Nuclear Energy for

Water Desalination

NUCLEAR ENERGY FOR WATER DESALINATION

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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

NUCLEAR ENERGY FOR WATER DESALINATION
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FOREWORD

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][1]

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.

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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 m³ of sea water (35 000 ppm) at ambient temperature is 0.7 kWh
(2.8 kWh/10³ 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/m³) for
different desalination processes, the form of energy used (thermal or elec-
trical) 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 con-
sumption, even so adjusted, is only one of the parameters for determining
the total energy cost to the desalination plant. For instance the cost of elec-
trical 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 ac-
cording 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 de-
monstrated 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 m³/d (10 000 gal/d). The advantages of this new con-
cept 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 de-
crease considerably above a capacity of 40 000 m³/d (10 Mgd²). The United
States programme, which also includes other distillation processes, pro-
vides for stepwise development in this connection. After design studies,
full-scale blocks or "modules" of a 200 000 m³/d (50-Mgd) unit will be con-
structed. This will make it possible to study simultaneously flash evapor-
ation operation and problems associated with high-capacity installations.

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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 m³/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 m³ 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-

portant 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 ef-
ficient 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 approp-
riate reactor types for anticipated desalination applications [18]. While
assessments are being made on a number of reactor systems, special at-
tention 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) ca-
pacity which could be operated in 1970. It would not be coupled to desalina-
tion plants to minimize any possible interference between them. If these
separated plants prove to be successful, the next step would be a combi-
nation 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 com-
missioned by 1968/1969.

TABLE I

WATER PRODUCTION COST (US $/1000 GALLONS)

Fixed charge rate	Fossil fuelled								Nuclear reactor							
	Low temperature (MW(th))				High temperature (MW(th))				Low temperature (MW(th))				High temperature (MW(th))			
	200	600	1000	1500	200	600	1000	1500	200	600	1000	1500	200	600	1000	1500
Dual-purpose plants [a]																
4%	0.365	0.307	0.319	0.320	0.349	0.275	0.320	0.318	0.392	0.227	0.202	0.197	0.438	0.233	0.238	0.228
7%	0.455	0.374	0.391	0.373	0.454	0.340	0.349	0.366	0.553	0.327	0.289	0.265	0.640	0.344	0.303	0.312
14%	0.605	0.503	0.506	0.517	0.613	0.480	0.455	0.463	0.964	0.589	0.521	0.478	(-)	0.658	0.586	0.536
Water only plants [b]																
4%	0.482	0.425	0.402	0.398	0.491	0.430	0.407	0.402	0.499	0.352	0.308	0.294	0.558	0.399	0.357	0.340
7%	0.582	0.505	0.481	0.476	0.598	0.516	0.490	0.484	0.656	0.458	0.408	0.383	0.724	0.518	0.466	0.443
14%	0.797	0.674	0.647	0.641	0.831	0.699	0.667	0.660	(-)	0.719	0.639	0.597	(-)	0.803	0.727	0.689

[a] Variable power credit.
[b] Power purchased at 6 mills/kWh.

TABLE II

SUMMARIZED RESULTS – DUAL PLANT OPTIMIZATION
Basis: 14% fixed charge rate, variable power credit factor

Heat source	Fossil fuelled								Nuclear reactor							
Steam conditions	Low temperature				High temperature				Low temperature				High temperature			
Input to dual plant (MW(th))	200	600	1000	1500	200	600	1000	1500	200	600	1000	1500	200	600	1000	1500
Investments (million $)																
Steam plant	1.383	3.197	4.955	7.141	2.973	6.040	9.119	12.963	15.664	21.955	25.974	30.649		30.089	40.847	52.209
Power plant	4.182	6.018	8.773	11.955	5.612	8.552	12.444	17.095	4.450	6.900	9.380	12.900		8.935	12.901	17.924
Water intake and canal	0.246	0.727	1.219	1.819	0.246	0.727	1.219	1.819	0.246	0.727	1.219	1.819		0.727	1.210	1.819
Indirects on above	1.810	2.695	3.882	5.430	2.580	4.210	5.840	7.840	6.200	8.000	9.000	10.200		9.000	10.750	12.400
Interest on construction money	0.269	0.518	0.881	1.386	0.401	0.800	1.338	2.088	1.482	2.320	3.233	4.346		3.014	4.592	6.448
Non-depreciating items	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	1.677	2.191	4.808	6.524		2.917	5.841	7.766
Water plant (including indirects and construction money)	7.770	24.385	40.009	61.550	5.447	18.736	30.051	42.745	21.109	33.695	42.778	51.740		36.595	48.246	56.333
TOTAL	15.720	37.600	59.779	89.341	17.319	39.125	60.071	84.610	50.828	75.788	96.392	118.178		91.277	124.396	154.899
Fuel cost (million $ per year)		5.897	9.829	14.744	1.965	5.897	9.829	14.744	1.213	2.629	4.179	5.967		3.487	5.464	7.915
Operating cost, steam and power plant (million $ per year)		0.576	0.709	0.768	0.496	0.576	0.709	0.768	0.889	1.152	1.439	1.680		1.308	1.665	1.998
Steam																
Million Btu per hour																
from steam plant	682.55	2047.65	3412.76	5119.14	682.55	2047.65	3412.76	5119.14	682.55	2047.65	3412.76	5119.14		2047.65	3412.76	5119.14
to water plant	546.00	1640.00	2735.00	4100.00	473.00	1420.00	2365.00	3545.00	562.00	1695.00	2815.00	4230.00		1420.00	2365.00	3545.00
to brine heater	531.49	1589.65	2648.68	3966.90	461.71	1380.38	2297.78	3444.94	534.84	1631.67	2723.79	4108.50		1385.85	2274.10	3426.12
Dollars per million Btu																
from steam plant	0.6247	0.5212	0.5049	0.4941	0.6977	0.5665	0.5434	0.5290	1.1737	0.6045	0.4908	0.4193		0.7774	0.6646	0.5877
to brine heater	0.1847	0.2379	0.2675	0.2786	0.1811	0.1870	0.2056	0.2092	0.8900	0.3751	0.2838	0.2182		0.5032	0.3897	0.3016

TABLE II (cont.)

Heat source	Fossil fuelled								Nuclear reactor							
Steam conditions	Low temperature				High temperature				Low temperature				High temperature			
Input to dual plant (MW(th))	200	600	1000	1500	200	600	1000	1500	200	600	1000	1500	200	600	1000	1500
Power																
Cost (mills per kWh)	10.980	7.194	6.346	5.898	9.045	6.404	5.845	5.557	12.546	7.636	6.561	6.007		6.486	5.877	5.568
Gross power generated (MW)	37.50	112.50	187.50	282.00	55.80	167.50	279.00	419.00	33.00	100.00	166.00	251.00		167.50	279.00	419.00
Power to water plant (MW)	3.16	11.82	21.97	34.36	2.88	8.89	15.90	24.39	6.85	16.72	23.52	29.87		17.77	25.40	31.68
Net salable power (MW)	34.34	100.68	165.53	247.64	52.92	158.61	263.10	394.61	26.15	83.28	142.48	221.13		149.73	253.60	387.32
Operating cost, water plant (million $ per year)		1.046	1.554	2.164	0.605	0.908	1.280	1.748	0.761	1.225	1.624	2.030		1.194	1.619	1.997
Water																
Plant performance factor (lb water per lb steam)	8.98	10.43	10.73	11.04	8.04	9.45	9.63	9.56	16.72	12.78	11.02	9.73		14.81	13.16	11.42
Plant production (million gallons per day)	14.69	51.03	87.48	134.88	11.43	40.15	68.12	101.41	27.52	64.18	92.43	123.14		61.97	92.12	120.48
Cost (dollars per thousand gallons)	0.605	0.503	0.506	0.517	0.613	0.480	0.455	0.463	0.964	0.589	0.521	0.478		0.658	0.586	0.536

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 $\not{c}/m^3$ (24.9 to 51.7 $\not{c}/10^3$ 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 m^3/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 m^3/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. Introduction

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,

TABLE III

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

Thermal capacity of reactor (MW)	Electric capacity (MW)	Fresh-water production		Cost of electric power (kopecks*/kWh)	Cost of fresh water (kopecks/t)
		(m³/h)	(m³/d)		
Beloyarsk atomic power station (Graphite - light water - nuclear superheat)					
250	75	2 320	55 600	1.64	29.6
500	150	4 170	100 000	0.92	19.8
1000	300	7 310	175 500	0.51	14.4
2000	600	14 620	352 000	0.45	14.1
Novovoronezh atomic power station (PWR)					
250	40	2 810	67 500	2.5	42.2
500	80	5 620	135 000	1.49	28.9
1000	160	8 850	212 000	0.74	18.7
2000	320	17 700	425 000	0.48	15.4
Shevchenko atomic power station (Fast reactor)					
250	75	2 320	55 600	2.1	47.0
500	150	4 640	111 000	1.09	26.4
1000	300	7 310	175 500	0.45	16.4
2000	600	12 600	302 000	0.30	11.0

* 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 co-operation 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 occurrance 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.

TEXT AND ABSTRACTS OF REFERENCE DOCUMENTS

THE WATER PROBLEM
AND DESALINATION

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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 ef-
ficient industrial practices as they relate to water use, grow crops that con-
sume 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 com-
pounds, 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 pro-
duced daily from saline sources, saline water conversion is still in its in-
fancy. The cost of desalination has been drastically reduced over the past
ten years, but is still relatively high. Nevertheless, in some areas desali-
nation 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 over-
all 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 rela-
tively 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 2×10^9 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.

TABLE I

ENERGY REQUIREMENTS FOR SIX DESALINATION PROCESSES

	Energy required per 1000 gal product water			
	1964 Technology		Estimate for 1980 Technology	
	$(Btu \times 10^3)$	(kWh)	$(Btu \times 10^3)$	(kWh)
Processes using heat				
Multistage flash distillation	1020	300	610[a]	180
Long tube vertical distillation (LTV)	1020	300	610[a]	180
Processes using electricity[b]				
Electrodialysis (brackish water only)	83	25	50	15
Vapour compression distillation	610	180	360	105
Freezing	610	180	360	105
Reverse osmosis	170	50	102	30

[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 para-
mount importance was the demonstration of membrane life under field con-
ditions. 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 pro-
gress 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 mem-
brane 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 mem-
branes 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 in-
crease 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 con-
structed and tested are the shell and tube configuration (Havens), the vertical
spiral configuration, and the narrow channel configuration. The latter con-
figuration, 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 (tur-
bulence promotion, pulsing, etc.) are being tested, evaluated, and brought
to fruition.

It must be recognized that reverse-osmosis desalination is a new tech-
nology. Technical and engineering problems will develop. However, pro-
gress 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 cap-
able 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 munici-
pal 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, ac-
cordingly, 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 inter-
mediate 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 evalu-
ated 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 com-
parable 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} deg F^{-1}h^{-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. H_2SO_4 is added to the sea water which reduces scaling by $CaCO_3$ and $MgOH_2$. Acid treatment is not effective for $CaSO_4$ 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 $CaSO_4$. 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. $MgNH_3PO_3$ 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.

Roswell (VC)

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 de-
veloped 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 oper-
ation. 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.

FRESH WATER FROM THE SEA*

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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 99.8%, i.e. less than 0.2% 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.

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 require-
ments 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 in-
stalled 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 electrici-
ty 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 civi-
lization. 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 con-
version 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 elec-
trical 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 elec-
trical 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 pro-
duced 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 dif-
ference of 10 degF, we can construct Table I.

TABLE I

CALCULATION OF ORDER OF MAGNITUDE OF POWER
REQUIREMENTS FOR VAPOUR COMPRESSION DISTILLATION
AND FREEZING

	Vapour compression	Freezing
Minimum order of temperature difference (degR)	10	10
Order base temperature (degR)	670	480
Thus order of Carnot refrigeration factor	67	48
Thus order of practical refrigeration factor	22	16
Thus order of power required (Btu/lb)	45	9
Thus order of power required (kWh/gal)	0.132	0.026
Thus gallons produced per kWh consumed	7.6	38.5

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 re-
quirements 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 com-
parable, 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.

<div align="center">TABLE II</div>

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

Water/power consumption ratio	Percentage addition due to flash distillation	Percentage addition due to vapour compression distillation	Percentage addition due to freezing
2	2. 5	26	5
5	6. 5	66	13
10	13	132	26

    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 con-
version would ease this situation, and benefit the economics of both pro-
cesses? 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 com-
pression 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

Water/power production ratio	Load factor per cent before combination with:		
	Flash distillation	Vapour compression distillation	Freezing
0	100	100	100
2	97. 5	79. 5	95. 2
5	93. 8	60. 2	88. 5
10	88. 5	43. 1	79. 5

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)

Flash distillation performance ratio 12 (already achieved)	Vapour compression (theoretical on minimal temperature differences) and full regenerative exchange	Freezing (theoretical on minimal temperature difference) and full regenerative exchange
1	3	0.59
1	2 or 3	0.55 - 0.59

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 $s(t_x - t_y)/L$.[1] 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 de-sired 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 ob-tained 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_r. 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 re-duced below p_0. A fraction flashes, becomes vapour at temperature T_1 cor-responding 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_r 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
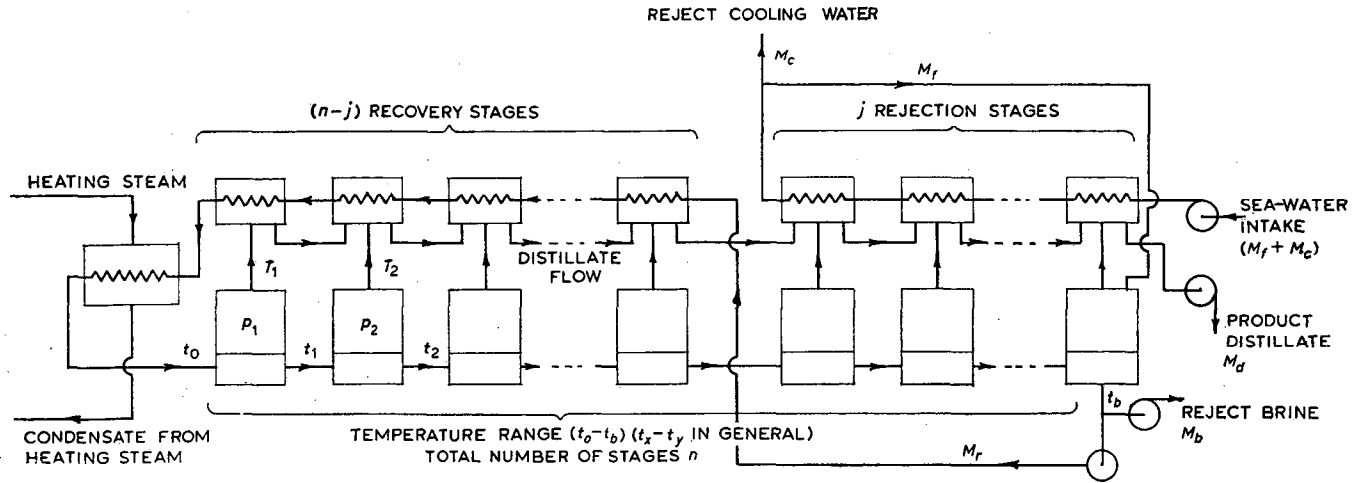
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[1] Notation is given in the Annex.

FIG. 1. Diagram of multi-stage flash process

recovery section. This term is precise in that all heat given out by conden-
sation 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 element-
ary 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 embodi-
ments 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 num-
ber 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

$$\frac{K}{M_d} = A + \frac{B}{\sqrt{M_d}}\sqrt{n} + Cn\ln\frac{n}{n-R} + \frac{E}{R} \tag{3}$$

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

$$R_0 = \frac{E}{2nC}\left[\sqrt{1 + \frac{4n^2C}{E}} - 1\right] \doteq \sqrt{\frac{E}{C}} - \frac{E}{2nC} \quad \text{where} \quad \frac{4n^2C}{E} \text{ is large} \tag{4}$$

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

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

$$= A + \frac{B}{\sqrt{M_d}}\left(\frac{E}{C}\right)^{\frac{1}{4}} + 2.69(EC)^{\frac{1}{2}} \tag{5}$$

(N. B.   The assumption of $n \approx 2R$ 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

$$\left(\frac{K}{M_d}\right)_{\infty} = A + 2.69(EC)^{\frac{1}{2}} \tag{6}$$

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 ma-
terial 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. 1.14×10^{-5} per hour, we obtain for A a value of order
3×10^{-6} £/lb product, i.e. 3×10^{-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 ex-
tended temperature range. This is the origin of all the relevant research on
scale formation, not only for improved heat transfer but also to permit ex-
tension 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 re-
duction 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 de-
signer 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 2.5×10^{-7} £/lb, i.e. 6×10^{-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 re-
gard 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 12×10^{-7} to 36×10^{-7} pence^2/lb^2
and $(EC)^{1/2}$ of order 1.1×10^{-3} to 1.9×10^{-3} pence/lb. Thus the second term
of Eq. (6) is of order 3×10^{-3} to 5×10^{-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, cor-
responding 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 phe-
nomena 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 3×10^{-4} £$/\sqrt{\mathrm{lb}\,\mathrm{h}}$.

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 2.6×10^{-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 approxi-
mately $2E/(E/C)^{1/2} = 2(EC)^{1/2}$, that is 2.2×10^{-3} to 3.8×10^{-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

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

to $$38 + 1.15(19) = 60d. /1000 \text{ gal}$$

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 sea-water 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 I we therefore have the energy costs as follows:

	Vapour compression distillation	Freezing
Energy portion of product water cost, d./lb	0.008	0.0016
d./1000 gal	80	16

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 (1.15×10^{-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 £8000-10 000 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:

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

Using the condenser parameter $\alpha = US/Q_c c = \ln[(T - t_1)/(T - t_2)]$, 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

$$T_1 - T = \frac{(T_1 - t_1)(1 - e^{-\alpha})}{1 - e^{-\alpha} + q} \tag{8}$$
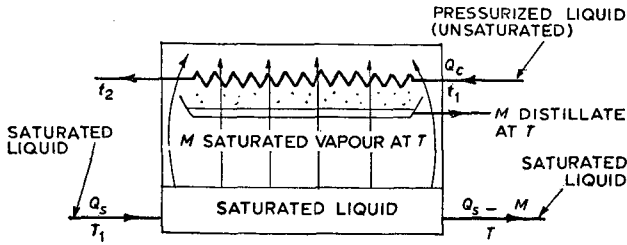
FIG. 2.   Diagram illustrating determination of chamber temperature

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 α. Any surging or variation of cooling flow quantity Q_c, any fouling which upsets 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 $T_1 - t_1$ depends on the operation of the stages above and below the one under consideration, since the upper determines T_1 and the lower determines t_1. 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 α 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 multistage 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 com-
ing 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 require-
ments, and it looked as if my extrapolation ideas had been unreliable. How-
ever, 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 accumul-
ated 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 under-
standing 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 pre-
sent a control problem as such. However, fluctuations in α are unfortunate-
ly possible and do enter the control problem if the behaviour of the recircu-
lation pump is not stable. Now the recirculating pump in large multi-flash
distillation has quite a new kind of duty, unprecedented in previous engineer-
ing. 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, other-
wise 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].

Present world population	3×10^9
Expected world population in A.D. 2000	6×10^9
Total current fresh water requirements per head in developed countries (including industrial and agricultural use)	220 000 gal/yr
Thus expected world total fresh water needs for all countries by A.D. 2000	1.3×10^{15} gal/yr
Maximum amount of utilizable fresh water flow from all sources in the world	1.4×10^{16} gal/yr

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.

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ANNEX

NOTATION

A	Volume or time parameter	s	Specific heat of brine
A_p	Plan area of vessel	S	Heat transfer surface
B	Staging parameter	T	Vapour saturation temperature
C	Surface parameter		
c	Specific heat of cooling water	T_1	Temperature of saturated water entering chamber
E	Energy parameter		
H_b	Enthalpy at bleed	T_1	Vapour temperature
H_c	Enthalpy at turbine exhaust	t_x	Brine inlet temperature
H_0	Enthalpy at boiler exit	t_y	Brine outlet temperature
K	Major operating cost	t_1	Cooling water inlet temperature
L	Latent heat of vapour		
M	Rate of condensate	t_2	Cooling water outlet temperature
M_d	Rate of distillate product		
M_f	Rate of feed	t_r	Temperature of brine leaving first stage
M_r	Recirculation rate		
n	Number of stages	t_1	Brine temperature in first stage
n_0	Optimum number of stages		
p_0	Saturation pressure corresponding to t_0	t_0	Temperature of brine leaving input heater
p_1	Pure water saturation pressure	t_b	Lowest stage brine temperature
Q	Rate of flow of saturated brine	Δ_{tx}	Boiling point elevation
		U	Overall heat transfer coefficient
Q_c	Rate of cooling water flow through a bank of tubes		
Q_s	Rate of flow of saturated water entering chamber	W	Weight of water required in gallons
		α	Condenser parameter
R	Performance ratio of plant	θ	Logarithmic mean temperature difference
R_0	Optimum performance ratio of plant		

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.

C, A INDICATE CATIONIC AND ANIONIC MEMBRANE
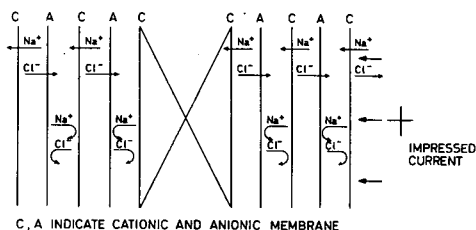
FIG. 1. Schematic electrodialysis stack

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:

$$\frac{i}{c} = yV^x \tag{1}$$

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 m² and for small plants, $300 to $500 per m². Only mass production of membranes and equipment can reduce those costs.

The net cell pair area can be calculated as follows:

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

where M = volume of liquid to be processed (m³/h), C_1 = salinity of influent (g equiv/m³), C_2 = salinity of effluent, F = 96 500 C, i = current density (mA/cm²), 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 m². 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:

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

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:

$$\text{Cost per } m^3 \text{ of water} = \frac{K_1}{i} + (i) (K_2) + K_3 \qquad (4)$$

K_1 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:

$$i = \sqrt{K_1/K_2} \qquad (5)$$

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.
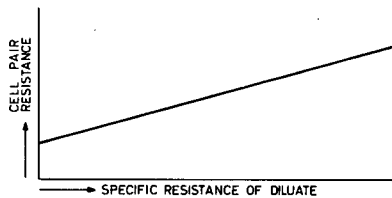
FIG. 2. Performance of electrodialysis apparatus

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:

$$R = K_1 + (K_2) (D) \qquad (6)$$

where R is the cell-pair resistance (Ωcm^2), D is the specific resistance of depleted liquid ($\Omega\ cm$), 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

factor. 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 equip-
ment usually guarantee an operating capacity reduction of $< 0.8\%$ per $1000\,m^3$
treated water for cation exchange resins (6-8% 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 communica-
tion). 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 oper-
ate 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 permselective mem-
branes. 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 demineralization 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.

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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.

60

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 fa-
cilities 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 desali-
nation plants. The evaporators in such plants in which fresh water is pro-
duced 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 equip-
ment which are already available and which have been tried out in practice,
and of well-established steam parameters and operationally-developed as-
semblies 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 pro-
duced 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 additonal 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 nucelar 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 ($S_{el.}$)

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

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 condensers. 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 turbine. 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 ($S_{h.s.}$):

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

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 difference 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.

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

where PC_e = prime cost, in kopecks/kWh, of electric power when the reactor 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:

$$S = S_{e.c.} + S_{h.s.} + PC_e \, W_p \tag{4}$$

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 circula-
tion 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 compo-
nent 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:

$$C^0_{f.w.} = \frac{S_{e.c.}}{M} = C_{a+m} + C_e + C_{s.w.} + C_w + C_{o.e.} \; ; \quad \left[\frac{\text{kopecks}}{t}\right] \qquad (5)$$

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

$$C_{f.w.} = f(T_{so}, \Delta T_{st}, n_{st}) \; ; \quad \left[\frac{\text{kopecks}}{t}\right] \qquad (6)$$

was carried out for variations in T_{so} ranging from 40 to 250°C, variations in ΔT_{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 (ΔT_{st}).

The graphs show that, as the n_{st} and ΔT_{st} values increase, the $C^0_{f.w.}$ values tend toward saturation.
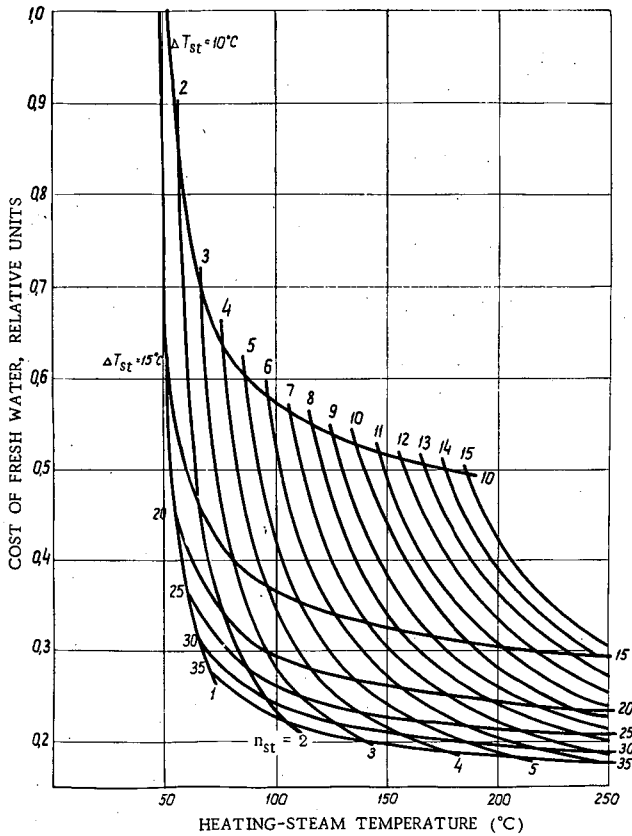
FIG. 1. Effect of heating-steam temperature on prime cost of fresh water excluding cost of heat

Cost of heating steam

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:

$$C_e = 0.457 + 3.8 \ \exp \ (-0.916 \times 10^{-2} \ N_e) \tag{7}$$

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

$$C_e = 1073 \ N_e^{-1.272} \ ; \tag{8}$$

for the Shevchenko atomic power station, where N_e = electric power, in MW.

An analysis of the cost of heating steam:

$$C_{h.s.} = \frac{S_{h.s.}}{Q_h} \; ; \; \left[\frac{roub.}{cal}\right] \tag{9}$$

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.
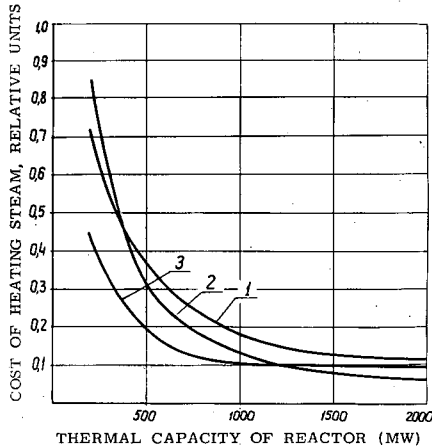
FIG. 2. Effect of reactor thermal capacity on cost of heat generated
1. Reactor of type used at Novo-Voronezh atomic power station
2. Reactor of type used at Shevchenko atomic power station
3. Reactor of type used at Beloyarsk atomic power station

Total cost of fresh water

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

$$C_{f.w.} = C^0_{f.w.} + C_{h.s.} \times q \; ; \; \left[\frac{kopecks}{t}\right] \tag{10}$$

where q = the specific heat rate required to produce one ton of fresh water.
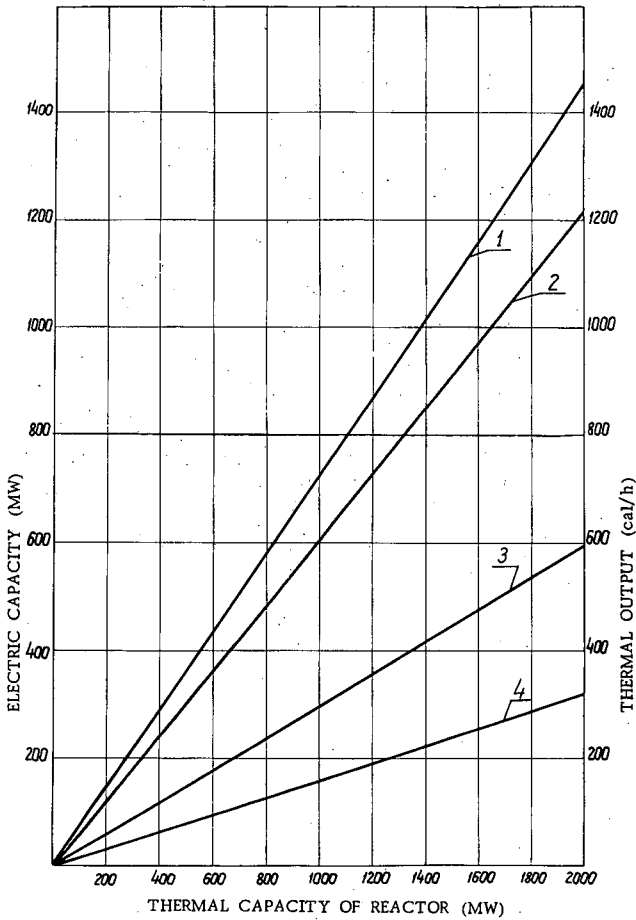
FIG. 3.   Electric capacity of plant and output of heat to produce fresh water with varying thermal capacity
of the reactor
1.   Output of heat for reactor of type used at Novo-Voronezh atomic power station
2.   Output of heat for reactors of type used at Shevchenko and Beloyarsk atomic power stations
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
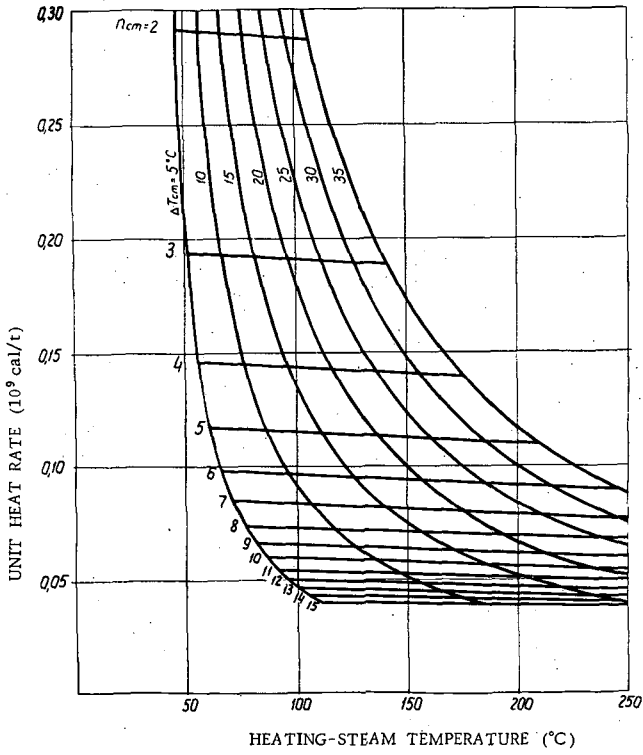
FIG. 4.   Unit cost of heat for producing fresh water as a function of heating-steam temperature
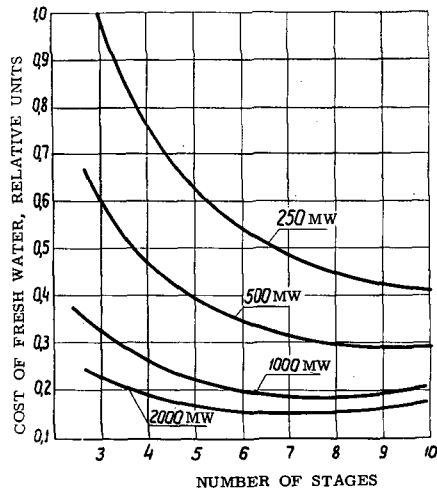
FIG. 5.   Effect of number of stages on cost of fresh water at various thermal capacities of reactor of type used at Novo-Voronezh atomic power station
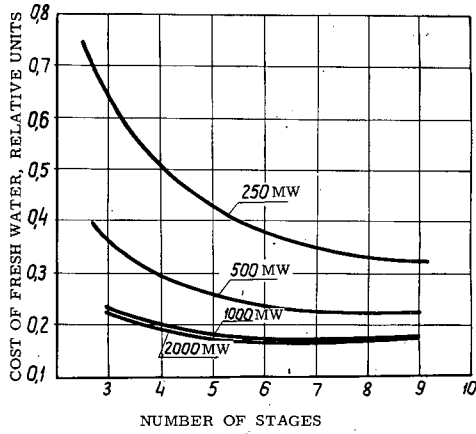
FIG. 6.   Effect of number of stages on cost of fresh water at various thermal capacities of reactor of type used at Beloyarsk atomic power station
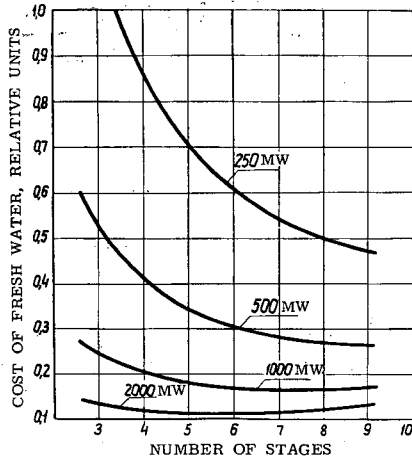
FIG. 7.   Effect of number of stages on cost of fresh water at various thermal capacities of reactor of type used at Shevchenko atomic power station

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 $C^0_{f.w.}$ and a reduction in the value of q.   In the descending part of the curve (Q_p = const.) the decrease in the value of q is more rapid than the decrease in that of $C^0_{f.w.}$, while in the ascending part the reverse is the case.   In addition, there is a specific ΔT_{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

Type of reactor	Thermal capacity of reactor (MW)	Electric capacity (MW)	Fresh-water production (t/h)	(t/d)	Cost of electric power (kopecks/kWh)	Cost of fresh, water (kopecks/t)
Beloyarsk atomic power station	250	75	2320	55 600	1.64	29.6
	500	150	4170	100 000	0.92	19.8
	1 000	300	7310	175 500	0.51	14.4
	2 000	600	14 620	352 000	0.45	14.1
Novo-Voronezh atomic power station	250	40	2810	67 500	2.5	42.2
	500	80	5 620	135 000	1.49	28.9
	1 000	160	8 850	212 000	0.74	18.7
	2 000	320	17 700	425 000	0.48	15.4
Shevchenko atomic power station	250	75	2320	55 600	2.1	47.0
	500	150	4 640	111 000	1.09	26.4
	1 000	300	7310	175 500	0.45	16.4
	2 000	600	12 600	302 000	0.30	11.0

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:

$$C = S_{f.w.} + S_{el.} + (K_a + K_{e.c.}) \times P; \quad \left[\frac{\text{roub.}}{\text{yr}} \right] \tag{11}$$

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.

ACKNOWLEDGEMENTS

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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.

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[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 ω 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,

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

It is a convenient definition, which will normally have a value between 0.1 and 1. However, its value may vary between 0 and ∞ 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, ω 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.[2]

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[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.

[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.

EXHAUST STEAM EVAPORATOR
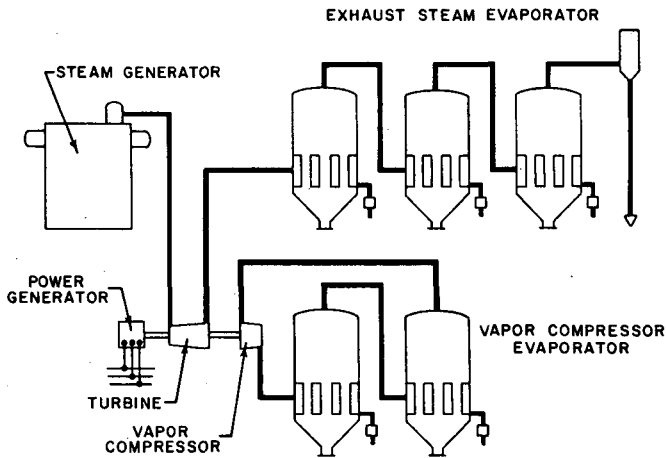
FIG. 1.   Multiple process desalination plant

When the mechanical output of the steam cycle exceeds the need for power, ω 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,[3] 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 ($t_{exhaust} - t_{condenser}$) diverted to the evaporator, and Δ 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

$$H = Sf = \frac{SD}{\Delta}$$

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

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[3] Some qualification of this statement is necessary if reheat steam cycles are included.
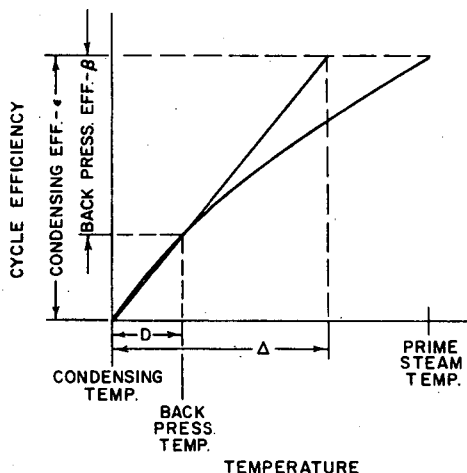
FIG. 2.   Cycle efficiency versus temperature

to the evaporator may be expressed in terms of temperature by the pro-
portionality in the lengths of sides of similar triangles; thus,

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

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,[4] 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 per-
formance of the heat transfer surface. It is assumed that the temperature
range is kept below the region where the evaporator suffers cost penalties.
Thus,

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

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[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,

$$W = k_1 + \frac{k_2 R}{D} + \frac{SD}{R\Delta}$$

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

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

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

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

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 ω 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 Δ, ϵ, and D. A general expression for S is

$$S = k_4 + \sum_{n}^{n} a_n (P)^{\gamma_n}$$

where k_4, a_n, and γ_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

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

where α 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

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

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 optimi-zation 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 correla-
tion 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 calcula-
tions 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 opti-
mization 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 eva-
porator. 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. Vari-
ables that may be optimized are the blow-down temperature, the brine velo-
city, 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
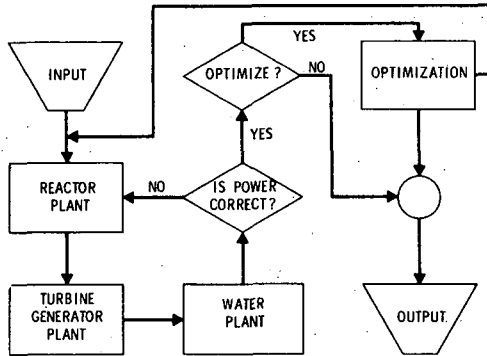
FIG. 3.   Simplified flowsheet for the dual plant optimization code

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

$$\left.\begin{array}{l}\text{Dual-plant turbine-}\\\text{generator efficiency}\end{array}\right\} = (0.76 + 0.00008\ T_S)\ \frac{T_1 - T_S - 460}{T_1}$$

$$\text{Reactor cost in } \$/\text{MW(th)} = \frac{41\,000}{\left(\dfrac{\text{MW(th)}}{1000}\right)^{0.643}} \qquad \text{MW(th)} \leq 1500$$

$$= \frac{37\,000}{\left(\dfrac{\text{MW(th)}}{1000}\right)^{0.37}} \qquad 1500 < \text{MW(th)} < 10\,000$$

$$= 15\,750 \qquad \text{MW(th)} \geq 10\,000$$

$$\left.\begin{array}{l}\text{Turbine-generator}\\\text{cost in }\$/\text{MW(e)}\end{array}\right\} = \frac{32\,000}{\left(\dfrac{\text{MW(e)}}{1000}\right)^{0.278}} + \frac{2668}{\left(\dfrac{\text{MW(e)}}{1000}\right)^{0.438}} \qquad T_S < 210$$

$$= \frac{23\,000 + 40\,T_S}{\left(\dfrac{\text{MW(e)}}{1000}\right)^{0.278}} + \frac{1982 + 3.36\,T_S}{\left(\dfrac{\text{MW(e)}}{1000}\right)^{0.438}} \qquad T_S \geq 210$$

The first equation is empirical and relates the thermal efficiency to the
temperature drop across the turbine. The next set of three equations re-
lates 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 re-
presented 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

Flash chamber size	Data from Richardsons Westgarth and Co. Report [1]
Heat transfer	
inside the tubes	Dittus-Boelter equation
condensation	Chen equation
fouling factor	0.0002 or a temperature function
Pumping friction	Koo equation
Heat losses	Negligible
Non-condensable gases in flash chambers	None
Boiling-point elevation	[2]
Enthalpy and brine transport	[3]
Cost equations	ORGDP estimates [4]

    Inputs to the code are deliberately separated into the categories of cus-
tomer'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

Chemical cost = $K_1(LF) (W_p + W_b)$

Deaerator cost = $K_2(W_p + W_b) + K_3$ (Deaerator power)

Pumping cost = K_4 (LF) . ΣWH

Pumps and motor cost = $K_5 \Sigma W + K_6 \Sigma$ (Pump power)

Electrical equipment = K_7 (Pump power)

Valves and piping = $K_8 W_f^{0.5}$

Water intake = $K_9 W_0$

Site work = $K_{10} W_0^{0.6}$

Area cost = $K_{11} A^{0.97}$

Shell cost = $K_{12} V$

Concrete, buildings, etc. = $K_{13} + K_{14} W_p$

Operating = $K_{15} W_p^{0.267}$

Maintenance and supplies = K_{16} (Capital cost)

Heat cost = K_{17} (LF)Q

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 para-meters 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

Reactor power (MW(th))	25 148.760
Gross electrical generation (MW(e))	4 715.914
Reactor auxiliaries (MW(e))	365.914
Water plant use (MW(e))	310.674
Net saleable (MW(e))	4 000.000
Price (mills/kWh)	2.119
Annual revenue (M$)	66.834

Temperatures (°F)

Turbine exhaust	265.000
Maximum brine	248.812
Brine blow-down	105.836
Ocean	65.000

Water plant

Capacity (Mgd)	1000.000
Performance ratio (lb/1000 Btu)	4.991
Water price (¢/1000 gal)	23.860
Annual revenue (M$)	78.381

Investments (M$)

Initial fuel charge	346.047
Reactor and steam plant	399.080
Turbine-generator	111.662
Interest on construction	46.671
Non-depreciable items	12.812
Water plant	201.904
Total	1118.176

Annual costs (M$)

Reactor investment	39.660
Water plant investment	14.133
Subtotal	53.793
Tubing replacement	2.982
Reactor operation and maintenance	2.796
Fuel	79.223
Water plant and maintenance	1.165
Water plant chemicals	5.261
Subtotal	91.427
Total	145.219

PRESSURIZED WATER REACTOR   10/12/64
ELECTRICAL PRODUCTION   600 MW
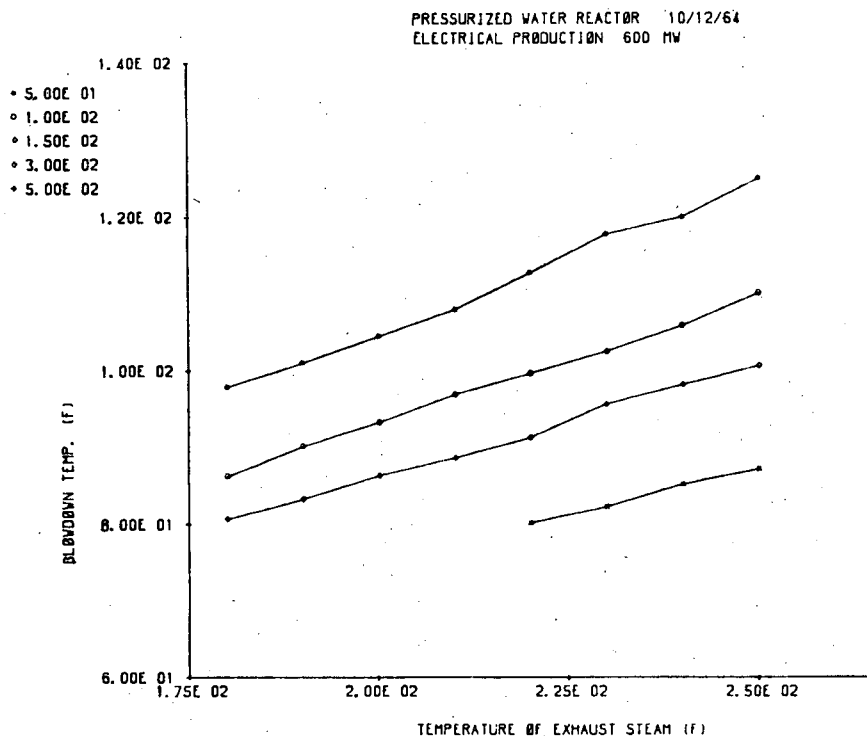
FIG. 4.   Typical graphical computer output

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

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WATER DESALINATION: PROPOSALS FOR A COSTING PROCEDURE AND RELATED TECHNICAL AND ECONOMIC CONSIDERATIONS*

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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*

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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.

SOME CONSIDERATIONS ON UTILIZING
A CANADIAN HEAVY-WATER REACTOR IN A
DUAL-PURPOSE POWER-DESALINATION PLANT

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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.
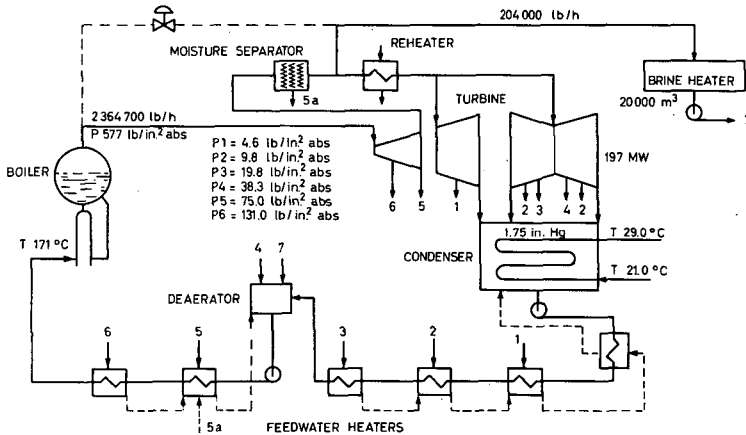
FIG. 1.   Simplified flow diagram of low water/power ratio plant

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 m³/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 cross-over 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 m³ 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 $37\frac{1}{2}\%$ increase in net power for an increase of only $12\frac{1}{2}\%$ 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_2O, 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-

tween $1.5 and 2.1 million (US) depending upon the fixed charge rate as-
sumed. 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 ap-
pears, 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. How-
ever, 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 de-
salination 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).

6 563 000 lb/h, 415 lb/in^2 abs, 1202.5 Btu/lb

REACTOR BOILER
1820 MW(t)

TURBINE   268 MW

240 000 lb/h, 68 lb/in^2 abs
1086 Btu/lb

6 323 000 lb/h
38.5 lb/in^2 abs
1060 Btu/lb

BRINE HEATER   126.2 x 10^9 Btu/d

DEAERATOR

6 563 000 lb/h   6 323 000 lb/h   260°F
290°F   228 Btu/lb
259.3 Btu/lb

HEAT TO DESALINATION PLANT 126.2 x 10^9 Btu/d
WATER PRODUCTION AT PR 9.5 (105 Btu/lb) = 144.3 Mgd
                  AT PR 8.22 (121.2 Btu/lb) = 125 Mgd

TURBINE OUTPUT   268   MW
STATION SERVICE   21   MW
                                247   MW
POWER TO DESALINATION PLANT   47   MW

                  NET POWER   200   MW

FIG. 2.   Simplified flow diagram of high water/power ratio plant

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

Item	US $1000
Site improvements	278
Buildings	5 400
Reactor boiler and auxiliaries	22 130
Heavy water at new Canadian price C$14.65/lb (US$13.55/lb)	11 000
Turbine generator and auxiliaries	6 750
Electrical system	3 400
Instrumentation and control	3 600
Common services	4 060
Indirects; construction plant, engineering services, training, commissioning, etc.	13 420
Interest during construction	8 325
Total capital cost excluding fuel	78 363
25% surcharge on all but D_2O	16 840
Total	95 203

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

$$\frac{1887}{9800} \quad (135) \; (69.40) \; 1000 = US \, \$1 \, 804 \, 000$$

Annual fuel cost at 85% c.f.

$$\frac{1887}{9800} \quad (365) \; (0.85) \; (69400) = US \, \$4 \, 146 \, 000$$

Total annual fuel cost

		Charge rate	
Item	10%	7%	5%
Annual fuel cost	4.146	4.146	4.146
Fuel write-off 1/2 charge	0.304	0.213	0.152
5% interest on inventory	0.090	0.090	0.090
Total	4.540	4.449	4.388

Note: The Hydro Electric Power Commission of Ontario predict fuelling prices to aver-
       age 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 in-
creased 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 tempera-
ture 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

$$C = a \, (PR)^{0.7} \quad \text{or} \quad C = \frac{b}{(Btu/lb)^{0.7}}$$

For the base plant C = 70 ¢/gal d C = 70 = a (9.5)$^{0.7}$ hence a = 14.44

and at 121.2 Btu/lb or PR 8.22

$$C = 14.44 \, (8.22)^{0.7} = 63.3 \; ¢/gal \; d$$

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 (5.9)$^{0.7}$ = 49 ¢/gal d 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 (7)$^{0.7}$ = 56.4 ¢/gal d 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 ¢/m^3, the operating costs about 4.4 ¢/m^3, and the fuel cost zero for a total water cost of about 6.6 ¢/m^3. At 10% fixed charge rate this water would cost about 7.8 ¢/m^3.

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 d 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 IV

WATER COST ESTIMATE

200 MW(e) net 125 Mgd (PR 8.2)

	Investment	Total (US $ million)		
(a)	Nuclear power plant	95.00		
	Water plant 125 gal/d at 63.3 ¢/gal d	79.13		
	Total	174.13		
	Annual cost	10%	7%	5%
	Power plant	9.50	6.65	4.75
	Fuel (Total)	4.54	4.45	4.39
	O and M (incl. $0.1 D_2O loss)	1.40	1.40	1.40
	Insurance	0.50	0.50	0.50
	Total conventional cost	15.94	13.00	11.04
	Less elect. credit (0.53 ¢/kWh)	9.70	9.70	9.70
	Evaporator steam cost	6.24	3.30	1.34
(b)	Evaporator			
	Fixed charges	7.91	5.54	3.96
	O and M	1.30	1.30	1.30
	Chemicals	1.10	1.10	1.10
	Interim replacement	1.60	1.60	1.60
	Pumping cost	1.90	1.90	1.90
	Steam cost	6.24	3.30	1.34
	Total annual water cost	20.05	14.74	11.20
	Total annual cost	27.85	22.54	19.00
(c)	Water cost ¢/kgal	51.7	38.0	28.9
	¢/m³	13.7	10.0	7.6
(d)	Total annual cost: US-Israel report	29.4	24.4	21.1
	Total annual cost: HWR system	27.9	22.5	19.0
	Annual saving	1.5	1.9	2.1

TABLE V

WATER COST ESTIMATE

200 MW(e) net 144.3 Mgd (PR 9.5)

	Investment	Total (US $ million)		
(a)	Nuclear power plant	95		
	Water plant 144.3 Mgd at 70 ¢/gal d	<u>101</u>		
	Total	196		
	Annual cost (in US $ million)	10%	7%	5%
	Power plant	9.50	6.65	4.75
	Fuel (Total)	4.54	4.45	4.39
	O and M (incl. $0.1 D_2O loss)	1.40	1.40	1.40
	Insurance	<u>0.50</u>	<u>0.50</u>	<u>0.50</u>
	Total conventional cost	15.94	13.00	11.04
	Less elect. credit (0.53 ¢/kWh)	9.70	9.70	9.70
	Evaporator steam cost	6.24	3.30	1.34
(b)	Evaporator			
	Fixed charges	10.10	7.07	5.05
	O and M	1.30	1.30	1.30
	Chemicals	1.20	1.20	1.20
	Interim replacement	2.00	2.00	2.00
	Pumping cost	2.20	2.20	2.20
	Steam cost	<u>6.24</u>	<u>3.30</u>	<u>1.34</u>
	Total annual water cost	23.04	17.07	13.09
	Total annual cost	30.54	24.57	20.59
(c)	Water cost ¢/kgal	51.5	38.1	29.2
	¢/m³	13.6	10.1	7.7

TABLE VI

COST OF WATER BASED ON PROJECTED FUEL COSTS

Cost estimate (144.3 Mgd)	10%	7%	5%
Annual water cost	23.04	17.07	13.09
Possible fuel reduction	1.58	1.55	1.53
Possible water cost	21.46	15.52	11.56
¢/kgal	47.9	34.6	25.8
¢/m³	12.6	9.2	6.8
Cost estimate (125 Mgd)			
Annual water cost	20.05	14.74	11.20
Possible fuel reduction	1.58	1.55	1.53
Possible water cost	18.47	13.19	9.67
¢/kgal	47.6	34.0	24.9
¢/m³	12.5	9.0	6.6

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 D_2O which will surely have a substantial salvage value, the actual value depending upon the price of D_2O 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 burnup, 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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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 electro- dialysis plant. On the basis of the costs taken, and assuming that adequate reliability can be obtained from both processes, it is confirmed that electro- dialysis 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 concen- tration falls. If additional water is needed, it is best produced by base-load distillation.

FEASIBILITY OF NUCLEAR REACTORS FOR SEA WATER DISTILLATION IN ISRAEL[*]

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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).

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[*] Israel Atomic Energy Commission report IA-979.

FEASIBILITY OF NUCLEAR REACTORS FOR SEA WATER DISTILLATION*

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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.

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 industri-alization 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 ex-tensive 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 responsi-bility 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 de-mand 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 ca-pacity of the system and the expected maximum demand in MW during the corresponding winter. The second half of the table shows the annual pro-duction 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

Period	Total system net capacity (MW)	Maximum demand (MW)	Year	Annual production capacity of the system (GWh)	Annual demand (GWh)
1961/62	530	507	1961	2 870	2 337,9
1962/63	685	552	1962	2 890	2 592,7
1963/64	685	667	1963	3 720	2 947,8
1964/65	776	765	1964	3 760	3 530,0
1965/66	1154	955	1965	4 420	4 323.0
1966/67	1373	1160	1966	6 780	5 904,0
1967/68	1533	1275	1967	7 150	6 617,0
1968/69	1628	1400	1968	8 080	7 190,0
1969/70	1743	1540	1969	8 980	7 860,0
1970/71	1943	1690	1970	9 730	8 574,0
1971/72	2103	1850	1971	10 530	9 349,0
1972/73	2298	2020	1972	12 350	10 190,0
1973/74	2547	2200	1973	13 480	11 000,0
1974/75	2727	2400	1974	14 380	12 000,0

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

TABLE II

DEVELOPMENT OF THE INSTALLED CAPACITY
AND OF THE ANNUAL PRODUCTION CAPACITY
OF THE INTERCONNECTED SYSTEM OF GREECE

Year	Power stations	Installed capacity (MW)			Annual production capacity (GWh)		
		Thermal	Hydro	Total	Thermal	Hydro	Total
1963	Existing power stations	469	265	734	3 100	700	3 800
1964	4 gas turbine units	56	-	790	60	-	3 860
1965	LIPTOL - unit	33	-		230	-	
	Kremasta I and II	-	200		-	770	
	St. George Power Station	60	-		400	-	
	Ptolemais III	125	-	1208	900	-	6 160
1966	Kremasta III and IV	-	200	1408	-	770	6 930
1967	Kastraki I and II	-	160	1568	-	800	7 730
1968	New thermal unit	150	-	1718	1 100	-	8 830
1969	Megalopolis I	125	-	1843	900	-	9 730
1970	Megalopolis II	125	-		900	-	
	Ptolemais IV	150	-	2118	1 060	-	11 690
1971	Topoliana	-	160	2278	-	860	12 550
1972	Lignite fired thermal unit	125	-		900	-	
	Kastraki III	-	80	2483	-	50	13 500
1973	New thermal unit	150	-		1 100		
	Kremasta V	-	100	2733		30	14 630
1974	Aliakmon I	-	180	2913		820	15 450
	T o t a l	1568	1345	2913	10 650	4800	15 450

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)

1932	11.8	1964	91	1971	159	1978	211
1935	17.2	1965	99	1972	167	1979	218
1940	20.9	1966	108	1973	175	1980	225
1945	15.8	1967	117	1974	183	1981	232
1950	25.6	1968	128	1975	190	1982	239
1955	36.9	1969	139	1976	197	1983	246
1960	63.1	1970	150	1977	204	1984	254

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 associ-
ated 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 de-
salination 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 guaran-
tee 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 dis-
solved 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 succesful,
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 Com-
mittee of Water Desalination sponsored by the UAR Atomic Energy Establish-
ment, 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 sub-
mitted. 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

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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.
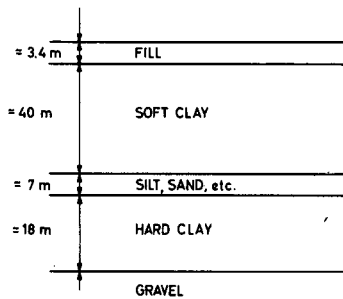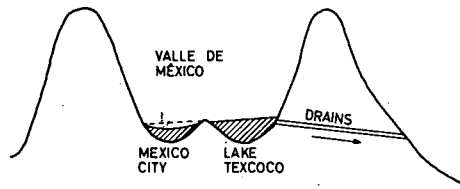
FIG. 1.   Strata of Mexico City subsoil

FIG. 2.   Elevation of Valle de Mexico showing Mexico City and Lake Texcoco basins

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.

PRELIMINARY STUDY ON COMBINATION SEA WATER DESALTING AND ELECTRIC POWER PLANT FOR ISRAEL

JOINT UNITED STATES – ISRAEL POWER AND DESALTING TEAM[*]

ABSTRACT

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.

* Members, Israel: A. Wiener, Water Planning for Israel, Tel-Aviv; C. Cats, Israel Electric Corporation; R. Thieberger, Israel Atomic Energy Commission, Tel-Aviv; United States of America: M. A. Chase, Department of the Interior, Washington, D. C.; S. F. Mulford, Office of Saline Water, San Diego, Calif.; I. Spiewak, Oak Ridge National Laboratory, Oak Ridge, Tenn. Copies available from US Department of the Interior.

SPECIFIC SITUATION IN THE FORTALEZA AREA IN BRAZIL

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ABSTRACT

Brazil, with a population of 80 million and a territory of approximately 8.5 million km² 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 km² 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 km². 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 m³/d. The minimum requirement in 1980 is estimated at 375 000 m³/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 m³/d. Thus the deficit for 1980 is still of approximately 300 000 m³/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.

PROGRAMME FOR ADVANCED DESALTING TECHNOLOGY – REPORT TO THE PRESIDENT*

DEPARTMENT OF THE INTERIOR, UNITED STATES OF AMERICA

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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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 ex-
traction 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 tem-
peratures. 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 flexi-
bility 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 in-
fluence of the assumed kWh value on the optimum design of the plant.

PERFORMANCE RATIO

A sub-committee of the Panel investigated the difference between op-
timum 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

INTERAGENCY TASK GROUP, An assessment of large nuclear powered sea-water distillation plants (1500-25 000 MW(th)), Office of Science and Technology, Govt. Printing Office, Washington, D.C. (Mar. 1964); Appendices (Aug. 1964).

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.

BURNS AND ROE Inc., REYNOLDS, SMITH AND HILLS, Florida Keys - water plan, Office of Saline Water, Dept.of the Interior, Washington, D.C. (Feb. 1964).

BURNS AND ROE Inc., Feasibility study of a dual-purpose nuclear reactor power plant for the Florida Keys, USAEC rep. (Mar. 1964).

(b) Reports submitted for information and questions

OFFICE OF SALINE WATER, 1963 saline water conversion report, Dept of the Interior, Washington, D.C. (1964).

BECHTEL CORPORATION, A study of large size saline water conversion plants, Office of Saline Water, Dept of Commerce, Washington, D.C. (Mar. 1964).

OFFICE OF SALINE WATER, Preliminary appraisal report on a sea-water desalting plant to supply fresh water for Tijuana, Baja California, Mexico, Dept of the Interior, Washington, D.C. (Dec. 1963).

INTERNATIONAL ATOMIC ENERGY AGENCY, Desalination of water using conventional and nuclear energy, Technical Reports Series No.24, IAEA, Vienna (Mar. 1964).

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

INTERNATIONAL ATOMIC ENERGY AGENCY, Report of the Panel on Use of Nuclear Energy in Saline Water Conversion, 23-26 Sep. 1963, IAEA, Vienna (Jan. 1964).

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

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

Vienna, September 1963

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 justi-fication 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 ap-propriate 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 mar-gin 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 m³/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 m³/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 m³/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.

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[2] 1 ppm (one part per million) is equal to 1 milligram per litre.

[3] Performance ratio = $\dfrac{\text{weight of distilled water produced}}{\text{weight of steam used}}$

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 m^3/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 m^3/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 m^3/d (3-6 Mgd) and 50 to 70 MW(e).

The Tunisian Atomic Energy Commisssion 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 $\cancel{c}/m^3$ or 10 cents/1000 US gallons. Only when this cost is of the order of 0.75 $\cancel{c}/m^3$ 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/m^3 or 1 kWh per 1000 gallons of water supplied to the consumer.

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