and used by us to calculate production costs in dual-purpose plants, reflect the level of reactor technology attained by 1964 and the efficiency with which nuclear fuel is used in the atomic power station projects now being carried out. It is obvious that large-scale manufacture of atomic power station equipment,
further improvement in reactor technology, higher burn-up of nuclear fuel and a number of other advances should lead to a substantial improvement in the economic characteristics of both condensing atomic power stations and dual-purpose plants. The economic data given in Table I must therefore be considered as conservative, but at the same time as enabling us to make an initial assessment of the technical and economic characteristics of dual-purpose plants.

The data available on the cost of producing electric power and fresh water in plants using various reactor types do not, as is well known, yet enable us to assess the efficiency and relative competitiveness of such plants from the national economic point of view. The criterion applied in making such a comparison, in line with the methods used in the Soviet Union [11], is represented by a multiple factor, viz. the calculated cost, which can be set out as follows for dual-purpose nuclear plants:

\[
C = S_{f.w} + S_{el} + (K_a + K_{e.c.}) \times \frac{P}{P輸} \quad (11)
\]

where \(K_a\) = capital investment in a nuclear plant generating electric power and heat for desalting water; \(K_{e.c.}\) = capital investment in the evaporating component of the plant; and \(P\) = the standard coefficient of capital investment efficiency (\(P = 0.125\)).

In addition to the cost of the main installation (in this case a dual-purpose nuclear plant), capital investment must cover the cost of associated operations, e.g. the fuel cycling required in the case of nuclear power.

In determining the efficiency of dual-purpose nuclear plants from the national economic point of view by means of the calculated cost method, the plants must of course be compared with other, conventional, heat and electric-power sources available with a view to ascertaining the minimum economic requirements in the case of nuclear plants. In doing so, the scale of the water and power supply and the relevant conditions in a particular region must be considered in the aggregate and co-ordinated with the planning and long-term development of the economy in that region. Such matters are, however, outside the scope of this paper.

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REFERENCES


FACTORS AFFECTING ANALYSIS OF DUAL-PURPOSE DESALINATION PLANTS*

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INTRODUCTION

The economics of water supply throughout the world are affected by many factors other than strictly technical ones. Desalination, as a relatively new means of water supply, must find its application where it is economically superior to other methods. Thus, it has grown up in an environment of harsh technical and economic appraisal. Now that development has reached the stage where major increments of water supply by desalination can be realistically considered, many attempts to compare desalting plants with conventional alternates are being made. What we find is the following:

(1) The price of water is not the same as its cost. Water use is heavily subsidized in some areas, excessively taxed in others. Some supplies arise from complex systems in which different sources with widely different costs are combined. Different users of the same supply often pay different prices. In many cases in the USA, the true cost of the water is very difficult to determine.

(2) The important factor is not current cost; rather it is the cost of the next addition to the supply. This would seem to be self-evident, but it is overlooked in many discussions. Conventional methods and desalination should be compared in each situation on the same basis — that of adding a given capacity to a given system.

(3) The analysis of cost must include long-range factors. Aspects such as depletion of underground reserves, availability of fuel, rate of growth of water market, and expected improvements in technology must be included in a valid study. For example, major water diversion projects (dams, canals, etc.) must usually be planned to anticipate needs many years in the future, and the cost of this excess capacity has to be taken into account in comparisons with water mining or desalination plants.

(4) The quality of the water is important. Often, semisaline river water is considered equivalent to distilled water, and yet the economic values are not the same. Also, the quality of the water is important in comparing alternate means of desalination.

(5) The size of the undertaking affects the weight of the factors. To solve a temporary or highly local water problem, emphasis is needed on short-range cost and current technology, while a commitment for a larger regional supply system must anticipate growth, depletion, and technical advances.

* Research sponsored by the US Atomic Energy Commission under contract with the Union Carbide Corporation.
All these factors are difficult enough to evaluate in studying alternate water supply methods, but the problem is compounded by the prospect of dual-purpose plants\textsuperscript{1}. The economic analysis of such plants is complex. In addition to all the factors mentioned above, another set relating to power must be reckoned with. Then there is a set of cross-products, as the mathematicians call them, in which a change in the water parameters has an effect in the power system and vice versa. One US executive, viewing this, proposed that we should not build dual-purpose plants because they would cause too much trouble with the bookkeeping.

We do not believe it will be necessary to forego the real advantage of dual-purpose plants, and we are presenting in this paper some of the methods we are developing at Oak Ridge to deal with the problems of optimizing and evaluating dual-purpose plants. The context for most of the work has been the use of nuclear reactors as heat sources and large regenerative evaporators for sea-water distillation, but the same principles would apply for other situations.

THE DUAL-PLANT PRODUCT RATIO

The dual plant produces two products in series, power and water, from a single source of heat. The products are not necessarily consumed by a single market, and thus it is necessary in the design to consider what product ratio can be marketed and how the cost of the two products is affected by varying the product ratio.

The product ratio may be given the symbol $\omega$ and be defined as the water output capacity in million-US-gallon-per-day (Mgd) increments divided by the power capability in million-watt increments. Thus,

$$\omega = \frac{\text{Mgd}}{\text{MW(e)}}$$

It is a convenient definition, which will normally have a value between 0, 1 and 1. However, its value may vary between 0 and $\omega$ for power-only and water-only plants, respectively. For a given quantity of heat produced by the steam generator, the power output is determined primarily by the inlet and outlet temperatures of the turbine, and the water output is determined by the amount of heat transfer surface used and the supply and discharge temperatures of the heat. Thus, $\omega$ is normally limited to relatively low values ($<0.5$) by the steam conditions at the turbine throttle and by the maximum brine temperature the evaporator can accept.\textsuperscript{2}

\textsuperscript{1}There are, of course, situations where water-only plants are required, and their development is included in the US programme. Our studies at Oak Ridge have shown that while there are prospects for reducing the penalty for a water-only plant, the dual-purpose system will produce cheaper water wherever power can be marketed equitably.

\textsuperscript{2}Temperatures in excess of 250°F create scale formation and corrosion problems in present-day equipment that cancel the benefits of a higher temperature.
When the mechanical output of the steam cycle exceeds the need for power, \( \omega \) can be increased by using the excess work internally in a second water-producing process. An example of such a multiple-process plant is shown schematically in Fig. 1. Prime steam is expanded in a turbine, and the turbine exhaust steam is used in the normal way as an evaporator heat source. The turbine shaft energy not needed for electricity is used to drive a vapour compressor. The compressor serves as a heat pump and supplies energy to a second evaporator for the production of more water. Similarly, the mechanical output could be used to operate freezing, reverse osmosis, or electrodialysis processes.

Returning now to the dual-product system, let us see how its economic behaviour can be analysed and its design optimized.

**ANALYTICAL PROCEDURE**

Analysis of all the possible combinations of processes and variations within a given process can be a very complex problem. It is frequently useful to analyse the effects of a few important parameters in a very simplified fashion to gain insight into how the system should respond. Then, when the behaviour of the controlling variables is understood, the less important considerations may be included in a more complete statement of the relationship. For the dual-purpose plant, a principal complication is the fact that the costs of production must be arbitrarily distributed between two products in a consistent fashion. A procedure for allocation of steam cost to the two products would provide the most straightforward analysis, since other parts of the cost are relatively separable into power and water groups.

We have developed a procedure that is consistent, direct, and widely applicable. The method has an attractive symmetry in that the costs of both power and water are essentially unaffected by changing the turbine exhaust
temperature in an optimized system. This means that between certain limits the product ratio can be adjusted arbitrarily without affecting the cost of either product. We developed first a simplified equation that solves the problem of assigning steam costs to the two products in approximate fashion, and we use the resultant relationship analytically to indicate solutions to problems such as the effect of turbine exhaust temperature on the final cost of water. Finally, we adjust the simple result to include less important factors and utilize a computer to carry out the operation.

From the standpoint of a power plant, the value of the turbine exhaust steam is measured by the remaining available energy that could have been obtained from it. Since it is well known that the electrical yield obtainable from steam expanding in a turbine is close to linear with temperature in the range below 250°F, the value of exhaust steam can be taken as proportional to the original cost of the prime steam and to the remaining temperature span above the condenser point (90°F, for example). Similarly, for evaporators, the value of steam in terms of driving force for heat exchange is also proportional to its temperature span above approximately the same condenser point. (The economic condenser temperature in either case is affected by the cooling-water or sea-water temperature.)

For the analysis we let the unit cost of prime steam be $S$ and let $f$ be the fraction of the electrical yield lost by diverting the steam to the evaporator in the dual-purpose plant; that is,

$$f = 1 - \frac{\text{back pressure efficiency}}{\text{condensing efficiency}} = 1 - \frac{\beta}{\epsilon}$$

Since yield is proportional to temperature, the yield lost is also proportional to the temperature lost, and thus we can define

$$\frac{D}{\Delta} = f$$

where $D$ is the turbine temperature range ($t_{\text{exhaust}} - t_{\text{condenser}}$) diverted to the evaporator, and $\Delta$ is the proportionality constant for given prime steam conditions. Thus, our condition of maintaining constant power cost gives the unit value of exhaust steam as

$$H = S f = \frac{SD}{\Delta}$$

which is approximately the cost of the heat to the evaporator.

The preceding analytical statements are shown graphically in Fig. 2, where turbine efficiency is plotted against steam temperature. It may be seen that the electrical yield, $\epsilon - \beta$, that is sacrificed by diverting steam

---

1 Some qualification of this statement is necessary if reheat steam cycles are included.
to the evaporator may be expressed in terms of temperature by the proportionality in the lengths of sides of similar triangles; thus,

$$\frac{\varepsilon - \beta}{\varepsilon} = \frac{D}{\Delta}$$

This expression is equivalent to the assumption that the power should cost the same from a dual-purpose plant as it would from a power-only plant using the same reactor. The cost of power thereby derives the benefit of being produced in a larger reactor, and the remainder of the combined-plant savings are credited to the cost of water. For the moment, we have neglected the credit due the water plant for providing a condenser for the turbine, but this and other corrections will be considered later.

Let us now ask: What is the optimum temperature at which the turbine should cease expanding steam to make power and turn it over to the water plant? We have provided that this variable make no difference to power cost — but what does it do to water cost? The unit cost of water can be divided into the cost of the evaporator plus the cost of heat. The evaporator cost, $E$, is linear with performance ratio, $R$, and can be represented by $k_1 + k_2 R/D$, where $k_1$ is a constant, $D$ is the temperature range available for the evaporator (as above), and $k_2$ is determined by the cost and performance of the heat transfer surface. It is assumed that the temperature range is kept below the region where the evaporator suffers cost penalties. Thus,

$$\text{Unit water cost} = W = E + \frac{H}{R}$$

---

$^4$The performance ratio, $R$, is a convenient index that relates the heat transfer surface required per unit of heat consumed by the water plant; thus

$$R = \frac{\text{pounds of water produced}}{1000 \text{ Btu of heat consumed}}$$
By substituting,

\[ W = k_1 + \frac{k_2 R}{D} + \frac{SD}{RA} \]

Then by differentiating \( W \) with respect to \( R \) and setting the derivative equal to 0, we find that,

\[ R_{\text{opt}} = D \left( \frac{S}{k_2 \Delta} \right)^{1/2} \]

By substituting \( R_{\text{opt}} \) for \( R \) in the equation for water cost, we find that \( D \) is eliminated, and the minimum water cost is

\[ W_{\text{min}} = k_1 + 2 \left( \frac{Sk_2}{\Delta} \right)^{1/2} \]

Thus the cost of water in a dual-purpose plant is (to a first approximation) independent of the cross-over temperature and dependent only on the prime steam cost, the steam conditions, and the evaporator heat-conductance cost. Our method of distributing costs has produced a system in which \( u \) may be varied at will by adjusting the cross-over temperature over a certain range without affecting either power or water cost. As you will recall, a similar result was obtained in an earlier study, the results of which were presented to this Panel one year ago. The conclusion there was reached by surveying the trend of a number of individual plant optimizations, whereas now we show it to be of general validity when the proposed allocation of energy cost is used.

Once a general relationship was formulated, we began to modify it to include less important effects. We first considered how \( H \), the cost of heat charged to the evaporator, might be affected by the modifications.

One item is the credit available to the evaporator for performing the condensing function for the power system. The credit is applied in the form of a reduction in the cost of exhaust steam, so that

\[ H = \frac{SD}{\Delta} - k_3 (\Delta - D) \frac{\epsilon}{\Delta} \]

where \( k_3 \) is a constant determined by the condenser cost. Although this credit is numerically small, it favours the systems with the lower cross-over temperatures wherein a large amount of power furnishes condenser credit to a small amount of water. Another modification to the value of \( H \) takes into account the fact that the evaporator does not receive the full quantity of heat going to the turbine. This correction introduces the factor \( \Delta/[\Delta - \epsilon(\Delta - D)] \). Finally, the value of \( S \) itself is a complex function of reactor size, fuel-cycle costs, capital charge rate, etc. Even the steam conditions
the reactor produces affect the steam cost, $S$. The steam conditions, in turn, affect $\Delta$, $\epsilon$, and $D$. A general expression for $S$ is

$$S = k_4 + \sum_{n=1}^{n} a_n P^n$$

where $k_4$, $a_n$, and $\gamma_n$ are constants, $P$ is the thermal power, and the number of terms, $n$, in the summation may be varied to include as many factors as desired but may be practically limited to about 10.

Thus the more detailed expression for the cost of heat to the evaporator assumes a form such as

$$H = \frac{1}{\Delta - \epsilon(\Delta - D)} \left[ D \left( k_4 + \sum_{n=1}^{n} a_n P^n \right) - k_3 P^\alpha \epsilon(\Delta - D) \right]$$

where $\alpha$ is the power exponent that reflects the scaling law applicable to the condenser cost. The improvement in evaporator heat transfer coefficients at a higher average plant temperature, which favours higher cross-over temperatures, has been neglected.

We have now reached the point where it is no longer obvious to state how $H$ (to say nothing of water cost) is affected by changes in one or more of the factors that determine its value. Since the corrections are small and partly cancel each other, it turns out that the conclusion reached in our very simplified analysis is, in fact, still valid, but it is not so neatly obtained.

It has become worthwhile to develop computer codes to calculate the effects and to determine the results of varying one or more of the parameters in the complete set of cost equations that define the costs of water and power from a given dual-purpose plant concept. With a properly arranged code, both analytical expressions and empirical data from actual designs can be assimilated. An extensive computer code programme being developed at Oak Ridge under USAEC sponsorship is briefly reviewed here, and some examples are given. We would like to emphasize, however, that a code never creates new information. It is merely a means of cataloguing and utilizing the available knowledge, and great care must be taken to apply computer results only in the situations where the input data are valid.

THE OAK RIDGE COMPUTER PROGRAMME

Computer codes have been developed as needed to handle special aspects or details of the overall dual-plant problem, as well as the main problem of desalination. New requirements arise frequently and, as time permits, new codes are developed. At the present time the code library contains ten volumes. Table I lists the three general classes of codes in the library and the names of the codes within each class. Since it is neither practical nor desirable to discuss all the codes in detail, each code is briefly described here and selected features of one of the codes are illustrated to show the general nature of these computational tools.
### TABLE I

**DESALINATION PROGRAMME COMPUTER CODE LIBRARY**

<table>
<thead>
<tr>
<th>Type</th>
<th>Code name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suboptimization codes</td>
<td>Fuel Element Design</td>
</tr>
<tr>
<td></td>
<td>Partial Unit Energy Optimization of Fuel</td>
</tr>
<tr>
<td></td>
<td>Energy Transport</td>
</tr>
<tr>
<td></td>
<td>Heat Transfer and Pressure Drop in Vertical Evaporator Tubes</td>
</tr>
<tr>
<td>Water-plant codes</td>
<td>Multistage Flash — Stagewise</td>
</tr>
<tr>
<td></td>
<td>Multistage Flash — Overall Basis</td>
</tr>
<tr>
<td></td>
<td>Vertical Evaporator</td>
</tr>
<tr>
<td></td>
<td>Vapor Compression</td>
</tr>
<tr>
<td>Dual-plant codes</td>
<td>Dual-Plant Optimization</td>
</tr>
<tr>
<td></td>
<td>Parametric Dual Plant</td>
</tr>
</tbody>
</table>

The codes included under the general category of suboptimization are those that optimize specialized components or systems in a plant as part of a larger code. Two fuel element design codes are included. The first code computes design criteria for a single fuel element module for a natural-uranium heavy-water-moderated reactor similar to the Heavy-Water Organic-Cooled Reactor (HWOCR). The design criteria computed include heat output, fuel content, dimensions of the double-ring configuration, etc. The second fuel element code for energy optimization is much more general. It accommodates the design of a fuel element with rod clusters or with annular rings. The coolant may be either water or organic material, either boiling or in forced convection. The code either designs an optimum fuel element or gives the performance of a fixed design. The code is intended to be coupled to a neutron physics code in order to determine the neutron flux through the fuel element. It is also planned to couple the code to fuel-cycle cost data so that a complete optimization can be done on the computer.

The energy transport code has been used to study the costs of moving large amounts of energy over the distances that might be encountered with a large desalination plant. Media included in the study were electricity, steam, water, heavy water, sodium, molten salt, and helium. The results of this study can be used to determine whether plant auxiliaries should be supplied with turbine drives or electric motors. It might also furnish information about whether or not the reactor coolant should be used for feed heating.

The object of the fourth code in the suboptimization group is the optimization of the tube geometry in a vertical-tube evaporator. Either the Wright
pressure-drop correlation for vertical tubes in downflow or the Martinelli pressure-drop correlations for two-phase flow in vertical tubes may be used by the code. For heat transfer, the code accepts either the Dukler correlation for an evaporative film or an empirical relation, such as experimental results with special high-performance tubes.

The four water-plant codes constitute the second category in the code library. Two of the four codes deal with multistage flash evaporators. The first of these makes detailed calculations at each stage and furnishes much of the information needed for plant design. The second code makes calculations on an overall evaporator basis and does not compute individual stage properties. The third and fourth evaporator codes are based on the multiple-effect vertical-tube evaporator concept, the difference being that the vapour compressor code utilizes a heat pump to furnish the heat required for the evaporation process. The purpose of the four evaporator codes is to make accurate material and enthalpy balances. The results may then be used to size the equipment required and to calculate costs.

The last two codes in the library are the dual-plant codes. The optimization code is useful for conceptual design studies and for advanced system analysis. The parametric code is much simpler, being essentially a cost assembly code. In the parametric code the equations describing the reactor, turbine-generator, and water plants are accessible, and system interactions can be considered using all the variables provided for each component. It is visualized that other systems may be added to this code. Examples of such additions might include power and water distribution systems, other processes utilizing excess power for additional water production, interaction of the market with the water system, etc.

The dual-plant optimization code is discussed in more detail below as an illustration of the nature of the codes in the library.

THE DUAL-PLANT OPTIMIZATION CODE

Figure 3 shows the simplified flowsheet for the Dual-Plant Optimization Code. From the input, the calculation route flows to the reactor plant, thence to the turbine-generator plant, and from there to the water plant. The water plant presently in use with this code is a multilevel multistage flash evaporator. At the first decision point, it is determined whether or not the power for the complex is correct. If it is not, an iterative calculation is made through the three-plant sequence. When the power is correct, the operator's input determines whether or not the power for the complex is correct. If it is not, an iterative calculation is made through the three-plant sequence. When the power is correct, the operator's input determines whether or not the plant will be optimized. If so, the optimization sub-routine is entered. If not, the case is computed and the results are tabulated. Variables that may be optimized are the blow-down temperature, the brine velocity, and the brine heater approach temperature. Future plans for this code include the capability of optimizing tube diameter, the overall height of the plant, the concentration ratio, and tube flow velocities in the heat reject and heat recovery sections of the evaporator. Typical simplified equations
FIG. 3. Simplified flowsheet for the dual plant optimization code

that may be found in the reactor and turbine-generator plant sub-routines are:

\[
\text{Dual-plant turbine-generator efficiency} = (0.76 + 0.0008 T_S) \frac{T_i - T_S - 460}{T_i}
\]

\[
\text{Reactor cost in $/MW(th)} = \frac{41000}{\left(\frac{\text{MW(th)}}{1000}\right)^{0.643}} \quad \text{MW(th) \leq 1500}
\]

\[
= \frac{37000}{\left(\frac{\text{MW(th)}}{1000}\right)^{0.37}} \quad 1500 < \text{MW(th)} < 10000
\]

\[
= 15750 \quad \text{MW(th)} \geq 10000
\]

\[
\text{Turbine-generator cost in $/MW(e)} = \frac{32000}{\left(\frac{\text{MW(e)}}{1000}\right)^{0.278}} + \frac{2668}{\left(\frac{\text{MW(e)}}{1000}\right)^{0.438}} T_S < 210
\]

\[
= \frac{23000 + 40 T_S}{\left(\frac{\text{MW(e)}}{1000}\right)^{0.278}} + \frac{1982 + 3.36 T_S}{\left(\frac{\text{MW(e)}}{1000}\right)^{0.438}} T_S \geq 210
\]

The first equation is empirical and relates the thermal efficiency to the temperature drop across the turbine. The next set of three equations relates the costs of the reactor plants in dollars per thermal megawatt to their respective sizes. These equations represent a particular reactor concept.
and are to a certain extent optimized. Other reactor types would be represented by similar sets of equations. The last two equations represent the cost of the turbine-generator plant in dollars per electrical megawatt of capacity. The two equations cover different temperature ranges for the exhaust steam.

The water-plant sub-routine uses the assumptions shown in Table II and the cost equations listed in Table III. For each case being studied with the code, the water-plant sub-routine computes all the flows, temperatures, volumes, power requirements, and areas in the plant. The costs are then computed as functions of these results. The water cost may be computed in two ways. In one of these the cost of power is calculated as though it had been produced in a power-only plant. The power cost thus determined is subtracted from the total cost of the dual plant and the left-over cost is assigned to the water. The disadvantage of this method is that accurate turbine-generator plant costs are required for the computation. In the other method the cost of power is simply a fixed input for each computer case.

**TABLE II**

**BASES FOR WATER-PLANT CALCULATIONS**

<table>
<thead>
<tr>
<th>Flash chamber size</th>
<th>Data from Richardsons Westgarth and Co. Report [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer</td>
<td>Dittus-Boelter equation</td>
</tr>
<tr>
<td></td>
<td>Chen equation</td>
</tr>
<tr>
<td></td>
<td>0.0002 or a temperature function</td>
</tr>
<tr>
<td>Fouling factor</td>
<td>Koo equation</td>
</tr>
<tr>
<td>Pumping friction</td>
<td>Negligible</td>
</tr>
<tr>
<td>Heat losses</td>
<td>None</td>
</tr>
<tr>
<td>Non-condensable gases in flash chambers</td>
<td>[2]</td>
</tr>
<tr>
<td>Boiling-point elevation</td>
<td>[3]</td>
</tr>
<tr>
<td>Enthalpy and brine transport</td>
<td>ORGDP estimates [4]</td>
</tr>
<tr>
<td>Cost equations</td>
<td></td>
</tr>
</tbody>
</table>

Inputs to the code are deliberately separated into the categories of customer's input, constants of nature, and designer's input. It is important to insist upon and maintain this separation so that the code user is constantly reminded that certain information is not suitable material for computation or optimization but must be (perhaps arbitrarily) selected by the customer. The input is included in the print out of the results of each case studied. This is to verify that the correct input was really used. The detailed output print-out is in computer code language. In addition to the detailed output, a formal cost summary in statement language is printed out. An example of the formal output is shown in Table IV.
### TABLE III

WATER PLANT COST EQUATIONS FOR THE DUAL-PLANT OPTIMIZATION CODE

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical cost</td>
<td>$K_1 (LF) (W_p + W_b)$</td>
</tr>
<tr>
<td>Deaerator cost</td>
<td>$K_4 (W_p + W_b) + K_3$ (Deaerator power)</td>
</tr>
<tr>
<td>Pumping cost</td>
<td>$K_4 (LF) \Sigma W H$</td>
</tr>
<tr>
<td>Pumps and motor cost</td>
<td>$K_4 \Sigma W + K_5 \Sigma$ (Pump power)</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>$K_7$ (Pump power)</td>
</tr>
<tr>
<td>Valves and piping</td>
<td>$K_8 W_{p,5}$</td>
</tr>
<tr>
<td>Water intake</td>
<td>$K_9 W_0$</td>
</tr>
<tr>
<td>Site work</td>
<td>$K_{10} W_{0.6}$</td>
</tr>
<tr>
<td>Area cost</td>
<td>$K_{11} A_{0.97}$</td>
</tr>
<tr>
<td>Shell cost</td>
<td>$K_{12} V$</td>
</tr>
<tr>
<td>Concrete, buildings, etc.</td>
<td>$K_{13} + K_{14} W_p$</td>
</tr>
<tr>
<td>Operating</td>
<td>$K_{15} W_{p,267}$</td>
</tr>
<tr>
<td>Maintenance and supplies</td>
<td>$K_{16}$ (Capital cost)</td>
</tr>
<tr>
<td>Heat cost</td>
<td>$K_{17} (LF) Q$</td>
</tr>
</tbody>
</table>

**Definitions:**

- $K$: Constant
- $W$: Flow rate
- $LF$: Plant load factor
- $H$: Pump pressure head
- $A$: Tubing surface area
- $V$: Shell volume
- $Q$: Brine heater heat rate

In addition to tabular outputs the code has the capability of presenting some of the computational results in graphical form. The sub-routine that produces these graphs has provisions for selecting any of 25 different parameters for the ordinate and any of six for the abscissa. A family of curves resulting from as many as six values of a third parameter may be plotted on each graph. An example of a typical plot is shown in Fig. 4 (the optimum brine blow-down temperature is plotted versus the turbine-exhaust steam temperature for four different water-production capacities and 600-MW(e) power production).
### TABLE IV

**FORMAL OUTPUT OF DUAL-PLANT OPTIMIZATION CODE**

#### Power

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power (MW(th))</td>
<td>25,148.760</td>
</tr>
<tr>
<td>Gross electrical generation (MW(e))</td>
<td>4,715.914</td>
</tr>
<tr>
<td>Reactor auxiliaries (MW(e))</td>
<td>365.914</td>
</tr>
<tr>
<td>Water plant use (MW(e))</td>
<td>310.674</td>
</tr>
<tr>
<td>Net saleable (MW(e))</td>
<td>4,000.000</td>
</tr>
<tr>
<td>Price (mills/kWh)</td>
<td>2.119</td>
</tr>
<tr>
<td>Annual revenue (M$)</td>
<td>66,834</td>
</tr>
</tbody>
</table>

#### Temperatures (°F)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine exhaust</td>
<td>265.000</td>
</tr>
<tr>
<td>Maximum brine</td>
<td>248.812</td>
</tr>
<tr>
<td>Brine blow-down</td>
<td>105.836</td>
</tr>
<tr>
<td>Ocean</td>
<td>65.000</td>
</tr>
</tbody>
</table>

#### Water plant

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (Mgd)</td>
<td>1,000.000</td>
</tr>
<tr>
<td>Performance ratio (lb/1000 Btu)</td>
<td>4.991</td>
</tr>
<tr>
<td>Water price (¢/1000 gal)</td>
<td>23.860</td>
</tr>
<tr>
<td>Annual revenue (M$)</td>
<td>78.381</td>
</tr>
</tbody>
</table>

#### Investments (M$)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial fuel charge</td>
<td>346,047</td>
</tr>
<tr>
<td>Reactor and steam plant</td>
<td>399,080</td>
</tr>
<tr>
<td>Turbine-generator</td>
<td>111,682</td>
</tr>
<tr>
<td>Interest on construction</td>
<td>46,671</td>
</tr>
<tr>
<td>Non-depreciable items</td>
<td>12,812</td>
</tr>
<tr>
<td>Water plant</td>
<td>201,904</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,118,176</strong></td>
</tr>
</tbody>
</table>

#### Annual costs (M$)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor investment</td>
<td>39,860</td>
</tr>
<tr>
<td>Water plant investment</td>
<td>14,133</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>53,993</strong></td>
</tr>
<tr>
<td>Tubing replacement</td>
<td>2,982</td>
</tr>
<tr>
<td>Reactor operation and maintenance</td>
<td>2,796</td>
</tr>
<tr>
<td>Fuel</td>
<td>79,223</td>
</tr>
<tr>
<td>Water plant and maintenance</td>
<td>1,165</td>
</tr>
<tr>
<td>Water plant chemicals</td>
<td>5,261</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>91,427</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>145,219</strong></td>
</tr>
</tbody>
</table>
CONCLUSION

Although we have only a beginning in the field of systems analysis and optimization of desalination plants, we believe that techniques of this kind will play an important role in fitting dual-purpose nuclear stations into their appropriate place in the power and water needs of society. We intend to rely heavily upon computers in this work with the restriction that continual scrutiny must be maintained to make sure that the input data employed in the code are appropriate to the problem at hand.

ACKNOWLEDGEMENTS

This report represents contributions from the combined staff of the Oak Ridge installation. In particular, C.T. Mothershed, R. Van Winkle and R.B. Winsbro were instrumental in the development of the code library.
REFERENCES


ABSTRACT

Water desalination is just one of the ways, and usually a relatively expensive one, by which fresh water can be made available. Its relative cost clearly indicates that its application should normally be considered only after all other sources of supply have been reasonably fully evaluated. Thus, hydrological and hydrogeological surveys should usually precede any detailed consideration of desalination possibilities.

In view of the fact that desalinated water must by its very nature be relatively costly, both in terms of investment per installed unit of capacity and of total cost per unit of product water, it is particularly important that a clear and simple costing method should be devised which would allow policy makers and administrators to establish an approximate, but realistic, true cost for product water.

The procedure outlined in this report provides a tool which should make it possible to establish the cost of water from existing installations on a uniform basis, and which may thus be used as a guide for rate setting policies. At the same time, the method should be equally applicable to plants which are not yet built, but for which basic data are available and for which principal technical specifications can be provided by manufacturers or consulting firms. If an adequate system for costing water from conventional sources is available, as may well be the case in many countries, the procedure outlined in this report should make it possible to compare the cost of desalinated water from a plant with given specifications with that of water from an alternative source for which it has been possible to establish the full cost per unit of product, using parameters comparable to those employed for desalination.

This study deals with problems of single-purpose and dual-purpose desalination plants. A single-purpose desalination plant may be defined as one which has fresh water as its only product, while a dual-purpose installation results from the combination of a power station and a distillation-type desalination plant into a single operating complex producing both water and electricity. In such cases, the desalination plant utilizes for the evaporation process the latent heat contained in the low-pressure steam which is exhausted from back-pressure or pass-out turbines. The advantages and disadvantages inherent in dual-purpose installations are discussed at greater length in part II.
A STUDY OF DESALTING PLANTS (15 TO 150 Mgd) AND NUCLEAR POWER PLANTS (200 TO 1500 MW(th)) FOR COMBINED WATER AND POWER PRODUCTION*

CATALYTIC CONSTRUCTION COMPANY
UNITED STATES OF AMERICA

ABSTRACT

The study identifies and analyses the various factors affecting the economics of water production in multi-stage flash evaporation type sea-water desalination plants operated in conjunction with electric power generation facilities.

The study includes the following:

(a) An economic comparison within the range of 200 MW(th) to 1500 MW(th), of four types of steam sources: (1) low-temperature nuclear reactor, (2) high-temperature nuclear reactor, (3) low-temperature, fossil fuelled boiler; and (4) high-temperature, fossil fuelled boiler. Calculations are made for plant capacities of 200, 600, 1000 and 1500 MW(th).

(b) Optimization, within the size range established by thermal input, of multi-stage flash evaporation plants.

(c) A comparison of the economics of desalting water and producing electric power in dual-purpose plants versus production of water in single-purpose water plants and electric power in single-purpose power plants.

(d) Determination of the effect of varying rates of fixed charges upon the economics of water and electric power production. Fixed charge rates of 4, 7 and 14% are considered.

(e) Evaluation of the effect of power credit factor upon water costs. Calculations are made assuming power credits ranging from 3.65 to 12 mills/kWh.

(f) Examination of the economic impact of operation of water plants at off-optimum conditions.

The study concludes that, all factors being equal, dual-purpose plants can produce water more cheaply than separate single-purpose plants of like capacities.

1. INTRODUCTION

The first requirement of a dual-purpose plant is to produce the specified power and fresh water at an optimum cost. To design for the optimum cost, however, one must have a set of firmly established ground rules. For example:

(1) Is the plant to produce maximum power and maximum water simultaneously?

(2) What capacity factor is required?

(3) What is the applicable interest rate and fixed charge rate?

(4) In assessing water cost, how is the power cost to be handled?

   (a) Credit power at some arbitrary rate; (b) credit power at the most competitive rate of alternative power sources; or (c) credit power at the cost of a nuclear-power only station.

The relative power and water quantities will determine whether a condensing or back pressure turbine is used. With relatively little water produced, a condensing turbine would be used, and the choice of extraction steam pressure is then determined not only by the desalination plant design temperature but also by the anticipated power loading on the turbine. The extraction pressure is a function of steam flow through the turbine, and if the electric load is to vary while the water load is constant, then a higher extraction pressure should be used.

If only a small amount of steam is to be used for desalination, present designs optimized for power-only stations can be used with little or no cost penalty.

If a large amount of steam is to be used for the desalination plant and hence a back pressure turbine used for power, there is an opportunity to design the nuclear power system with different parameters which offer cost reductions.

These two approaches, using present reactor designs, are illustrated here:

(A) Use of Douglas Point design with a condensing turbine to produce mainly power but with some steam extracted to produce a moderate amount of desalted water.

(B) Use of typical Pickering reactor with a back pressure turbine to produce a large quantity of desalinated water and a moderate amount of power.
2. DOUGLAS POINT STATION – LOW WATER/POWER RATIO APPLICATION

A simple illustration will indicate the small effect of adding a moderately sized desalination plant to an existing nuclear plant design. Suppose the Canadian Douglas Point plant were built on the Mediterranean Sea coast and a moderate amount of water was to be produced from an adjoining multi-stage flash evaporator plant. A simplified steam cycle diagram for such a plant is shown in Fig. 1. In Canada we have ample supplies of low-temperature condenser cooling water which, at Douglas Point, varies from about 32°F (0°C) to 52°F (11°C). With 52°F (11°C) cooling water, the turbine-generator will produce 220 MW(e) gross, and after allowing 17 MW for station service power a net output of 203 MW(e) is provided. With 70°F (21°C) cooling water, and the same heat input, the turbine-generator will only produce 210 MW(e) gross.

The Douglas Point steam cycle happens to be well suited for a dual purpose plant because at 75 lb/in² abs all the steam is taken from the high-pressure turbine cylinder and passed through a moisture separator and live steam reheater. The steam from the reheater is then led to three low-pressure sections of the turbine. The cross-over pipe between the moisture separator and reheater is an ideal place to extract steam for the desalination plant. Ordinarily, 35 lb/in² abs steam is adequate for a multi-stage flash evaporator. At partial loads the cross-over pressure falls as follows:

- Full Load: 75.0 lb/in² abs
- 75% Load: 56.7 lb/in² abs
- 50% Load: 40.0 lb/in² abs
- 25% Load: 21.7 lb/in² abs

Therefore, even at part loads, the steam condition to the desalting plant can be controlled to a fixed pressure in the order of 35 lb/in² abs.
If 204,000 lb/h of steam is taken from the pipe between the moisture separator and reheater and fed to the desalination plant, 20,000 m$^3$/d (5.28 million US gal/d) of desalted water can be produced at a performance ratio of 9.5. It should be noted that the extraction of steam from the crossover pipe eliminates the need for either a separate extraction point on the turbine casing or the use of an oversized feedwater bleed point extraction nozzle.

The steam extraction for the desalination plant reduces the turbine-generator output from 210 MW to 197 MW(e). With 17 MW station service power, the net output becomes 180 MW(e).

In summary, the Douglas Point nuclear station built on the Mediterranean would produce 180 MW(e) net and 20,000 m$^3$ of desalinated water daily. Ten MW of electrical capacity is lost because of the difference in cooling water temperature and 13 MW of electrical capacity is lost because of the steam extracted for the desalination plant.

Operating experience on NPD and construction experience on Douglas Point has led to many design improvements. For example, a higher fuel rating gives a 37% increase in net power for an increase of only 12% in the number of reactor fuel channels. Improved reactor building layout and shielding design has resulted in simpler structures with reduced capital cost and improved availability and reliability.

Existing Canadian heavy-water reactor designs, utilizing pressure tubes with natural uranium on-power refuelling, offer economically attractive costs for large scale power-desalination projects. Development work on improved coolant systems such as boiling D$_2$O, boiling light-water direct cycle, and organic cooling, offers further cost reductions with time. In addition, the basic design is well suited for extrapolation to the large thermal ratings needed for the ambitious programmes foreseen in the United States and elsewhere. There will be much less difficulty in providing the nuclear plant than in providing desalination plant for the large sizes foreseen. Put in another way, the present reactor designs need only be extrapolated by a factor of two or three, whereas the present desalination plant designs must be extrapolated by a factor of 100 or more.

The low fuelling cost available in the natural uranium HWR design can reduce the desalination plant design extrapolation problem to a considerable extent. It appears, for example, that with an HWR system the optimum performance ratio is about 6 or 7. This means that the physical size and cost of the desalination plant would be considerably less than with the present forecasts of performance ratios from 12 to 14.

3. PICKERING TYPE REACTOR – HIGH WATER/POWER RATIO APPLICATION

The relative merit of the HWR system has been analysed using the ground rules from "Report of the United States – Israel Desalting and Power Team" dated October 1964.

Based on the same ground rules as used in the report, i.e. local prices plus 25% increase for transport and installation in Israel for 200 MW(e) net and 125 million US gal/d (Mgd), the HWR system offers an annual saving be-
between $1.5 and 2.1 million (US) depending upon the fixed charge rate assumed. The calculations are based upon the present day cost of fuel, but if the lifetime average cost of fuel were assumed the same as that used by the Hydro Electric Power Commission of Ontario in their cost assessments, the annual savings would be increased by an additional $1.5 million. It appears, therefore, that the HWR can offer up to $3.6 million annual saving.

The HWR thermal rating is somewhat larger than the enriched water reactor in order to give 200 MW(e) net with lower steam pressure. However, the extra heat available results in a smaller desalination plant. For 125 Mgd, the performance ratio would be 8.2 rather than the 9.5 assumed for the enriched reactor system. The estimated cost reduction for the desalination plant is $8.4 million. On the other hand, 144.3 Mgd could be produced at a performance ratio of 9.5. The attached cost analysis shows approximately the same unit water cost for both capacities (10.0 cents/m$^3$ with 7% fixed charges and today's fuel cost, or 9.0 cents/m$^3$ with projected fuel costs).

A simplified flow diagram is shown in Fig. 2. It should be noted that although the reactor thermal rating is 1887 MW(t), the heat to the boiler is 1820 MW. This difference reflects the heat lost in the moderator which is partially offset by heat added by the work of the primary coolant pumps.

The relative costs for two dual-purpose plants are shown in the tables. One plant produces 200 MW(e) net after providing power to the desalination plant and also produces 125 Mgd of desalinated water. The second plant has the same power output but produces 144.3 Mgd of water. Table I gives the capital cost estimate for the nuclear plant. Table II gives the fuel cost estimate for the nuclear plant. Table III gives the capital cost estimate for the desalination plant. Table IV gives the annual costs and unit water costs for a fixed charge rate of 10, 7 and 5% with 125 Mgd output. Table V gives
TABLE I
CAPITAL COST ESTIMATE FOR DUAL-PURPOSE HWR - DESALINATION PLANT
1887 MW(th), 200 MW(e) net 125 Mgd
Turbine 268 MW, stn. serv. 21 MW, desalt 47 MW

<table>
<thead>
<tr>
<th>Item</th>
<th>US $1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site improvements</td>
<td>278</td>
</tr>
<tr>
<td>Buildings</td>
<td>5400</td>
</tr>
<tr>
<td>Reactor boiler and auxiliaries</td>
<td>22 130</td>
</tr>
<tr>
<td>Heavy water at new Canadian price C$14.65/lb (US$13.55/lb)</td>
<td>11 000</td>
</tr>
<tr>
<td>Turbine generator and auxiliaries</td>
<td>6 750</td>
</tr>
<tr>
<td>Electrical system</td>
<td>3 400</td>
</tr>
<tr>
<td>Instrumentation and control</td>
<td>3 600</td>
</tr>
<tr>
<td>Common services</td>
<td>4 060</td>
</tr>
<tr>
<td>Indirects; construction plant, engineering services, training, commissioning, etc.</td>
<td>13 420</td>
</tr>
<tr>
<td>Interest during construction</td>
<td>8 325</td>
</tr>
<tr>
<td>Total capital cost excluding fuel</td>
<td>78 363</td>
</tr>
<tr>
<td>25% surcharge on all but D₂O</td>
<td>16 840</td>
</tr>
<tr>
<td>Total</td>
<td>95 203</td>
</tr>
</tbody>
</table>

Note: contingency assumed to be included in surcharge.

The annual costs and unit water costs for a fixed charge rate of 10, 7 and 5% with 144.3 Mgd output. Table VI gives the unit water cost for the two plants based on projected fuel costs.

The dual-purpose plant was not optimized for this study but it appears that substantial savings could be effected by an optimization study. For example, the reactor flux could be flattened further, the reactor coolant temperature rise increased, the boiler terminal temperature differences increased and moderator heat used in a separate flash evaporator. The indications are that the primary coolant system and boilers would be decreased in size with a corresponding reduction in cost and heavy-water hold-
TABLE II
FUEL COST ESTIMATE FOR DUAL-PURPOSE HWR - DESALINATION PLANT
1887 MW(th), 200 MW(e) net 125 Mgd
Turbine 268 MW, stn. serv. 21 MW desalt 47 MW

Fuel charge 85,540 kg U
Cost at US $69.40/kg U = $6,075,300

135 days full power fuel inventory
\[ \frac{1887 \times (135) \times (69.40) \times 1000}{9800} = \text{US$1,804,000} \]

Annual fuel cost at 85% c.f.
\[ \frac{1887 \times (365) \times (0.85) \times (69400)}{9800} = \text{US$4,146,000} \]

Total annual fuel cost

<table>
<thead>
<tr>
<th>Item</th>
<th>10%</th>
<th>7%</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual fuel cost</td>
<td>4.146</td>
<td>4.146</td>
<td>4.146</td>
</tr>
<tr>
<td>Fuel write-off 1/2 charge</td>
<td>0.304</td>
<td>0.213</td>
<td>0.152</td>
</tr>
<tr>
<td>5% interest on inventory</td>
<td>0.090</td>
<td>0.090</td>
<td>0.090</td>
</tr>
<tr>
<td>Total</td>
<td>4.540</td>
<td>4.449</td>
<td>4.388</td>
</tr>
</tbody>
</table>

Note: The Hydro Electric Power Commission of Ontario predict fuelling prices to average out at US $46/kg U and at this price the total annual fuel cost would be $3 million.

up. The primary coolant pumps would be smaller, less costly and use less power. Similarly, the boiler feed pumps would be smaller, less costly and use less power.

There is a small penalty in burn-up if the reactor is operated with increased moderator temperature. However, it seems feasible to increase the normal moderator temperature and, using a closed loop system, heat brine in a separate multi-stage flash evaporator. Assuming a moderator temperature of about 180°F and a performance ratio of 4, it would be possible to produce about 3.7 Mgd. At a performance ratio of 4, the fixed charges on
TABLE III

DESALINATION PLANT COST FROM US-ISRAEL REPORT

125 Mgd at PR 9.5 (105 Btu/lb),
Cost in Israel = $87.5 million = 70¢/gal. day

From the US-Israel report and data from OSW report PB 181470 - A Study of Large Saline Water Conversion Plants - it appears that a good approximate cost for varying performance ratios (and hence varying heat transfer surface area) can be obtained from a 0.7 exponential rule, i.e. for a given capacity

\[ C = a \left( PR \right)^{0.7} \text{ or } C = \frac{b}{(Btu/lb)^{0.7}} \]

For the base plant \( C = 70 \frac{¢}{gal \ day} \), \( C = 70 = a \left(9.5 \right)^{0.7} \) hence \( a = 14.44 \)

and at 121.3 Btu/lb or PR 8.22

\[ C = 14.44 \left(8.22 \right)^{0.7} = 83.3 \frac{¢}{gal \ day} \]

The capital cost = 125 M (0.633) = $79.125 million or a saving of $8.375 million

It appears that the optimum heat rate for an HWR dual-purpose plant is between 170 Btu/lb and 145 Btu/lb or a PR between 5.9 and 7.

For 125 Mgd and a PR of 5.9, the desalination plant would cost \( C = 14.44 \left(5.9 \right)^{0.7} = 49 \frac{¢}{gal \ day} \) or 125 M (0.49) = $61.2 million. The further saving in desalination plant would be 79.1 less 61.2 or $17.9 million.

For 125 Mgd and a PR of 7, the desalination plant would cost \( C = 14.44 \left(7 \right)^{0.7} = 56.4 \frac{¢}{gal \ day} \) or 125 M (0.564) = $70.5 million. The further saving in desalination plant would be 79.1 less 70.5 or $8.6 million.

this section of the desalting plant at 7% would amount to 2.2 ¢/m³, the operating costs about 4.4 ¢/m³, and the fuel cost zero for a total water cost of about 6.6 ¢/m³. At 10% fixed charge rate this water would cost about 7.8 ¢/m³.

Previous work done by CGE in assessing the dual-purpose plant indicated an optimum performance ratio between 5.9 and 7. The US-Israel report indicates that the cost of the desalination plant varies as the performance ratio to the 0.7 power (PR^{0.7}). The basic cost in the US-Israel report, therefore, was $87.5 million at a PR of 9.5. The first assessment suggested a PR of 8.2 in order to get 200 MW(e) net using the same turbine back pressure. The desalting plant then became $79.1 million which gave $8.4 million saving. The cost at a PR of 5.9 falls to 49 ¢/gal day or $61.2 million saving some additional $17.9 million. The added reactor cost, including interest during construction, would amount to about $8.5 million which indicates a net saving of about $9.4 million in total capital cost. It appears
<table>
<thead>
<tr>
<th>Investment</th>
<th>Total (US $ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Nuclear power plant</td>
<td>95.00</td>
</tr>
<tr>
<td>Water plant 125 gal/d at 63.3 $/gal d</td>
<td>79.13</td>
</tr>
<tr>
<td>Total</td>
<td>174.13</td>
</tr>
<tr>
<td>Annual cost</td>
<td></td>
</tr>
<tr>
<td>Power plant</td>
<td>10%</td>
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<tr>
<td>Fuel (Total)</td>
<td>9.50</td>
</tr>
<tr>
<td>O and M (incl. $ 0.1 H2O loss)</td>
<td>4.54</td>
</tr>
<tr>
<td>Insurance</td>
<td>1.40</td>
</tr>
<tr>
<td>Total conventional cost</td>
<td>15.94</td>
</tr>
<tr>
<td>Less elect. credit (0.53 $/kWh)</td>
<td>9.70</td>
</tr>
<tr>
<td>Evaporator steam cost</td>
<td>20.05</td>
</tr>
<tr>
<td>Total annual water cost</td>
<td></td>
</tr>
<tr>
<td>Total annual cost</td>
<td>27.85</td>
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<tr>
<td>(b) Evaporator</td>
<td></td>
</tr>
<tr>
<td>Fixed charges</td>
<td>7.91</td>
</tr>
<tr>
<td>O and M</td>
<td>1.30</td>
</tr>
<tr>
<td>Chemicals</td>
<td>1.10</td>
</tr>
<tr>
<td>Interim replacement</td>
<td>1.60</td>
</tr>
<tr>
<td>Pumping cost</td>
<td>1.90</td>
</tr>
<tr>
<td>Steam cost</td>
<td>6.24</td>
</tr>
<tr>
<td>Total annual water cost</td>
<td>20.05</td>
</tr>
<tr>
<td>Total annual cost</td>
<td>27.85</td>
</tr>
<tr>
<td>(c) Water cost $/kgal</td>
<td>51.7</td>
</tr>
<tr>
<td>$/m³</td>
<td>13.7</td>
</tr>
<tr>
<td>(d) Total annual cost: US-Israel report</td>
<td>28.4</td>
</tr>
<tr>
<td>Total annual cost: HWR system</td>
<td>27.9</td>
</tr>
<tr>
<td>Annual saving</td>
<td>1.5</td>
</tr>
<tr>
<td>Investment</td>
<td>Total (US $ million)</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>(a) Nuclear power plant</td>
<td>95</td>
</tr>
<tr>
<td>Water plant 144.3 Mgd at 70 ¢/gal d</td>
<td>101</td>
</tr>
<tr>
<td>Total</td>
<td>196</td>
</tr>
<tr>
<td>Annual cost (in US $ million)</td>
<td>10%</td>
</tr>
<tr>
<td>Power plant</td>
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</tr>
<tr>
<td>Fuel (Total)</td>
<td>4.54</td>
</tr>
<tr>
<td>O and M (incl. $0.1 D₂O loss)</td>
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</tr>
<tr>
<td>Insurance</td>
<td>0.50</td>
</tr>
<tr>
<td>Total conventional cost</td>
<td>15.94</td>
</tr>
<tr>
<td>Less elect. credit (0.53 ¢/kWh)</td>
<td>9.70</td>
</tr>
<tr>
<td>Evaporator steam cost</td>
<td>6.24</td>
</tr>
<tr>
<td>(b) Evaporator</td>
<td></td>
</tr>
<tr>
<td>Fixed charges</td>
<td>10.10</td>
</tr>
<tr>
<td>O and M</td>
<td>1.30</td>
</tr>
<tr>
<td>Chemicals</td>
<td>1.20</td>
</tr>
<tr>
<td>Interim replacement</td>
<td>2.00</td>
</tr>
<tr>
<td>Pumping cost</td>
<td>2.20</td>
</tr>
<tr>
<td>Steam cost</td>
<td>6.24</td>
</tr>
<tr>
<td>Total annual water cost</td>
<td>23.04</td>
</tr>
<tr>
<td>Total annual cost</td>
<td>30.54</td>
</tr>
<tr>
<td>(c) Water cost ¢/kgal</td>
<td></td>
</tr>
<tr>
<td>$/m³</td>
<td>13.6</td>
</tr>
</tbody>
</table>
TABLE VI
COST OF WATER BASED ON PROJECTED FUEL COSTS

<table>
<thead>
<tr>
<th>Cost estimate (144.3 Mgd)</th>
<th>10%</th>
<th>7%</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual water cost</td>
<td>23.04</td>
<td>17.07</td>
<td>13.09</td>
</tr>
<tr>
<td>Possible fuel reduction</td>
<td>1.58</td>
<td>1.55</td>
<td>1.53</td>
</tr>
<tr>
<td>Possible water cost</td>
<td>21.46</td>
<td>15.52</td>
<td>11.56</td>
</tr>
<tr>
<td>$/kgal</td>
<td>47.9</td>
<td>34.6</td>
<td>25.8</td>
</tr>
<tr>
<td>$/m³</td>
<td>12.6</td>
<td>9.2</td>
<td>6.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost estimate (125 Mgd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual water cost</td>
</tr>
<tr>
<td>Possible fuel reduction</td>
</tr>
<tr>
<td>Possible water cost</td>
</tr>
<tr>
<td>$/kgal</td>
</tr>
<tr>
<td>$/m³</td>
</tr>
</tbody>
</table>

that the fixed charge saving on this amount of capital would balance the increased fuel cost depending upon the fixed charge rate.

Similarly, at a performance ratio of 7, the additional saving in desalination plant cost is $8.6 million. With an added reactor cost of about $3.8 million the net saving is about $4.8 million and the fixed charge saving more or less balances the increased fuel cost.

One obvious advantage in considering an installation with a low performance ratio is the opportunity of adding evaporator capacity at a later date and increasing the performance ratio. Thus, as the demand for water goes up, the performance ratio could be increased with minimum incremental investment. At a performance ratio of 9.5, the total water output would then be about 200 Mgd.

There are two factors associated with the heavy-water power reactor that are normally not considered in economic comparisons. One is the salvage value of heavy water and the other is credit for plutonium. The reactor being considered here contains $11.0 million worth of D₂O which will surely have a substantial salvage value, the actual value depending upon the price of D₂O in 30 years.

Each kilogram of spent fuel from an HWR contains about 2.9 grams of fissile plutonium. With a reactor rating of 1887 MW(th), 9800 MWD/t burn-up, and 85% capacity factor, the fuel throughput will amount to about 60 tonnes per year which will contain about 174 kg of fissile plutonium. The interesting question is: "How much is this plutonium worth?" At $8/g it
has a potential worth of $1.4 million per year. If accumulated in the fuel storage bay for 30 years, it would have a potential worth of $42 million. The net possible credit depends upon the cost of processing which in turn depends upon the capacity of the processing plant. It is estimated to cost $4/kg U to process at the rate of 10 t per day and, therefore, it is reasonable to assume that the fuel could be stored until sufficient quantity was available to take advantage of market conditions. The salvage value of the spent fuel on this basis would be $23.20 less $4.00 or a net of $19.20/kg of fuel. The lifetime salvage value could be $34.7 million.

4. CONCLUSION

It appears that the present Canadian HWR design is well suited for use in a dual-purpose plant. For relatively low water/power ratios, the present steam cycle can be used without complicating the turbine design. For high water/power ratios, the low fuelling cost can be used to substantially reduce the size and cost of the desalination plant. Present development programmes indicate a continuing cost improvement. Finally, there are potentially large salvage values available at the end of the plant's useful life.
NUCLEAR POWERED ELECTRODYALYSIS
FOR DESALINATION*

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ATOMIC ENERGY ESTABLISHMENT, WINFRITH,
DORCHESTER, DORSET, UNITED KINGDOM
AND
A.A.L. MINKEN AND J.W. MINKEN**

ABSTRACT

The paper is concerned to compare electrodialysis and flash distillation
as means for the production of water when a nuclear reactor also producing
power is the heat source. Special attention is paid to the flexibility introduced
by the possibility of diverting electric power from the primary load to electrodialysis
plant. On the basis of the costs taken, and assuming that adequate
reliability can be obtained from both processes, it is confirmed that electrodialysis
is not an economic process as compared with flash distillation for
the desalination of sea water but is fully competitive with salt contents up
to 5000 ppm. (Use of nuclear power does not affect the situation.)

In the case where a nuclear reactor is supplying an isolated economy
with power and water and the electric load factor is less than the reactor
availability, it can be economic to use off-peak electricity to produce fresh
water by high-current electrodialysis of brackish water (up to 10,000 ppm).
At the higher salt contents the amount of water which can be produced in this
way is comparatively small, but it rises rapidly as the initial salt concentra-
tion falls. If additional water is needed, it is best produced by base-load
distillation.

* Published by EURONUCLEAR (Feb. 1965).
** Correspondence address: 22 Duval Drive, Toronto 15, Ont., Canada.
FEASIBILITY OF NUCLEAR REACTORS FOR
SEA WATER DISTILLATION IN ISRAEL*

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TECHNION-ISRAEL INSTITUTE OF TECHNOLOGY,
HAIFA, ISRAEL

ABSTRACT

The use of nuclear energy for the conversion of sea water to fresh water is compared technically and economically with corresponding conventional plants, under conditions in Israel.

The plants considered are conventional oil-fired plants and nuclear heavy-water natural uranium, boiling and pressurized light-water, and gas-cooled reactors. Five different generator ratings are considered initially, namely 50, 75, 125, 150 and 200 MW(e).

FEASIBILITY OF NUCLEAR REACTORS
FOR SEA WATER DISTILLATION*

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TECHNION - ISRAEL INSTITUTE OF TECHNOLOGY,
DEPARTMENT OF NUCLEAR SCIENCE,
HAIFA, ISRAEL

ABSTRACT

This document is the first annual report of research made under contract with the IAEA. As such it constitutes an interim report which will not be published. Results reported in this document will be included in the final report of the research.

Several types of reactors, PWR, BWR, HWN and GCN, are considered as heat sources for dual-purpose installations. Several design schemes are examined and optimization of both steam plant and distillation plant are studied.

* Technion - Israel Institute of Technology report TNSD-102.
THE DEVELOPMENT OF THE ELECTRICAL ENERGY DEMAND IN GREECE AND OF THE WATER SUPPLY OF THE ATHENS AREA

A. DELYANNIS
ATHENS, GREECE

1. INTRODUCTION

The rapid economic development and the continuing high rate of industrialization of Greece have caused a high rate of increase in the demand of electric energy. This is expected to continue and is reflected in the extensive construction programme of new power stations that has been prepared by the competent authorities in Greece to meet the demand in the period up to 1974.

On the other hand, it is estimated that a shortage in the water supply of Athens should be expected in the next few years. Short-term and long-term programmes to cover the water demand of the town are well under way.

2. POWER PRODUCTION AND DEMAND

The production and distribution of electricity in Greece is the responsibility of one utility company, the Public Power Corporation (PPC). It is a state-owned organization, working as a private enterprise.

The expected demand and the capacity of the interconnected electrical system of Greece for the period up to 1974 have been estimated by the PPC, which has also worked out the programme of new power stations to come on-line during that period. Table I illustrates the development of the demand and of the capacity of the interconnected system for the period from 1961 up to 1974. The first half of the table gives the total power net capacity of the system and the expected maximum demand in MW during the corresponding winter. The second half of the table shows the annual production capacity of the system for each year of the period under consideration and the anticipated annual demand.

The programme for an adequate increase of the capacity of the PPC electrical system by the interconnection of new power stations is shown in Table II. This programme provides the construction both of hydro and thermal power stations so that the installed capacity of the system will be tripled in ten years. The data and the programmes presented in Tables I and II are based on estimations made in 1964.

3. CONCLUSIONS FROM THE PROGRAMME OF THE PPC

In the case of a dual-purpose plant, considered for power generation to supply the national grid and for sea-water conversion to face the expected...
### TABLE I

DEVELOPMENT OF THE PRODUCTION AND CONSUMPTION OF ELECTRICAL ENERGY IN GREECE

<table>
<thead>
<tr>
<th>Period</th>
<th>Total system net capacity (MW)</th>
<th>Maximum demand (MW)</th>
<th>Year</th>
<th>Annual production capacity of the system (GWh)</th>
<th>Annual demand (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961/62</td>
<td>530</td>
<td>507</td>
<td>1961</td>
<td>2870</td>
<td>2337.9</td>
</tr>
<tr>
<td>1962/63</td>
<td>685</td>
<td>552</td>
<td>1962</td>
<td>2890</td>
<td>2592.7</td>
</tr>
<tr>
<td>1963/64</td>
<td>685</td>
<td>687</td>
<td>1963</td>
<td>3720</td>
<td>2947.8</td>
</tr>
<tr>
<td>1964/65</td>
<td>776</td>
<td>765</td>
<td>1964</td>
<td>3760</td>
<td>3530.0</td>
</tr>
<tr>
<td>1965/66</td>
<td>1154</td>
<td>955</td>
<td>1965</td>
<td>4420</td>
<td>4323.0</td>
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<tr>
<td>1966/67</td>
<td>1373</td>
<td>1160</td>
<td>1966</td>
<td>6780</td>
<td>5904.0</td>
</tr>
<tr>
<td>1967/68</td>
<td>1533</td>
<td>1275</td>
<td>1967</td>
<td>7150</td>
<td>6617.0</td>
</tr>
<tr>
<td>1968/69</td>
<td>1628</td>
<td>1400</td>
<td>1968</td>
<td>8080</td>
<td>7190.0</td>
</tr>
<tr>
<td>1969/70</td>
<td>1743</td>
<td>1540</td>
<td>1969</td>
<td>8980</td>
<td>7860.0</td>
</tr>
<tr>
<td>1970/71</td>
<td>1943</td>
<td>1690</td>
<td>1970</td>
<td>9730</td>
<td>8574.0</td>
</tr>
<tr>
<td>1971/72</td>
<td>2103</td>
<td>1850</td>
<td>1971</td>
<td>10530</td>
<td>9549.0</td>
</tr>
<tr>
<td>1972/73</td>
<td>2298</td>
<td>2020</td>
<td>1972</td>
<td>12350</td>
<td>10190.0</td>
</tr>
<tr>
<td>1973/74</td>
<td>2547</td>
<td>2200</td>
<td>1973</td>
<td>13480</td>
<td>11000.0</td>
</tr>
<tr>
<td>1974/75</td>
<td>2727</td>
<td>2400</td>
<td>1974</td>
<td>14380</td>
<td>12000.0</td>
</tr>
</tbody>
</table>

Water shortage of the town of Athens, the following items are essential and should be determined from the power development programme of PPC:

(a) The size of large base load thermal units to be added to the system
(b) The year of interconnection to the system of large base load thermal units
(c) The site of the large base load thermal units planned to come into operation.

It should be noted that the power stations to come into operation in the period up to 1967 are already under construction. Furthermore, tenders have been invited for the thermal unit to be commissioned in 1968. This unit is to be located at the site of the existing power station Aliveri, some 100 km from Athens. The next large thermal units to come on-line in 1969 and 1970 are respectively Megalopolis I and II. These will be located at the site of the Megalopolis lignite deposits in Peloponnese. Should, however, for one reason or another the construction of these units be delayed, Megalopolis I should inevitably be replaced by another thermal unit of the same size at least. It is most probable that this additional thermal unit will be located in the vicinity of Athens.

The largest size of thermal unit anticipated to be integrated to the system up to 1970 is 150 MW. Therefore, it can be assumed that the size of
### DEVELOPMENT OF THE INSTALLED CAPACITY AND OF THE ANNUAL PRODUCTION CAPACITY OF THE INTERCONNECTED SYSTEM OF GREECE

<table>
<thead>
<tr>
<th>Year</th>
<th>Power stations</th>
<th>Installed capacity (MW)</th>
<th>Annual production capacity (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Thermal</td>
<td>Hydro</td>
</tr>
<tr>
<td>1963</td>
<td>Existing power stations</td>
<td>469</td>
<td>265</td>
</tr>
<tr>
<td>1964</td>
<td>4 gas turbine units</td>
<td>56</td>
<td>-</td>
</tr>
<tr>
<td>1965</td>
<td>LIPTOL - unit</td>
<td>33</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Kremasta I and II</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>St. George Power Station</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ptolemais III</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>1966</td>
<td>Kremasta III and IV</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td>1967</td>
<td>Kastraki I and II</td>
<td>-</td>
<td>160</td>
</tr>
<tr>
<td>1968</td>
<td>New thermal unit</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>1969</td>
<td>Megalopolis I</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>1970</td>
<td>Megalopolis II</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ptolemais IV</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>1971</td>
<td>Topoliana</td>
<td>-</td>
<td>160</td>
</tr>
<tr>
<td>1972</td>
<td>Lignite fired thermal unit</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Kastraki III</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>1973</td>
<td>New thermal unit</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Kremasta V</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>1974</td>
<td>Aliakmon I</td>
<td>-</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1568</td>
<td>1345</td>
</tr>
</tbody>
</table>

the thermal unit that will probably be needed to replace Megalopolis I could be 150 MW. Nevertheless, a larger unit, of the order of 200 MW, might also be considered as acceptable for the system by the time of its integration.

In conclusion, the above discussion of the PPC programme shows that it seems probable that by 1969-70 an additional thermal unit of the size of 150 MW or even of 200 MW, will be required, if the construction of the Megalopolis lignite-fired power station is delayed and that this unit can be located in the neighbourhood of Athens. It will inevitably be an oil-fired power station.
TABLE III

DEVELOPMENT OF THE ANNUAL WATER CONSUMPTION IN THE ATHENS AREA
(million m$^3$)

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.8</td>
<td>17.2</td>
<td>20.9</td>
<td>15.8</td>
<td>25.6</td>
<td>36.9</td>
<td>63.1</td>
<td>91</td>
<td>1971</td>
<td>159</td>
<td>175</td>
<td>183</td>
<td>190</td>
<td>225</td>
<td>1981</td>
<td>232</td>
<td>239</td>
<td>246</td>
<td>254</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

4. WATER DEMAND OF ATHENS

The municipal water supply of Athens covered in 1932 an area of 37 km$^2$ with 70,021 consumers. By 1964 this area had increased to about 150 km$^2$ and the number of consumers to about 387,000. As a consequence, the annual water consumption of the Athens area has increased roughly by a factor of three within two decades (1932-1953) and by the same factor in the following eleven years. The actual figures are: 1932: 11.8 million m$^3$, 1953: 32 million m$^3$ and 1964: 91 million m$^3$. Table III shows the development of the annual water consumption in the Athens area and the expected water demand for each of the next 20 years as it has been estimated by the Ministry of Public Works.

A shortage in the water supply of the Athens area is expected for the time after 1970. Various projects, based on conventional methods are studied, to face the anticipated water shortage. The most important of them aiming to solve the water problem of Athens for a long period of time, provides the transportation of water from the Mornos river. A 120-m high dam will form a storage lake with a capacity of 340 million m$^3$. The 165-km long aqueduct will partly consist of tunnels having a total length of about 40 km. The total cost of the aqueduct is estimated to be about $54 million. The connection to and extension of the distribution system will need additional capital of $50 million.

Whereas the end of the Mornos aqueduct will be at a level of 254 m above sea level and a new water treatment plant is necessary, the consumers are spread over an area starting at sea level and reaching 309 m above sea level.

About half of the water consumption corresponds to an area of a level from 0 to 100-125 m. On the other hand it can be noted from Table III that an increase in the water consumption of about 48 million m$^3$ is to be expected by 1969, when a new thermal power plant will probably be erected in the neighbourhood of Athens. A further increase of about the same amount
of water is to be expected by 1974, when an additional thermal unit (Table II) is scheduled to start operation, probably again in the Athens area.

5. CONCLUSION

It follows, therefore, that by 1969, a dual-purpose plant for power production and sea-water desalination, having a capacity of about 100,000 m³/d (25 million gal/d), could both meet the needs of electrical energy and of the water supply provided that the construction of this plant is feasible by that time and the cost of its products competitive. The water of the existing supply system could serve the areas situated at a level higher than 100-125 m, whereas the needs of the lower level areas could be satisfied by desalination.

A further dual-purpose plant for the Athens area could be anticipated to meet the demand in power and water by 1974. This plant might be a nuclear fuelled unit.
A BRIEF ACCOUNT OF WATER DESALINATION 
AND USES IN THE UNITED ARAB REPUBLIC

HIGH COMMITTEE FOR WATER DESALINATION 
UNITED ARAB REPUBLIC

INTRODUCTION

In our last statement presented to the panel of experts held during the third Geneva Conference on the Peaceful Uses of Atomic Energy the proposal to use desalinated water, obtained from a dual-purpose plant, for agricultural purposes was stressed. The UAR National Committees for Nuclear Power and Water Desalination initiated a full-scale study of the situation of water and power demands of the different regions of the country with the advent of the development potential inherent in dual-purpose plants. Thorough investigations covered such aspects as:

1. Electrical power demands and load evolution to satisfy the growing demand of the population and the needs of the programme of industrialization
2. The population trends in the country, particularly in the developing areas
3. Petroleum production, imports and exports and oil trade deficiency during the last decade
4. Meteorological conditions in the areas under development
5. Land reclamation programmes on present water resources and the possibilities for their extension
6. Future water demands
7. Survey of ground water supplies
8. Possibilities of reuse of drainage water from agricultural lands
9. Rainfall, soil analysis, suitable crops, water utilization and consequent economic potential of the Mediterranean coastal region, and
10. Desalination of sea and brackish waters as the future source to meet the increasing water demands.

Three main regions have been studied by the committees.

THE WESTERN DESERT REGION

This region extends from Alexandria to the border, terminating at El-Salloum (about 600 km West of Alexandria). It ranges in depth from 2 to 20 km from the sea shore, constituting an estimated area of about 3 million acres, most of which is very fertile in nature. Many important cities are located along the shore, including Burg-El-Arab, El-Alamien, El-Dabaa, Ras-El-Hekma, Mersa-Matrouh, Sidi-Barrani and El-Salloum. This region is well served by first class means of communication and transport.

Bids have already been received from different leading companies for installing a dual-purpose 150-MW(e) nuclear power and 20,000 m³ of water per day desalination plant at Burg-El-Arab, 30 km West of Alexandria.

As previously indicated in the statement made to the panel held during the last Geneva Conference, this first UAR nuclear dual-purpose plant is
intended to furnish data on the production and use of desalinated sea water mainly utilized for agriculture. The purpose for which it is intended, as well as the present state of the art, have imposed the low water-to-power ratio. However, it is expected that once the feasibility of the progressive reclamation of the potential 3 million acres in the region concerned is well established and justified by the results revealed by the experiment associated with the first plant, the required dual-purpose plants would be of the high water-to-power ratio type.

Studies of available fresh-water resources, expected population growth, and future increase in demand for water and power have been conducted for most of summer resorts along the Mediterranean Coast.

Mersa-Matrouh is here surveyed as an example. At present 400 m$^3$/d fresh water of 200 ppm total dissolved solids and 600 m$^3$/d brackish water of 1000 ppm total dissolved solids are distributed in Mersa-Matrouh through a dual distribution system. The fresh water is conveyed to Mersa-Matrouh through a 300-km long pipeline from Alexandria. The population of Mersa-Matrouh is presently about 30,000 and increases to 40,000 during the season. Assuming a rate of increase of 3.5%, the population is expected to reach 70,000 by 1980. The shortage of fresh water is the main handicap for the development of Mersa-Matrouh.

A water development programme has been worked out to be executed within the next 15 years. The main features of the study are:

1. Sea-water conversion by flash evaporation process
2. Establishment of one water system instead of the present dual piping system through mixing, maintaining 600 ppm total dissolved solids, instead of the existing supply containing 1000 ppm
3. Increase of the total supply of water from approximately 1000 to 5000 m$^3$/d, and
4. Increase in per capita daily water consumption from 27 to 75 litres/d.

Taking all this into consideration, the study revealed the possibility of obtaining fresh water at a cost of 15 piastres/m$^3$ (equivalent to $1.4/1000$ US gal) in comparison to the present 42 piastres/m$^3$ (equivalent to $4/1000$ gal).

THE EASTERN REGION

This region comprises the desert area East of the Nile Valley up to the Red Sea, and the Sinai Peninsula. It differs from the western region in being the main UAR mining and petroleum area. Development and activities in this part have been greatly impeded so far by the shortage of fresh water.

Distillation plants of the submerged-tube type were erected nearly 40 years ago at the phosphate mining districts of Qussier and Safaga. This type of plant is still in operation, producing water at about 50 piastres/m$^3$ (equivalent to $4.6/1000$ gal).

The increase in fresh water demand at most of these localities along the Red Sea area has necessitated fresh water transport by tanker at a cost of 1 Egyptian pound/m$^3$ (equivalent to $9.3/1000$ gal).

The latest sea-water desalination plant in this region is at Abu-Zuneima. It is a combined 7500-kW gas turbine and 2400 m$^3$/d flash-evaporation desalination plant. As this plant is located at the head of an oil field, natural
gas and naphta are used as fuel. The plant is now in operation under guarantee tests.

THE DELTA REGION

Large amounts of drainage water from irrigation are being pumped to the sea. At present a programme is being pursued for the reconditioning and reuse of this water for reclaiming land in the Nile Delta in areas beyond that which would be supplied by Nile water from the High Dam Scheme. The salinity of this brakish drainage water does not exceed 4000 ppm total dissolved solids. Electrodialysis is expected to be the most suitable process for this water conversion.

To solve the problems expected to be encountered, and to complete the economic studies concerning this project, a well-known international firm has been approached about the supply of an experimental electrodialysis plant for obtaining all the required information and data. This plant, if successful, will justify installing larger plants of the same type for use in the North Delta.

PRESENT DESALTING ACTIVITIES IN THE UAR

In addition to the activities and studies carried out by the National Committee of Water Desalination sponsored by the UAR Atomic Energy Establishment, the feasibility of water desalination in the UAR has been studied by a United Nations team of experts. Their final report has not yet been submitted. Other technical teams from the USA and UK have also contributed studies. The interest and collaboration shown by the International Atomic Energy Agency and the Food and Agriculture Organization are very much appreciated.

In the development and experimental field, the Committee is at present engaged in building in Alexandria a flash-evaporation experimental plant where various technical modifications have been introduced. As most of component parts for a flash distillation unit can be manufactured locally, it is anticipated that building flash-evaporation plants of moderate size will be possible to meet the plans of the UAR programme.

The related serious extensive studies and endeavours, supported by research work carried out in various research centres and universities, will furnish the way to the UAR to take a lead in serving all arid and semi-arid regions of the world by contributing knowledge and sharing experience in the field of water conversion.
WATER PROBLEMS IN MEXICO CITY

N. CARRILLO
COMISION NACIONAL DE ENERGIA NUCLEAR, MEXICO

SUMMARY OF STATEMENT

The use of nuclear energy in a dual-purpose plant for generating electricity and desalting water could solve a number of problems which are particularly acute in Mexico City. Apart from water and electrical power requirements, these problems relate to maintenance of the condition of the subsoil, which has very special characteristics, in order to prevent subsidence of the ground on which the city is built. The average rate of subsidence is 0.30 metre per year, an extremely high figure. The main reason for the subsidence is that the city is meeting its needs by taking water from the subsoil.

The ground on which Mexico City stands consists of a number of strata (fill, clay, sand and gravel), as shown in Fig. 1. As an indication, the thicknesses of the strata commonly met with are given in the figure. Rock is usually found at a depth of more than 1000 m. The subsoil is saturated with water. The soft clay contains seven parts by volume of water to one part solid, while the hard clay contains four parts by volume of water to one part solid. The wells (which have an average depth of 300 m) extract 8 m$^3$ of water per second from the gravel strata, thereby exerting a suction effect on the higher strata and leading to subsidence of the ground.

The cost, in terms of building-foundations, of solving this problem has been very high. It has been necessary either to support buildings on extra large piles (reaching down to the sand or hard clay strata) in order to offset the downward-acting frictional forces exerted by the ground itself under the suction effect, in addition to the forces exerted by the weight of the buildings themselves, or to resort to expensive solutions such as "floating structures."

Structures with less elaborate foundations tend to lean or develop cracks. According to official estimates the cost to the municipal authorities alone of Mexico City's maintenance work necessitated by subsidence amounts to US $80 000 per day. This gives an idea of the expenditure which is incurred by private individuals for the same purpose. The price of water to the consumer varies according to the amount consumed, ranging from about US $0.024/m$^3$ to US $0.06/m^3$. However, the cost of the water to the city could be more than US $0.50/m^3$, due to the problems discussed above. The average price of electricity to the public at present is 30 mills/kWh.

The Valle de Mexico contains a number of natural basins, including those in which Mexico City lies and the former Lake Texcoco (see Fig. 2). The water of Lake Texcoco is brackish and is present in a number of strata of the subsoil in a concentration of 16 parts by volume to one part solid. The region has an annual rainfall of 750 mm which, if stored, would be sufficient to supply Mexico City with water. However, this is not possible because the rain is torrential and must be drained away to prevent flooding. Lake Texcoco has been partly drained by means of a canal and two tunnels.
At present the surface of the former Lake Texcoco consists of fine solid particles which constitute a new problem for Mexico City, i.e. dust storms. A small part of the brackish water in the former lake is used in producing salt by solar evaporation.

There is no evidence of underground communication between the subsoil of the Lake and that of Mexico City: (a) the water in the subsoil beneath the city is not brackish; (b) the pressure of the water in the subsoil beneath the lake is sufficient to make it rise in artesian wells, which would be very difficult if such communication existed since the distribution of pressure beneath the city is not hydrostatic due to the pumping of water.

The responsible authorities have made a thorough study of methods of solving these problems and, scarcely two months ago, the idea was put forward of considering the installation of a dual-purpose nuclear plant for desalting the brackish water of Lake Texcoco as a way of supplying the city with water and power. No technical or economic study has yet been made, and the purpose in setting forth this problem at such an early stage has simply been to obtain the opinions of members of the Panel on the feasibility of the scheme. The dual-purpose plant would also make it possible to prevent subsidence of the ground, with consequent large savings in expenditure on laying, maintaining and repairing the foundations of buildings.
This document is a preliminary study on combination sea-water desalting and electric power plant for Israel. The report reviews projected water and power needs of Israel, analyses the possibility of satisfying these needs with a large dual-purpose desalting plant, and contains recommendations for a more detailed engineering feasibility study. In addition, the report describes a proposed programme for development of large-scale water-desalting plants including letting of conceptual design, design, construction and testing of large modular sections. The construction of a prototype desalting plant or at least of partial modules is essential for a successful and economic design of a plant of the size under consideration.

Finally, the report gives a tentative time-table of the main steps of the project considering that the installation would start in 1971.
SPECIFIC SITUATION IN THE FORTALEZA AREA
IN BRAZIL

F. B. FRANCO-NETTO
RESIDENT REPRESENTATIVE TO THE IAEA
BRAZIL

ABSTRACT

Brazil, with a population of 80 million and a territory of approximately 8.5 million km$^2$ presents an uneven pattern of population density and economic development. My remarks will be directed to the possibility of installing a dual-purpose nuclear facility in the city of Fortaleza which is situated in a semi-arid region presenting a high population index and a low development rate. This is in the northeastern region of Brazil, with 1.2 million km$^2$ and a population of approximately 22 million. The main factor conditioning under-development is the shortage in the supply of fresh water, either for utilization in agriculture or consumption in urban centres.

Fortaleza, a coastal city on the Atlantic, has now 700 000 inhabitants. Its radius of economic influence is 300 000 km$^2$. The estimated population in 1980 will be 1.5 million including immigration. The range of industrial activity comprises a moderate production of carnauba wax, vegetable oil, textile fibres and canned fishery. Industrial expansion is seriously handicapped by the lack of power.

The following analysis of factors pointing to the desirability of building a dual-purpose facility is a summary of a paper presented at the recent Puerto Rico Inter-American meeting on the technical and economic aspects of the production of nuclear power. The authors of the paper, both members of the Technical Staff of the Brazilian Nuclear Commission, are Dr. H. A. Ferreira Junior and Dr. W. Pollis.

The shortage in the supply of fresh water for public consumption in Fortaleza is acute. Running water is available to only 15% of the population. The situation can hardly be corrected unless non-conventional methods are adopted. As a matter of fact, precipitation in the northeastern area of Brazil amounts to a mere 300 to 400 mm/yr. Water streams have a very reduced flow and dams have to be constructed. Underground water is limited but still provides the necessary water for public buildings, hospitals and schools, which keep individual wells. There are no sanitary drains. Water dealers sell their merchandise out of pipe-lorries, pulled by animals.

The present availability is 12,200 m$^3$/d. The minimum requirement in 1980 is estimated at 375,000 m$^3$/d. Projects under development, which comprise duplication of aqueducts, enlargement of dams and the use of underground water will enlarge the present availability of 75,000 m$^3$/d. Thus the deficit for 1980 is still of approximately 300,000 m$^3$/d.

The situation as regards electric power supply is not more encouraging. The total installed power is 34,000 kW, or 48 W per inhabitant. Electric light is provided to only 50% of the city. The need for power in 1980 can be estimated on the basis of 162 W per inhabitant, which corresponds to the index of São Paulo in 1962. The desired installed capacity would conse-
quently be 250,000 kW. Projects now under way will raise the installed capacity to 90,000 kW in 1980. The deficit to be met is of approximately 160 MW.

The only possible source of hydro-electric power that could be used to mitigate this deficit is the Paulo Afonso plant, on the São Francisco river, 700 km from Fortaleza. One line transmitting 20,000 kW to Fortaleza is being pulled at present. But plans for the duplication of this line have already been abandoned for economic reasons. The Paulo Afonso plant has been designed to cover a 450-km range. Consequently, a thermal power station of one or more units will have to be built. Both coal-fired and oil-fired stations are uneconomical in this case. Brazilian coal is poor in grade and the mines are situated 4000 km away from Fortaleza. Oil extracted and refined in Brazil accounts for less than 50% of consumption; a station fired by imported oil would not be competitive with nuclear powered plants.

The reasons in favour of the installation of a dual-purpose reactor in Fortaleza have recently been reinforced by the results of a study relating to the construction of a 66-MW plant in Brazil. This study has shown that both in the case of coal and oil the delivered kW would be priced at 14.8 mills.
ABSTRACT

The report presents a programme developed co-operatively by the US Department of the Interior and the US Atomic Energy Commission to advance the technology of water desalination.

The report is presented in two complementary parts. The Department of the Interior proposes an accelerated programme designed to achieve new techniques for desalination and to improve existing processes to satisfy both the large and small needs that arise. Specifically, the report recommends:

1. Extension of the Anderson-Aspinall Act through 1972, the monetary authority be increased by $200 million, and clarification of the Department's authority to build experimental facilities.

2. Establishment of a West Coast test facility where modules and full-size components of distillation plants can be tested under sea-water conditions applicable to prototype plants.

3. Construction of at least one intermediate-size prototype plant started by 1967. Prior to that time, an accelerated effort ranging from basic research to conceptual design, to be conducted on distillation processes.

4. Comprehensive study of all phases of comparative water costs and needs.

5. Increased basic research efforts to discover entirely new desalting techniques, to develop the promising reverse-osmosis process, and to perfect distillation processes.

The US Atomic Energy Commission proposes a programme designed to provide economic nuclear energy sources to serve the near-term and long-range energy needs for intermediate and large-scale desalination of sea water. The programme includes:

1. Supplementation of its reactor development programme, including appropriate prototype plants, to provide economic nuclear energy sources for anticipated intermediate and large-scale desalination needs.

2. Development of the heavy-water moderated, organic-cooled reactor concept as the reference reactor system to support the large-scale desalting programme as well as single-purpose electric power applications.

3. Continuing assessment, evaluation and necessary developments of promising reactor concepts to provide economic nuclear energy sources for the near-term, intermediate-size desalination needs.

4. Engineering analyses, studies, and developments to explore more fully the coupling of nuclear power plants to desalination facilities in order to establish a broader technological base for dual-purpose plants and specific applications.

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ANNEX I

RÉSUMÉ OF PANEL ON THE USE OF NUCLEAR ENERGY FOR WATER DESALINATION

Vienna, April 1964

The Panel's activities were devoted mainly to discussions relating to operating experience with demonstration plants, specific regional situations where dual-purpose plants might be considered, design and economics of such plants, and optimum performance ratios. Some of the major points emerging from the deliberations of the Panel are summarized below.

DEMONSTRATION PLANTS OPERATING EXPERIENCE

A comprehensive report, which is referred to below, submitted by the Office of Saline Water (USA) on its demonstration desalination plants, gave a summary of the experience gained so far with such installations in USA.

CONSIDERATIONS FOR DUAL-PURPOSE PLANT APPLICATIONS

Any technical and economic study for a dual-purpose plant should pay due consideration to the environment under which the plant is to be installed and operated. To begin with, a thorough survey of the requirements of water and electricity in reference to the area to be served by the plant should be made. The available water resources should be fully investigated, including the existence of underground water reserves, surface water resources, possibility of building dams for water resources, requirement of water for agriculture and the cost of water in relation to crop yields, and the social factors influencing the economic development of the area.

The conditions would vary from country to country and even from area to area within a given country. In a highly industrialized country served by an extensive network of transmission lines the governing factor in selecting the size of a dual-purpose plant would most likely be the water output. The electric power generated would be a by-product and could be fed into the grid.

In the case of a developing country the situation would be quite different. In an area served by a small grid and having acute shortage of water the size of the dual-purpose plant might be determined largely by the maximum power which could be absorbed by the grid rather than the water output as such.

The lifetime plant utilization factor for a dual-purpose plant would be higher than for a single-purpose power only plant. While a thermal station normally tends to be displaced by more efficient newer plants, a dual-purpose
installation, because of better utilization of heat energy, would continue to produce power at lower operating costs for a longer period.

Dual-Purpose Plants Design and Economics

In general the dual-purpose plants may employ back pressure or extraction turbines, the former being more suitable for higher water-to-power ratio. There exists a zone in which both types can be used, i.e. around 27 litres/kWh (7 US gal/kWh) depending on prime and extraction steam temperatures. Operating reliability of the desalination plant can be improved by using a steam by-pass line in which the prime steam is throttled and desuperheated before feeding the brine heater. Besides, the addition of a dump condenser in a dual-purpose plant using a back-pressure turbine would make it possible to generate electric power even in the case of the desalination plant being shut down. These devices also increase the flexibility of the plant.

Another way of improving the flexibility would consist in adding to the steam consuming desalination plant another plant using electricity (e.g. electrodialysis), which could be operated according to the variation of the power demand.

The power credit method was discussed and emphasis given to the influence of the assumed kWh value on the optimum design of the plant.

Performance Ratio

A sub-committee of the Panel investigated the difference between optimum performance ratios used for studies in the USA and UK, which are lower for the latter.

The main reason is that the unit cost of heat exchangers is much lower in the United States. In addition, the assumed heat transfer coefficient is 20% higher in the US studies. This obviously leads to higher performance ratios.

Another reason, although more difficult to establish, is the effect of the power credit procedure used only in US studies. Low power credit favours higher performance ratios.

Papers Submitted

A list of reports submitted as background material for the Panel is given below.

In addition, three papers were prepared specially for the Panel. Since they are not published elsewhere, brief résumés are given below.

(1) "Present Status of Demonstration Plants in the USA", statement by R.H. Jebens, Chief of Demonstration Plants Division, Office of Saline Water, US Department of the Interior, United States of America.

This report indicates the experience gained by the Office of Saline Water in operating their four demonstration plants (San Diego, Freeport, Webster
and Roswell). With regard to the distillation process, several tests have been made at different temperatures in the brine heater and at different concentration factors. Attention has been mainly devoted to corrosion and scale control.

(2) "An Assessment of Certain Avenues of Improvement for Nuclear Desalination Technology", by R. Philip Hammond, Oak Ridge National Laboratory, Oak Ridge, Tenn., United States of America.

In the near future, desalination, even using nuclear power, will not be in most cases the best way of obtaining water supplies. However, progress in technology can make this alternative applicable later on for more and more regions. In each case the customer should specify the input data for designing and optimizing the plant.

In a dual-purpose plant using a back-pressure turbine, power, if considered as a by-product, is generated with an efficiency of nearly 100%. As a first approximation, it appears, therefore, that the cost of prime steam is controlling and should govern the choice of heat source by taking into account some constraints such as maximum acceptable temperature of the exhaust steam and water-to-power ratio.

A study of the optimum evaporator temperature in a dual-purpose plant has been carried out. With some simplifying assumptions it shows that for a given source of primary steam, water cost is fairly independent of the cross-over temperature. More refined considerations should lead to the conclusion that there would be some advantage in selecting lower temperatures for the brine heater if the criteria is to minimize water cost, thus yielding a low water-to-power ratio. High temperature is justified only for single-purpose plants and for situations where a high water-to-power ratio is desired.

A reactor is built at present into a pressure tight enclosure for safety reasons. The same applies to evaporators in order to exclude the atmosphere. It is therefore suggested to construct one large shell to contain both, which would involve substantial cost savings.

(3) "Progress Report on Studies in UK", by Dr. A. Hitchcock, Atomic Energy Establishment, Winfrith, Dorchester, Dorset, United Kingdom.

Gas-cooled reactors of the Magnox and AGR types have been investigated for desalination applications. For the 50-300 MW(e) range considered, the latter is superior due to its lower capital cost.

Both extraction and back pressure turbines were considered and attention was paid to flexibility by adding to the latter a by-pass line and a dump condenser. It appears that up to about 6-7 gal/kWh (25 litre/kWh) the extraction system is better suited.

The results seem to indicate that for the systems considered there is no incentive to improve water plant performance ratios or maximum brine temperature beyond presently obtainable values and that the development of desalination plants need only be in terms of size; unless indeed there is some reason for giving a water/electricity ratio exceeding that of mean consumption in developed communities.
LIST OF REPORTS

(a) Reports presented for discussion


CATALYTIC CONSTRUCTION COMPANY, A preliminary report of a study on dual-purpose plants ranging from 200 to 1500 MW(th), (US) Dept.of the Interior and USAEC (1964); final report presented at the Fifth Panel, April 1964.


(b) Reports submitted for information and questions


UNITED NATIONS, The Experience of the UN - Department of Economic and Social Affairs in the Field of Water Desalination, United Nations, New York (April 1964).

(c) Reference documents


UNITED NATIONS, Water desalination in developing countries, UN rep. ST/STEA/82, UN publication sales No. 64-11-B-5, United Nations, New York (July 1964).
GENERAL OBSERVATIONS

While assessing the potential role of nuclear desalination plants for application in developing countries, reasonable-sized installations should be considered. The most appropriate range of sizes for developing countries seems to be between 200 and 1000 MW(th).

Studies performed by Member States to date have indicated that while a reactor can be designed to produce low-pressure and low-temperature steam, the resulting advantages are not important enough to justify extensive studies on the subject.

In general the dual-purpose plants generating simultaneously electric power and low-pressure steam offer some economic advantages over single-purpose plants. Under special conditions, however, there may be a justification for a single-purpose plant producing water only. High utilization factors benefit nuclear plants more than the conventional ones.

Selection of these specific desalination processes and the optimum ratio between power and water production would depend on the economic conditions governing a specific case. The present state of technology permits the building of a distillation plant composed of one or several units of 40,000 m³/d (10 Mgd\(^1\)). There are economic advantages in the development of larger units and these can be combined with reactors, the characteristics of which are already known.

Considering the current state of technology, it does not seem likely that desalinated water could be used for irrigation in the foreseeable future. It may, therefore, be necessary to subsidize irrigation water by some appropriate financial arrangements.

With reference to irrigation, particularly in arid zones, leaching is not economically feasible with expensive or subsidized water. Moreover, the desalinated water must be very low in sodium and other detrimental salts.

The power generated by diesel stations in arid zones has a fairly high cost. It seems reasonable to assume that power costs in a dual-purpose plant could be lowered sufficiently so as to be attractive and still have a margin to subsidize the cost of water. This possibility should be kept in view.

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\(^1\) Mgd = million gallons per day.
DESALINATION PROCESSES

Information presented to the Panel on the status of different desalination processes is summarized below.

Processes using thermal energy (distillation)

The distillation processes provide water containing several tens of ppm\(^2\) of salt. This content is acceptable for domestic and municipal use and also for certain industrial purposes. Where irrigation is concerned, a lower quality water may also be satisfactory and could be obtained by mixing desalinated water with brackish water.

Two of these processes have already been tried in large installations operated commercially.

Flash evaporation

With this process the maximum temperature of the brine can be relatively high, thus resulting in a high performance ratio\(^3\).

The Point Loma demonstration plant in the United States of America was initially designed for the production of 4000 m\(^3\)/d (1 Mgd), using a maximum brine temperature of 93°C (200°F). This temperature has been progressively increased to 116°C (240°F) which has raised production to 5600 m\(^3\)/d (1.4 Mgd). During a trial at 121°C (250°F) the plant's pumping equipment proved to be insufficient. The plant will be converted for a temperature of 177°C (350°F) and an output of 8400 m\(^3\)/d (2.1 Mgd). At this temperature it will be necessary to use materials which are more resistant to corrosion, and special water treatment techniques will have to be developed to avoid scale formation.

During trials a plant recently constructed by the Weir Westgarth Company, a performance ratio of 12 was reached; this value represents a maximum under present conditions.

It should be mentioned that flash evaporation is at present the most technologically advanced process for water desalination. In addition it has a considerable scaling up potential which is particularly attractive for use in conjunction with nuclear heat sources.

Multiple effect distillation (long vertical tubes)

Plants using this process are more sensitive than those mentioned above to the effects of corrosion and to the maximum temperature of the brine. This explains why the demonstration plant at Freeport, in the United States, designed for 121°C (250°F) had to be operated at a reduced temperature of 110°C (230°F). An appreciable reduction has been noted in the plant's productive capacity owing to the formation of surface deposits, which have adversely affected heat transfer.

\(^2\) 1 ppm (one part per million) is equal to 1 milligram per litre.

\(^3\) Performance ratio = \(\frac{\text{weight of distilled water produced}}{\text{weight of steam used}}\)
Processes using electrical energy

The three most advanced processes, from the technological standpoint, are the following:

Electrodialysis

This process is a proven one. The cost of water desalination using this process depends on the quantity and the nature of the salts contained in the water. The conductivity of saline water becomes very low for salt contents of less than 500 ppm, so that it would be expensive to use this process to obtain water with lower salt contents.

The cost of desalted water from electrodialysis being a function of the reduction in salinity, this process is, in general, considered only in the case of brackish water (up to 8000 ppm). Electrodialysis does not eliminate the organic matter often contained in water. One of its main advantages is that it is capable of being operated at part load by varying the intensity of the electric current, thereby providing a high degree of flexibility. Another advantage is short start-up time.

It should also be mentioned that this process involves the use of membranes which have to be replaced periodically and are at present expensive.

Vapour compression process

After a number of pilot installations, the first demonstration plant with an output of 4000 m³/d (1 Mgd) was recently put into operation at Roswell in the United States.

Freezing process

This process has been tried in numerous pilot plants, with good results. A demonstration plant is being built in the United States.

NUCLEAR INSTALLATIONS PRODUCING WATER ONLY

The studies made to date show that the use of a nuclear reactor for the sole purpose of desalination may be an expensive way of obtaining water. The possibility of building reactors to supply steam at the lower temperature and pressure conditions required by the distillation processes has been investigated for light-water, heavy-water and gas-graphite reactors. Preliminary results seem to show that the saving achieved would not be sufficient to justify the expense involved in developing new reactor types.

The studies show that the most economical low-pressure steam is obtained by expanding high-pressure steam in a turbine. This explains the interest of dual-purpose plants.
REACTOR TYPES FOR DUAL-PURPOSE PLANTS

Proven types of power reactors, i.e. the light-water/enriched-uranium, heavy-water/natural-uranium and gas-graphite/natural-uranium are considered to be suitable for dual-purpose operation.

Light-water/enriched-uranium reactors

A number of studies have been made to evaluate the cost of heat for a desalination plant. These studies, undertaken by the USAEC, relate mainly to reactors of 1500 to 4500 MW(th), feeding back-pressure turbines.

To meet the requirements of developing countries, it would be desirable to undertake studies of plants in a thermal capacity range of 200 and 1500 MW(th). Light-water reactors seem to be at present quite attractive in the lower capacity range.

Heavy-water/natural-uranium reactors

The moderator of these reactors is generally cooled by circulation in a heat exchanger. The heat thus removed is usually not recovered. If the moderator is slightly pressurized, its temperature can be high enough for it to be used as a heat source for a distillation plant. The recovery of several per cent of the reactor’s thermal power constitutes a considerable advantage. A recent study of a 400 MW(th) reactor in Canada has indicated that the heat removed by the moderator would be about 20 MW(th).

Gas-graphite/natural-uranium reactors

In France studies have been carried out to evaluate the economics of 1000 MW(th) reactors of this type on the basis of present prices and techniques.

SPECIFIC PROJECTS AND SELECTED EXAMPLES FOR POSSIBLE DUAL-PURPOSE APPLICATIONS

The following projects were reviewed:

Key West (USA)

It was reported that a study of a plant producing 40-60 MW(e) salable and 21 000-32 000 m³/d (7-8 Mgd) was under way.

South Tunisia

The expected demand near the town of Gabes seems to be favourable for the consideration of a dual-purpose plant producing 12 000-24 000 m³/d (3-6 Mgd) and 50 to 70 MW(e).

The Tunisian Atomic Energy Commission was undertaking a detailed study for initiating a project for a dual-purpose plant in the area. The Panel
took special note of this proposed project and recommended that Tunisian authorities make detailed investigations by using appropriate consultants.

Others

Several other regions were mentioned where applications of dual-purpose plants could be considered, including Tijuana (Mexico), Israel, South East of Australia, Karachi (Pakistan) and some areas in the United States of America.

AGRICULTURE AND DESALINATED WATER

The use of desalinated water in agriculture depends on its price. At present, most irrigation networks are subsidized. Quite often the price paid by the customer does not even cover the cost of operation. After studying numerous cases throughout the world, FAO arrived at the following conclusion, on the assumption that Governments could subsidize irrigation water up to 40%:

"Except in very specific cases, it will not be possible to consider the economic use of desalted water for irrigation as long as its production cost without subsidy is above 2.5 €/m³ or 10 cents/1000 US gallons. Only when this cost is of the order of 0.75 €/m³ or 3 cents per 1000 US gallons will the use of desalted water for agriculture develop on a large scale".

The demand for electric power in the regions needing agricultural water is very small. Irrigation itself requires about 0.25 kWh/m³ or 1 kWh per 1000 gallons of water supplied to the consumer.
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