IAEA-TECDOC-574

USE OF NUCLEAR REACTORS FOR SEAWATER DESALINATION

FOREWORD

The purpose of this report is to provide a state-of-the-art review of desalination technologies and how they can be coupled to nuclear reactors. Between 1964 and 1967, the Agency published the Technical Report Series Nos. 24, 51, 69 and 80, as part of its programme on nuclear desalination. The last activity of the Agency in this field was organizing a Technical Committee Meeting on Heat Utilization from Nuclear Reactors for Desalting of Seawater, which was held in Vienna from 29 June to 1 July 1977. The interest in nuclear desalination, as indicated from the meeting papers and discussion, was less strong than in other applications, such as district heating and industrial use of process steam. The reasons were uncertainty in costs, mismatch between the size of nuclear power plants being constructed and desalination plants, and the safety issues related to location of nuclear power plants close to large consumers of desalted water. However it was recommended that developments in nuclear desalination should be followed closely, and a meeting arranged when enough interest existed.

During the 33rd regular session of the IAEA General Conference in 1989, renewed interest in nuclear seawater desalination was indicated by some Member States. The General Conference, in accordance with its resolution GC (XXXIII)/515, requested that the Director General assess the technical and economic potential of nuclear reactors for seawater desalination in the light of experience gained during the past decade, and report to the conference at its thirty-fourth regular session in 1990. In order to address this subject thoroughly, it was decided, at the technical level, to prepare a state-of-the-art report based on experience gained and studies conducted in the past decade.

A Consultants Meeting was convened from 6 to 8 December 1989 in Vienna, with experts from countries involved in desalination efforts, such as the Federal Republic of Germany, Japan, Israel, USA and USSR. The purpose was to define the scope of this report, and to recommend future action.

This group of experts prepared the draft of this report, which was then thoroughly discussed and reviewed at an Advisory Group Meeting

convened by the Agency from 16 to 18 May 1990 in Vienna. A total of 15 experts from 9 different countries (Argentina, Canada, Egypt, Federal Republic of Germany, Israel, Japan, the Libyan Arab Jamahiriya, USA and USSR) participated in this meeting, and presented their comments and suggestions, which were then incorporated into the report by consultants. A final editorial meeting was convened from 23 July to 1 August 1990 in Vienna, and the report completed.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. Objectives of the Report

The last International Atomic Energy Agency (IAEA) status report on desalination, including nuclear desalination, was issued nearly 2 decades ago. The impending water crisis in many parts of the world, and especially in the Middle East, makes it appropriate to provide an updated report as a basis for consideration of future activities.

This report provides a state-of-the-art review of desalination and pertinent nuclear reactor technology. Information is included on fresh water needs and costs, environmental risks associated with alternatives for water production, and data regarding the technical and economic characteristics of immediately available desalination systems, as well as compatible nuclear technology.

1.2. Need for Nuclear Desalination

1.2.1. Need for Water

Large quantities of water are required in many parts of the world for agricultural, industrial and residential uses. The world is becoming more and more aware of its shortage of fresh water. A United Nations Fund for Population Activities (UNFPA) report, published in May 1990, predicts a dramatic increase in world population. For example, the population in Africa is expected to increase from about the 650 million people at present to over 1580 million by the year 2050. Another report, published in December 1987 by the Center for Strategic and International Studies (CSIS) and titled "US Foreign Policy on Water Resources in the Middle East", also supports this data. The CSIS report notes recent population growth rates in excess of 3% in several countries in the Middle East. It further predicts that the population growth rate will remain at the current level in the near term.

It is understood, from experience, that a growth rate above 1% creates a difficult situation for an existing infrastructure, and especially for

the fresh water situation. The population growth rate of more than 3% in the water-short Middle East is a clear indication of a coming water catastrophy. This point cannot be overemphasised. The problem is compounded by increasing pollution, and increasing salinity of the rapidly disappearing natural fresh water resources. It also has to be emphasized that existing natural water resources must be conserved for future generations and for the prevention of desertification.

Conservative predictions for the year 2000 indicate a shortage of water in the Mediterranean Area alone of some 10 million m^3/day. Other locations where water is becoming scarce include most of the Arab countries, regions in India, Pakistan, China, South and Middle America, and on some South Pacific Islands. The shortage of water in these areas is expected to be not less than 10 million m^3/day.

The extent of the shortage noted above implies that water may become a question of life or death in those areas, not just one of convenience. Other locations will experience a decline in the quality of life, due to the fact that the specific daily water consumption will have to be reduced considerably, as a result of the exhaustion and/or pollution of natural fresh water resources. Some examples are: Europe (Greece, France, Spain, Italy, UK), United States of America (California, Florida), Mexico, Chile, Brazil, Australia, Africa and Asia (USSR, Bali, Tahiti).

1.2.2. Reasons for Seawater Desalination

Seawater is the largest water source available. Compared with existing fresh water natural resources, its availability is essentially unlimited in the foreseeable future. Seawater is still relatively unpolluted compared with natural fresh water sources and in many parts of the world fresh water is not easily available, whereas brackish water and seawater are readily available.

1.2.3. Reasons for Nuclear Energy

Worldwide concern with the negative aspects of the "Greenhouse Effect" is intensifying, and has led to an understanding that CO_2 emissions must

be limited to at least their present level if not curtailed. This concern makes it necessary to target the most significant CO_2 sources, with a view to affecting reductions. In addition to energy conservation measures especially with the expected growth in population, it is expected that changes in the key energy and transportation sectors will be required. A related concern is acid rain and it's negative effect on forests (an important CO_2-sink). Taking these factors into account, any new production of energy should be based on non-CO_2 and SO_2 emitting sources. Equally important is conserving our limited oil resources for future generations. Oil is too valuable a material to simply be burned, rather, it should be conserved as an essential raw material for the petrochemical industry, and lubrication.

The foregoing leaves us in the near term, with only one industrially proven, large scale, non-fossil energy resource: nuclear energy. Further, in addition to the environmental aspects discussed above, nuclear energy may also have a positive impact on water cost, as it has had on electricity cost in many countries. For those countries with a need for water, but with few or no fossil energy resources, nuclear fuel is the cheapest form of imported energy.

1.3. Cost as a Barrier to be Overcome

The specific cost of the water produced $(cost/m^3)$, as well as capital investment cost, are the main barriers to the implementation of any large scale desalination programme to counteract the impending water crisis.

Drinking water needs to be considered as a fundamental need, and be subsidised such that water cost is no longer a huge fraction of income as it is for many people. Such considerations indicate a target production cost for potable water of $< US\$ \ 1/m^3$.

The real cost of not providing sufficient water, or providing water at unacceptable cost, is very difficult to predict. It can be said that the major effect will be a decline in economic growth, but the unavailability of water at an acceptable cost is predicted by some to lead to uncontrollable action by the population and interstate conflict. It is not unreasonable to assume that the cost of "Not Doing It" is far higher than "Doing It" even with large subsidies.

1.4. Environmental Incentives

The environmental incentives for nuclear desalination are quite convincing. Assuming an increase in the daily water production of 10 million m^3 up to the year 2000, using nuclear instead of fossil powered energy production and using advanced desalination technologies, emission of about:

$$20\ 000\ 000\ \text{t/year}\ CO_2$$
$$200\ 000\ \text{t/year}\ SO_2$$
$$60\ 000\ \text{t/year}\ NO_x$$
$$16\ 000\ \text{t/year}\ HC$$

can be avoided in the Mediterranean area alone. The potential worldwide reduction in emissions would be more than double these figures.

1.5. Outline of the Report

This report includes two major sections addressing the technical and economic aspects of nuclear desalination. Section 3 provides a detailed discussion of desalination technologies and identifies those with significant near-term potential. Section 4 addresses the practical and theoretical experience of coupling nuclear plants with desalination processes.

Section 5 identifies data on the water situation from various sources and summarizes the various data into global shortage figures for the next decade. The shortages are compared with the potential availability from the various sources. Using the summarized data, the positive and negative aspects of nuclear and fossil desalination are presented. Section 6 summarizes the institutional issues.

Section 2 is an executive summary of Sections 3 through 6. In particular, Subsections 2.3 and 2.4 provide important conclusions regarding our understanding of the incentives and problems related to Nuclear Desalination and recommendations for future action.

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2. SUMMARY AND CONCLUSIONS

This section highlights the principal conclusions of the IAEA review of desalination using nuclear energy. Desalination technologies are summarised in Section 2.1, nuclear technology in 2.2, while major considerations affecting the potential for nuclear desalination are summarized in Section 2.3, and finally, the conclusions and recommendations arising from the study are given in Section 2.4.

2.1. Desalination Technologies

Many desalination technologies have been suggested based on different principles of separation. Some of them have been successfully developed, and these are discussed in detail in Section 3 of this report. For near term application, the most useful are summarised below.

2.1.1. Distillation Processes

Multi Stage Flash (MSF) Distillation. This process is the most widespread (capacity-wise) at present. The technology is well proven and mature, but seems to be approaching the limit of its technical potential.

Multi Effect Distillation (MED). Experience with several generations of this old process have led to two advanced types of evaporators – one with vertical tubes as heat transfer elements, the other with horizontal tubes. The latter has shown good results, especially at temperatures below 75°C, where low cost materials are used. Such evaporators have proven to be easy to operate and maintain. They also demonstrate relatively good economy, both when external steam is used as a heat source or when mechanically driven Vapour Compression (VC) is applied. Both these methods seem to have the best potential for low cost water of all the distillation processes, and may prove to be the best among all desalination processes.

An additional improvement in the economy of distillation processes may come from combining two of the above processes into a hybrid system (e.g. MSF preheater for MED or VC).

2.1.2. Membrane Processes

Reverse Osmosis (RO): This process has more recently shown the most remarkable improvement among existing desalination processes, owing to

advancement in membrane technology. With a proper post-treatment, drinking water of adequate quality to meet World Health Organization (WHO) standards can now be obtained with a single-stage. Both investment and operating costs of this process are estimated to have a potential of being lower than MSF and MED. The RO process is considered as one of the most promising for the next generation of desalination plants.

Other Processes: Electrodialysis (ED) has been successfully applied to seawater desalination, but implementation in actual applications has so far been limited to small capacities. Meanwhile improvements to RO have overtaken those of ED, and so it is questionable whether this process can survive in the near future. Another membrane process, membrane distillation, also attracts attention. Although this process has many advantages, the energy consumption can not be reduced drastically, and hence this process is expected to be only applied where cheap waste heat exists. Vacuum freezing Vapour Compression (VFVC) is a very promising process as well, and its' potential to reduce capital and operating costs justifies further R & D.

Combination with Distillation Processes: Combining distillation processes with membrane processes into hybrid systems has certain merits where the specific advantages and disadvantages of each of the processes enable mutual compensation.

2.2. Nuclear Technologies

Current experience with nuclear desalination is limited, however, continuing interest is reflected in several recent studies.

2.2.1. Current Experience

The only reactor currently being used for seawater desalination is a Liquid Metal Cooled Reactor (LMCR), the BN-350, which was put into operation in July 1973 at the town of Shevchenko (USSR). This dual purpose plant can produce 125 MW of electric power and 100000 m^3/d of potable water.

The thermal output of the reactor to the desalination process is 75 MW. The BN-350 reactor is also being used for experiments in nuclear physics, physical metallurgy and sodium engineering.

The development and improvement of different desalination processes
such as the 5-effect Long Tube Vertical (LTV), 10-effect LTV and 34 stage
MSF are being pursued at the Mangyshlak peninsula complex in the town of
Shevchenko (USSR). The total operating capacity of this complex is
140 000 m^3/d.

In general, the BN-350 reactor has operated satisfactorily with the
only large defect being in the steam generators of the third reactor loop.
This was due to defects during the manufacturing and welding of the lower
ends of the heat transfer tubes. In addition, two small leaks in the
sampling and oxide indication sub-systems were detected and repaired.

The prolonged operating experience of the BN-350, which couples the
Liquid Metal Cooled Reactor with Multi-Effect Vertical Tube Evaporators has
proven the reliability of nuclear desalination. On the basis of this
experience, the development of different desalination processes is planned
in the USSR, such as Low-Temperature Horizontal Tube Multi-Effect
Distillation (LT-HTMED) and Horizontal-Tube Thin-Film Evaporators (HT-TFE)
to be coupled with thermal reactors providing distillate production to
several hundred of thousand m^3/d.

2.2.2. Recent Studies and Related Experience

The use of nuclear energy for seawater desalination has been both
directly and indirectly addressed in a series of recent studies. These
studies have included the three main reactor types: Water Cooled Reactors,
Gas Cooled Reactors and Liquid Metal Reactors.

In the case of Water-Cooled Reactors (WCRs), no explicit recent study
of nuclear desalination was identified. However, considerable recent work
has been done on the generalized application of such reactors for process
steam and heated water, and considerable experience in such applications
has been accumulated in Canada, The Czech and Slovak Federal Republic, The
German Democratic Republic, Poland and the Soviet Union.

In these latter cases, where operational experience has been obtained,
the primary product of the nuclear station has usually been electricity
production and the reactor systems are correspondingly large. Energy for
process steam and/or heating is taken mostly as a byproduct, using steam
extraction or, alternatively, utilizing the otherwise wasted heat that is

rejected through the condenser. In areas of significant electricity demand, such approaches could also be employed for desalination. Specific additional issues that must be addressed are the location of such large reactors in close proximity to water production facilities, and possibly large population centers, and the additional safety measures that are required when coupling WCRs (particularly those of the boiling water reactor type) to the desalination process.

Of further interest, when considering desalination applications, is the recent work toward developing relatively small, specialized WCR types for process steam and district heating. Examples of such reactors ranging in capacities from 10-500 MW(th) are being developed in Canada, France, Germany and the Soviet Union. Additional WCR designs primarily intended for shipboard applications could also be considered for desalination purposes.

Examples of small WCRs in current operation include a prototype of the SLOWPOKE reactor in Canada and a number of small reactors at Bilibino in the USSR. Energy outputs from existing and proposed small reactor types range from heated water at 80°C to steam at pressures normally associated with electricity generation (7-8 MPa). Obviously the specific means of coupling the various small reactor types with a variety of desalination technologies is a key factor to be addressed. With respect to this latter point, a degree of experience was obtained through an experimental programme at Ashdod, Israel in 1983. In those tests, a large LT-HTMED prototype was coupled with an existing fossil facility in a manner that closely simulated coupling with a nuclear heat source. The heat supply system, unit size, and mode of operation were designed as close as possible to nuclear steam supply. Positive results were attained from the one year operation period.

Before specific conclusions regarding desalination with WCRs can be made, one or more specific studies would be required. The following should be addressed for each case:

o Identification of appropriate siting and economic groundrules as a
   basis for the evaluation
o Selection of an appropriate combination of reactor type and
   desalination process
o Development of the coupling interface. If this is in the form of
   thermal energy, particular attention should be paid to special safety

requirements related to the potential for water supply contamination
with radionuclides

o Technical and economic evaluations of the resulting concept.

It would be particularly useful to accomplish the above for a typical
dual purpose cogeneration application as well as a typical single purpose
application in which the reactor energy is exclusively used for the
desalination process.

In a recent study sponsored by the Metropolitan Water District of
Southern California (MWD), in cooperation with the U.S. Department of
Energy (DOE), the Modular High Temperature Gas Cooled Reactor (MHTGR) was
evaluated for seawater desalination. The study was based on a modified
version of the reference 4 x 350 MWt Modular/HTGR, operating in a series
cogeneration mode with a Low Temperature Horizontal Tube, Multi-Effect
Distillation (LT-HTMED) process. The combined facility would provide
approximately 466 MW of electrical generation capacity and 401 000 m^3/day
of desalted water at 40 ppm Total Dissolved Solids (TDS) content.
Additional product water at a higher, but acceptable, TDS content could be
produced by blending with locally available brackish water.

The particular combination of the MHTGR with the LT-HTMED process was
found to result in significantly reduced product costs, when compared with
prior evaluations. An additional key parameter was found to be the
assigned value of the electricity which, in the MWD/DOE study, tended to
minimize the cost of heat energy to the desalination process. While the
resulting costs (US\$ 0.34/m^3 - US\$ 0.49/m^3) were not quite competitive
with existing sources of water in the California region, they gave
encouragement that competitive costs could be achieved in the foreseeable
future.

Further, while care must be taken in extrapolating the results from
one region to another, the costs predicted in this MWD/DOE study are
already extremely competitive with current alternatives in the Middle
East. Further they are dramatically lower than prices projected until now
for conventional desalination processes.

Another study of the use of Gas-Cooled Reactors for Nuclear
Desalination was carried out in the Federal Republic of Germany (FRG).
This study considered integral barge mounted power and desalination plants

in two sizes, corresponding to the use of two and four reactors respectively, to produce 100 000 m^3/day or 200 000 m^3/day of desalted water at 450 ppm TDS. The reactors considered were the HTR-Module type with a thermal rating of 200 MW(th) each. The desalination plant is of the Reverse Osmosis (RO) type with numerous parallel trains arranged in two stages. Energy input to the RO process is both in the form of electricity and heat. For each two reactors, 164 MW(e) is generated, with 30 MWe required for the RO process and 12 MW(e) for internal uses. The remaining 122 MWe is available for sale. Thermal energy input is provided by preheating seawater feed in the condenser, thus using waste heat from the turbine generator exhaust.

The barge mounting concept is expected to have a number of advantages relative to the fixed land based type. First, construction at a central shipyard type facility is expected to reduce cost and improve quality. Secondly, the plant may be towed to any location with sea or river access where it would be fixed upon a foundation prior to operation. If required, the plant could be relocated after appropriate preparation for transport, and refloating of the barge.

While on first consideration, the costs of water from the FRG study are somewhat higher than predicted from the US study, taking account of the technical progress in RO technology since 1985 and currently lower nuclear fuel costs would tend to bring the results closer together.

The only recent example in which a Liquid Metal Cooled Reactor (LMCR) is being considered for future nuclear desalination is found in Japan. The Central Research Institute of the Electric Power Industry (CRIEPI) of Japan initiated a conceptual design effort in 1989 to consider a group of small (125 MW(th) each) LMR modules to provide input power to a desalination process. The purpose of the study is the prevention of desertification of the world. This focus on agriculture is unique among recent desalination study efforts.

The LMR modules are described as being simple in concept and having largely passive safety characteristics. Hence, the name "4S" (Super-Safe, Small and Simple). The core consists of U-Pu-10%Zr based metal fuel pins, and its life is forecasted to be 10 years without refueling.

For the desalination process, Reverse Osmosis was selected because of low energy consumption, simplicity in operation, and low maintenance.

Energy output from the reactor modules is in the form of steam, and both mechanical and electrical coupling of the steam turbines to the RO pumps is being considered. The total range of water production to be addressed is up to 3 million m^3/day.

The CRIEPI study of the 4S LMR is at an early stage relative to the HTR studies in the USA and FRG, and results are not yet available regarding possible water costs.

2.3. Major Considerations

The following important issues are of special significance for nuclear desalination.

2.3.1. Size Compatibility

The relative scale of nuclear power and desalination facilities must be taken into account when considering a combination of these two technologies. As an indication of the current differences in scale, consider the energy requirements of a modern Reverse Osmosis process which, including an allowance for product pumping and unrelated auxiliaries of 2.5 kW(e).h/m^3, might typically be on the order of 9 kW(e).h/m^3. For an average size desalination plant of 25 000 m^3/day, this would imply an electrical capacity of some 9.4 MW(e). Clearly this is small compared to present electricity generation plants where 1000 MW(e) is typical. Even with the few very large desalination plants that have been deployed or are being discussed, the mismatch in scale is significant.

The relative scale of the nuclear energy source and the desalination plant may be more or less important depending upon the following factors:

- If there is a large market for electricity in the region with an integrated electrical grid, the mismatch in size may be relatively unimportant. This is because the energy input to desalination plant (either electricity or waste thermal energy) can be provided as a co-product or by-product of electricity production for the grid.

- In the case of single purpose nuclear plants directly coupled to the desalination process, the need for very small nuclear plants would be indicated. This is typical of some middle-eastern areas without well developed electrical grids.

2.3.2. Costs of Desalination

Costs of technical options for various desalination plants depend on the required output, the selection of the desalination process and the energy source coupled to the desalination plant for the generation of electricity and/or heat. Costs for one selected combination of a desalination process and an energy source may vary for different locations and countries. Several other parameters, such as site specific conditions, infrastructure requirements and indigenous supply have to be taken into account in a comparative economic analysis of nuclear desalination versus desalination with fossil energy sources in order to estimate costs of water production.

2.3.3. Safety Considerations

In addition to the current detailed safety requirements for all nuclear installation, and the trend to develop even simpler and more inherently safe designs, some specific precautions against possible minute leakage from the nuclear system into the desalination-systems are needed. Various types of reactors need various precautions, but no insuperable difficulties are foreseen.

2.3.4. Environmental Considerations

The environmentally negative aspects of Nuclear Desalination concern the potential for harmful effluent in an accident. Conversely, desalination could improve the environment considerably, e.g., if the water is used for irrigation purposes in arid regions providing food and trees and thereby an important CO_2 sink. The availability of fresh water in itself is a very important positive environmental factor.

Fossil powered desalination plants release at least carbon dioxide and sulfur dioxide and some other environmentally harmful substances. The deterioration of air quality on a global basis has become a subject of intense discussion around the world. In addition to the acidification effects of nitrogen and sulfur oxides (acid rain), the long term effects of increasing carbon dioxide levels in the air (global greenhouse warming) is causing concern.

The degree to which nuclear desalination can contribute to reduced environmental pollution depends on the future development of nuclear desalting capacity and on the specific types of fossil fuel replaced by nuclear.

This situation is similar to that in the field of electricity generation although energy consumption for seawater desalination is orders of magnitude lower. When compared to the combustion of coal (sulfur content 2%, without flue gas cleaning) each MW of nuclear thermal power avoids a corresponding CO_2 emission of about 3200 t per year and a SO_2 emission of up to about 50 t per year. Compared to oil or natural gas, the avoidable CO_2 emission is lower (about 2000-2900 t CO_2 per year). SO_2 emissions may reach almost zero if desulfurized natural gas is used as fuel.

Thus, if the worldwide desalting capacity in 1990 (about 13 million m^3/day for plant sizes > 400 m^3/day installed out of which about 10 million are in operation) could be powered by nuclear instead of fossil fuel, an emission of 32 million tons of CO_2 and about 0.2 million tons of sulfur and nitrogen oxides would be avoided.

This is not much compared to emissions from total worldwide electricity generation capacity, particularly if one takes into account that a 100% market penetration by nuclear desalination plants is unrealistic.

None the less significant environmental improvement can be achieved by Nuclear Desalination in those regions where a large desalination capacity is concentrated. A global effect will be noticeable if desalination capacity increases as drastically as is predicted in the future.

2.3.5. Other Institutional Barriers

A number of institutional barriers must be overcome in addition to the separate issues of finance, safety and environmental inputs which have been discussed above. Important among these are public acceptance and the organizational aspects of facilities that combine nuclear energy, desalinated water, and perhaps, electricity production.

The lack of public acceptance has been a significant barrier to the further use of nuclear energy in many countries. This lack of public

acceptance may be attributed to concerns with the possibility of nuclear accidents, higher than expected costs experienced in some projects (notably in the USA) and the tendency of the public to associate nuclear power plants with nuclear weapons.

A general trend toward improved public acceptance is beginning to become evident. This improving trend is associated with the following factors:

- The general recognition that additional energy resources will be needed,
- Increasing concern with environmental issues associated with the use of fossil fuels,
- The emergence of a new class of smaller nuclear reactors with improved, and in some cases passive safety characteristics.

Organizational aspects must also be addressed. With the notable exception of the USSR experience in Shevchenko, nuclear energy and water production have traditionally existed as separate functions. Nuclear energy, in particular, has been more commonly associated with electricity production, rather than water supply and distribution. When combining these technologies, a number of additional organizational considerations arise of which the following are examples:

- Will the combined plant be owned by the electric utility, water utility, both utilities or an independent organization?
- Will the plant be operated as an integrated entity or will the nuclear plant be operated separately from the water plant?
- How will the income, costs and risks be shared among the parties involved?

While such questions do not constitute insuperable barriers, they do indicate the importance of the principle that, before project commitment, all involved parties must clearly understand and agree on the allocation of risk, reward and responsibility for the financing, construction and operation of the plant.

2.4. Conclusions and Recommendations for Future Actions

On the basis of the USSR experience and the above mentioned recent studies, conclusions and recommendations for future actions were discussed

and agreed upon by all the participants of the Advisory Group Meeting convened by the Agency from 16 to 18 May 1990 in the Vienna International Centre. These conclusions and recommendations are provided below.

2.4.1. Conclusions

1. The fresh water shortage is becoming a question of life in many areas of the world, such as the Middle East and the southern part of the Mediterranean Sea. In other areas such as certain parts in USA, Spain, Italy and France water shortage may have an increasing impact on the quality of life.

2. About 70 - 80% of all conventional desalination plants of about 10 million m^3/day are in operation in the Mediterranean area and the Middle East.

3. There is a strong need to build additional seawater desalination plants, in particular in the Mediterranean area and the Middle East. A rough estimate indicates that by the year 2000, there will be a shortage of about 12 million m^3/day.

4. Beneficiaries and desalination technology holders in different countries have shown their high interest in solving the water shortage problem and have performed feasibility studies for some selected areas, such as "Southern California Desalination Study" (USA), "Super-Safe, Small and Simple Liquid Metal-Cooled Reactor" (Japan) and "HTR-Module for Seawater Desalination" (Federal Republic of Germany).

5. The expected increasing shortage of water in the near term future in many parts of the world makes it necessary to consider more advanced/more economic production schemes than are available today.

6. Energy has been found to be a significant contributor, about 35 to 55 % in recent plants and 25 to 40 % in future modern plants to the total cost of desalination. Nuclear energy has the potential to reduce that cost.

7. Nuclear Desalination is technically feasible based on currently available technology and the USSR experience at Shevchenko bears it out. Currently available technology includes various thermal

distillation processes using low temperature heat and electrically-coupled processes using Reverse Osmosis techniques.

8. The economic feasibility of Nuclear Desalination has been demonstrated in the USSR. Recent studies have indicated possible feasibility in other areas but these results must be confirmed on a site specific basis. Capital costs are a still major concern.

9 The use of nuclear energy for large scale desalination would have less environmental impact than fossil-fired thermal energy sources.

10. There is a mismatch in the power output of nuclear plants and power requirements from present desalination plants, a typical plant producing 500,000 m^3/day may require about 500 MW_{th} (140 bar; 530°C).

   o In areas with a developed infrastructure and large populations this mismatch can be overcome by sale of excess electricity (electrically coupled desalination technologies) or by dual purpose (cogeneration of electricity and low temperature heat) plants.

   o In areas without an established infrastructure or large population concentrations, such as occurs in many middle-east countries, smaller reactors would be required.

   o For single purpose coupling of reactors to the desalination process, very small reactors would be required. This could pose the problem of spreading out thinly the skilled operating personnel required.

11. Large nuclear reactors for electrical generation are available on a commercial basis but commercial experience with modern smaller reactors is limited.

12. Institutional barriers (e.g. regulatory issues, financing and public acceptance) comprise additional barriers to Nuclear Desalination.

13. The current state of technology indicates that production of desalted water solely for agricultural purposes is not economic.

14. Further development of technologies such as advanced membranes and hybrid processes are expected to further reduce costs.

2.4.2. Recommendations

1. A comparative technical and economic evaluation of nuclear vs fossil desalination is required to find the optimum solution for potable water production.

2. The technical and economic feasibility of desalination for specific sites require more detailed studies.

3. It is desirable to continue monitoring promising reactor developments and desalination technologies for producing potable water economically.

3. REVIEW OF CURRENT TECHNOLOGIES FOR SEAWATER DESALINATION

Seawater desalination has become a reliable industrial process. Two major processes dominate the market today, namely the Multi-Stage-Flash-Process (MSF) with about 80% of the market, and the Reverse Osmosis (RO) process with about 10%. Multiple effect processes such as HTME (Horizontal Tube Multieffect) and VTE (Vertical Tube Evaporation) play only a minor role at this time, but this will change.

Various processes for seawater desalination can be categorized as shown in figure 1. Over the last 30 years many processes and process combinations have been tested, especially in the USA under the sponsorship of OSW and later OWRT. Earlier hopes for "energy efficient" systems such as the freezing process, have not been fulfilled to date.

According to Ref. [2], the theoretical minimum energy requirement based on ideal thermodynamic cycles is 0.765 kW(th).h/m^3. Due to certain losses (irreversibility, mechanical losses, thermal losses) it is impossible to reach this figure. In 1956, when this OSW report was written, the obtainable power consumption for RO systems was predicted to be 5.5 kW(e).h/m^3, and for Multiple Effect Vapor Compression systems 3.0 kW(e).h/m^3. Today, some 35 years later, it seems probable that these values can be obtained, and that the leading, but relatively energy inefficient, MSF-process will very quickly lose it's dominating role.

3.1. Product Water Quality

The water produced by nearly all seawater desalination processes cannot be used directly as drinking water. The thermal processes produce pure water (aqua destillata) with only few minerals/salts (2-25 ppm TDS on average), and the membrane processes produce an unbalanced mineral distribution. Both process types produce a water free of hardness with a non-optimal pH-value. Therefore, the water produced has to be treated to obtain drinking water. A post treatment is also sometimes necessary if process water is required.

3.1.1. Drinking Water Standards

The drinking water produced shall satisfy the standards of both the World Health Organization (WHO) and the European Community. The drinking
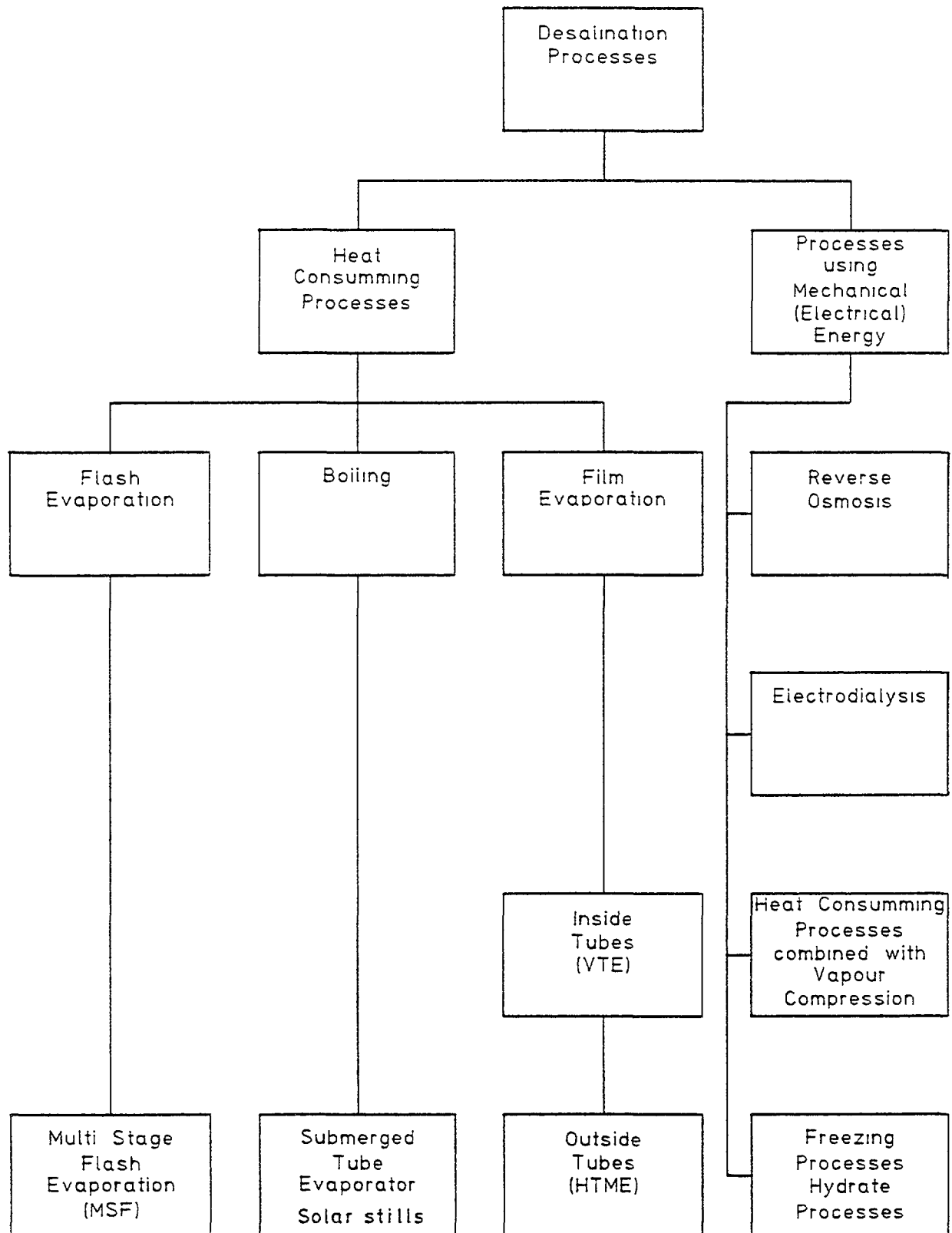
Fig. 1. General classification of desalination processes.

water standards as recommended by the WHO are given in reference [1]. These standards are continuously improving by WHO, but their summarized version is not yet available. The European Community standards for drinking water are as follows, some parameters having lower limits than that of the WHO.

Parameter	Recommended	Highest permissible concentration
Chlorides (Cl)	25 ppm	200 ppm (recommended)
Sulfates (SO$_4$)	25 ppm	250 ppm
Calcium (Ca)	100 ppm	
Magnesium (Mg)	30 ppm	50 ppm
Sodium (Na)	20 ppm	150 ppm
Potassium (K)	10 ppm	12 ppm
Aluminium (Al)	0.05 ppm	0.2 ppm
Nitrate (NO$_3$)	25 ppm	50 ppm
Nitrite (NO$_2$)	--	0.1 ppm
Ammonium (NH$_4$)	0.05 ppm	0.5 ppm
Iron (Fe)	0.05 ppm	0.2 ppm
Manganese (Mn)	0.02 ppm	0.05 ppm
Copper (Cu)	0.1 ppm	3 ppm (under special conditions)
Fluorine (F)	--	0.7 ppm
Chromium (Cr)	--	0.05 ppm
Lead (Pb)	--	0.05 ppm
PCT/PCB/Pesticides	--	0.005 ppm (total)
Polycyclic Hydrocarbons	--	0.002 ppm (total)
Chlorinated/hollogenated Hydrocarbons	--	0.010 ppm (total)
Conductivity	400μScm^{-1}	2000μScm^{-1}
pH	6.5-8.5	9.5
Total Hardness	> 60 ppm as Ca	
Alkalinity	> 30 ppm as HCO$_3$	

American and Japanese standards have similar parameters. It might be worthwhile to have worldwide common standards for drinking water, taking into account all medical aspects recognized during the last decade.

According to the above recommendations and limits, a "good drinking water" will have between 200 to 300 ppm TDS. For thermal desalination plants it is easy to obtain these values with a good post treatment. Most RO plants built till now do not meet these requirements, however the new membranes being developed, and those recently marketed, can fulfill the requirements in combination with a post treatment.

For thermal desalination plants the low recommended level of metals (Fe = 0.05 ppm, Cu = 0.1 ppm, Al = 0.05 ppm) might be problematic, if stainless steel or titanium are not used.

3.1.2. Process Water Requirements

Process water for most applications in the chemical or petrochemical industry is satisfactory if it has 2 to 5 ppm TDS and zero hardness. For applications such as boiler feedwater, ultra-pure water for the electronic industry, and medical purposes, a post-treatment has to be added such as ion-exchange (mixed bed filters) or bidistillation. In general, thermal desalination plants are able to produce 2-5 ppm TDS. With RO plants it is not possible to obtain these values in a single step. In plants where process water has to be produced with an RO system, a multistage system or enlarged ion exchangers have to be used. Another advantage of thermal desalination is the fact that deaerated water is produced. In case of RO an additional deaerator has to be added.

3.1.3. Post Treatment Requirements and Costs

The water produced by desalination processes has to be hardened to obtain drinking water. Hardened water is obtained when the "soft" water is passed over a bed of burnt limestone with CO_2 added at the same time. To improve the quality of product water other minerals such as magnesium may be added in addition to the burnt limestone.

Chlorine is also added in small amounts to keep the water free from bacteriological contamination during storage and distribution. The costs to harden the water depends on the methods used to obtain CO_2 and chlorine. In the case of RO, acid (in general H_2SO_4) is added to the seawater and transforms the carbonates contained in the seawater to calcium sulfate and CO_2. The CO_2 passes through the membrane and forms calcium carbonate in the filter bed. Surplus CO_2 can be vented. In the case of the thermal desalination process, the carbonates are reduced thermally at temperatures above $90^{\circ}C$ to calcium and CO_2. The CO_2 can be cleaned and recycled to the product. In case of low temperature desalination processes, the CO_2 can be produced by burning oil, and extracting the CO_2 from the waste gases.

Chlorine can be produced locally, as well as by using electrodialysis where NaCl is dissolved in product water and sent through an electrolyzer. In one compartment of the electrolyzer Cl_2 is formed and in the other NaOH. In the case of RO with chlorine resistant membranes, it is possible to produce chlorine on-line by sending a small stream of seawater through

an electrolyzer. The Cl_2 and CO_2 pass through the membrane simultaneously with the permeate.

For a small plant (capacity below 1000 m^3/d), the post-treatment costs (including write-off of equipment) are in the range of 0.1 to 0.15 US $/m^3$, and for large plants (capacity above 100 000 m^3/d) these costs can be reduced to 0.03 - 0.06 US $/m^3$ of product water. When raw water which contains low volatile organics is used as feedwater to a thermal desalination plant, the product water may need an additional post-treatment step such as passing through activated charcoal.

3.2. Seawater Pretreatment

3.2.1. Seawater Qualities

Seawater is not a homogeneous solution, and can vary not only by location, but also by the time of the year, in some areas even by the time of the day. The major analytical characteristics are the salinity or the Total Dissolved Solids (TDS as ppm). Standard seawater, as well as the Atlantic Ocean, has about 37 500 ppm TDS. The Mediterranean seawater has about 38 500 to 39 500 ppm TDS. In the Red Sea the average is 42 500 to 45 000 ppm TDS, and in the Gulf Area the values vary from an average of 45 000 to 52 000 ppm TDS in extreme cases. For the desalination process itself, the contents of seawater such as calcium sulfate, calcium carbonate, and magnesium hydroxide, are more important.

3.2.2. Pretreatment Requirements and Costs

In thermal desalination plants, calcium carbonate starts to precipitate on the heat transfer areas at 56°C at normal concentrations (120 to 145 ppm $CaCO_3$). Calcium sulfate and magnesium hyrdoxide precipitate at temperatures above 135°C for once through seawater desalination plants, and 120°C for desalination plants with brine circulation, depending on concentration and pH value.

For thermal desalination plants it is important to avoid the precipitation of scale forming components, in order to keep the thermal efficiency at its highest level. There are various ways to hinder the formation of scale:

a) Adding acid (HCl, H_2SO_4) to remove carbonates (max. operation temperature 120°C for brine recycle arrangements, and 135°C for once-through arrangements).

b) Ca removal by selective ion-exchange (max operation temperature 150°C).

c) Adding polyphosphates to reduce the precipitation of carbonates (max operation temperature 90°C)

d) Adding "advanced" additives to reduce the precipitation of carbonates and sulfates (max operation temperature 120°C)

Nowadays in the majority of plants method d) is used. The influence of this method on water cost is relatively small. Depending on the seawater and operating temperature, the pre-treatment cost is only in the range of 0.01 to 0.03 US$/m^3. Depending on the material used for construction of the evaporator, a separate deaerator has to be installed. Modern plants using high grade stainless steel and titanium tubing do not need separate deaeration equipment.

For RO plants, carbonates and sulfates do not produce a problem, as RO operates at ambient temperatures and with maximals at most a double seawater concentration at the outlet. With few exceptions, for example the Red Sea in some areas near Hurghada where up to 250 ppm $CaCO_3$ has been found, or some areas in the Caribbean sea with elevated sulfate content, no special pre-treatment is required.

The major problem with RO plants is the presence of suspended matter in the seawater. These suspended solids have to be removed down to a "Silting Index" (SDI) of 3 to 5 depending on the module type. In general, this is done by flocculation and subsequent removal of the flocced suspend matter in filters (sandfilter, depth filter, pre-coat filter). With the reduction in membrane costs, a pretreatment with a tubular micro-filtration system may be able to compete with the conventional systems. In the case of conventional filters, chlorine has to be used to avoid biological growth.

Membranes of the first generation need additional pre-treatment steps as they are not resistant under certain conditions. These pre-treatment steps might be pH-adjustment, dechlorination, iron removal, and deaeration. Second generation membranes, which are just coming on the market, are relatively stable, and in general it is only necessary to remove suspended matter. Pre-treatment for RO systems is a major cost factor. Specific capital costs (1990), vary in the range from 100 US$/m^3 to 250 US$/m^3 of water produced, and specific operation costs, including pumping energy, are in the range of 0.10 to 0.25 US$/m^3 of water produced.

3.3. Desalination Processes

3.3.1. General

The first generation desalination systems have reached a high degree of reliability. First generation desalination systems, such as MSF or RO with membranes of limited stability, are still too expensive in capital and operating costs. If "low cost" or "socially acceptable cost" water has to be produced, new desalination systems are required. The most promising second generation desalting systems are RO with advanced membranes, and hybrid thermal systems such as MED combined with Vapor Compression. Desalination process development continues, and new systems may further reduce costs in the future. Further R&D activities are still required since water cost from the second generation desalination systems is still relatively high. All processes for desalination (1st, 2nd and even 3rd generation) are extremely well described in the literature, for example in the OSW/OWRT reports, and in the proceedings of various desalination congresses and in many other publications. Hence, it is not necessary to describe the various processes in detail here. The following merely summarizes the major desalination processes (see figure 2).

Fig. 2. Distillation processes.

1st STAGE | 2nd STAGE | 3rd STAGE

Steam from Boiler →

BRINE HEATER

Condensate Returned to Boiler ←

Seawater Feed ←

FW

Vapor

Brine

Freshwater Product →

Brine Discharge →

HIGH TEMPERATURE
HIGH PRESSURE STAGE
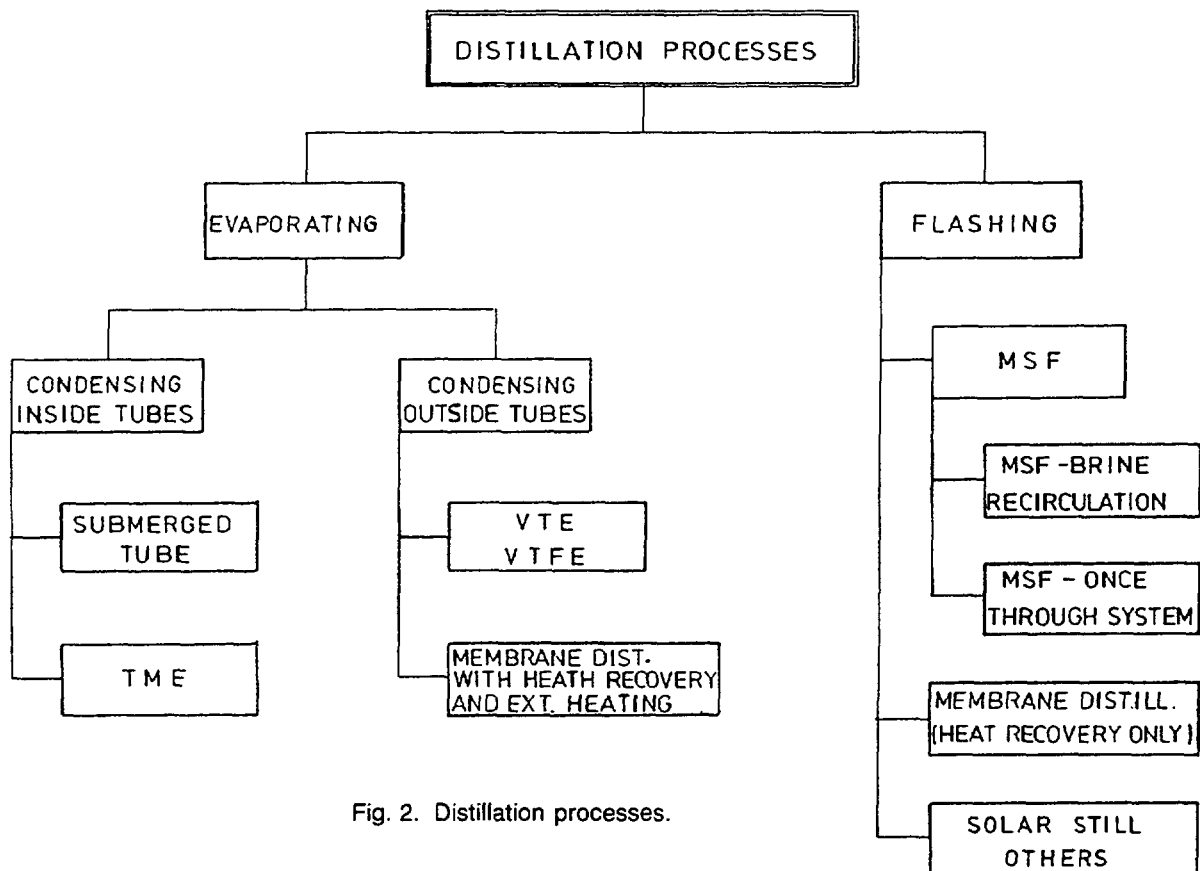
LOW TEMPERATURE
LOW PRESSURE STAGE
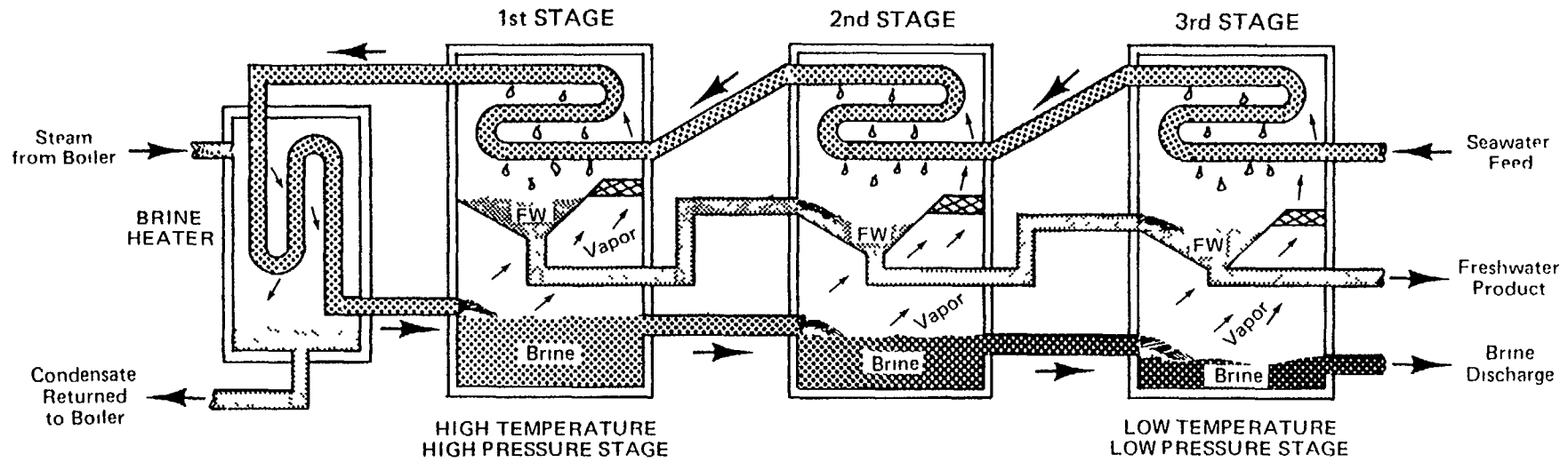
Note For simplicity, no heat rejection section is shown in this diagram—see Figure 3 15

FW = Freshwater

STEAM EJECTOR
→ To remove non condensable gases

The seawater feed increases in temperature as it moves toward the brine heater where sufficient additional heat is added to permit it to flash boil in the first stage →

HEAT RECOVERY AND CONDENSER

Tube bundle which serves as a heat recovery and condenser section Incoming seawater inside the tubes is heated by vapor condensing on the outside of the tubes

The freshwater produced by condensation in each stage is flashed in subsequent stages to recover additional heat →

FW

Vapor

Demister—Usually screening or wire mesh which removes saltwater droplets entrapped in the vapor

Flashing Brine

Brine flashes when introduced into the stage which has a reduced pressure, permitting rapid boiling to occur immediately →

FLASH CHAMBER

Brine

Brine moves to the next stage to be flashed again to produce additional vapor and transfer heat to the heat recovery section
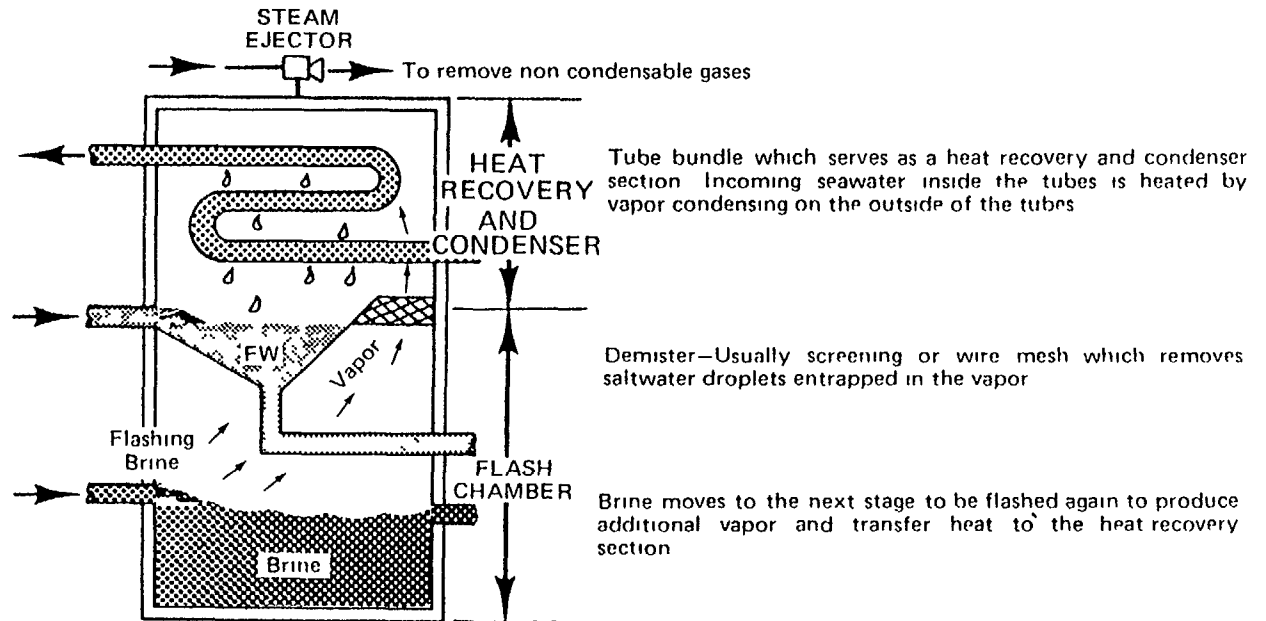
Fig 3 Conceptual diagram of the multistage flash (MSF) process
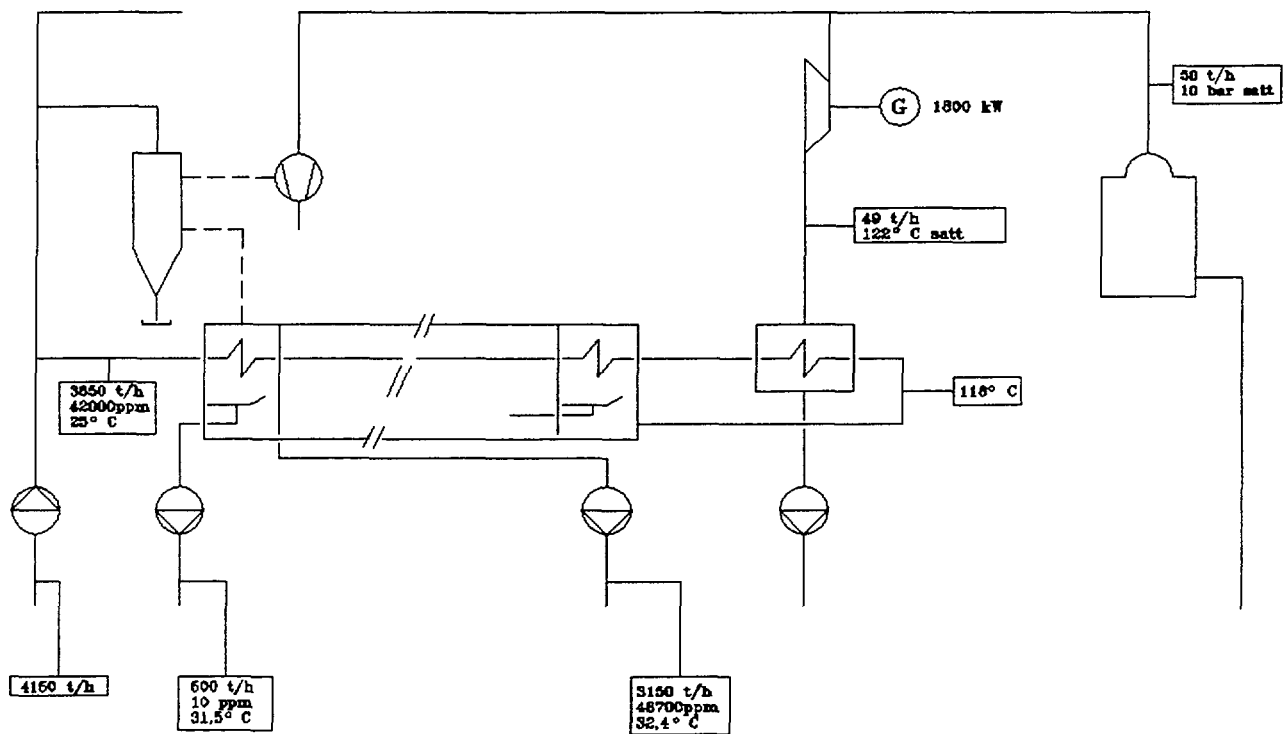
Fig. 4. Once through — multistage flash OT-MSF.

3.3.2. MSF - Multi-Stage Flash Distillation

3.3.2.1. Description of Process and Equipment

The MSF-process is pictured schematically in figures (3) and (4). Basically, the process involves heating saline water progressively up to a maximum operation temperature of 90 to 130°C, then flashing this water in a number of successive stages operating under progressively lower pressures. In each stage the vapour produced is condensed by heat exchange with the incoming feedwater. There are 2 principal arrangements used in MSF, the brine recycle system (figure 3), and the once-through system (figure 4). The majority of the MSF-plants built are still working in accordance with the brine recycle principle. The brine recycle systems were invented in the early years of desalination when seawater corrosion resistant materials and advanced additives were not available in the market. In the brine recycle systems, a major part of the cooling water is rejected, and only a small part is used as make-up water (about 2.5 times the amount of the product water). The make-up water is then deaerated in a low temperature vacuum deaerator. The carbonates are eliminated by adding acid. In this way acid consumption can be reduced by a factor of about 3 to 4, and carbon steel with a high corrosion allowance can be used due to the absence of oxygen in the make-up water. The required amount of feedwater to produce a

certain amount of fresh water (depends on temperature difference) is recirculated and kept below a maximum salinity by constantly removing a certain amount of blow-down and adding make-up. This process arrangement necessitates the use of a brine recycle pump, which in general is the most sensitive equipment in a desalintion plant. With the once-through system, all the cooling water is deaerated in the first stage and additives are injected before the feedwater enters the plant. The total amount of "advanced additives" is practically the same in both cases, although the flows are different, as the required dosage levels depend largely on the salinity in the plant. The main advantage of the once-through principle is that no expensive brine recycle pump is required, and a smaller heat transfer area is needed due to the lower boiling point elevation.

3.3.2.2. Current Status and Future Developments

MSF plants have reached a mature stage of development. Unit sizes of 42 000 m^3/d are under construction, and from the size and technology viewpoint no further important development or progress is anticipated. As MSF plants are very reliable, they will still be used for a certain time especially as once-through systems.

3.3.2.3. Energy Requirements

In general, the thermal efficiency of a MSF-plant is expressed in kg of water produced per kg of steam used. This ratio is called the Gain Output Ratio (G.O.R). The G.O.R. today is in the range of 8 to 10, with a practical maximum of 14. When free waste energy is available, a G.O.R. as low as 3 is acceptable, e.g. in the chemical industry. A G.O.R. of 3 corresponds without losses to 216 kW(th).h/m^3, a G.O.R. of 8 to 82 kW(th).h/m^3, and a G.O.R. of 10 to 65 kW(th).h/m^3 water produced. Additionally, a MSF plant consumes 3.5 to 5.0 kWh of electricity for the pumps per cubic meter of water produced .

3.3.2.4. Pretreatment Requirements

All MSF plants need pretreatment to avoid scaling. If low cost materials are used in the evaporator, deaeration is also required.

3.3.2.5. Other Special Requirements

Depending on the total temperature difference in the plant a MSF plant needs about 7 to 12 times the amount of cooling water (seawater) per amount

of product water. This leads to high costs for the seawater intake which is the highest single cost factor in desalination processes.

3.3.2.6. Investment Costs

The investment cost (turnkey 1990), for an MSF plant within its boundary limit, is in the range of 1200 US$/m^3/d to 1800 US$/m^3/d of water produced, depending on G.O.R. and materials used. These figures are without energy production, product storage and seawater intake costs. The seawater intake may cost in addition 200 US$/m^3/d to 900 US$/m^3/d of water produced, depending on the location and the conversion ratio.

3.3.3. MED - Multi-Effect Distillation

The MED system is the oldest large scale evaporation process. In spite of the fact that it is a straight-forward process, it could not compete in the past with the Multi Stage Flash process. The main reason for this was not the process itself, but the components and materials used. It now seems that the problems have been solved, and it will take a more important role in the future especially in combination with Vapor Compression. In the MED system two arrangements are used, namely the HTME-Horizontal Tube Multiple Effect, and the VTE-Vertical Tube Evaporation system.

3.3.3.1. HTME - Horizontal Tube Multiple Effect Desalination

3.3.3.1.1. Description of Process and Equipment

Desalination installations with horizontal-tube thin-film evaporators (see figures 5 and 6) are considered at present to be the most promising ones for the production of fresh water from the sea. Many manufacturers of desalination equipment such as Sidem, Aiton Ltd, IDE Technologies Ltd, Sasakura Engineering Co. Mitsubishi Co. Aqua Chem. Inc., deliver installations with horizontal tube thin-film evaporators of different size to the world market, and constantly introduce improvements [3]. Active development work and use of such installations is also being conducted in the Soviet Union [4], in Israel [5], and elsewhere.

The main element of the desalination installations of the horizontal tube thin-film type is the evaporator, in which heating steam condenses
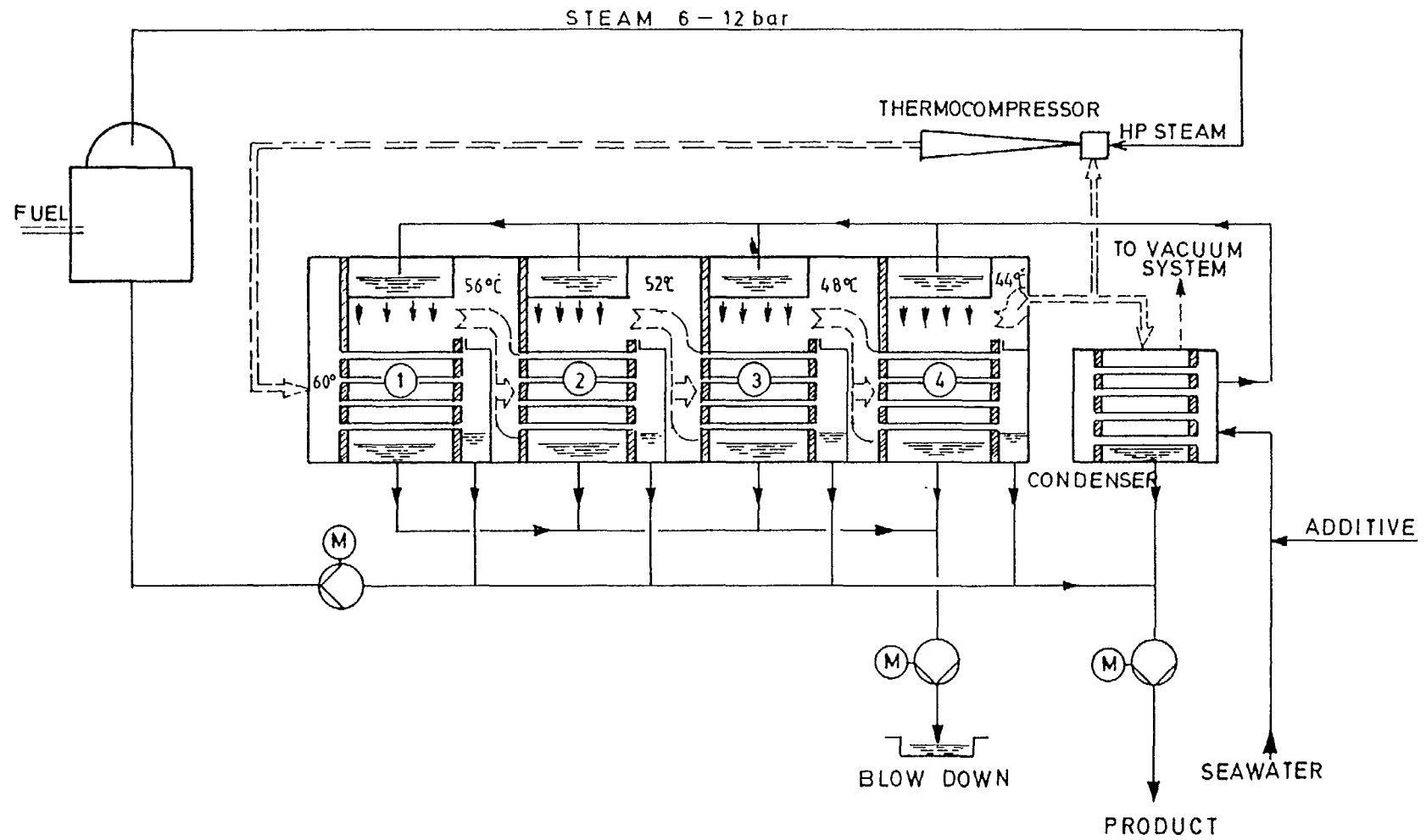
Fig. 5. Basic principle of LT-HTME-desalination plant combined with thermal vapour compression (thermocompressor).
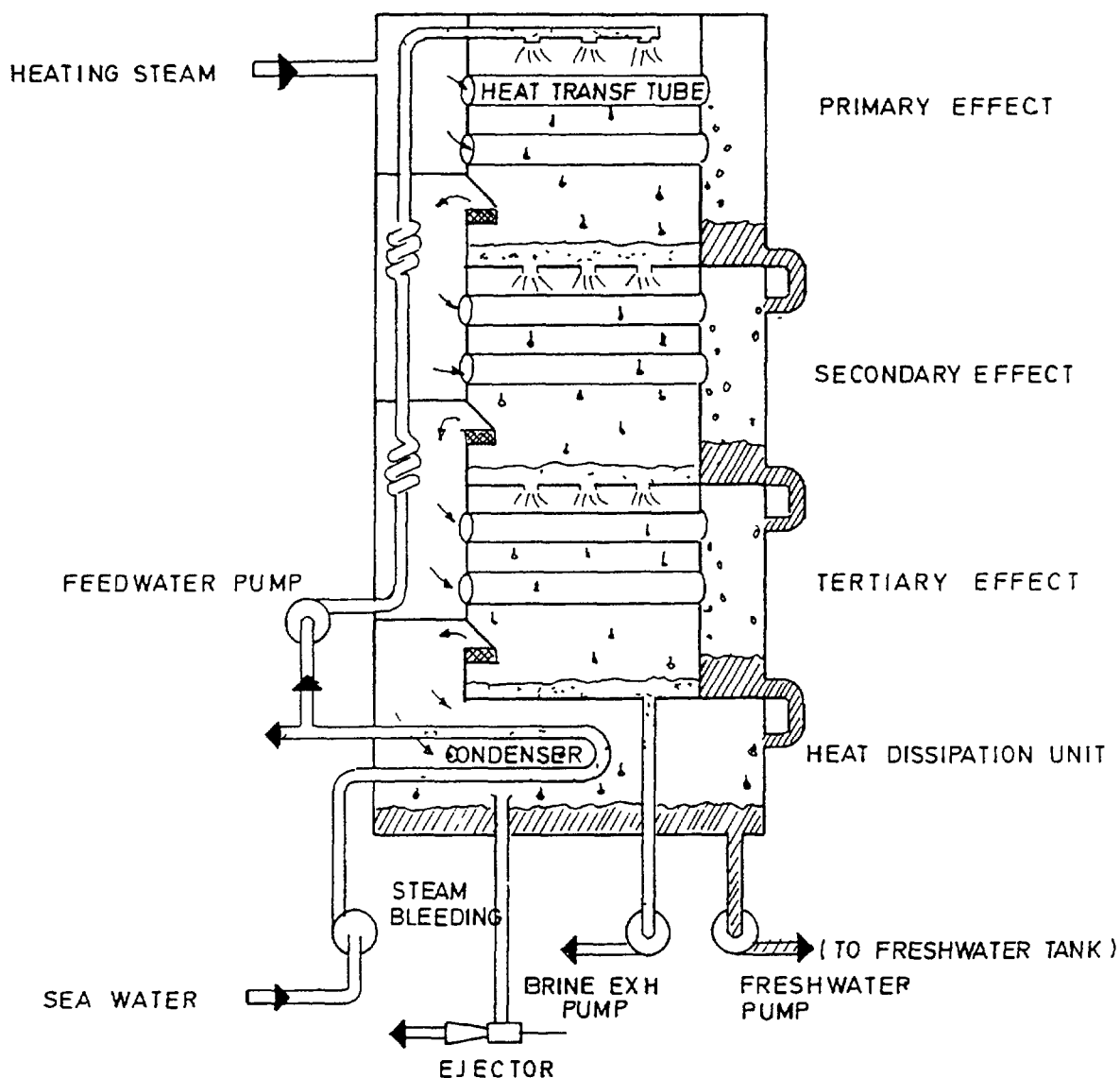
Fig 6 Horizontal tube multi-effect desalination evaporation (LT-HTME stacked arrangements of effects).

inside horizontal tubes, and a thin film of seawater is sprayed over the external surface. Steam, produced from the evaporating seawater, is separated from water droplets with the help of a demister, and is directed towards the subsequent stages. The desalination installation diagram includes several stages or effects operating in series.

Depending on the method of interaction of the heat exchanging media (steam-seawater), installations of the HTME process may be co-current (forward feed), countercurrent (backward feed), concurrent (parallel feed), and partially cocurrent or countercurrent with concurrent feeding.

According to the technical and economic data, specific consumption of energy (steam, water, electrical energy), weight of the evaporator unit, and building area, are at least 20% lower for this type of installation than for installations of the MSF process.
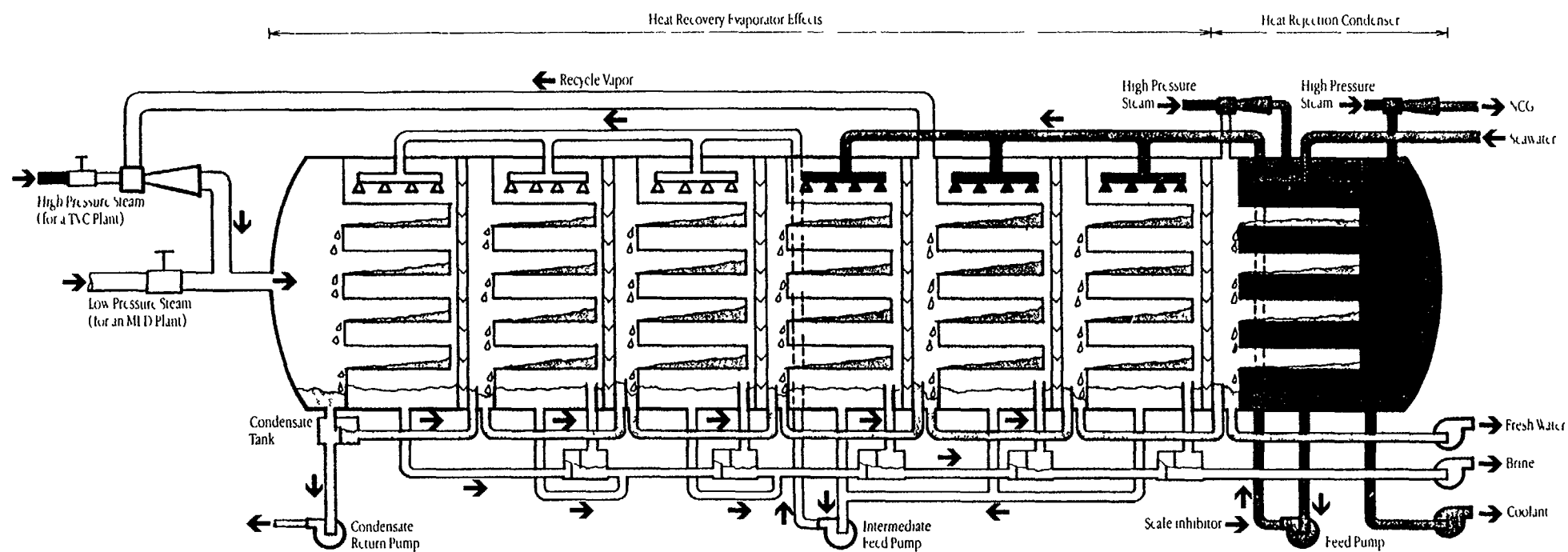
Fig 7 MED and TVC process schematic

3.3.3.1.2. Current Status and Future Developments

Desalination installations of the HTME process gained wide recognition
and began to be applied for industrial purposes at the end of the 60s and
at the beginning of the 70s, though the idea of horizontal-tube thin-film
evaporator was patented in 1888 [6]. The company Sidem (France) offers a
large choice of desalination installations to the users ranging from 10 to
5000 m^3/d, with 1 to 6 effects combined with steam-jet [7] and Mechanical
Vapour Compression [8]. The largest installations of this company,
manufactured by the company IHI (Japan), were mounted on the Antigua Island
(Fig. 8). Two 10-effect installations were erected, each with an output of
4500 m^3/d. The installations were put into operation in 1987 and have
operated successfully till now [9].

At the first World Congress on Desalination and Water Reuse in 1983, a
project was presented for a 16-effect installation with an output of 25000
m^3/d [10], however, information about its realization has not appeared in
the literature. In its developments, Sidem uses arrangements with
concurrent feeding. Installations with an output up to 3000 m^3/d have
been built in FRG [11] and Japan. These installations usually use the
cocurrent process arrangment.

Israel Desalination Engineering Ltd. has carried out a large amount of
scientific development work on horizontal-tube thin-film evaporators [12].
This company manufactures a large number of desalination installations of
various capacities. In 1981-1983 this company built the Virgin Islands
desalination installations with an output of 2100 m^3/d (three
installations in 1983), and 4800 m^3/d (two installations in 1982 and one
installation in 1981) [13].

In the town of Ashdod (Israel), one of the largest installations in
the world became operational in 1984 as shown in figs. 7 and 9. Its output
amounts to 20 000 m^3/d, and consists of six effects, the heat exchange
surfaces being made of Aluminium tubes (Alloy 5052). The seawater
evaporation temperature is 60°C in the first effect, and scale prevention
is by polyphosphate dosing. Steam is supplied to this installation, by
flashing the cooling water used in a backpressure turbine condenser
[14, 15].

Another large IDE Company project was presented at the Third World
Congress on Desalination and Water Reuse. This installation has
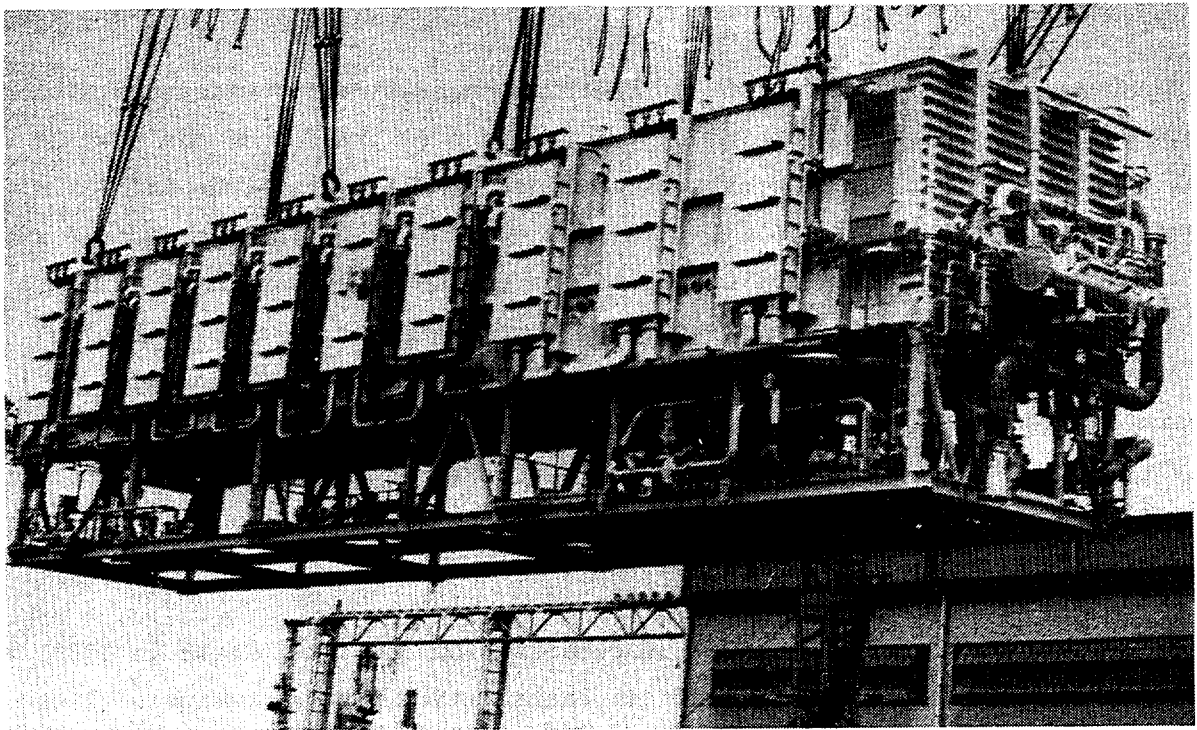
Fig. 8. Antigua desalination installation.
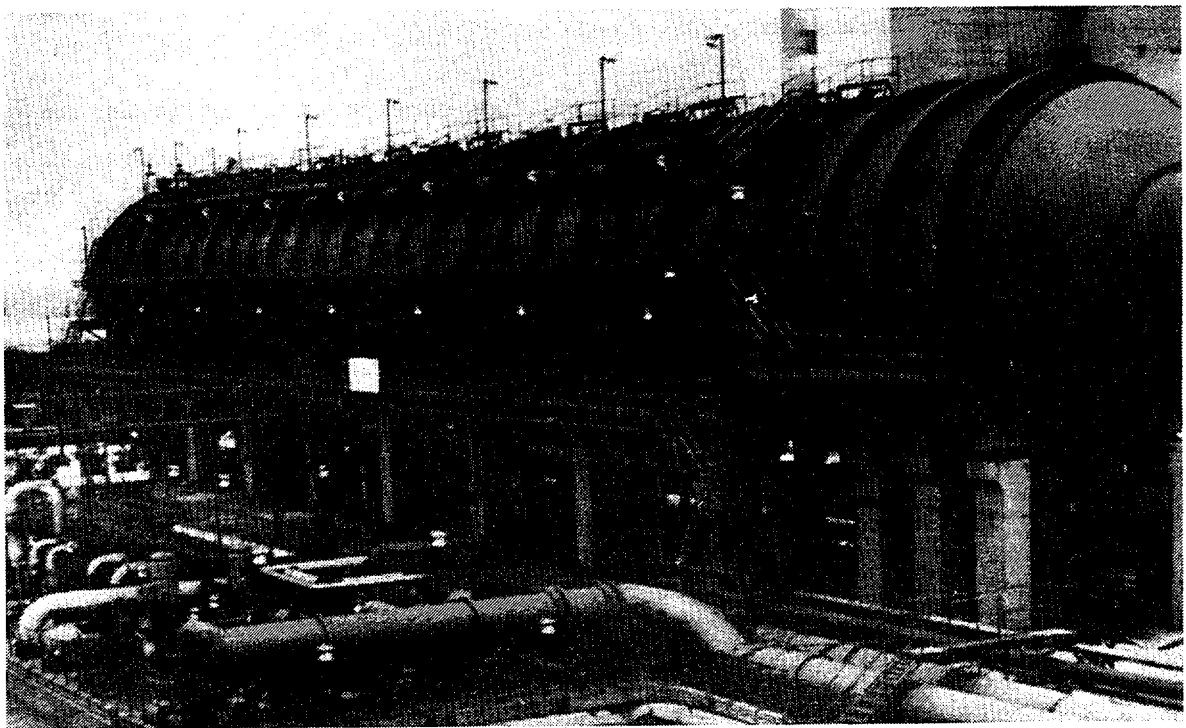
Fig. 9. Ashdod desalination installation.
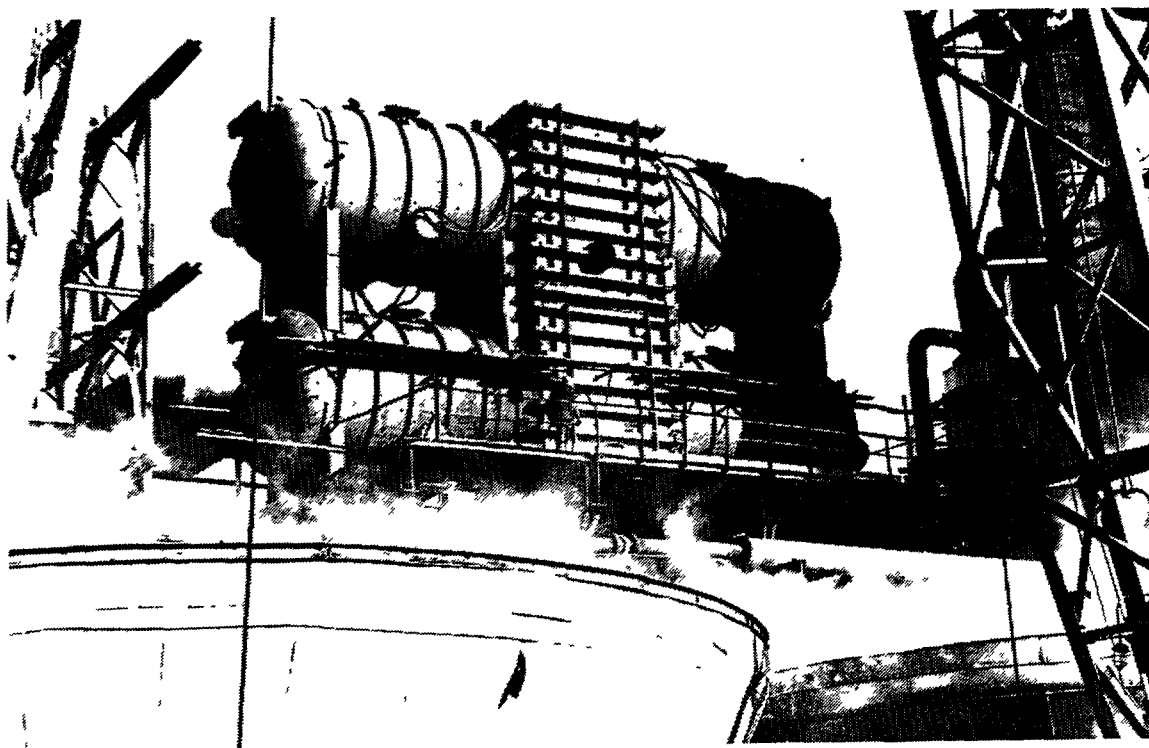
Fig. 10. Shevchenko desalination installation

12 effects, is equipped with an auxiliary back pressure turbine and a
steam-jet compressor. Steam from the backpressure turbine is used as a
heat input to the plant, and in this case the steam-jet compressor is not
used. When the turbine is shut down, steam is supplied to the installation
directly from the boiler through the steam-jet compressor.
The capacity of the installation is 10 000 m^3/d [15]. For all large
installations of the IDE Company, backward-feed/parallel-feed arrangements
are used.

In the USSR, on the basis of the results of research and experimental
work, as well as operating experience with prototypes of two desalination
installation types, the installations were developed and realized with
outputs of 10, 25, 140, 350, 700 m^3/h [16]. These installations use
cocurrent and partially concurrent feeding. The prototypes of the
evaporators of a large 700 m^3/h installation have operated in Shevchenko
since 1975. Photographs at the time of erection are shown in Fig. 10.

Technically, the HTME is well developed, but many details may be
improved. Use of more noble materials could be used in the future. This
trend results from higher requirements in water purity (the European
Community recommended level for drinking water is Al = 0.05 ppm, Fe = 0.05
ppm, Cu = 0.1 ppm). The change to more noble materials such as high grade

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stainless steel or titanium will not have a negative effect on prices. Higher specific costs, as well as lower thermal conductivity of the more noble materials, will be fully offset by a weight reduction through reduced wall thickness (for example titanium tubes of 0.3 mm thickness can be used), giving increased heat transfer rate. Also, polymeric materials for the tubes can be considered as the pressure difference is very low (less than 100 mm W.C. between inside and outside), and the internal pressure is slightly higher.

3.3.3.1.3. Energy Requirements

As in the case of desalination installations of the MSF and VTE processes, the HTME installations consume the same types of energy resources: steam at a pressure of 0.08-0.3 MPa for the realization of the evaporation process and at a pressure of 0.6-2 MPa for the vacuum unit, electric energy for feed pump drives, chemicals supply, pumping-out of condensate, distillate, brine (on some installations also for the liquid ring vacuum pumps or water-jet vacuum pumps), and cooling water (raw seawater) for vapour condensation in the last effect of the installation. The range of main technical-economic data of the HTME installations are as follows:

Output	16-20 000 m^3/d
Effect number	2-24
Specific heat consumption	30 kW(th).h/m^3 to 350 kW(th).h/m^{3*}
Specific energy of simultaneously operating pumps (without the drive of mechanical vapour-compressors)	1.5-3.5 kW(e).h/m^3
Seawater specific consumption	1.5-12 m^3/m^3
Distillate salinity	less than 10 mg/l
Specific unit weight	0.5-2.0 t/m^3/h
Specific building area	0.8-3.0 m^2/m^3/h

* G.O.R. = 2 - 20

3.3.3.1.4. Pretreatment Requirements

The HTME desalination process uses the same methods of water pretreatment as those used in the MSF and VTE processes. It should be noted that for some designs more stringent requirements are specified for the filtration of seawater for the HTME process than for other desalination

processes. Because of the small nominal diameters of the distributing devices, the presence of suspended particles greater than 1 mm is not permissible in seawater. Hence, scale prevention method using additives were largely applied. To treat high carbonate alkalinity, partial acidification is performed together with applying additives.

3.3.3.1.5. Other Special Requirements

Horizontal-tube thin-film evaporators are sensitive to the quality of the brine sprayed on the heat exchange surfaces. Accurate horizontal alignment of the heat exchange tubes and distributing devices is necessary. The seawater supply to each effect should be large enough to prevent dry spots occurring on the heat exchange surfaces. At the same time, the heat flux on these surfaces should be lower than the value at which nucleate boiling of seawater starts.

3.3.3.1.6. Investment Costs

Heat transfer coefficients are up to 2 times larger for the horizontal-tube thin-film evaporators than for MSF. The consequence of this fact is that the overall dimensions and specific heat transfer area of the HTME units are smaller than MSF desalination evaporators. Due to the low peak temperature in HTME plants, low cost materials can be used. A lower cost of the heat exchange equipment allows an increase in the number of effects in the installation, and this in turn reduces the specific thermal energy consumption for the process. At present desalination installations of this type are under consideration with more than 20 effects.

Another rather important advantage of the horizontal-tube apparatus is that the distillate quality remains high even with small holes in the heat transfer tubes created by corrosion. This is due to the fact that the seawater vapour pressure (thin film) over an opening is lower than the corresponding pressure at the inside of the tube. Because of this, seawater cannot get into the tube when the plant is under operation.

These installations consume less electric power than other desalination processes, as recirculation of large volumes of seawater is not required for them as in the case of the MSF process or some VTE-arrangements.

HTME plants are also characterized by reliability and stability of the process, and by flexibility of operation that permits a wider change of output range than for the MSF and the majority of VTE installations. The start-up and operation of such desalination installations are carried out easily; they only need a short period to come to full operation; specific heat consumption does not change noticeably upon operation at partial loads.

For a LT-HTME process, where the maximum process temperature is 70°C to enable use of low-cost materials, the relatively narrow temperature range allows at most 17 effects.

The corresponding specific investment is about 1200 US$/t/m^3/day capacity for a 6 effect plant and 1500 US$/t/m^3/day for a 20 effect plant.

All the advantages of the HTME process taken together result in expenditures being reduced by a factor of 1.2 compared to other thermal distillation processes under similar conditions [10].

3.3.3.2.   VTE – Vertical Tube Evaporation

3.3.3.2.1. Description of Process and Equipment

The VTE desalination process can be realized in evaporators of different construction such as falling-film evaporators (Figs. 11 and 12), rising film evaporators (Fig. 12), and evaporators with forced and natural solution circulation (Figs. 13 and 14). Normally several effects are used in series along the direction of steam flow in a desalination plant. The evaporators in operation at present desalination installations have 1 to 24 effects.

According to the direction of steam and seawater flow, installations are subdivided into cocurrent (in conventional terminology = "forward feed"), countercurrent (In conventional terminology = "backward feed") and those with concurrent feeding. In cocurrent evaporation installations, steam and seawater move as parallel flows from the first high temperature evaporator to the last low temperature one. In countercurrent desalination installations, steam and seawater move through the evaporators in opposite directions. In installations with concurrent feeding of seawater, steam moves from the first high temperature apparatus to the last low temperature one, but make-up water flows at right angles to the steam flow.

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BRINE NOZZLE

UPPER STAGE BRINE CHAMBER

120°C
2.02 ata

BRINE OF 120,5°C
FROM PREVIOUS
EFFECT

BRINE WATER
LEVEL

UPPER TUBE
END PLATE

STEAM FROM
PREVIOUS EFFECT

HEATING STEAM
CHAMBER

120° C

LOW TUBE
END PLATE

120 °C

GENERATED
FRESHWATER

113,4°C

1,63 kg / cm²

STEAM TO
NEXT EFFECT

STEAM AND
BRINE

BRINE TO EFFECT
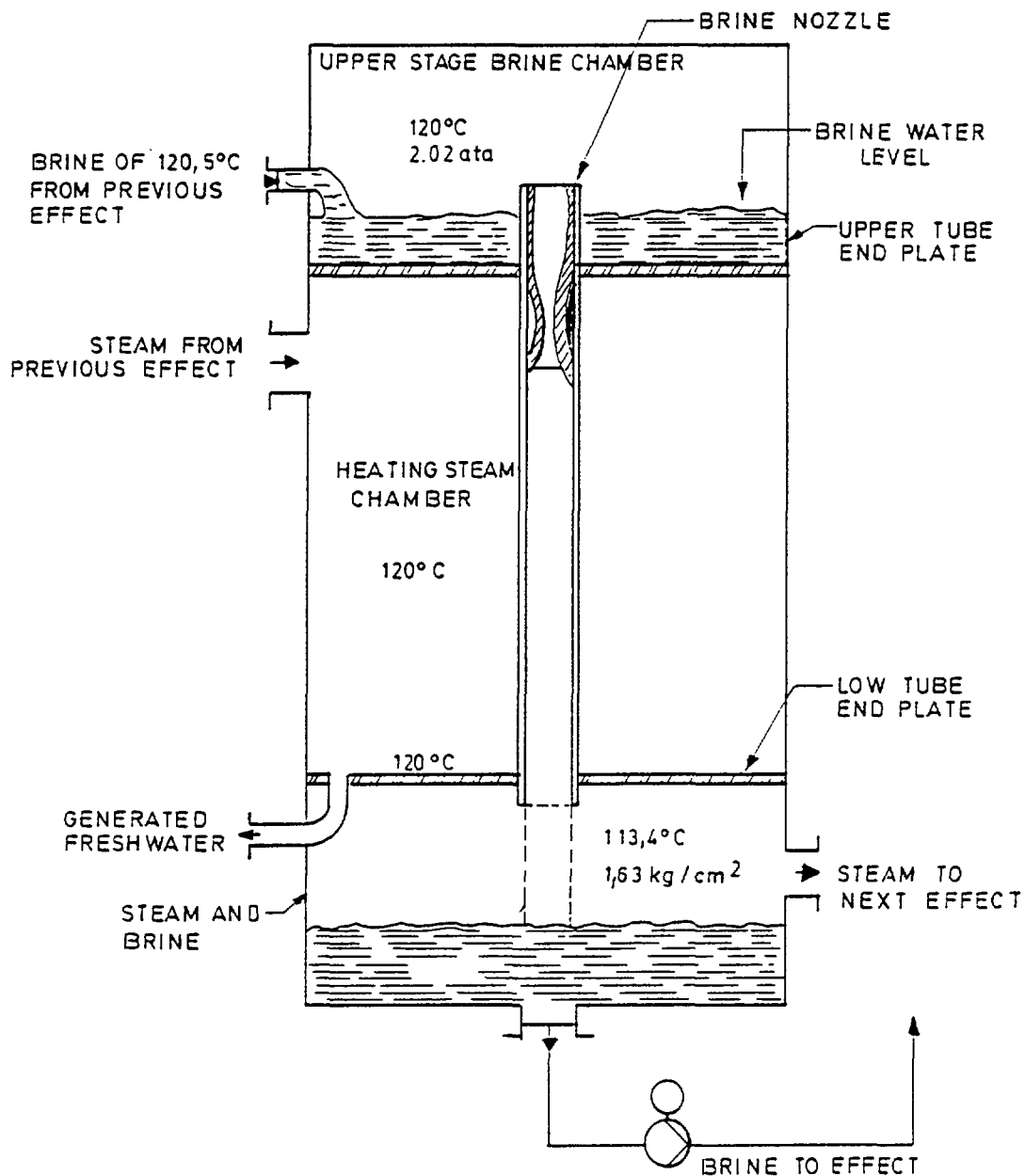
Fig. 11. Falling film evaporator — 1 effect basic principle.

A Falling-film evaporator (Figs. 11, 12) operates as follows. Heating steam enters the intertube space of the vertical heating chamber 1. It condenses there on the outer surface of heat exchange tubes, transferring heat to seawater, flowing downwards inside the tubes as a film. At the inlet upper end of heat exchange tubes, distributing devices are installed to uniformly distribute liquid over the tubes. A great variety of distributing device designs exist. After the heat exchange tubes, seawater together with the vapour formed enters the separator 2. Here, seawater droplets are separated from the vapour with the help of demister 3, then part of it continues as heating steam into the heating chamber of the following evaporator, and seawater from the lower part of the separator is

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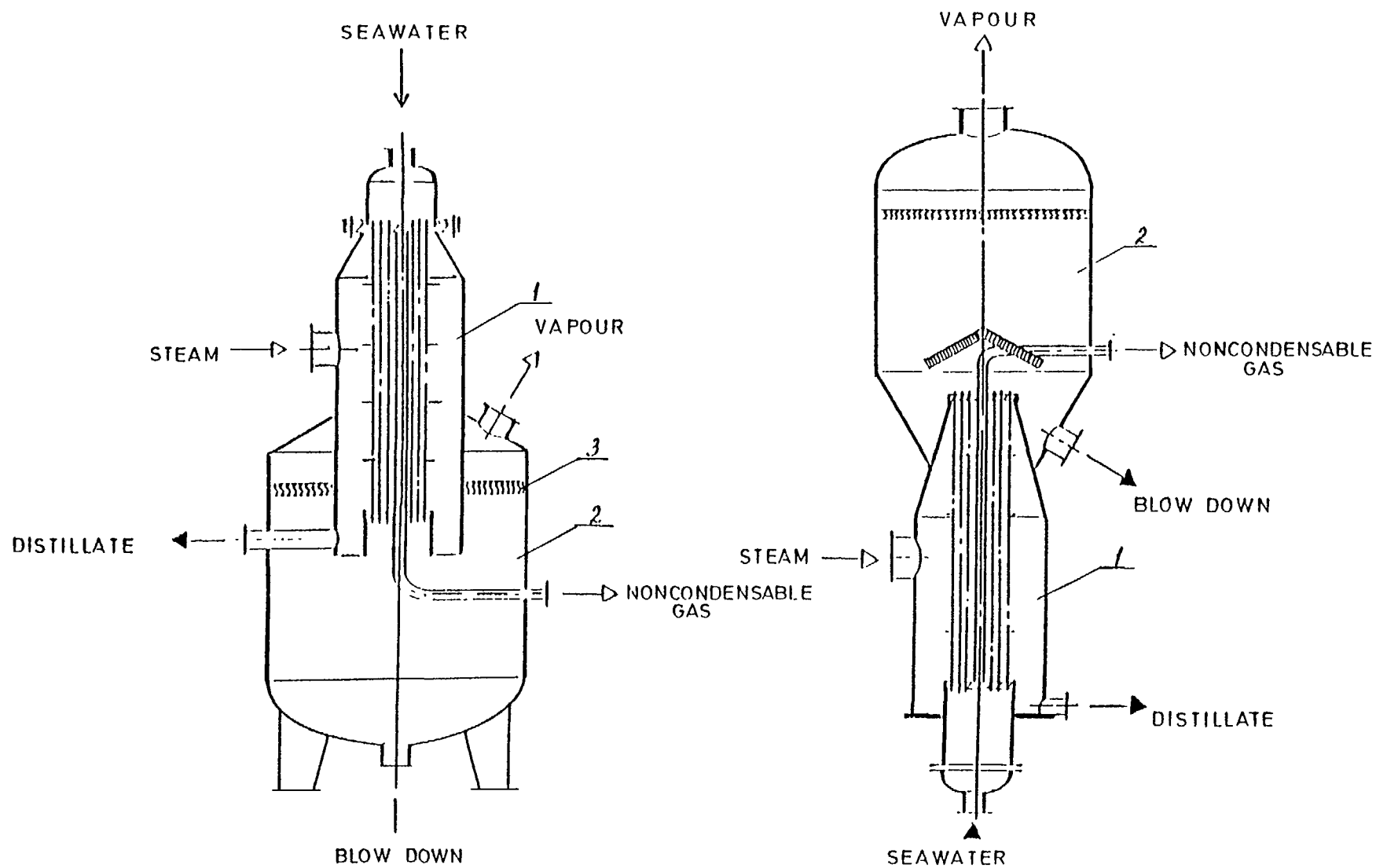
Fig. 12. Falling and rising film evaporators.
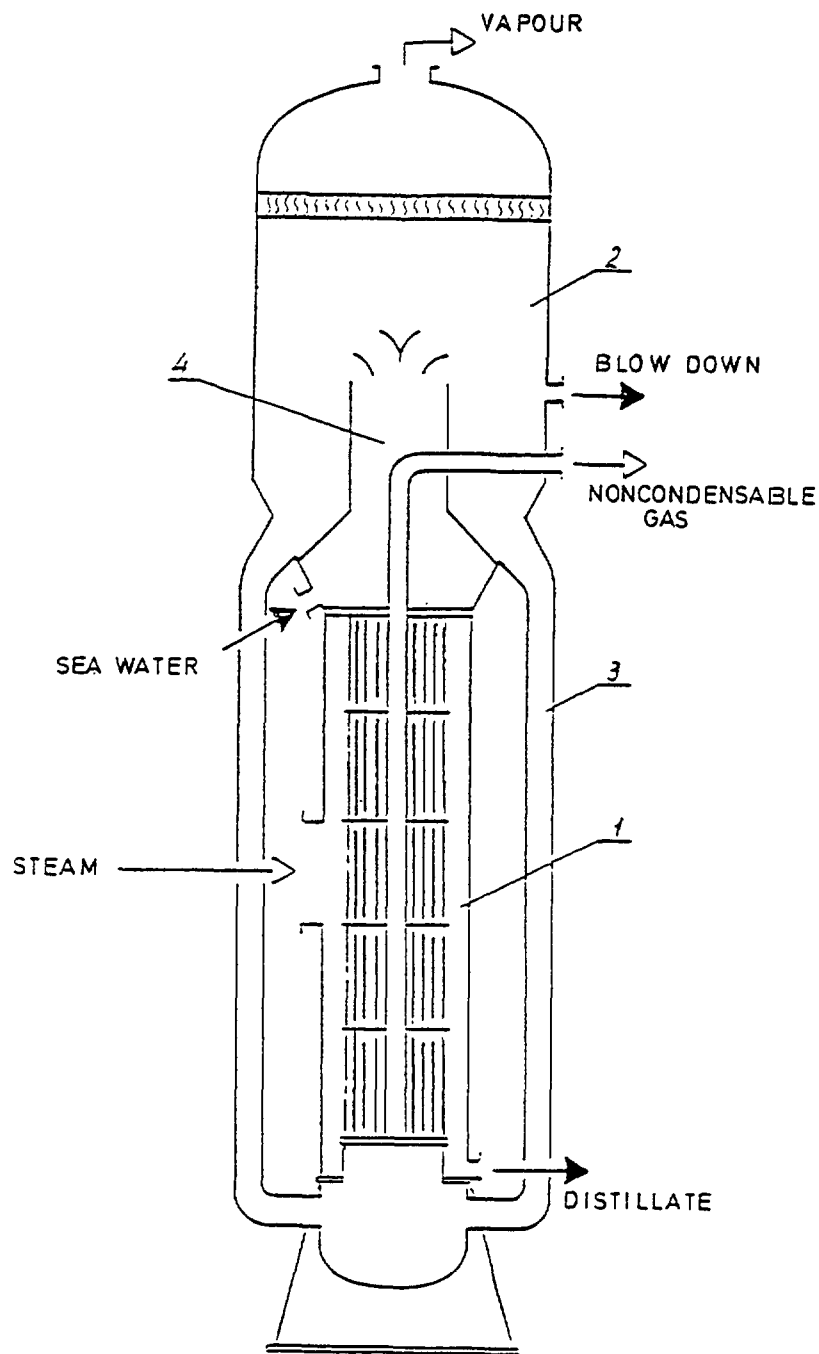
Fig. 13. Evaporator with natural circulation.

supplied via a pump into the distributing device of the next evaporator. The other vapour part is delivered into the regenerative heat exchanger, in which pre-heating of seawater entering the desalination plant occurs.

In a rising-film evaporator (Fig. 12), the main construction elements are a vertical heating chamber 1 and steam separator 2, arranged over the upper (outlet) ends of the heat exchange tubes. Heating steam is supplied into the intertube space, and within the tubes seawater flows vertically upwards. Condensation of the steam occurs outside the tubes and
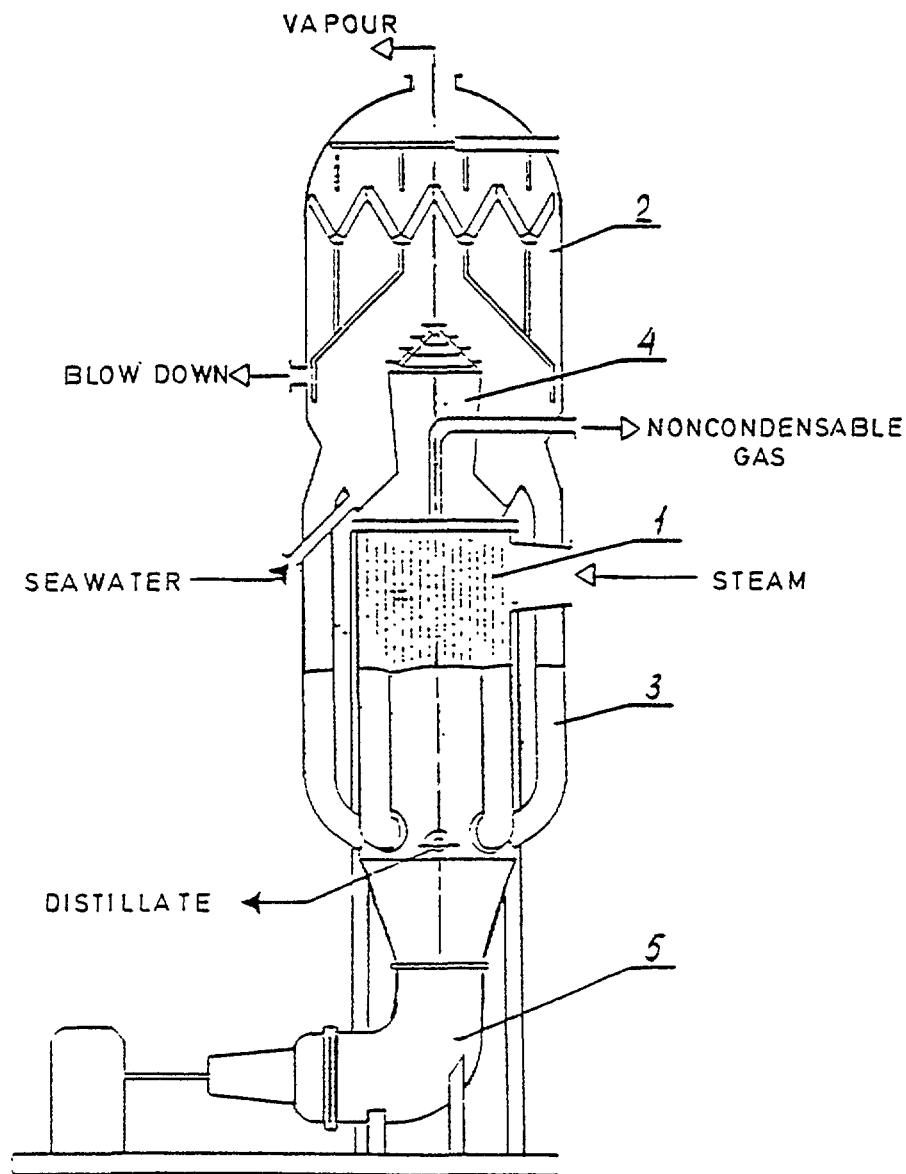
Fig. 14. Evaporator with forced circulation.

evaporation of seawater inside. Boiling creates a flow of seawater/vapor mixture inside the heat exchange tubes and creates a thin film along the tube walls. The mixture of steam and seawater is separated in the separator space with the help of splash separation devices. The purified vapour becomes the heating medium in the next evaporator's heating chamber.

The flow of the vapour/seawater mixture in the tube can be amplified by injecting a surface active agent to initiate foaming of the seawater, which enhances heat transfer and results in a lower film temperature drop.

Evaporator with natural circulation (Fig. 13) differs from the rising liquid film type in that the lower part of the separator 2 is connected by means of a circulation tube 3 with the lower solution chamber. This

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results in partial overflow of the seawater being evaporated into the following evaporator, however most of the liquid enters the lower chamber of its own effect. In certain designs a lifting tube 4 is installed over the heating chamber 1. It provides for the removal of liquid from the heat exchange tubes, and contributes to increase the liquid circulation velocity inside the evaporator. The heating steam is introduced into the intertube space of the heating chamber of evaporator 1 as in the previous designs. The heat transfer in a natural of circulation evaporator can also be improved by the injection of a surface active agent creating multi-phase flow conditions.

In the evaporator with forced circulation of liquid (Fig. 14), a circulation pump of special construction 5 provides the forced circulation of seawater along the loop, which consists of a lower chamber, tube space of the heating chamber, lifting tube, separator, circulation tube, and circulation pump which is installed in the circulation tube.

3.3.3.2.2. Current Status and Future Developments

A 12-stage falling-film evaporator demonstration desalination installation in Freeport, USA, is an example of the VTE process. In 1971 this installation was overhauled. Instead of the first seven effects with flatwalled heat exchanger tubes, heat exchangers with double fluted tubes were used. Instead of regenerative shell-and-tube heat exchangers, a Multi-Stage Flash (MSF) plant was installed, having spirally arranged heat exchange tubes of 22 mm in diameter [17]. The VTE/MSF hybrid arrangement, realized in the overhauled desalination installation in Freeport, was considered at the beginning of the 70s as a major step towards process efficiency improvement. Other examples of the application of VTE processes follow.

The installation in Fountain Valley (USA), which was put into operation in 1973, represents a 4-stage demonstration module with the capacity of 475 m^3/h for a finally intended 16-stage installation with a total output of 2400 m^3/h [18]. In this installation the same improvements were applied as those in the overhauled one in Freeport, MSF preheating, fluted heat exchange tubes in VTE evaporators, spirally arranged tubes in the MSF preheater.

In Gibraltar, in the same year, an installation with an output of 1385 m^3/d, was put into operation with 13 stages [19]. The installation

"MEDA" was built with an output of 5000 m^3/d, using mechanical steam-compression and a VTE foamy upwards-flow arrangement with the aim of reducing heating steam consumption [3].

In the Virgin Islands a 7-stage installation with an output of 3000 m^3/d was put into operation in 1969, and two 17-stage installations each with the capacity of 8500 m^3/d in 1975 [20].

In Italy [3] and Japan [21] desalination installations of the VTE process with the vertical evaporators arranged over each other were developed. Such an arrangement requires the use of only one pump for seawater, whereas in the horizontal arrangement the number of the seawater pumps corresponds to that of the evaporation stages.

The installation "Snamprogetti" has been assembled at an oil treatment plant in Taranto (Italy); the output is 1440 m^3/d. A 4-stage installation with an output of 50 m^3/d has been assembled in Japan. In this installation the regenerative heat exchangers are made as coils mounted directly in the steam space of each stage with the aim of decreasing the installation dimensions and the land surface being occupied.

The improvement of the VTE process with falling liquid film evaporators may occur according to the following trends.

Firstly, the replacement of the metal heat exchange surfaces by those made of thin polymer films. In France an evaporation installation was developed, made according to the countercurrent flow of the heat exchange medium (steam-seawater), in which plastic films with a thickness of 0.1 mm were applied. On the basis of plastic stability to aging and hydrolysis, the temperature in the first stage is limited to 70°C [22]. Development work is also being carried in the USSR. At present an installation for processing highly mineralized effluents of a metallurgical plant is in operation. The installation consists of 6 effects, operating in cocurrent flow with an output of 50 m^3/h. The heat exchange surfaces are made of polypropylene sleeves, 30 mm in diameter with a wall thickness of 0.06 mm. The temperature at the first stage is 90°C.

Applying surface-active agents to seawater may provide foaming flow evaporation. This method was suggested by Kirschbaum and H. Sephton. It was tested in industrial-scale on "MEDA", and an important increase in heat
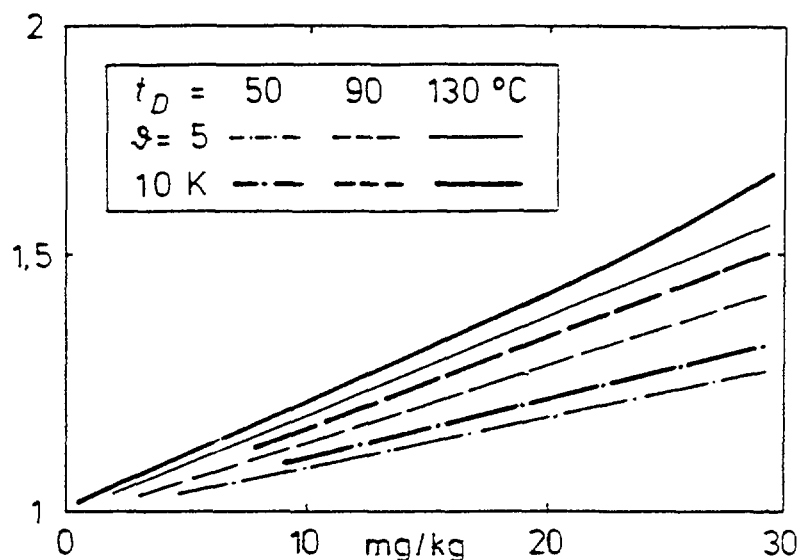
Fig. 15. Influence of amount of surface active agent on heat transfer.

transfer factor was obtained in comparison with plants without surface-active agents. Improvements in heat transfer coefficient corresponded to > 1% per 1 ppm of surface active agent (see Fig. 15).

Thirdly, an orbital-tubular evaporator is being developed. Basically it is the same falling film evaporator, but installed in a platform, performing rotational-vibrational movement around a vertical axis. For further increase in the heat transfer factor a rod is inserted into each heat exchange tube, that contributes to the formation of a uniform thin wetting liquid film inside the tube. Tests with a three-tube and a 12-tube evaporator have proved their high efficiency.

Fourthly, partial replacement of falling-film evaporators with a rising liquid film type. The aim of such a replacement is to reduce the number of seawater pumps. The Japanese company "Ishikawajima-Harima Heavy Industries Ltd" has developed the installation" Rising Film-Falling Film Evaporator (RF-FF)", in which a high temperature apparatus uses the rising film and a low temperature one the falling film.

The same company has developed a 10-stage installation, equipped with rising-film evaporators with an output of 1700 m^3/d [3]. The heat exchange surface in these evaporators is made of double-fluted tubes.

Rising-film plants are more widely used for desalination installations in the USSR. A desalination station with an output of 2600 m^3/h is being assembled in Tobolsk for the preparation of make-up water for high pressure

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boiler units (14 MPa). The station comprises four 9-effect installations, in which from one to six effects use the rising film, and the final three use forced solution circulation; each installation has a nominal output of 650 m^3/h. The first installation was put into operation in 1975, the second in 1988, the third is being assembled with a start-up planned for 1990, and the fourth one in 1992. In 1986-1988 at the industrial complex "Uralelectromed", four 6-effect desalination installations were put into operation. These installations were intended for treatment of mineralized process effluents. The output of each of these installations amounts to 100 m^3/h. In the first five effects the rising-film principle is applied and the last, the sixth one, uses the forced circulation of liquid. The heat exchange surfaces are made of tubes with longitudinally-fluted external surfaces and smooth internal surfaces.

The 9-effect desalination installations, erected at the Turkmen nitrogen-fertilizer plant (Mary town), are equipped with the same apparatus. In these installations the first eight effects are the rising film type, and the last, ninth one, uses forced circulation. The output of each installation amounts to 100 m^3/h. Two installations will be put into operation in 1990 and two more - in 1992.

To further improve, rising liquid film apparatus, H.Sephton [23] suggested adding a small amount of surface-active agent to the seawater. Test results indicate an increase in the heat transfer factor of such systems by a factor of 2.

Evaporators with natural solution circulation were used in the USSR [24]. The 4-effect installations with an output of 160 m^3/h [22] were put into operation in 1963. On the basis of operating experience, more efficient 5-effect desalination installations were developed and put into operation in 1967, 1969 and 1970: three installations in the town of Shevchenko, each with a capacity of 600 m^3/h, and one in Krasnovodsk in 1975 with a capacity of 550 m^3/h [3]. All these installations provide fresh water for every-day use and industrial purposes from Caspian seawater.

Improvement of the desalination installations was accomplished by increasing the number of effects, and by using the forced circulation principle at the last effect, by the application of longitudinally-shaped heat exchange tubes, and by the development of efficient low cost scale prevention methods. In 1975-1981 for the treatment of mineralized

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wastewater of Pervomaisk Chemical Combinat (Kharkov region), the oil refinery in Lisichansk, Ufa, Angarsk, the metallurgical plant in Sverdlovsk, various plants have been installed, for example, a seven effects plant with an output of 135 m^3/h (three installations at the Pervomaisk chemical Combinat) and a six effect plant, having an output of 160 m^3/h (per 2 installations at each oil refinery). At the metallurgical plant, two 6-effect installations with the output of 100 m^3/h have been installed. The first four effects of this installation use natural circulation (the mineralized effluents are processed in them), and the following two with forced circulation (the mineralized oil-laden effluents and the blowdown of the first four effects are processed in them) [18].

The first attempt to use forced circulation evaporators for desalination purposes was undertaken on the fourth demonstration installation by OSW at the Roswell testing ground in New Mexico, USA. The installation, consisting of two effects, each installed in a separate evaporator vessel, was equipped with a mechanical steam compressor by which the vapour of the second effect was introduced as heating steam into the heating chamber of the first evaporator vessel. It was put into operation in 1963; a distillate production of 3785 m^3/day was planned using underground water [25].

The main type of the installations, used for distillate production plant (DPP) in the town of Shevchenko are a 10-effect units with forced circulation, having an output of 600-620 m^3/h. From the total present output of the DPP of 140 000 m^3/d, approximately 120 000 m^3/d is obtained from 10-effect installations. Their erection began in 1971 and has continued at one installation every two years. The improvements, developed on the basis of the operating experience of the preceding installations [26], were introduced into the design and technological process of each of the subsequent installations. The installations of the same type, but somewhat adjusted according to local conditions, were put into operation in 1979 in Krasnovodsk (one installation), and in 1989 in the Republic of Yemen (two installations).

3.3.3.2.3. Energy Requirements

The energy sources, required for the accomplishment of desalination by the VTE process, are thermal (steam, waste heat), electric power and

cooling water. The thermal energy is usually supplied to the installations as steam. The use of hot water or waste heat is also possible.

The consumption of the types of energy listed above depends on the local conditions for which the desalination installation was built. In regions with relatively cheap thermal power, installations with a small number of effects are built, resulting in relatively inexpensive installations. The optimum number of effects is determined by the minimum of operating plus capital costs required for the production of 1 m^3 of distillate. For the desalination installations in operation today, the number of effects varies from 1 to 24, and specific heat consumption is in the range from 30 kW(th).h/m^3 to 600 kW(th).h/m^3. A relatively small additional amount of heat is supplied to the desalination installation as steam at high pressure, usually at 1.0–2.0 MPa. This steam is necessary for the operation of the vacuum unit; it amounts to 2–6% of total steam consumption.

Electric power is consumed in desalination installations for pump drives, seawater, chemical reagents, distillate including solution recirculation, and pumping-out distillate, heating steam condensate from the installation, and blowdown. At some installations, vacuum liquid ring pumps and water-jet ejectors are used, which also consume electric power [26]. The total consumption of electric power for the desalination installations of the VTE process amounts to 1.5–4.5 kW(th).h/m^3 of distillate.

The quantity of cooling water fed to the desalination installation depends on the specific heat consumption and cooling water temperature. Specific consumption of seawater is in the range 2.5–10.5 m^3/m^3 of distillate.

Technical and economic data for the VTE process are given below:–

Nominal technical-economic data for desalination installations of the VTE process

Output .... 50–16000 m^3/d
Number of effects 1–24
Specific heat consumption .... 30–700 kW(th).h/m^3*
Specific consumption of cooling sea
  water .... 2.5–10.5 m^3/m^3
Specific consumption of electrical power
  for simultaneously operating pumps .... 1.5–4.5 kW(e).h/m^3
Distillate salinity .... 0.05–25 ppm

* G.O.R. = 1 – 20

3.3.3.2.4. Pretreatment Requirements

The economic necessity for prolonged operation necessitates pretreatment of seawater before desalination. Depending on the evaporator design and local conditions, the pretreatment of seawater is done as explained in section 3.2.

3.3.3.2.5. Other Special Requirements

The efficiency and operating period between cleaning cycles for falling-film evaporators at higher temperature (90°C -130°C) depends greatly on the uniformity of liquid distribution over the heat exchange tubes. Distribution devices of different construction are installed in the inlet ends of the tubes to create the necessary uniformity of distribution. During erection the vertical position of the heat exchange tubes in the evaporator should be controlled. The evaporators with rising film and natural circulation are rather sensitive to the effective temperature difference between the heating steam and the liquid inside the tubes. For efficient and stable operation without pulsation, the useful temperature difference required should be equal to 5-12°C. The use of surface-active agents for rising foamy flow lowers this difference to < 2°C.

3.3.3.2.6. Investment Costs

The advantages of the VTE process are as follows:
- fewer effects at the same heat efficiency
- better quality of distillate produced
- good reliability and stability of the desalination process
- flexibility of operation over a wide range of outputs

According to cost investigations and operational experience gained at VTE and MSF plants working under similar conditions, distillate cost from VTE is slightly less than from MSF plants. On this basis, and taking into consideration the number of technological advantages mentioned above (stability, flexibility of operation, better distillate quality), desalination installations of the VTE process equipped fully or partially with forced circulation, have been the logical choice in several cases, for example in Shevchenko [27]. Practically the same costs are obtained as for HTME (1200 US$/$m^3$/day) under the same conditions.

3.3.4. RO – Reverse Osmosis

3.3.4.1. Description of Process and Equipment

Reverse Osmosis (RO) can be thought of as a filtration process at the molecular/ionic size level (see Fig. 16). It uses a semi-permeable membrane, meaning that the membrane permits the passage of solvent in either direction, but retards the passage of solute. Normal osmosis is a natural process by which water flows through such a membrane from pure water or from a dilute solution into a more concentrated solution. Every solution has a specific osmotic pressure which is determined by the identity and concentration of the dissolved materials. This flow continues until the resulting osmotic head equals the osmotic pressure of the solution.

If the solution compartment is now enclosed, and a pressure higher than the natural osmotic pressure of the solution is applied to it, the direction of water flow is reversed. The solution becomes more concentrated, and purified water is obtained on the other side of the membrane, hence the term Reverse Osmosis.

The rate of flow of purified water depends on various factors such as the chemical properties of the membrane polymer itself, membrane thickness, area, pressure, concentration, pH, and temperature. Under any set of fixed conditions, product flow is proportional to the difference between applied pressure minus the osmotic pressure of the solution, and the permeate pressure.

The small amount of dissolved material passing through the membrane, on the other hand, is not pressure dependent. It depends on the difference in concentration on the two sides of the membrane.

Two common terms used in discussions of RO are "salt passage" and "conversion" or "recovery ratio". "Salt passage" is the amount of dissolved material permeating through the membrane to the permeate side, expressed in percent. A term often used is "Rejection", which means exactly the opposite of salt passage.

"Conversion" is defined as the percentage of the solution which is recovered as purified water. Another term used for this is "recovery".

OSMOSIS
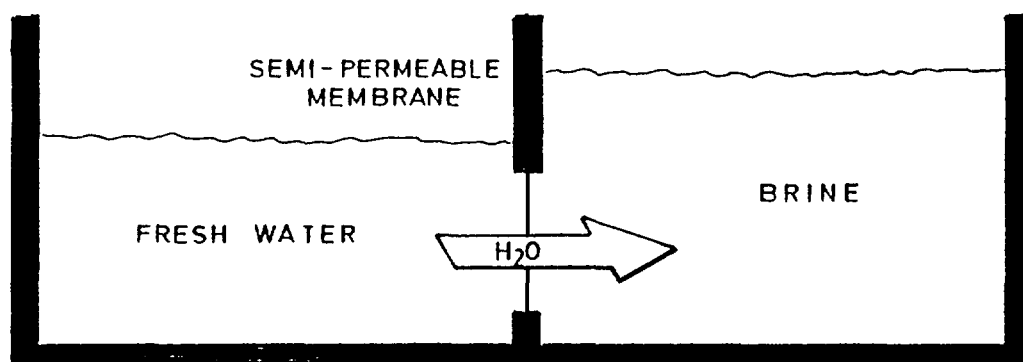
REVERSE OSMOSIS
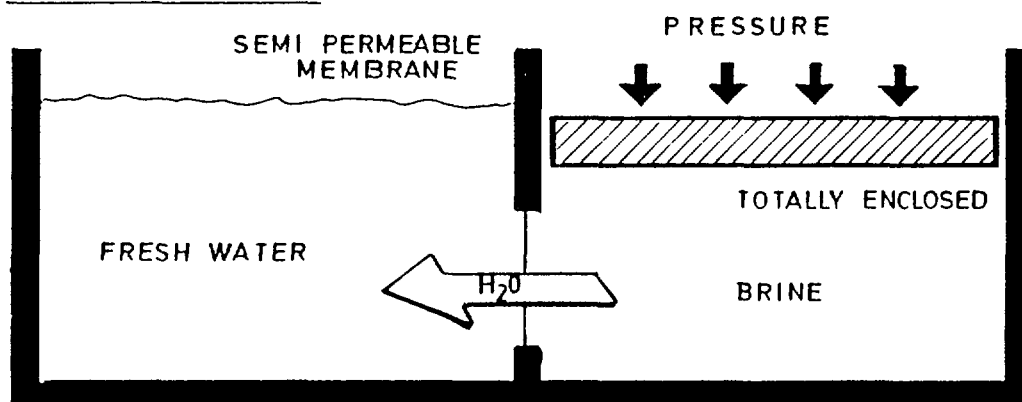
Fig. 16. Principle of reverse osmosis process.

Purified water, called permeate, or product water, is recovered at atmospheric pressure. The pressure of the concentrate, which is also referred to as brine, retentate or reject, is reduced to atmospheric pressure through a flow control valve, or more efficiently, in an energy recovery turbine or a reverse running pump.

In the Reverse Osmosis desalination process the solution, or feed, is pumped into a pressure vessel containing the membrane. Membrane modules are of tubular type, plate and frame type, spiral-wound type and hollow-fiber type. All of the module types have technological and cost advantages and disadvantages. The most widely used modules today are the spiral-wound and hollow-fiber ones. Plate and frame, and tubular modules offer overall cost advantages, if water with a high content of suspended matter or large amount of scale forming elements is used.

RO plants for seawater desalination usually are operated with a conversion of about 20-50%.

Some of the basic principles of RO with composite membranes which influence operation are given below:

a)   As conversion is increased, so is the concentration of the brine, and the osmotic pressure. The increase in average osmotic pressure reduces the driving force and then the flux (ie. fresh water flow per unit area). Increase in brine concentration also results in increased salt passage, and poorer product quality. (see figure 17a).

b)   With increased temperature the flux is increased as well, whilst the salt rejection is reduced. Increasing the temperature from 25°C (an average seawater temperature in the Middle East) to 50°C results in a flux increase of about 100%, including the negative effect of the higher temperature on the osmotic pressure and compaction behaviour of the membrane (see figure 17b).

c)   Increased feed pressure results in higher fluxes, as the flux increase is nearly directly proportional to the increase in useful pressure difference (ratio of actual feed pressure minus osmotic pressure minus losses and the permeate pressure). The increase in the feed pressure also reduces salt passage, and increases the compaction of the membrane (see figure 17c).

d)   A pH-value between 3 and 10 has a slight influence on the flux (except CA-membranes), but a large influence on the salt passage (see figure 17d).

e)   The concentration of seawater varies from about 35 000 ppm Total Dissolved Solids (TDS), to as high as 60 000, TDS. In the Arabian Gulf, for instance, TDS are about 50 000 ppm. A rough approximation is that each 1000 ppm (mg/l) of solute contributes about 0.7 bar of osmotic pressure, so the osmotic pressures are in the range of 25 to 40 bar in the feed, and subsequently higher. Thus, a conversion ratio of 50 percent would roughly double the concentration of the brine, resulting in an average osmotic pressure in the brine 1.5 times greater than that in the feed, and at the end of the module an osmotic pressure 2.0 times greater. This means that with a feed water of 50000 ppm and a conversion of 50% the osmotic pressure at the end of the module would be about 70 bar. To this osmotic pressure, a pressure loss of 5-10 bar in the module itself should be added.

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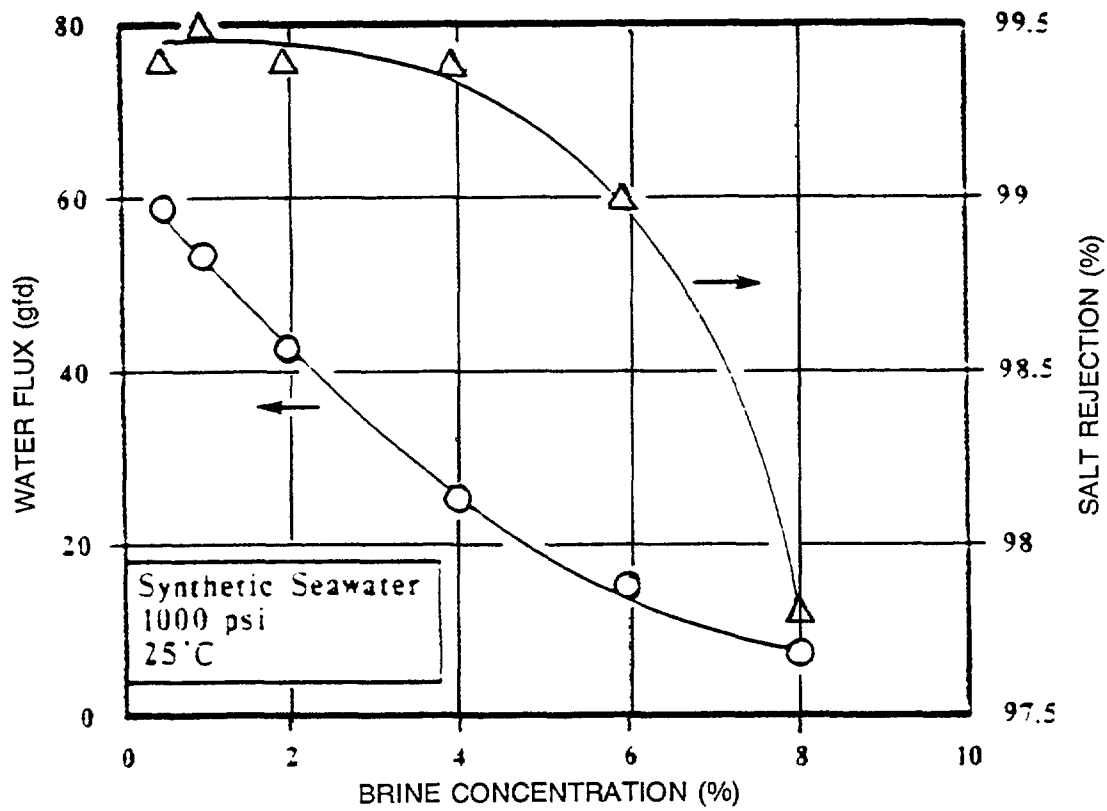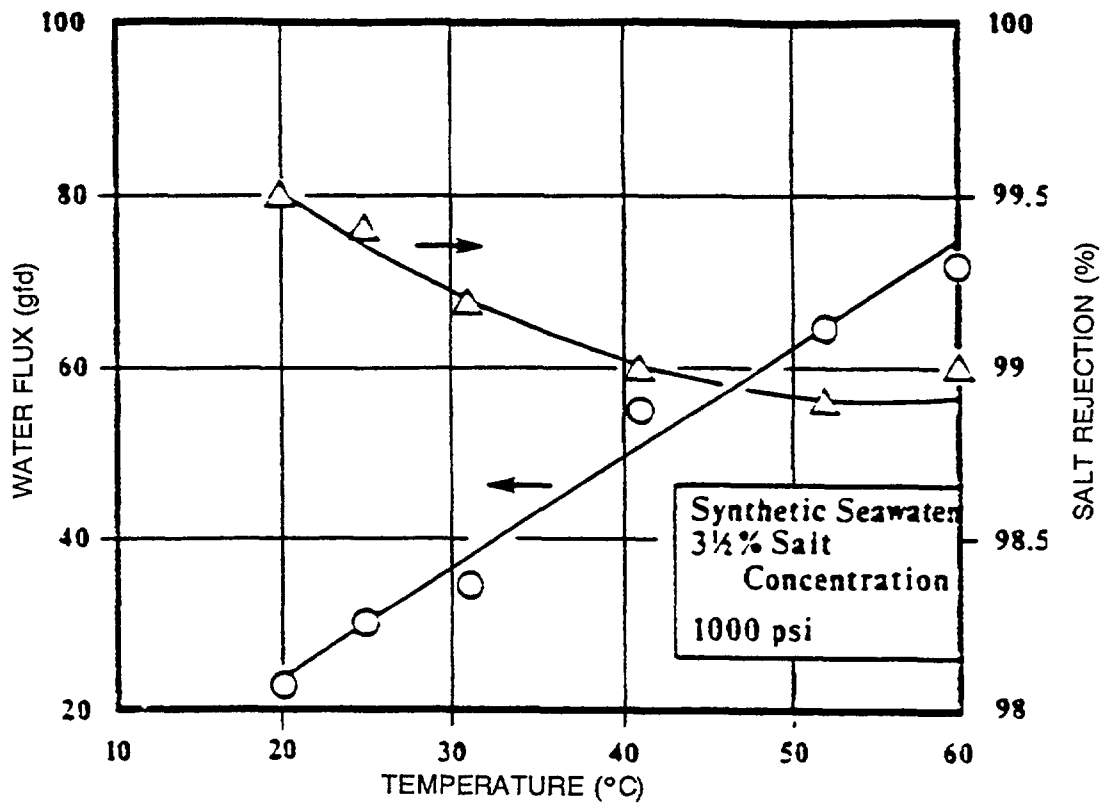
Fig. 17-1. Water flux and salt rejection as a function of temperature.
Water flux and salt rejection as a function of brine concentration
(according to Cadotte, Peterson, Larson, Erickson) (1980).
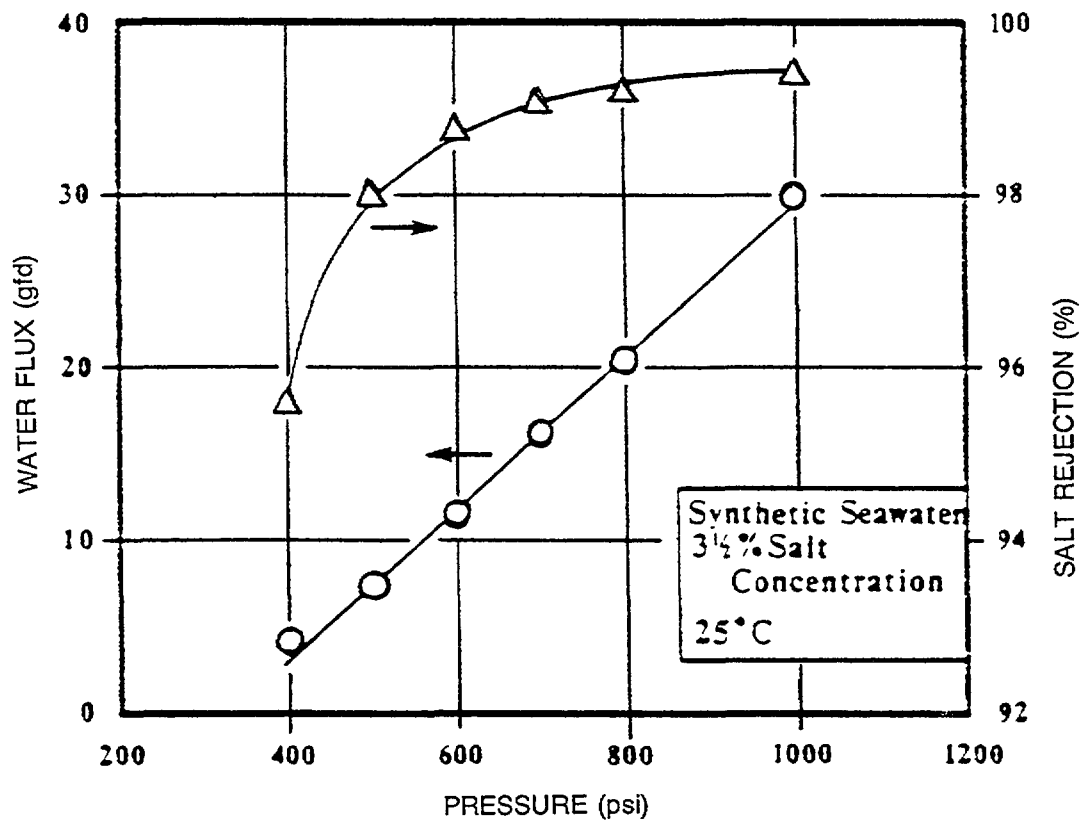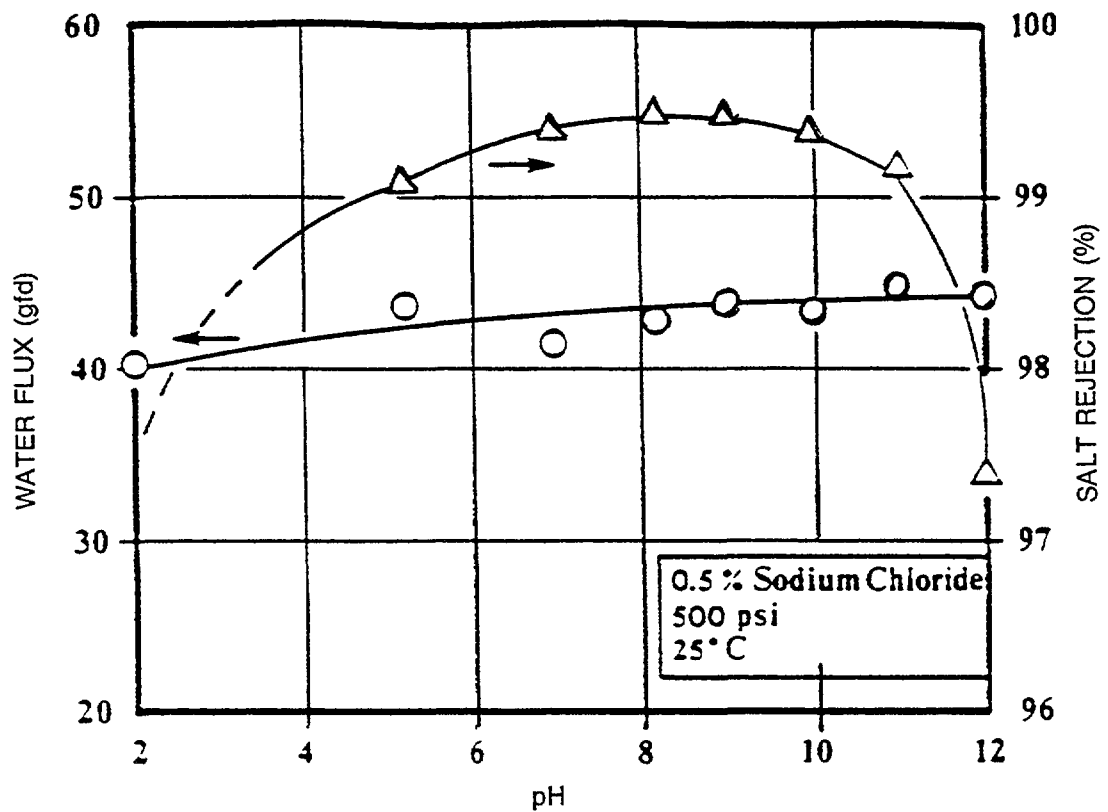
Fig. 17-2. Water flux and salt rejection as a function of pH.
Water flux and salt rejection as a function of pressure
(according to Cadotte, Peterson, Larson, Erickson).

f)   With better prefiltration a higher flux is achieved and a longer
     lifetime of the membrane.

g)   Two stage systems, with optimized design parameters, may result in
     lower water cost than single stage systems, especially when water with
     high salinities and high pollution is used, and the EC drinking water
     standards have to be fulfilled.

It can be concluded from these observations that modules able to
operate at high pressures are needed, and that there will be physical and
economic limitations to the conversion ratio (see Fig. 18). The pressures
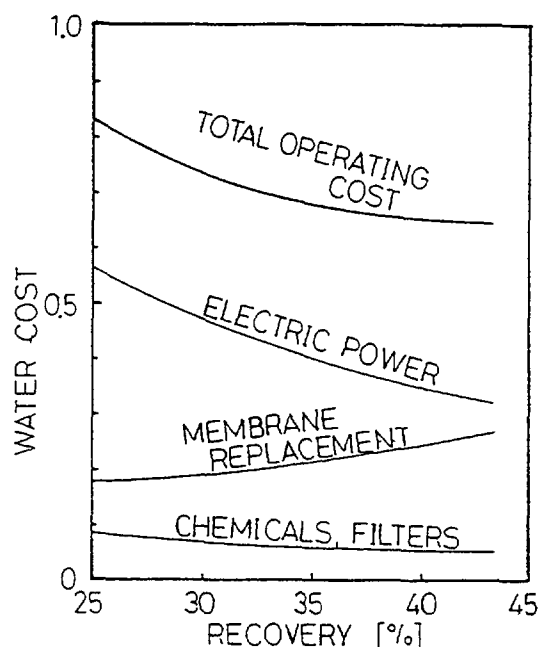
Fig. 18. Effect of recovery on operating cost.

used in seawater RO range normally from about 55 to 70 bar, and the
conversion ratios range from 20 percent to 50 percent. In the case of feed
water with 50000 ppm TDS and 50% conversion ratio, the minimum pressure at
pump discharge should not be less than 80bar, if the losses are 5bar. A
pressure of 70 bar at pump discharge would limit the conversion ratio to
41%. This is in marked contrast to RO for brackish waters containing only
a few thousand ppm (mg/l), where operating pressures of 10 to 20 bar are
adequate, and conversion ratios can range from 60 to 95%.

A RO desalination plant consists mainly of a pre-treatment section, a
high pressure pump section, a membrane module section and a post-treatment
section. Figure 19 shows the principle arrangement of RO-systems with
second generation chemically resistant membranes.
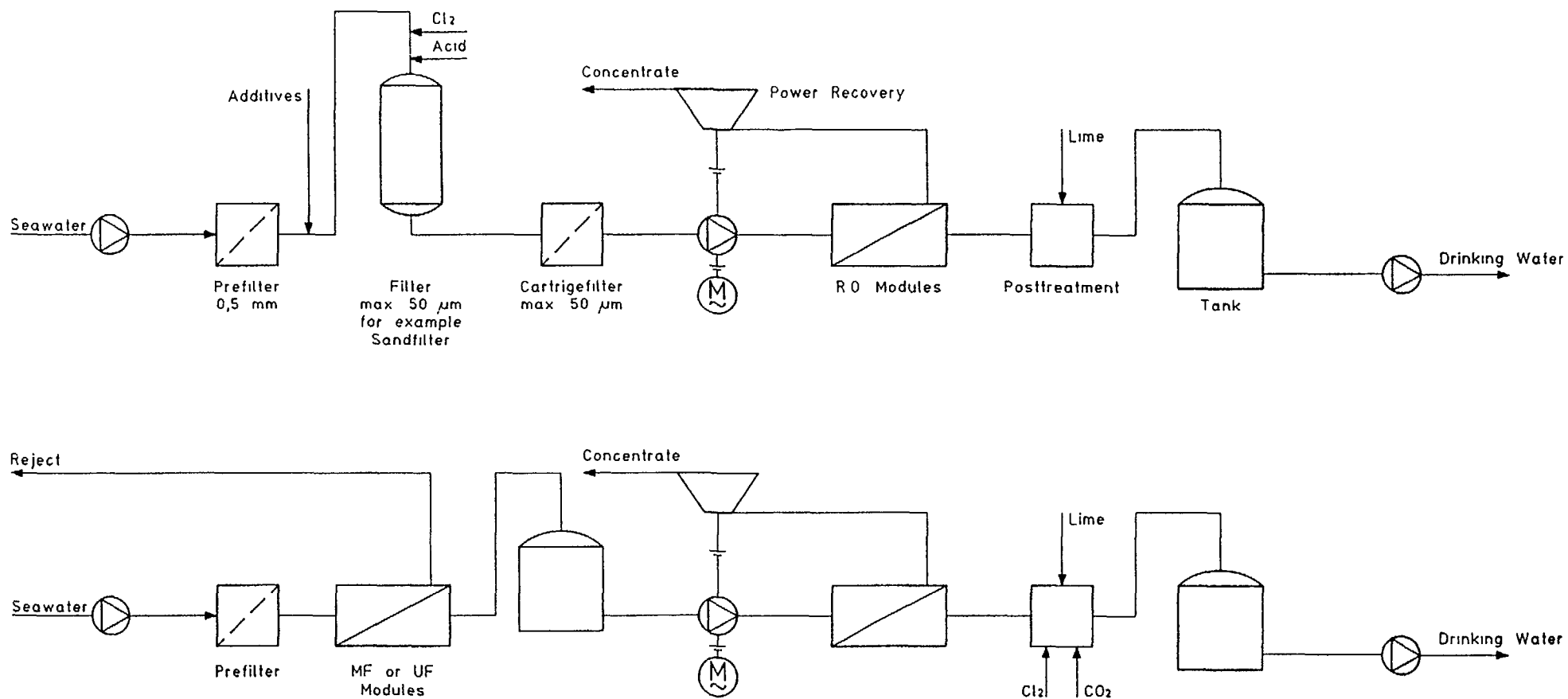
Fig. 19. Principal arrangements of R.O. systems with second generation R.O. membranes (recovery: 35-48%, specific power consumption: 5-6 kW·h/m³).

3.3.4.2. Current Status and Future Developments

The RO desalination process was developed into a commercial process in the USA in the 1960s, and a first test plant was built in 1965. Since its commercial application to seawater in 1970, plants of larger and larger capacity have been designed, constructed and operated successfully.

The first large scale industrial plant having a capacity of 12 000 m^3/day was built at Jeddah, Saudi Arabia by UOP of the USA, and operated for few years since 1979 before overhaul. Thereafter, a plant of 45 000 m^3/day was constructed at Al Dur, Bahrain by Weir Westgarth of the UK. This plant was completed, but does not operate under commercial conditions. Construction of the largest plant in the world with a capacity of 56 800 m^3/day was finished at Jeddah, Saudi Arabia by the Japanese Company Mitsubishi Heavy Industries Ltd, and has successfully operated since April 1989. This plant, Jeddah-1 Rehabilitation Phase I, is a replacement for the old Jeddah-1 MSF plant in operation since 1970. Even though the product water was envisaged for blending with product water from other MSF plants, it has a quality of 120 ppm TDS starting from Red Sea water with 43 300 ppm TDS. Construction of Phase II with the same capacity is planned.

Recently studies have been made for two large RO seawater desalination plants powered by nuclear power plants, as explained in section 4.2.2. and 4.3.2 of this report. One has a capacity of 100 000 m^3/day and is powered by Modular High Temperature Gas Cooled Reactors, the study being started in 1985 by Howaldtswerke-Deutsche Werft AG and Interatom GmbH of the Federal Republic of Germany. The other has a capacity of 3 000 000 m^3/day and is powered by Liquid Metal Cooled Fast Reactor Modules, designed by CRIEPI of Japan.

Two plants with a capacity of 130 000 m^3/d each will be constructed in Saudi Arabia in 1991. (Information obtained from published Tender results).

All modern large scale RO plants in general use power recovery turbines. In smaller plants reverse running pumps or pressure changing devices are used. Power recovery turbines of the Pelton type have efficiencies of more than 90%. Assuming a conversion ratio of 40%, a pressure loss in the module of 10 bars, a feed pressure of 70 bars, and a

pump efficiency of 75%, then about 35% of the power required to drive the feed pump can be recovered with a Pelton turbine. In smaller plants with reverse running pumps a recovery of about 30% can be obtained. Power changing devices, which use the retentate to operate a piston pump, can recovery 35% or slighly more of the pumping energy. Over the operating period or life time of the membrane (between 3 - 6 years), the membrane "ages" and flux decreases while salt passage increases. This effect can be offset partially by increasing the operating pressure. In order to avoid oversizing pumps and drives by throttling the unused pressure at start of life, some plants now use speed control for optional efficiency and to facilitate start-up and automation of the system.

A new generation of membranes with better chemical stabilities (stable over a wider pH-range, higher temperature tolerance, better stability against compaction, lower inner pressure losses, slightly higher specific fluxes) are now on the market. These new membranes will reduce the cost of plants and make them more reliable.

New membrane manufacturing techniques, such as plasma polymerization or radiation induced grafting, may allow in the next 4 to 10 years, use of new classes of polymers capable of operating at higher specific fluxes, temperatures to 100°C, with high chemical stability and antifouling behaviour. Improved backing materials will allow production of composite membranes with a very high resistance to compaction. New low-priced tubular micro-filteration membranes with a certain permanent surface charge will simplify pretreatment, largely eliminating the use of chemicals, and provide a high quality of water. This again will allow operation at higher pressures resulting in a lower energy consumption. A conversion ratio of 50% for seawater desalination will become more common.

In general, the above trend will reduce operation and capital costs and therefore specific water costs.

3.3.4.3.   Energy Requirements

The energy required for RO seawater desalination is not thermal heat but mechanical power. This can be supplied by electric motors or directly by shaft power from turbines or diesel engines.

The energy requirement depends largely on local conditions such as salt content, temperature of the seawater, and on the overall plant design,

e.g. on the pressure required or the conversion rate chosen. Also, the type of membrane and the frequency of their replacement affects the energy requirement.

The total energy requirement usually is about 7 to 10 kW(e).h/m^3 of product water. About 85% of the energy consumption is required for the high pressure pumps. About 30% of the energy input can be recovered with energy recovery equipment. This percentage increases as the plant size increases because the pump and motor efficiencies improve with sizes. Thus, the energy requirement of RO plants with energy recovery system amounts to about 4 - 7 kW(e).h/m^3.

3.3.4.4. Pretreatment Requirements

Successful long-term performance of RO systems depends largely on proper pre-treatment of the feedwater. As almost all untreated water will foul the system, the purpose of pre-treatment is to eliminate or minimize fouling. All aspects of fouling involve trapping material within the fiber bundle or on the surface of the membrane. Depending on seawater quality and the chosen type of membrane, fouling can be caused by different phenomena and thus pre-treatment has to be different from case to case.

3.3.4.5. Other Special Requirements

Compared with distillation processes, the RO process has the following advantages:
-   Low energy consumption
-   Simplicity of operation and relatively low maintenance cost
-   Low land and space requirements
-   Reduced equipment corrosion problems due to ambient temperature operation
-   Short construction period
-   Short start-up period when in operation
-   Ease of partial load operation due to modularization.

3.3.4.6. Investment Costs

The investment costs for RO seawater desalination plants given in the literature vary over a broad range. Some examples are given in the following table:

Plant	Capacity 1000 m^3/d	Investment 10^6\$	Cost \$/m^3/day of product water
Malta, Ghar Lapsil[28]	20	17.5	875
Jeddah[29]	12	31	2580
Tanajib[29]	13.6	38	2790
Key West[29]	13.3	10	885
Bahrain[29]	45	110	2440
Jeddah - 1 Rehab.[30]	56.8	43	760
Yanbu/Medina	2 X 130	250	960

It can be assumed that a turn key plant, without seawater intake and excluding power production, will produce water in the range of 1000 to 1200 US\$/m^3/day using second generation membranes.

3.3.5. Other Thermal Processes

Beside MSF and MED plants, many other thermal desalination systems have been proposed, and some have even been extensively investigated, as discussed below:

a) Freezing Processes

Of the various freezing processes the VFVC - Vacuum Freezing Vapour Compression process (see Figs. 20, 21) has been regarded by many experts as the most promising process. The process works as follows. When saline water gradually freezes, the ice crystals that form are salt-free. By freezing about 30 to 50% of the fresh water contained in the saline solution, the solid-liquid phase difference simplifies mechanical separation of the theoretically salt free ice from the brine. The separated ice is then melted to obtain fresh water. The separation step, which can be executed for example by simple screening, has to be followed by a cleaning step for example by cross or counter washing or centrifugation.

In the VFVC-process, latent heat of fusion is given up when pre-cooled feedwater is introduced into the chamber under low pressure. Figure 22 gives the schematic flow diagram of the process. Feedwater is pumped into the system after deaeration, cooled down by cold product water and cold brine leaving the plant, and fed into the freezer where a simultaenous boiling-freezing process takes place. The low pressure causes the water to boil and part of it evaporates, extracting heat
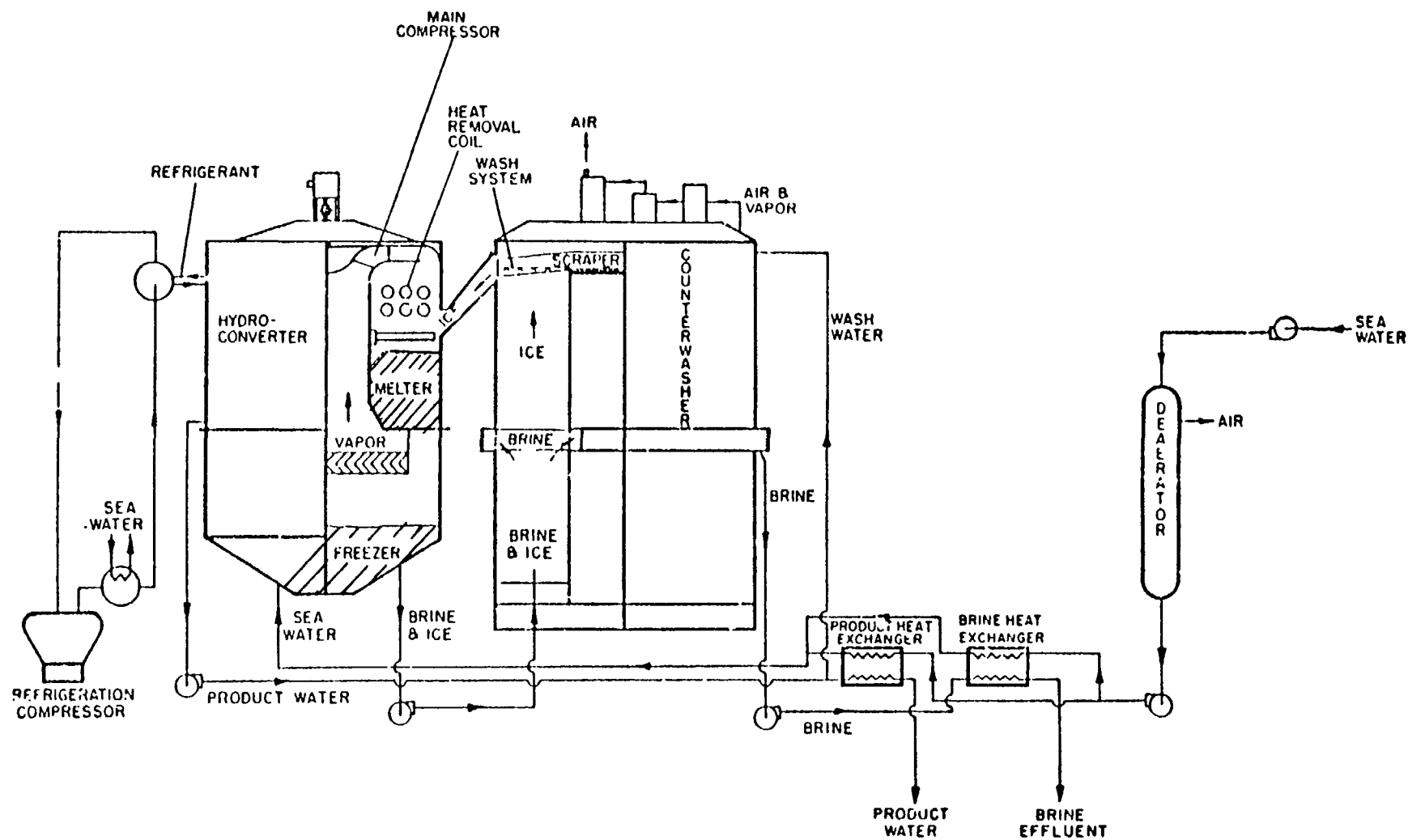
Fig. 20. Colt Industries (Fairbanks Morse) VFVC process.
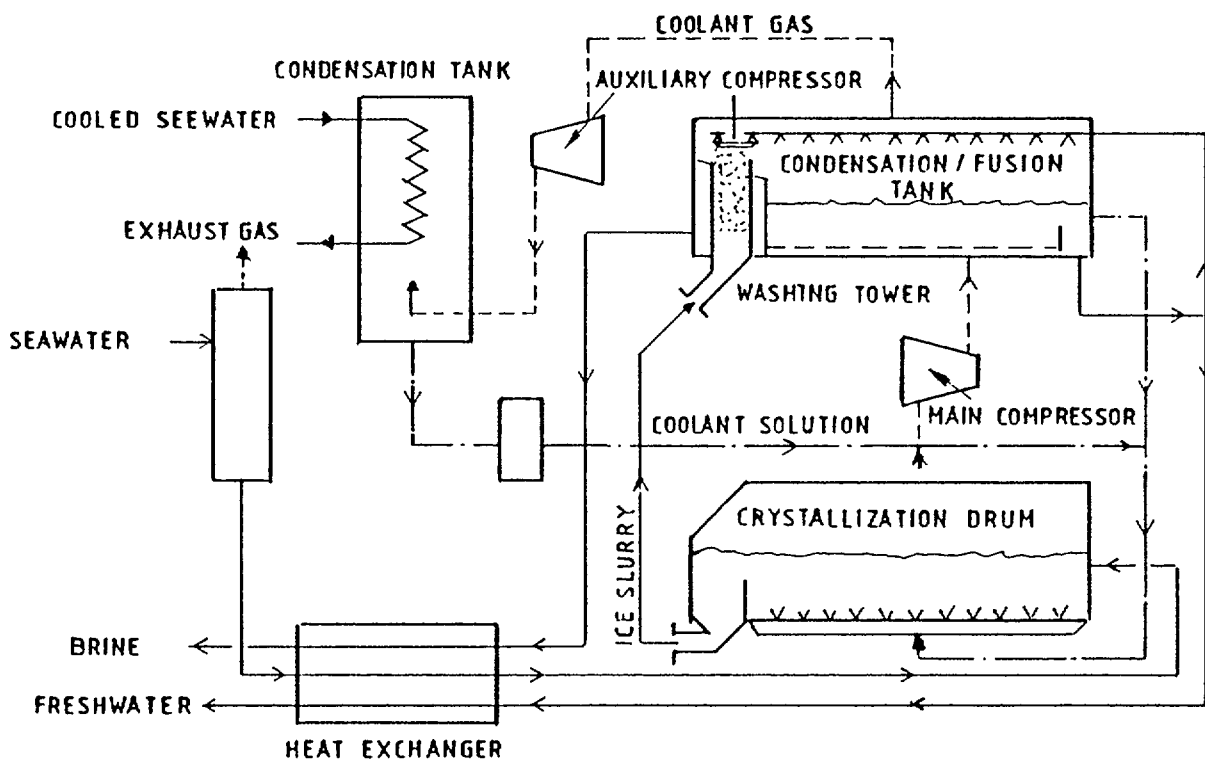
Fig. 21. Improved direct contact freezing process.

from the remaining feedwater, part of which freezes. The water vapor produced in the freezer is compressed by means of a mechanical vapour compressor and discharged at about 0.5°C higher temperature into the melter. This vapor condenses on the screened out and washed ice. The melted ice is the product. Other methods for heat pumping have been tested and various test plants in a range up to 1000 m^3/day product water have built.

Freezing processes have many theoretical advantages. The main advantage is that the latent heat of freezing is about 8 times lower than the latent heat of evaporation. Theoretically this means that for the direct conversion process itself, evaporation need 8 times more energy than freezing. In the VFVC process theoretically the heat pump (vapour-compressor) needs only 1.6 kW(e).h/m^3 with compressor efficiencies in the range of 80%. These compressors are now on the market. For cooling, venting, pumping, controls etc. about 1.0 kW(e).h/m^3 are theoretically required. Thermal losses are in the range of 0.5 - 1.0 kW(th).h/m^3.

The total consumption should therefore be about 3.0 kW(e).h/m^3. In practice however, a specific energy consumption of not less than 12 kW(e).h/m^3 (see Fig. 23) has been experienced. The main disadvantage of the freezing processes has been the complexity of the
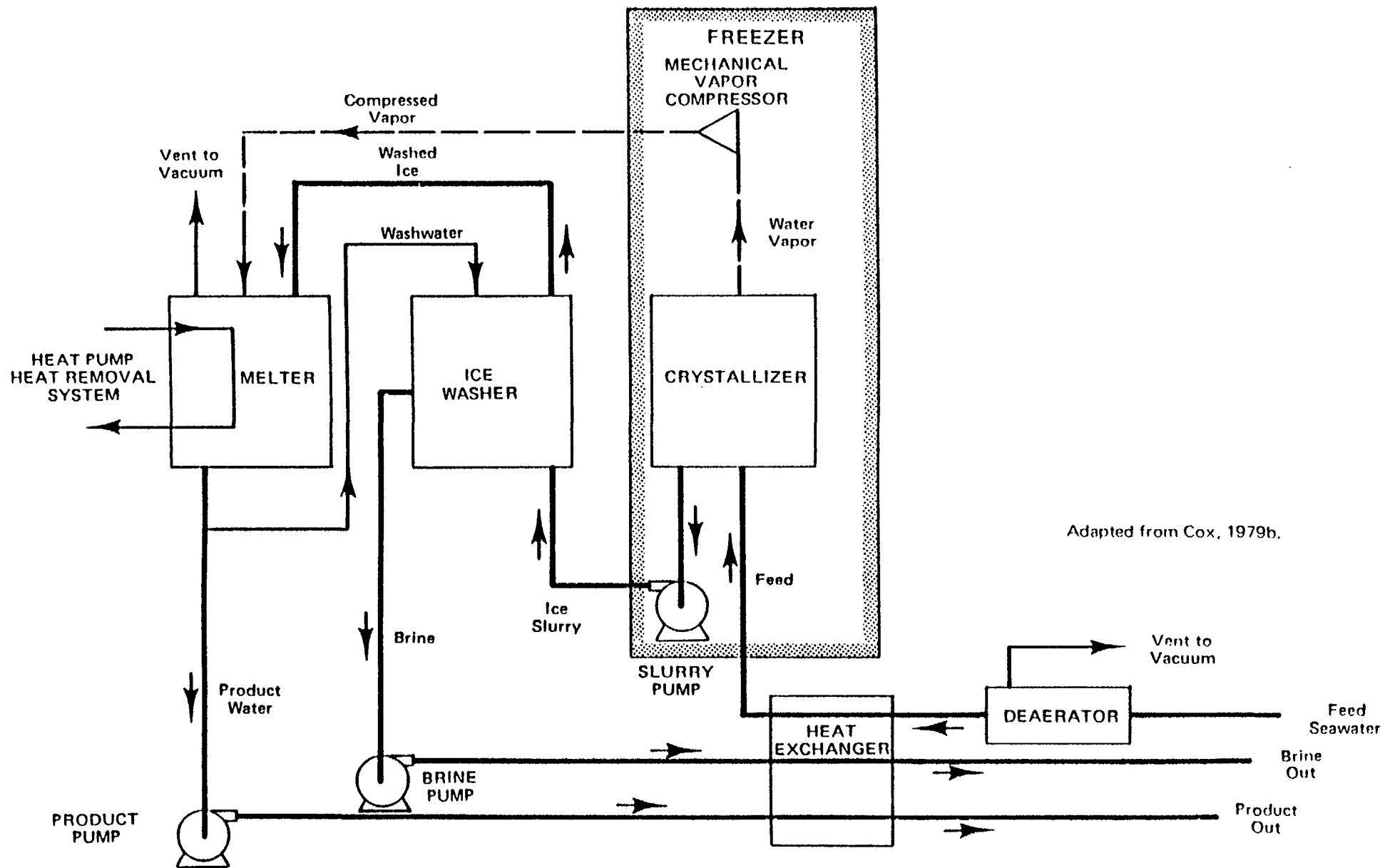
Fig. 22. Block diagram of a vacuum-freezing vapour-compression (VFVC) freezing process for desalting seawater.

POWER ANALYSIS
COLT VFVC PILOT PLANT

		KW TOTAL	KW HR. 1000 GAL.
I.	Compressor	68	15.6
II.	Refrigeration System		
	Compressor	61	14.03
	Circulation Pump	1.9	.43
		62.9	14.5
III.	Pumps		
	Feed	16.9	3.89
	Brine	12.7	2.92
	Slurry	10.0	2.30
	Recirculation	4.4	1.01
	Product	3.65	.84
	Wash	3.0	.69
	Coolant	.55	.13
		51.2	11.8
IV.	Agitators & Scrapers		
	Freezer	13	2.99
	Melter	2.2	.51
	Counterwasher		
	Scraper	2.2	.51
		17.4	4.0
V.	Air Removal		
	Blower	6.0	1.38
	Vacuum Pump	2.2	.51
		8.2	1.9
		207.7	47.8

Based on Production of 208,600 gallons March 4 & 5, 1967, and total power consumption of 9972 Kw.

Fig. 23. Power analysis of colt VFVC pilot plant.

components required to operate the system. Although some plants have been in operation for several months, too much operator intervention is required for their smooth operation, and this is unacceptable for commercial plants.

The other advantages of the freezing processes, especially of the VFVC, are low corrosion, low scaling tendency, no fouling, no heat transfer surfaces, no other pretreatment requirements except deaeration. Thus it is worthwhile to check periodically to see if improved components or partial system solutions can overcome the

operational problems. Since the end of the 1970s practically no important development work has been undertaken. In several feasibility studies, units of nearly 40 000 m^3/d size have been investigated. As the fundamental freezing process offers lowest energy cost, highest conversion rate, and theoretically a low capital cost due to use of low cost materials (for example concrete), it should be a challenge for every engineer to attempt to overcome the practical problems.

b)   Solar Stills

The oldest evaporation process used is the solar still (see Fig. 24). In solar stills, solar radiation is used to evaporate fresh water directly from a saline solution. The vapour produced is condensed on the inside of inclined glass or transparent plastic walls, which are cooled by ambient air. Theoretically production up to 1.5 kg/m^3 of solar still is possible under optimal radiation conditions. Practically however only 2 to 5 kg/day/m^3 (see Fig. 25) is achieved depending on the location and time of the year. Multistage

arrangements may increase this rate by a factor of 4 to 5. The investment costs however will limit the use of solar stills to very special and relatively small applications.

3.3.6.   Other Membrane Processes

a)   Electrodialysis

The first membrane process for commercial seawater desalination was the ED-electrodialysis process (see Fig. 26). Today this process is widely used for brackish water desalination. In seawater desalination however it was not successful. Power consumption has been reduced to 8.3 kW(e).h/m^3 according to reports published on the seawater desalination conference November 1989 in Kuwait [31], and further reduction down to 6 kW(e).h/m^3 might be possible. Relatively high investment costs and operational complexity will hinder large scale use. One of the cases where seawater desalination by ED might be considered is the desalination of high TDS seawater containing high amounts of scale forming substances, for example in the case of a further concentration of the brine coming from RO plants.

b)   Membrane Distillation

Membrane distillation is in principle an evaporation process using porous membranes made of hydrophobic polymers. These membranes allow

BASIC ELEMENTS IN SOLAR DISTILLATION
1) Incoming Radiation (Energy)
2) Water Vapor Production from Brine
3) Condensation of Water Vapor (Condensate)
4) Collection of Condensate

Sun

Incoming
Solar
Radiation

Clear Glass or Plastic
(To Transmit Radiation and
Condense Vapor—Must Remain Cool)

Condensation

Water
Vapor

DISTILLATE
OR CONDENSATE
TROUGH

Brine

BASIN

Collection of
Condensate

The inside of the basin is usually black to efficiently absorb
radiation and insulated on the bottom to retain heat.

Fig. 24. Basic elements in a solar still.

Date Still	27 Jan 1970	31 Jan 1970	11 Feb 1970	15 Feb 1970	24 Feb 1970	6 Mar 1970	19 Mar 1970	21 Mar 1970	Mean Yield
Mark I	4.03	3.36	3.26	3.83	3.86	3.49	3.76	3.49	3.64
Mark II	3.26	2.95	2.71	3.28	3.06	2.91	3.41	2.87	3.06
Mark III	4.18	3.48	3.58	4.32	4.20	4.18	4.12	3.75	3.98
Mark IV	- *	5.03	5.15	5.86	5.49	5.28	5.06	4.63	5.21
Mark V	4.13	3.50	3.87	3.97	3.88	3.88	3.50	3.48	3.78
Mark VI	- *	- *	4.70	5.10	5.07	4.79	4.73	4.42	4.80

Fig. 25. Daily production rates in L/m^3 in solar still plants observed by O.S.C. Headly and B.G.F. Springer on the island of Trinidad.

the passage of water vapour but not of water itself. Therefore it is possible to separate the water and the water vapor, which is produced by evaporation. The vapour passing through the membrane due to a difference in partial pressure is condensed and recovered as product. In principle membrane distillation is identical to the MSF process, the only difference being that the vapour space and the demister of the MSF plant are replaced by the hydrophobic membrane, hence the energy consumption is in the same range as in MSF plants. The number of stages in an MSF plant are represented in Membrane Distillation by the length of the membrane over which the heated seawater flows and is gradually cooled down by evaporation. Membrane distillation is an interesting alternative for small scale applications where cheap energy (solar energy, waste heat from diesel engines, geothermal energy) is available, and the seawater is free of organic seawater pollution. In case of organic seawater pollution, the hydrophoby of the membrane material may change to a hydrophilic behaviour within the pores due to coating the pores with organic materials.

c) Pervaporation

Pervaporation is a membrane process in which a component permeates out of a liquid mixture through a porefree membrane. The properties of the membrane polymer allow the absorption of a specific component (for example water) out of a liquid mixture into the membrane material. The absorbed component is then transported by diffusion through the membrane and desorbed on its reverse side. The driving force in this process is the difference in the chemical potential on both sides of

Concentrated seawater outlet

Desalinated water outlet

Cl₂ Λ K Λ K Λ K Λ K Λ K H₂

(+) (−)

Na⁺ Na⁺ Na⁺ Na⁺ Na⁺

Na⁺ Na⁺ Na⁺ Na⁺ Na⁺

Cl⁻ Cl⁻ Cl⁻ Cl⁻ Cl⁻

Cl⁻ Cl⁻ Cl⁻ Cl⁻ Cl⁻

D C D C D C D C D

Solution in anode chamber

Solution in cathode chaml

Seawater intake

Seawater intake

Cation exchange membrane

Spacer

Dilution gasket

Anion exchange membrane

Spacer

Concentration chamber gasket

Cation exchange membrane

Fig. 26. Principle of electrodialysis.

the membrane. This chemical potential difference can also be expressed as the difference of partial pressures of the permeating component on both side of the membrane. When applying a vacuum on the reverse side of the membrane (for example 6mbar), and a saline feed solution with 35°C on the other side of the membrane, the net difference in partial pressures of about 40mbar is sufficient to transport water through a PVA or CA membrane. The desorbed vapour is condensed on the reverse side of the membrane at low temperature (+0.5°C).

This process will only be used in special cases as investment costs and energy consumption (700 kW(th).h/m^3) are very high. One case where a small scale plant might be meaningful, is to concentrate saline liquid mixtures up to the limit of pumpibility, as the porefree structure of the membrane is free of pore fouling problems.

d)   Other membrane processes have been described in the literature but it is doubtful that they will reach industrial scale in the near future.

3.3.7. Other Processes

Some other processes are:
Solvent extraction
Ion exchange
Hydrate formation
and various others.

With the hydrate formation process interesting results were obtained in the early 1980s, however, the hydrate forming agents on which the technical progress was based are now recognized to be potentially carcinogenic. Harmless hydrate forming agents, such as CO_2, do not offer the required energy advantages.

Solvent extraction and ion exchange are interesting from the theoretical point of view, but practical and economic solutions have yet to be found, so these processes should not be considered for a "low cost" water scheme in the near future (1990-2000).

3.4.   Energy Input and Consumption

3.4.1.   Primary Energy Input, Degree of Coupling and Relative Scale

Energy costs must be calculated separately for each location/country, since the results may vary significantly. Recent studies give conflicting results. Political aspects may influence costs more than technical parameters.

A recent study, published in the Federal Republic of Germany by the Ministry of Research and Technology, ranked the cost of electricity produced by various primary energies in the following order, from the cheapest to the most expensive: 1) hydropower 2) windpower 3) fossil fuel 4) nuclear fuel 5) solar energy. Other publications show nuclear energy, especially for large scale energy production, as the cheapest. In trying to provide guidance on primary energy costs, the following ranking might be not too far from the true situation:- 1) Wavepower (in areas with constant wave action) 2) nuclear fuel and fossil fuel (comparable costs normally over a narrow range); 3) Wind energy 4) Solar energy. Hydropower can be disregarded as a primary energy source for desalination.

An OECD study, "Projected Costs of Generating Electricity", [32] published in 1989, probably provides the best source for evaluating the energy cost portion of water production cost.

Desalination plants need energy, either in the form of heat, in the form of mechanical energy, or as electricity, and these secondary energies can be produced in various ways from different primary energy sources as discussed below:-

a)   Nuclear fuel
      With nuclear fuel, steam, hot water or a hot thermal fluid can be
      generated and used directly or indirectly in the form of heat and/or
      electricity in desalination plants. Nuclear fuel is the
      environmentally cleanest form of energy, and for large plants it
      offers economic advantages as well.

b)   Fossil fuels
      Fossil fuel is today the most widely used primary energy source for
      the production of fresh water from seawater. The majority of the

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plants in the Middle East use crude oil. Smaller plants or
desalination plants in combination with gas turbines use gasoil. In
some cases Bunker "C" is used for the production of steam in larger
steam boilers, or used as fuel to produce mechanical (electrical)
energy in low speed diesel engines. Coal can be disregarded as a fuel
for desalination systems in the regions of major interest.

c)   Wind energy

Windmills are used today on a commercial scale in sizes up to about
1000 kW unit size. The majority of windmills provide 50 to 500 kW per
unit. Large units with outputs above 1000 kW unit size have been
tested, but it is doubtful that they can become as reliable as smaller
units. The investment cost for a 1MW wind park on a Greek island,
consisting of 5 units each of 200 kW, is in the range of US$
2 000 000, based on 1990 dollars and on a turnkey basis. Cost per
kilowatt will not vary very much with larger sizes, and seems very
attractive since operating costs are low. However, availability of
the wind has to be considered, as well as fluctuations, hence even in
windy areas the plant will produce only 50% of its rated capacity.
Therefore, when evaluating wind power, standby facilities (e.g. diesel
generators), battery systems or downscaling factors have to be
considered.

d)   Solar energy

Solar energy can be used in several forms. Actually the most
expensive one is production of electricity by photovoltaic cells.
Dramatic progress in developing photovoltaic cells over the last few
years indicates a further decrease of costs can be expected. In the
mid 1970s, 1kW(e).h cost about 15 US$, and this has since dropped to
0.4 - 0.5 US$/kW(e).h, and by the year 2000 about of 0.10 US$/kW(e).h
might be expected. Again, the problem is limited availability of the
sun during one 24 hour cycle. For continuous operation of a
desalination plant, large battery systems are required. Advanced
battery systems able to store electricity in the range of 1 to
10MW(e).h are under development, but it will take another 5 to 10
years till such systems are commercially available. Combining
photovoltaic cells with advanced large scale battery systems (e.g.
Redox batteries) may result in 0.3 US$/kW(e).h when electricity is
needed conventionally.

Location	Power	Collector data			Erection year
		Type	t_{out} °C	Field size m²	
White Cliff, Australia	25 kW$_e$	P.D.		275	1981
Perth, Australia	35 kW$_e$	P.T.	300	300	1982
Meekatharra, Australia	50 kW$_e$	P.T. two axes	300	960	1982
Sulaibiya, Kuwait	100 kW$_e$	F.C.F.M.	250	1.100	1984
Ein-Boquek, Israel	150 kW$_e$	Solar pond		7.500	1980
Almeria, Spain	500 kW$_e$	P.T. 1+2 axes	295	2.674+2.688	1981
	500 kW$_e$	C.T. heliost.	530	3.655	
Sikuku Island, Japan	1 MW$_e$	C.T. heliost.	249	12.912	1984
	1 MW$_e$	C.S.I.F.	530	11.160	
Eurelios, Sicily, Italy	1 MW$_e$	C.T. heliost.	510	6.216	1981
Cesa I, Almeria, Spain	1.2 MW$_e$	C.T. heliost.	520	11.400	
Themis, Taragasonne, Fr	2.5 MW$_e$	C.T. heliost.	450	10.740	1983
Solar 1, U S A	4.9 MW$_e$	P.D.	277		1984
Beith-Ha Arava, Israel	5,0 MW$_e$	Solar pond		250.000	1984
Solar plant 1, Barstwo California, U S A	10.0 MW$_e$	C.T. heliost.	510	72.000	1983
Carrizo Plains, Calif. U S A (design)	30.0 MW$_e$	C.T. heliost.	670 to 1050	11x10^5	shedull. for 1986
Phase 1, Sacramento, California, U S A	100.0 MW$_e$	Photovoltaics	-	-	1984

Fig. 27. Plants in operation for the production of electricity (E.E. Delyannis).

The production of thermal energy using the sun's radiation seems to be almost economic today (see Figs. 27, 28, 29, 30). Four systems have been investigated extensively out of many concepts, and these are:-

Power Towers (Central receiver systems)
Linear Throughs
Point Focus Dishes
Solar Salt Ponds

For the first three systems, thermal fluids are raised to high temperature, and then used to produce steam. Overall efficiency is relatively high, and energy costs may soon reach an economic level. Storage of heat, for the first three cases, can be achieved via storage tanks of sufficient size with good insulation. Specific energy costs for these systems may come down to levels of 0.025 - 0.04 US$/kW(th).h.

Solar ponds may be an attractive solution to provide energy for desalination plants. A solar pond stores incident solar radiation, and in the lower layers of a pond 75°C to 110°C can be maintained in Middle East countries. This heat can be used for direct heating of a

| movement around one axis | movement around two axes |

PARABOLIC
TROUGH

Linear focus
$C_f = 20$ to 100
2a

Noon

Tracking
receiver

FIXED MIRROR
$C_f = 20$ to 80
2b

Linear
focus

FRESNEL LENS
REFRACTOR
$C_f = 10$ to 40
2c

$C_f = 100$ to 1000

Point
focus

FRESNEL LENS REFLECTOR
2d

$C_f < 1000$

HELIOSTAT
Point focus
2f

$C_f = 100$ to 5000
Point
focus

PARABOLIC DISH
2e
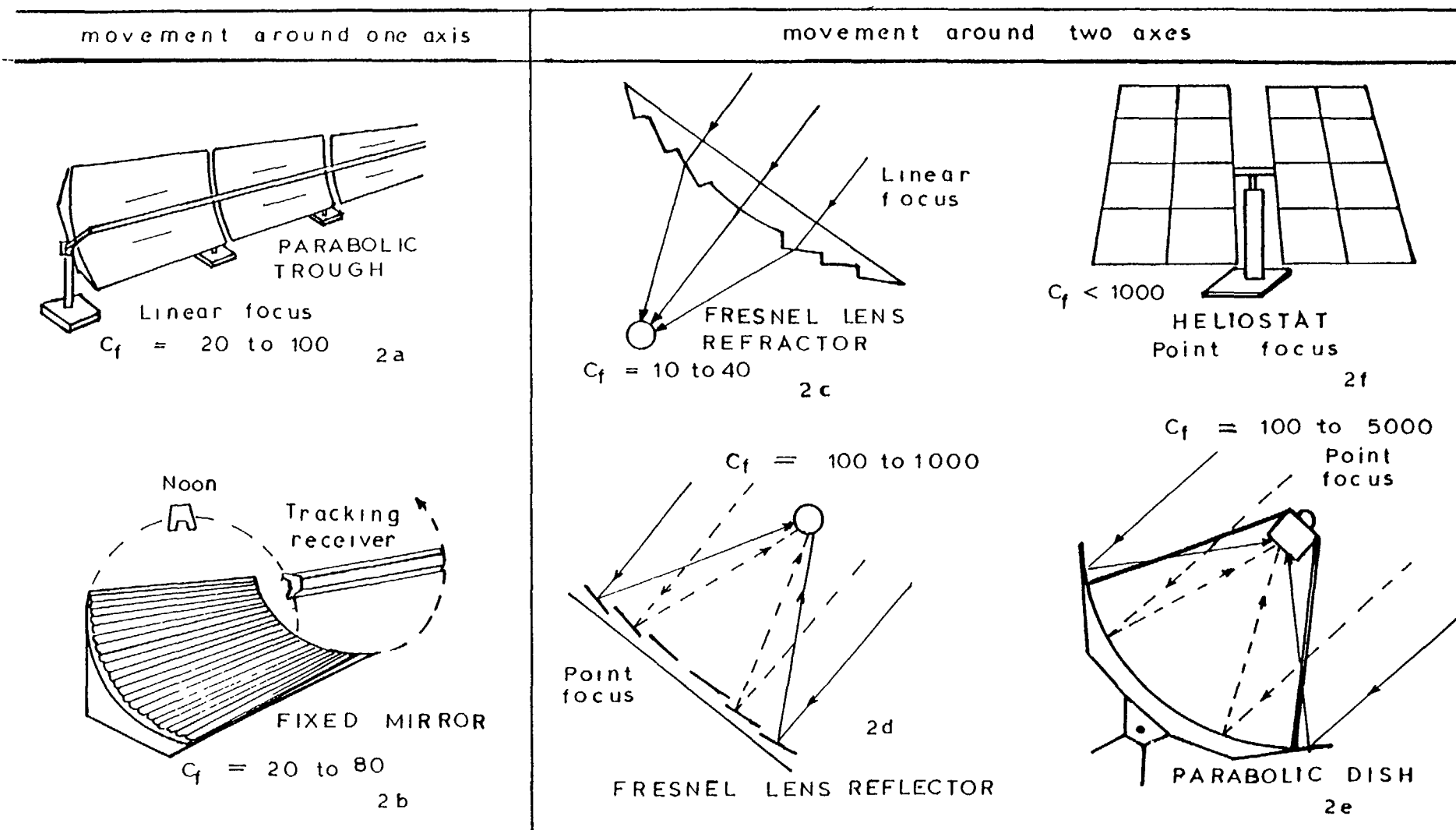
Fig. 28. Various types of concentrating solar collectors (E.E. Delyannis).

Prime Contractor	Water type	Plant location	Desalination technology	Capacity m³/d	Solar energy technology	Collect area m²	Operat. temp.°C
Boeing	Brackish	Ranking, Texas, U S A	Single stage R O	-	Central receiver heliostats	20.448	277-788
Catalytic Inc.	Seawater	Yabu, Red Sea, Saudi Arabia	R O two-stage in series	-	Wind gener., Fresnel line focus collect.	12.800	204-302
Chicago Bridge and Iron Inc.	Seawater	Yabu, Red Sea, Saudi Arabia	Indirect freezing	210	Point focus thermal collectors	43.800	253-378
D H R Inc.	Seawater	Yabu, Red Sea, Saudi Arabia	One stage R O in series with E D	-	Line focus thermal collectors & flat plate photovoltaics	56.000 5.000	215-300
Exxon	Seawater	Yabu, Red Sea, Saudi Arabia	Two-stage R O in // with 24-effect dist.	3.478 2.520	Heliostats, central receiver	22.800	285-566
Atlantis Energ. Ltd., Switzerl.	Seawater	Kuwait	12-stage M S F	100	Parabolic trough	220	-
M B B , Germany KISR, Kuwait	Brackish	Sulaibiya Kuwait	Reverse osmosis M S F	20 25	Point focusing parabolic collectors	1.000	350
Sasakura Eng. Co.(Pilot Plant)	Seawater	Takami Island Japan	16-effect M E S	16	Flat-plate collect.	-	55-75
Sasakura Engen. Co.	Seawater	Umm-Al-Nar Abu-Dhabi	18-effect M E S	120	Evacuate tube collectors	1.862	74-99
Dornier, M A N	Seawater	La-Paz, Baja Cal., Mexico	10-stage M S F	10	Flat-plate cpllect. Parabolic concentr.	194 +160 160	100-110 120-130
K G S S , A E G	Brackish	Concepcion del Ore, Mexico	S P R O	1.5	Photovoltaics 2.5 kW (peak)	-	-
General Atomic Design	Exhaust steam	Arabian Gulf	M E D	6.000	Parabolic cocentr.	53.960	196-288
Tebodin - Esmil Design	Seawater	Al-Ain U A Emirats	20-effect M S F 55-effect M E S	600 500	Flat-plate collect.	5180	35-82

Fig. 29. Solar assisted desalination plants (E.E. Delyannis).
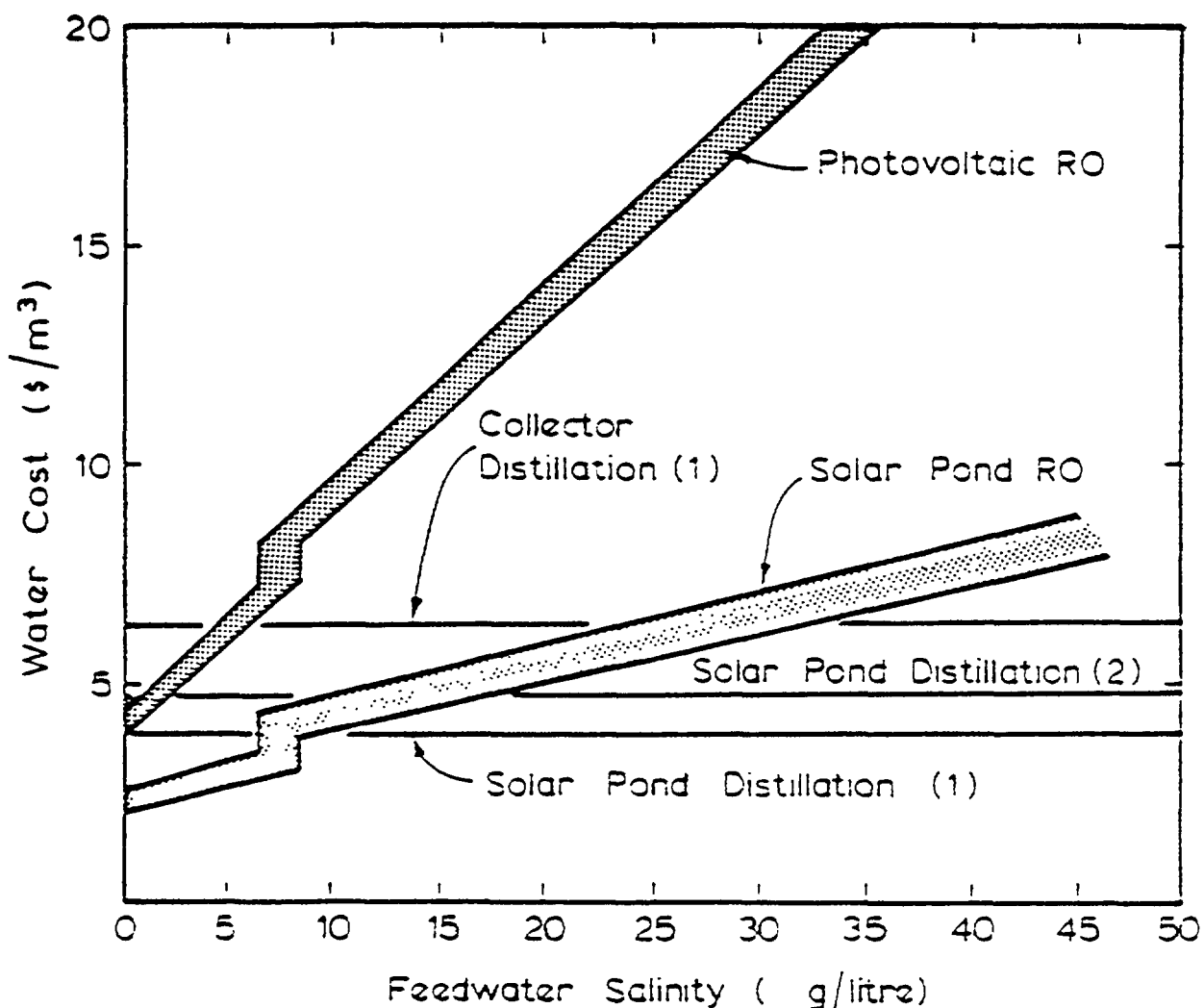
Fig. 30. Water costs as a function of salinity (electricity from (1) diesel or (2) solar pond).

HTME low temperature (60-70°C) desalination plant. Using an ORC (organic Rankine cycle) turbine, electricity can be generated to drive pumps and plant controls. Optimisation studies indicate that at least 200 m^2 of solar pond area is required to produce 1 m^3 of fresh water from seawater on a continuous basis. This figure gives some indication of area requirements for a desalination plant combined with a solar pond.

e)   Wave Power

In certain parts of the world's oceans, waves with 1.5-3 m amplitude and constant frequency are available around the year. These waves can be used directly to pump water with the help of a double piston-type pump into an elevated storage region. From here, the water flows to a lower level and produces electricity in a Pelton turbine driven generator. For isolated smaller islands this could be an economic solution, as reports predict electricity costs of about 0.2 US$/kW(e).h.

f) Other forms of primary energy might be used, for example
   Large differences in tidal movement in some coastal areas are used to
   produce electricity already today. Thermal and electrical energy can
   be produced in fuel cells. Demonstration units are in operation for
   example in the United States. Geothermal power is a relatively cheap
   form of energy and has been used for many years in New Zealand in
   relatively large units. Consideration has been given even to using
   the osmotic pressure of flowing water streams to operate a Reverse
   Osmosis plant, where sufficient salinity gradients are available.

3.4.2.   Secondary Energy Input

3.4.2.1. Steam

The steam needed for heating in desalination plants is at a low
temperature and pressure in general. The high temperature version of MSF
and MED-plants use saturated steam in the range of 100°C to a maximum of
140°C. Some plants use saturated steam of 80°C to 100°C, while the low
temperature (LT) HTME system operates with steam in the range of 60°C to
80°C.

The temperature difference between the incoming heating steam and the
heated seawater should be kept as small as possible, as there is a direct
relationship between heat flux, wall temperature to fluid temperature
difference, and surface scaling. At top brine temperatures of 120°C, a
Δt of significantly less than 2°C at clean conditions will reduce the
scaling effect. This low Δt of course leads to a relatively large heat
transfer surface being required, but the extended time between cleaning
cycles compensates for the higher capital cost.

If steam with the required conditions is not directly available it has
to be wastefully throttled. Steam in the range of 6–20 bar will be used
for the vacuum units, and high grade steam for electricity generation or to
drive the pumps and compressors directly via turbines. High grade steam is
used to heat seawater directly in only a few exceptional cases.

3.4.2.2. Electricity

Electricity is used to drive pumps and vapour compressors via electric
motors. In the case of electrodialysis plants, it is used in the D.C. form

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Total specific consumption (steam + electricity)
(MJ/t of water evaporated)
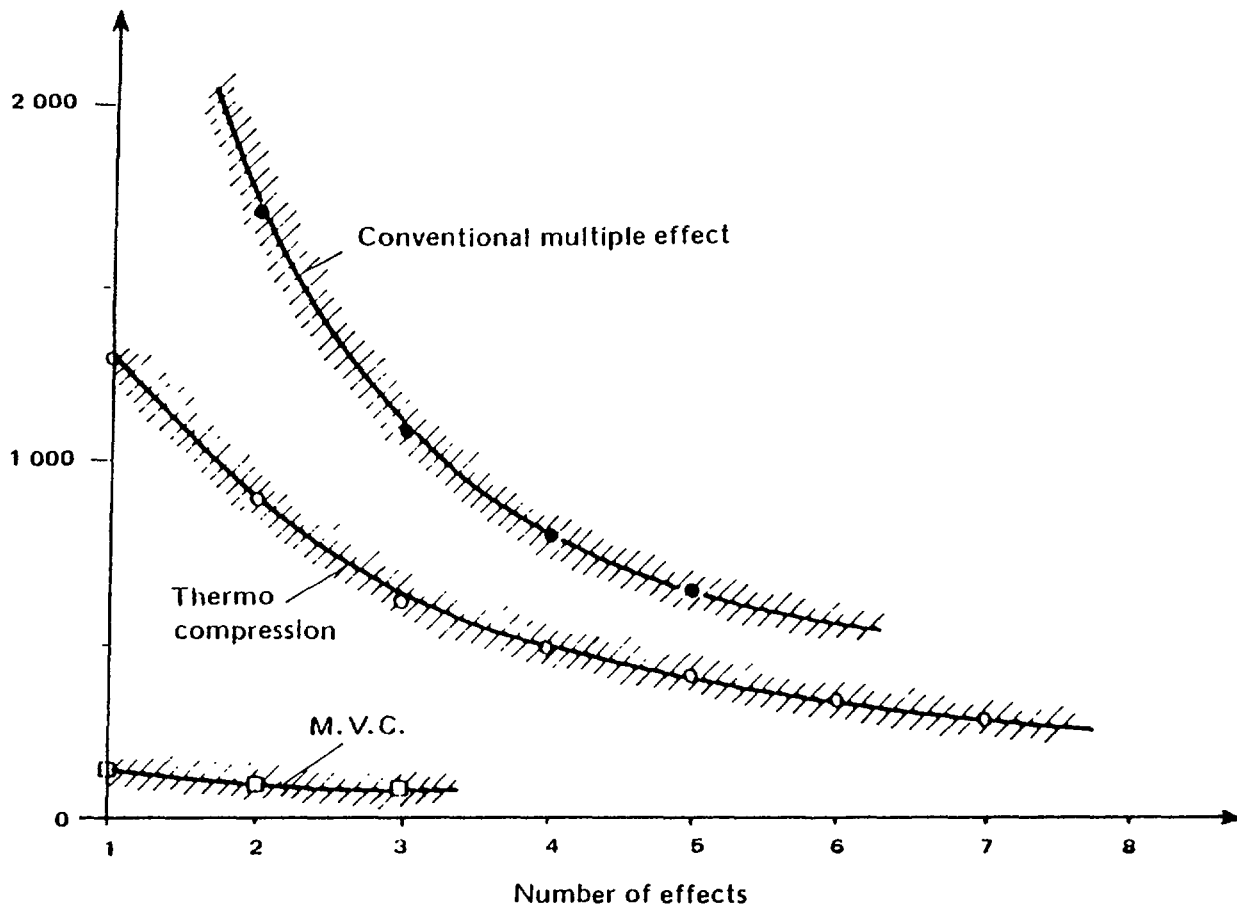
Fig. 31. Specific consumption as a function of the number of effects.

to create the required electrochemical potential. Electricity is sometimes used in smaller MED-VE plants for direct heating during start-up.

3.4.3. Heat pumps

Heat pumps are used in seawater desalination to increase the enthalpy of steam produced in an evaporator from a lower level to a higher level, such that the steam can be used to heat an evaporator stage or effect working at a higher temperature. The necessary energy to increase the enthalpy can be introduced either via a mechanical vapour compressor driven by an electric motor, gas turbine, steam turbine, diesel engine or any other drive, or via a thermal vapour compressor driven by high or medium pressure steam. As shown in figure 31 the net energy consumption of an evaporation plant heated by steam directly can be reduced quite considerably using vapour compression. It has to be noted however that for any comparison, the value of primary and secondary energy input has to be evaluated as well. Without considering capital investment in a modern
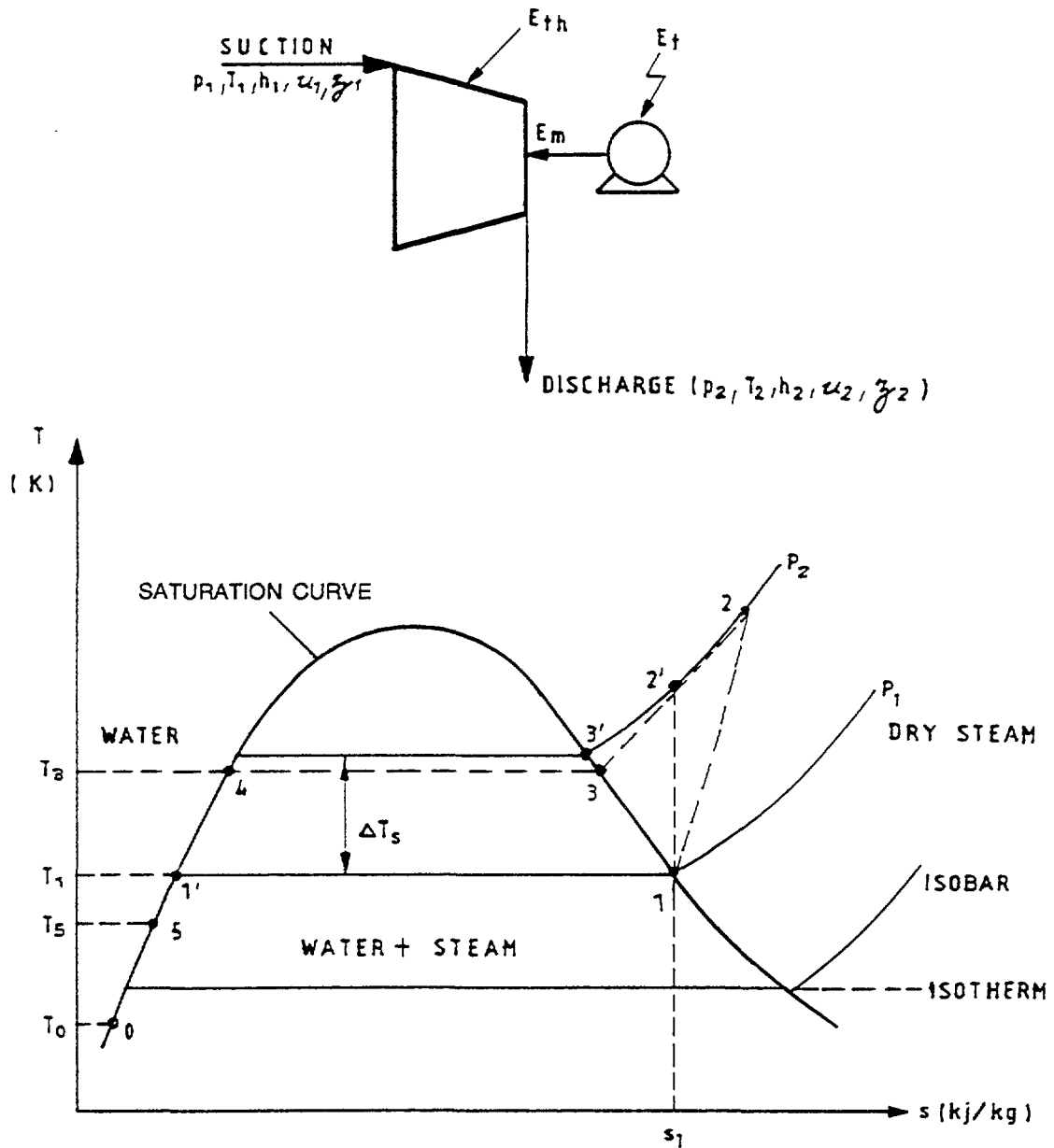
Fig. 32. Mechanical vapour compression principle.

higher temperature power plant, 1 kW(e).h is equivalent to 2.5 kW(th).h.
In a low temperature heat producing reactor, 1 kW(e).h has to be compared
with 7 to 9 kW(th).h. This means with a high temperature power plant, an
electricity or mechanical energy based desalination concept should be more
economic than straight-forward MED. With a low temperature reactor system,
the opposite might well be the case. The same principle is valid for
dual-purpose plants, where the high grade energy should be used for
electricity production, and the low grade energy for water production in an
MED plant.

3.4.3.1. Vapour Compression – Mechanical

A typical arrangement of a mechanical vapour compression system and the relevant compression analysis on a T–S diagram are shown in figures 26 and 32. Point 1 characterizes vapour leaving the evaporator, hence entering the compressor with T_1, P_1, S_1. Vapour will be compressed in the compressor from P_1 to P_2. This transformation is analyzed in the T–S diagram. The actual compression includes internal losses and heating which are irreversible. The result is point 2, the entropy of which is larger than that of point 1, but smaller than theoretically obtainable with ideal compression. The ratio between the theoretical and practical value is called isentropic efficiency (η_{iso}).

During the last few years, important improvements have been made in compressor development. Many reliable types and sizes are now on the market. Axial compressors with up to 500 000 m^3/h inlet volume and compression ratios of 1.2 to 1.8 per stage, with a stage efficiency of more than 90% are commercially available. For smaller entrance volumes (< 10 000 m^3/h), centrifugal compressors, with isentropic efficiencies of more than 70%, can be used. For larger compression ratios (up to 6), the screw compressor is an alternate to the multistage axial compressor.

3.4.3.2. Vapour Compression – Thermal

Steam (jet) ejectors are used to enhance the enthalpy by thermal vapour compression. The principle of such a system is shown in figure 33. This system is very reliable as it has no moving parts, and consists only of a "supply box" with integral steam nozzle, where steam pressure is transformed into kinetic energy, the vapour entry region, and the diffuser region. The disadvantage is low efficiency, which is 5 to 8 times smaller than that of a mechanical vapour compressor. Again the real value of the thermal energy level used has to be considered, in which case steam jet ejectors may not as uneconomic as a simple comparison of the isentropic efficiencies would suggest. The advantage of the steam ejectors are low cost and low maintenance requirements.

3.4.3.3. Others

Other heat pumps systems for example Organic Rankine Cycle (ORC) systems are not yet widely used in desalination. These have been proposed
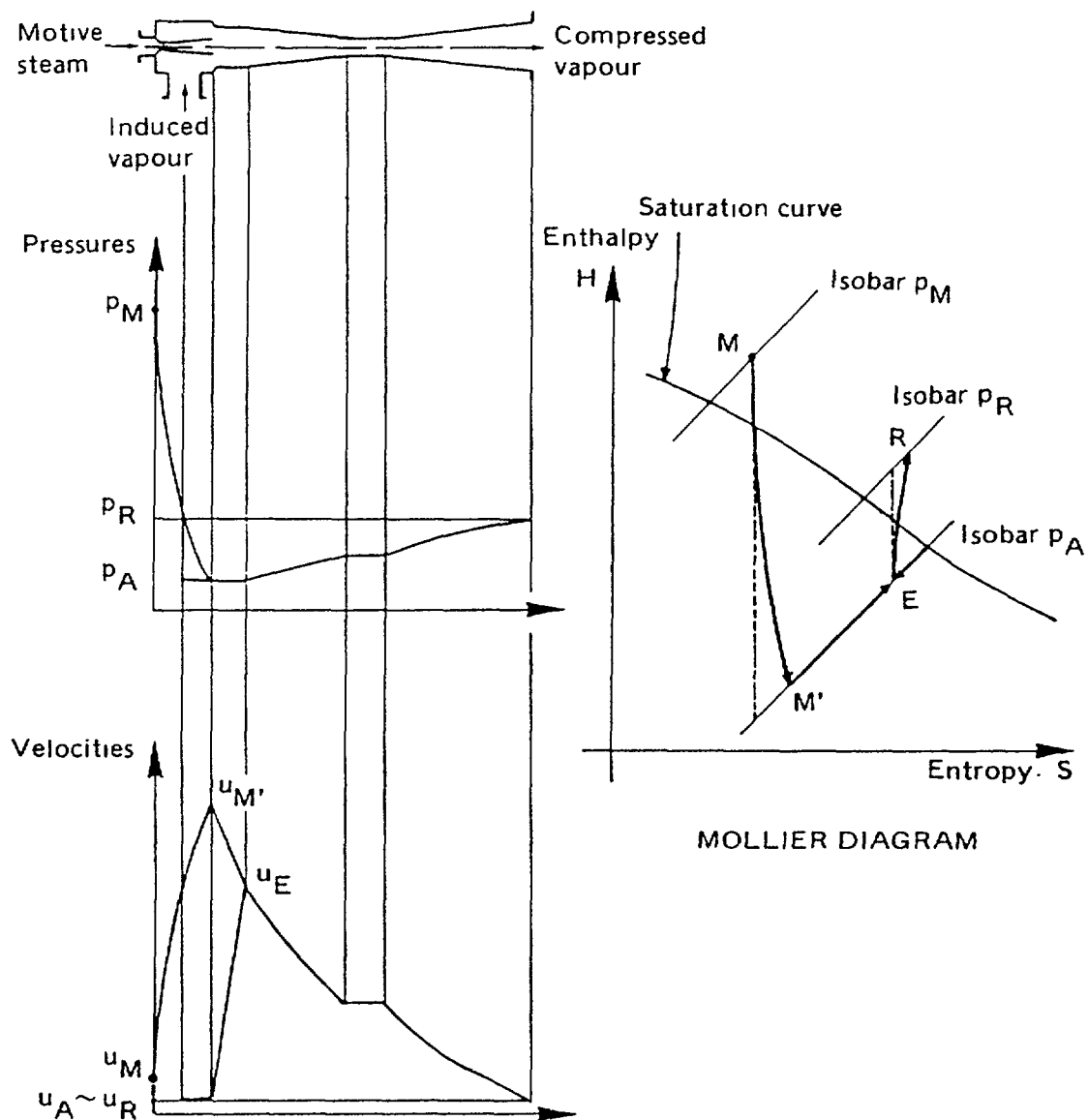
Simplified diagrams showing variations in pressures, velocities and enthalpies in an ejector.

Fig. 33. Thermal vapour compression principle.

in combination with ocean thermal energy conversation (OTEC) systems, and in combination with solar ponds. Many experimental systems have been built for energy recovery. ORC systems might be useful with low-cost/free waste heat where a low enthalpy level is available. Before they can be considered for large scale systems, R&D work on larger sizes is desirable.

3.4.4. Energy Consumption (Summary)

According to figures 34a-i, energy costs are between 35 to 58 % of total water costs. Cost figures do not always represent the real value of energy consumption. The energy consumption of desalination processes should be compared with the value, which is 0.765 kWh/m^3 based on an
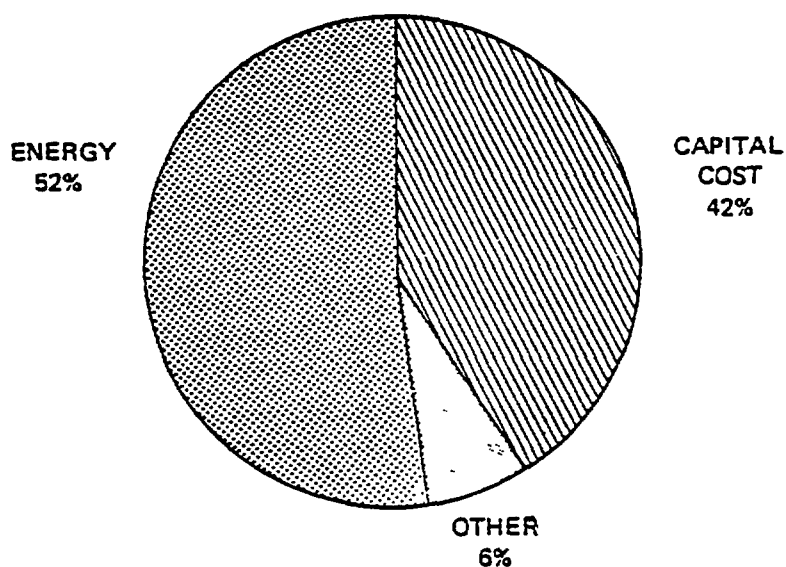
Fig. 34a. Water cost from sea-water via single purpose multi-stage flash plant, acid added, source of energy — low sulphur fuel oil (last quarter 1982 Dollars).

ENERGY
52%

CAPITAL
COST
42%

OTHER
6%

TOTAL COST OF PRODUCT WATER = S2,900 PER ACRE/FT
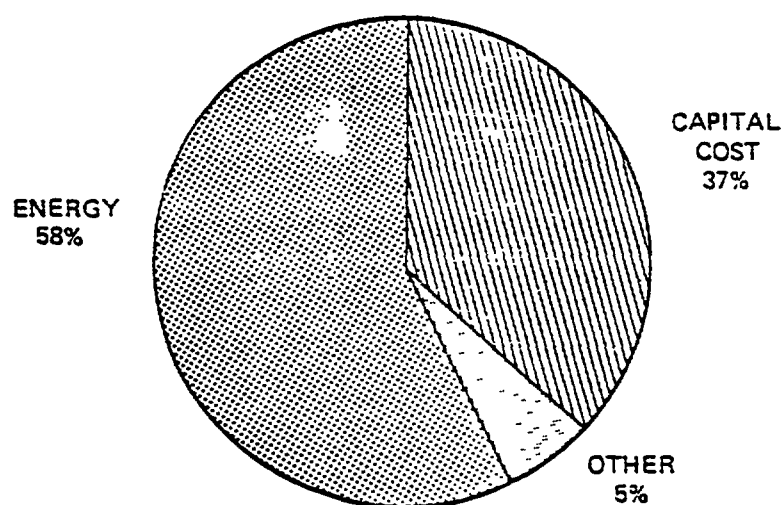
Fig. 34b. Water cost from sea-water via single purpose multi-effect vertical tube evaporation, acid added, source of energy — low sulphur fuel oil (last quarter 1982 Dollars).

ENERGY
58%

CAPITAL
COST
37%

OTHER
5%

TOTAL COST OF PRODUCT WATER = S2,600 PER ACRE/FT
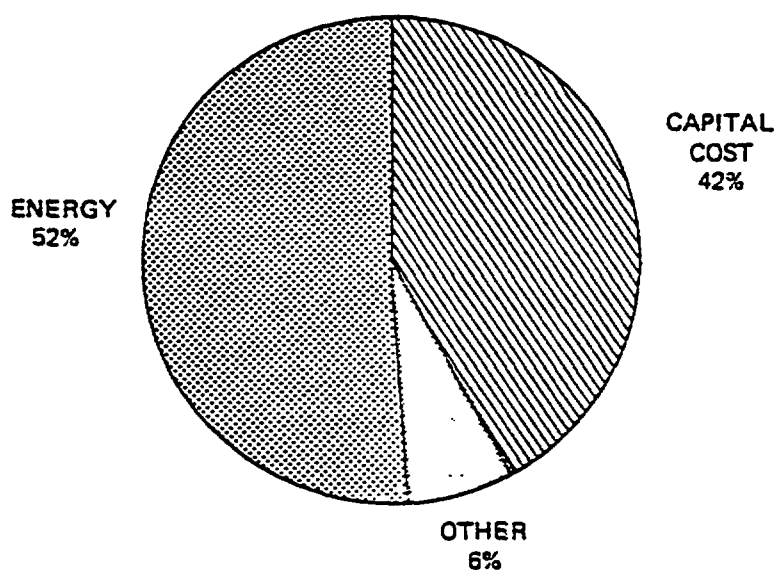
Fig. 34c. Water cost from sea-water via distillation in a low-temperature vapour compression plant (last quarter 1982 Dollars).

ENERGY
52%

CAPITAL
COST
42%

OTHER
6%

TOTAL COST OF PRODUCT WATER = S1,400 PER ACRE/FT

ENERGY
36%

CAPITAL
COST
33%

OTHER
31%
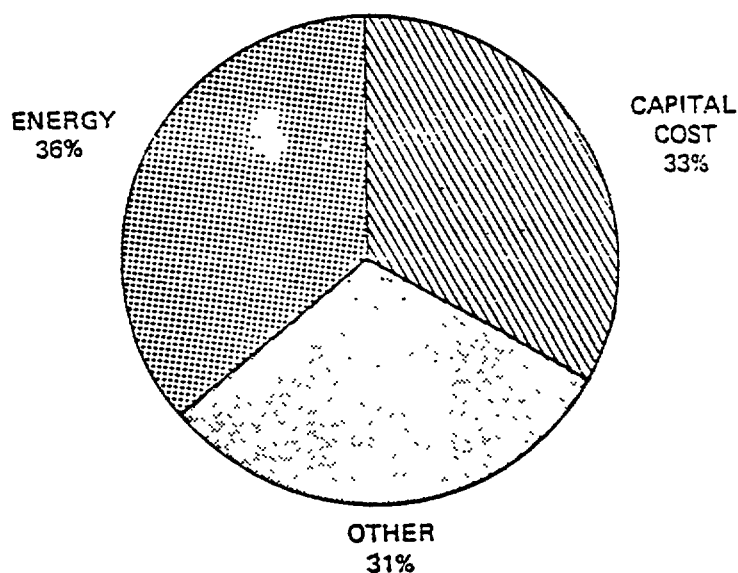
TOTAL COST OF PRODUCT WATER = $1,570 PER ACRE/FT

Fig. 34d. Water cost from sea-water via reverse osmosis with energy recovery (last quarter 1982 Dollars).

ENERGY
35%

CAPITAL
COST
57%

OTHER
8%
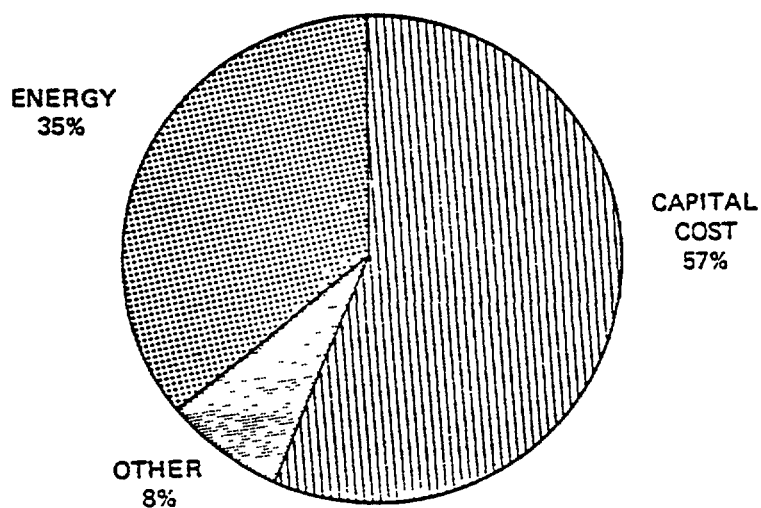
TOTAL COST OF PRODUCT WATER = $2,200 PER ACRE/FT

Fig. 34e. Water cost from sea-water via dual purpose multi-stage flash plant, acid added (last quarter 1982 Dollars).

ENERGY
38%

CAPITAL
COST
54%

OTHER
8%
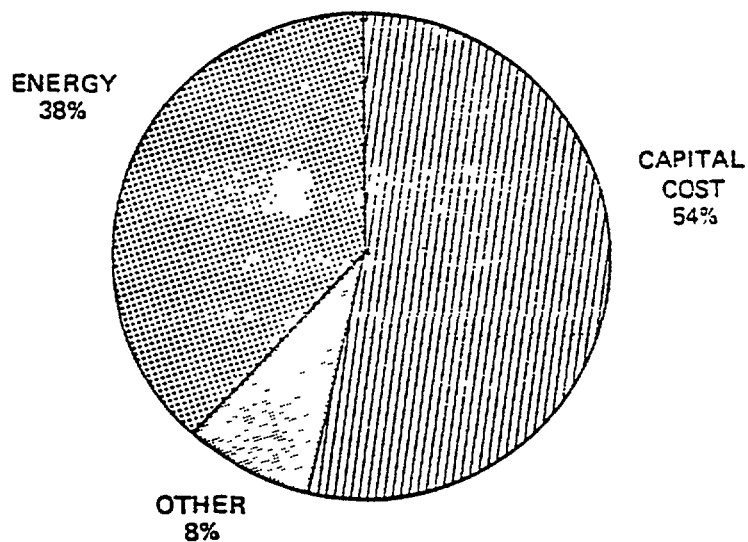
TOTAL COST OF PRODUCT WATER = $1,800 PER ACRE/FT

Fig. 34f. Water cost from sea-water via multi-effect vertical tube evaporation in a dual purpose plant (last quarter 1982 Dollars).
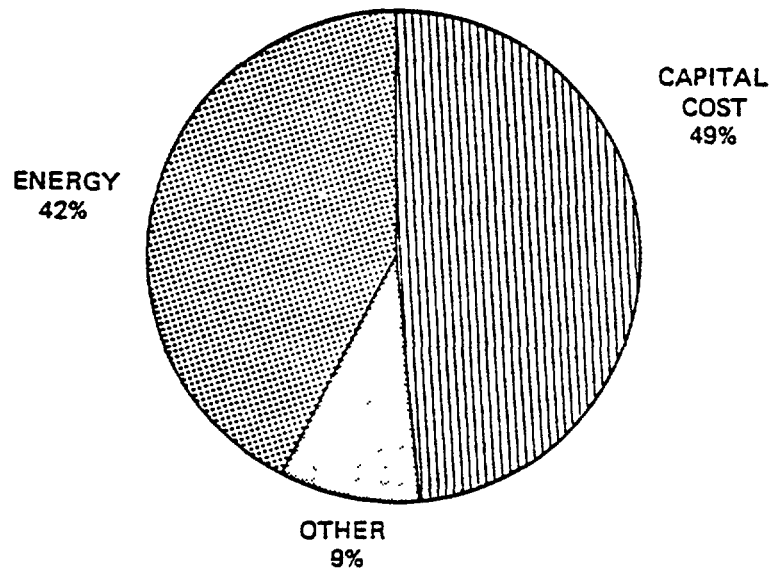
Fig. 34g. Water cost from sea-water via multi-effect horizontal tube evaporation in a dual purpose plant (last quarter 1982 Dollars).

ENERGY
42%

CAPITAL
COST
49%

OTHER
9%

TOTAL COST OF PRODUCT WATER = S1,500 PER ACRE/FT

Fig. 34h. Water cost from sea-water via dual purpose multi-effect horizontal tube, low-temperature distillation (last quarter 1982 Dollars).

ENERGY
34%

CAPITAL
COST
58%

OTHER
8%

TOTAL COST OF PRODUCT WATER = S1,200 PER ACRE/FT

(S/m³) (S/kgal)

WATER COSTS

OIL FIRED MED

COAL FIRED MED

MSF

OIL FIRED

COAL FIRED AND NUCLEAR

OIL FIRED

VTE

(mgd) 0 1   0 2   0 5   1   2   5   10   20   50   100

(m³ day) 0 5   1   2   5   10   20   50   100   200 (X 10³)

PLANT CAPACITY
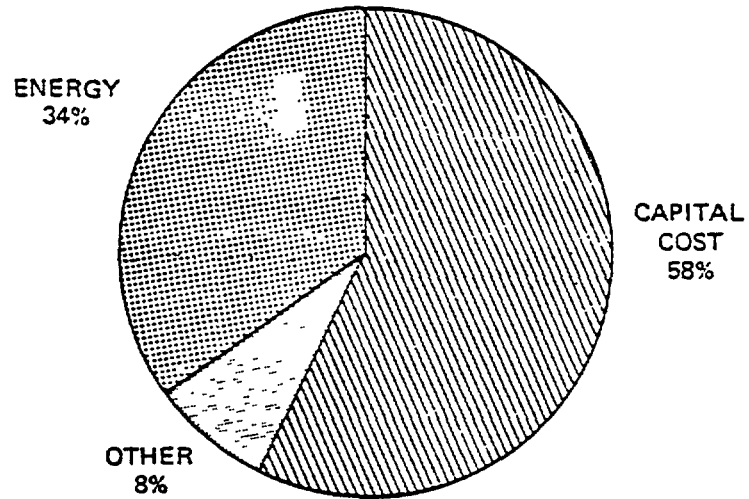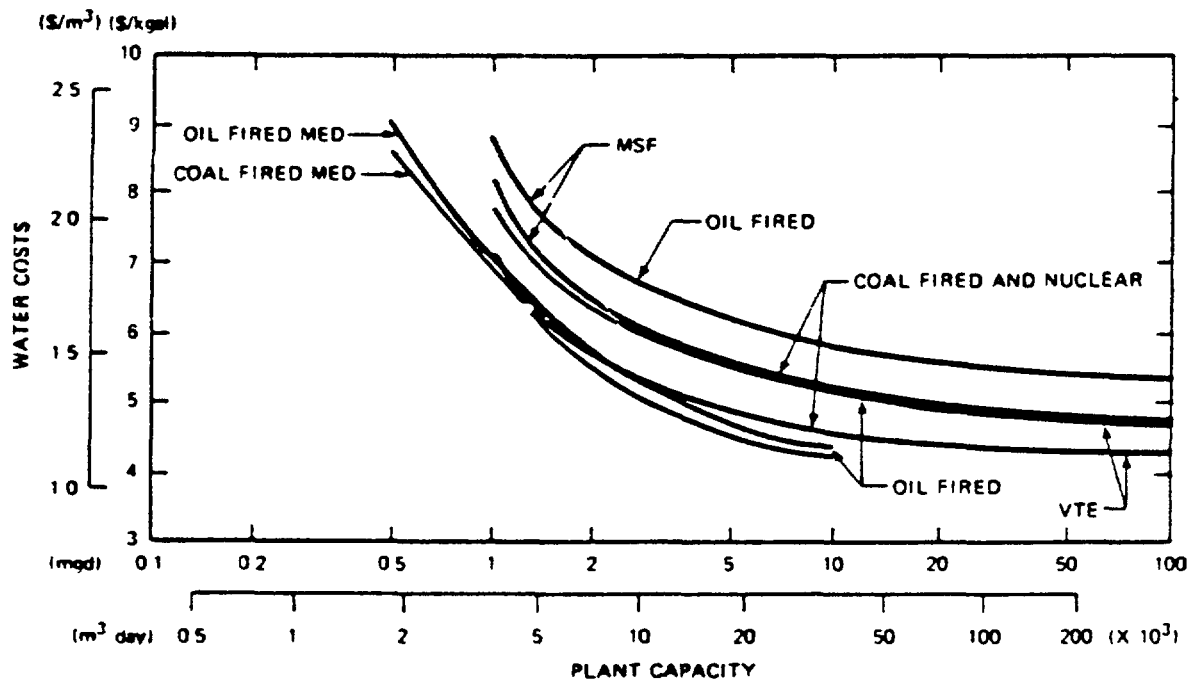
Fig. 34i. Water cost — seawater desalting by distillation.

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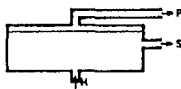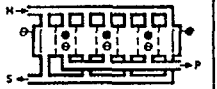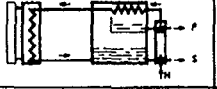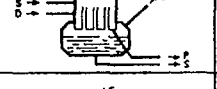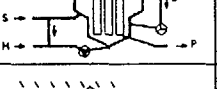
Process	Abreviation	Schematic	Type of process	Phase change	Secondery energy Input kWh/m³ ⓧ	Approx Investment costs (1990) $/m³day ⓧⓧ	Potential for low cost seawater de-salination
1. Reverse osmosis	RO		Membrane	NO	Electricity 5,5 - 7,5 (with power recovery)	~ 1000 - 1200	high
2. Electrodialysis	ED		Membrane	NO	Electricity 6,5 - 12,5	~ 1500	low
3. Multi stage flash once through	MSF-OT		Evaporation	Liquid/vapour	Electricity 3 - 4,5 + Thermal 50 - 300	1200 - 1800	low - medium
4. Multi stage flash brine recycle	MSF-BR		Evaporation	Liquid/vapour	Electricity 3,5 - 5,0 + Thermal 50 - 300	1400 - 2000	low
5. Multiple effect destillation (vertical)	MED VTE VTFE		Evaporation	Liquid/vapour	Electricity 1,5 - 4,5 + Thermal 30 - 300	1200 - 1500	medium - high
6. Multiple effect destillation (horizontal)	MED HTME LT-HTME		Evaporation	Liquid/vapour	Electricity 1,5 - 3,5 + Thermal 30 - 300	1200 - 1500	medium - high
7. Combination with thermal or mechanical vapour compression	VTE/VC VTFE/VC HTME/VC LT-HTME/VC		Evaporation	Liquid/vapour	Electricity 6,5 - 18 (advanced systems)	1500 - 2000	high
8. Solar destillation	SD		Evaporation	Liquid/vapour	Radiation of sun 0,8-max.1,5 kW/m² ~ 1000 kW sun-radiation	~ 4000	low
9. Freezing process	FP VFVC VFMPT		Freezing	Liquid/solid	Electricity 1) 11 (pilot plant) 2) 10 (bench scale)	~ 2500 (study)	high if R&D sucessfull
10. Hydrate process	HP		Crystallisation	Liquid/solid	Electricity 12	~ 2500 (study)	low

Fig. 35. Range of energy consumption for the various processes.

ideal thermodynamic cycle excluding losses. The actual energy consumptions obtained today are much higher. Figure 35 shows the range of energy consumption for the various processes. The lowest specific energy consumption is obtained by the RO system with only 5.5 KWhe/m^3, including seawater pumping. The widest range is obtained with MSF, VTE and HTME. In comparing the energy consumption of these processes, one should remember that the energy consumption depends on the number of stages. A single stage, or single effect, system needs about 1 ton of steam to produce 1 m^3 of distilled (desalted water), excluding losses. Including losses the specific energy consumption will be about 720 kW(th).h/m^3 for a single stage plant. The 300 kW(th).h/m^3 mentioned in Figure 35 is based on 2 to 3 effects for VTE or HTME, and at least 6 stages in the case of inefficient MSF which are sometimes built. An optimal high temperature VTE or HTME plant without VC can reach a G.O.R. of 22. This will result in a specific consumption of 30 kW(th).h/m^3 mentioned in Figure 35. Additional electricity is required for pumps and other consumers. The exact electricity consumption again depends on the number of effects or stages, and seawater pumping criteria.

The real value of the energy must be considered as well. Applying an efficiency of 33,3% for power production, the optimal RO system will use equivalent to 16.5 kW(th).h/m^3 compared with 37.5 kW(th).h/m^3 for an optimal HTME system. With a power production efficiency of 10% (e.g. a low temperature heat source of about 90°C.), the RO plant is equivalent to 55 kW(th).h/m^3.

The values in Figure 35 can only be give a general indication, and each case has to be examined. In comparing the energy levels, identical base conditions should be used.

The evaluation of hybrid energy systems and dual-purpose plants is rather complicated. A dual purpose plant, producing power and water, may result in a lower specific energy consumption than RO systems, when the water comparison is based on "loss of electricity". Based on the numerous factors involved in desalination and power plants, and their dependance on local or project specific conditions, it is clear that a separate energy consumption study has to be done for each case.

3.5.   Hybrid Desalination Processes

There are many ways to improve the efficiency of the basic desalination plants, the easiest being to combine one or several basic

desalination systems. In addition, vapour compression can be added, which results in an efficiency equal to about 30 VTE or HTME effects when added to a single VTE or HTME stage. A four effect HTME plant equipped with thermal vapour compressor is nearly twice as efficient. Some of the possibile combinations are described below.

3.5.1. Combination of MSF with VTE

The VTE/MSF combination is one of the most promising of those described in the literature (OSW reports). For example, a MSF-plant with 1 to 3 stages for each VTE effect is combined with a VTE plant. In the MSF-plant, the feed is preheated, whilst at the same time additional use of the ΔT between 2 effects is made for water production. This combination was tested sucessfully in two large scale test plants of the OSW (Freeport and Orange County) and some commercial test plants. In all cases the heat transfer area was reduced and production was increased.

3.5.2. Combination of Multi-Effect Systems with Vapour Compression Systems

a) VTE/MSF/VC

In this case a once-through MSF plant is used to preheat the feed to the required temperature. In 1 to 4 VTE topping effects combined with VC, the main amount of water is produced, and the blow-down and distillate of the VTE plant are flashed down in the MSF plant. In such a case about 75% of the water is produced in the VTE/VC part and about 25% in the MSF portion. A plant of 48 000 m^3/d production (36 000 m^3/d in VTE/VC and 12 000 m^3/d in MSF) would need a total electrical (mechanical input) of about 18 MW(th) and 50 t/h of steam at 125°C. The specific capital investment of such a plant would be 1250 US$/$m^3$/d. The main advantage of such a combination is that existing MSF plants can be increased in capacity by a factor of 4 at relatively low specific capital cost using the infrastructure of the existing plant.

b) Vertical and Horizontal Tube Evaporation combined with Vapour Compression

The basic principle is the same as in the previous case. Only the MSF-train is replaced by a VTE or HTME train (Figs. 36 and 37). Basically everything is the same as in the previous section, except that the steam consumption can be reduced slightly and the blow-down concentration can be

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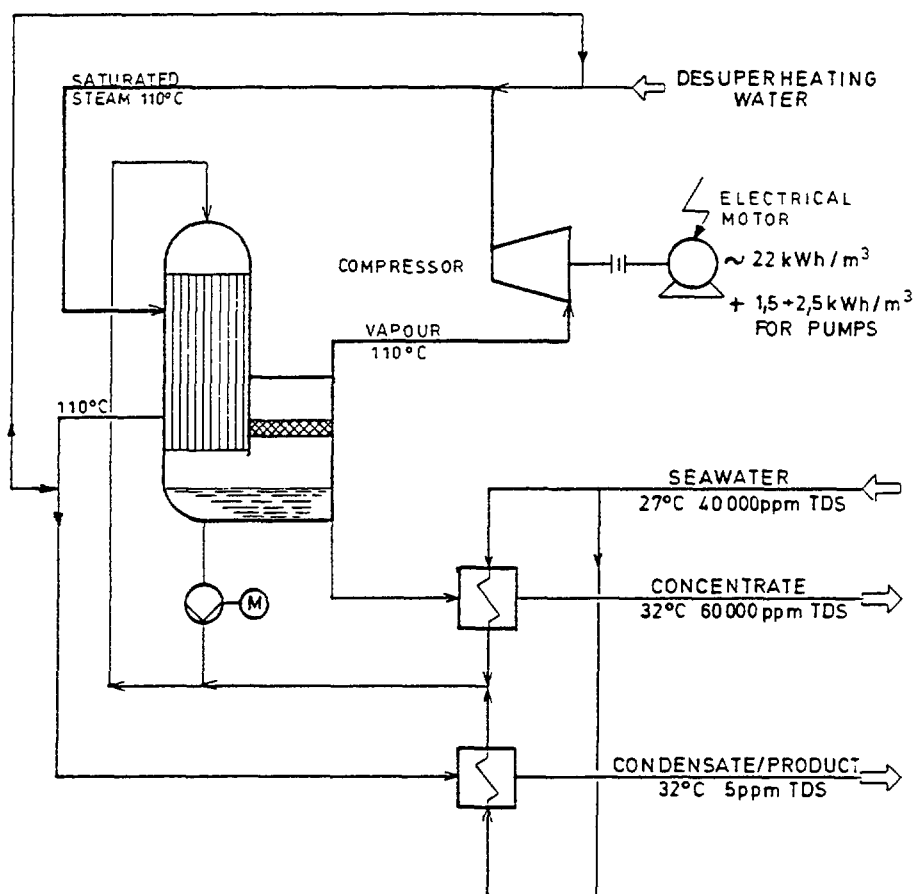
Fig. 36. Classical vapour compression seawater desalination plant (with recirculation pump or natural circulation).
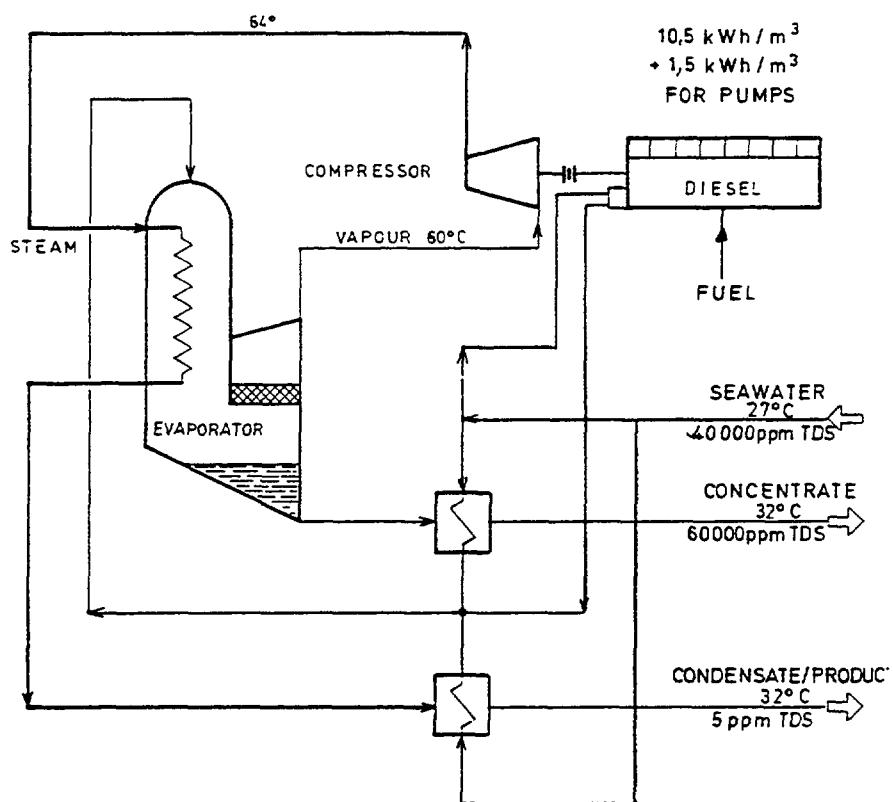
Fig. 37. Modern low temperature vapour compression seawater desalination plant.

95
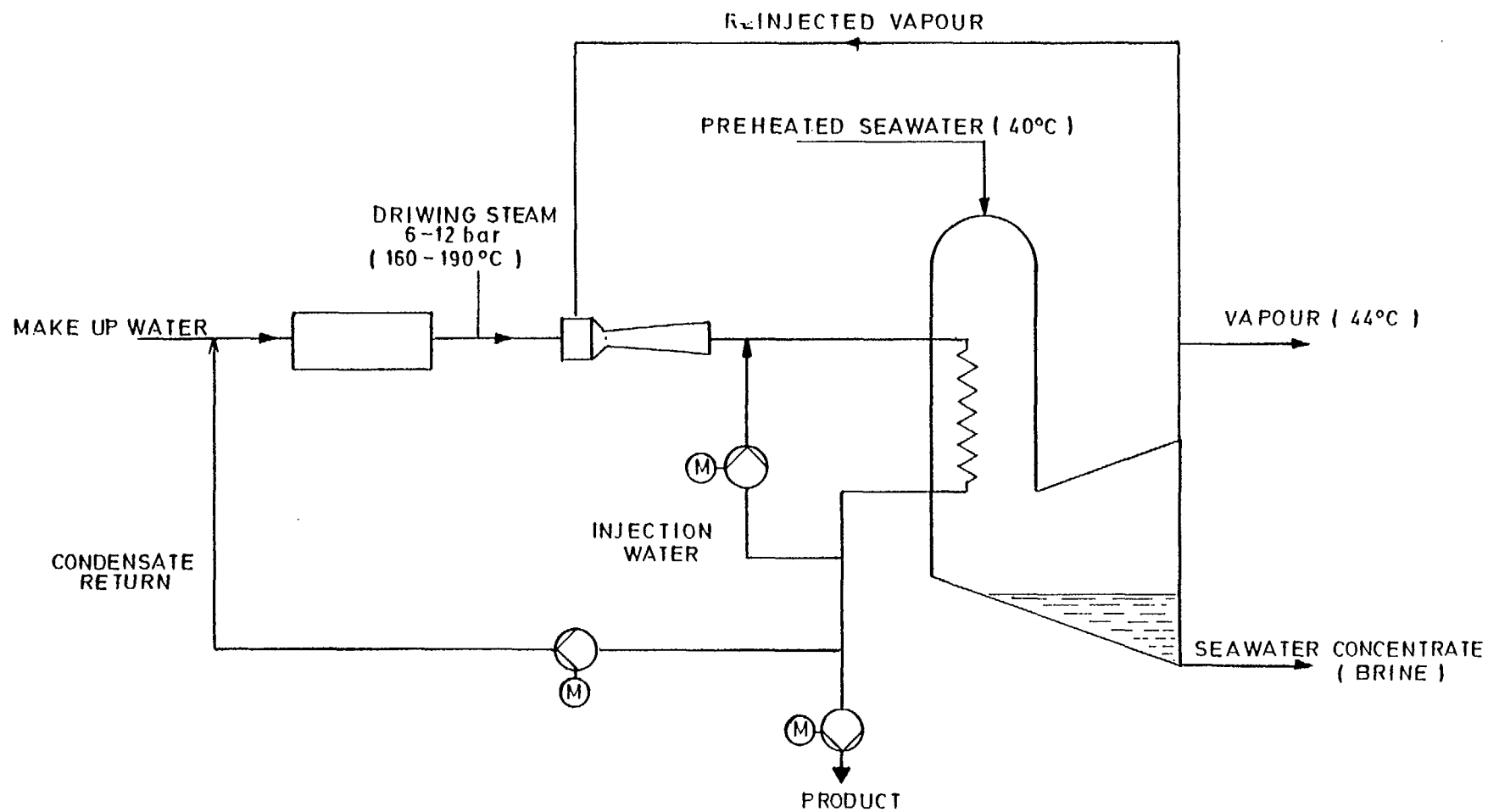
Fig. 38. Principle of thermo-compression.

increased. The advantage of the increased blow-down concentration is that the blow-down could be used (starting from about 120 000 ppm TDS) as regenerant of an Ion Exchange system removing Ca from the feed water.

Using an in-line electrolysis system on a small side steam for acid production in addition to the ion exchange system, a high temperature MED plant (max. 150°C) can be built without "external" additives. This system (VTE + VTE/VC + ion exchange + acid) has been successfully tested in the German "Meda" - project. For smaller plants, 1 to 4 VTE effects combined with VC, but without a separate VTE preheating train, can be used.

c)   ME/VC thermal

Many HTME plants have been built combined with thermal vapour compression (Fig. 38). The sizes are relatively small, and range from 10 m^3/d to 5000 m^3/d. The units are mainly used in the chemical/petrochemical industry producing process water. The reason for this is that, especially when using low top temperatures (< 60°C), units can be built for a relatively small capital investment with minimal maintenance requirements. The thermal VC system (steam jet ejector) increases the efficiency by a factor of about 2. As energy costs are in general low in a petrochemical complex, a G.O.R. of about 6 is acceptable for these plants. Thermal VC plants are limited in size, due to the size of the ejectors. Also as it is possible to use several ejectors in parallel, a capacity of a MED/VC thermal system of 12 000 m^3/d might be considered as the upper limit. Therefore, this system cannot be considered for low cost and a large water production.

3.5.3.   Combination of RO with Distillation Processes

a)   RO/MSF

There are several possible ways to combine RO and MSF. In the Jeddah RO plant which started up in 1989, the high TDS product water from the RO plant (2500 ppm TDS foreseen) is blended with the low TDS water of the existing MSF plants (10-50 ppm TDS). This solution might be of interest to increase the capacity of existing MSF plants, but is not the best for new plants.

An interesting combination is to use an MSF once-through plant as a pretreatment plant, and desalting the blowdown further in a RO plant. For

example in a MSF plant producing 12 000 m^3/d, and having a feed water flow of 3200 m^3/h, the salinity is raised from about 38 000 ppm to 44 000 ppm. This blow-down can produce about 24 000 m^3/day of desalted water with about 350 ppm TDS. Combining the 2 product stream together then hardening the water result in first class drinking water.

Although a higher TDS at the inlet of the RO plant decreases the specific flux through the membrane, it is still advantages, as the increased temperature of the blow-down fully compensates the negative effect. Additionally water leaving the MSF-plant results in full sterility and deaeration, and hence needs only simple filtering (< 50mμ), so overall pretreatment costs when combining RO and MSF can be reduced. This arrangement is especially attractive with some "first generation membranes", which are not stable against chlorine and aerated seawater.

b) RO/HTME

HTME plants have certain advantages with respect to other plants, when they are working at low temperatures. They can operate with a relatively high G.O.R. make use of heating steam with only 0.4 bar pressure. The seawater, required as cooling water to condense the vapour produced in the last effect, is heated up by 3 to 5°C. The slightly preheated seawater is used as feedwater of a RO system. As can be seen in Figure 17-1, a temperature increase of 1°C will increase the specific flux by 4%. 5°C temperature increase means 20% more production, or 20% less membrane area. The concentrate leaving the RO plant is used as feedwater for the LT-HTME plant. By this arrangement the thermally unavoidable losses can be reduced by half. Especially for very large systems, this arrangement has a large potential for the production of "Low Cost" water in a large quantities.

3.5.4. Others

Other combinations are possible, but at present are not economic for "low cost" water production. Where by-product production is considered as well (for example Magnesium is produced today in large quantities from seawater), the addtion of an ED-system will be economic. The same is also valid for NaCl - production. The advantage of the ED-system, in this case, is the fact that ED with polarity reversal is less sensitive to high TDS and saturation than other systems.

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3.6. Environmental Impact Resulting from Desalination

Often people fear that the concentrated blow-down will have a negative effect on the environment, but this is not the case. The amount of seawater used for desalination is small, as is the concentration factor increase only by about 2. Hence the increase in salinity near large scale desalination plants is negligible, and does not present a problem, especially when additional seawater currents exist, as is practically always the case.

The increase in temperature is also only a theoretical problem, due to the high dilution ratio between blow-down and seawater which occurs.

A major problem might arise however, from the additives used in pretreatment, and from corrosion products from the plants. Ref [32] mentions, for example, Fe between 0.3 and 0.9 ppm and Cu between 0.15 and 0.25 ppm in the blow-down. Much higher values have frequently been observed in practice, and often the colour of the blow-down indicate excessive Cu corrosion. In plants using acid dosing as a pretreatment, the pH in the blow-down is often quite low. The Cu content in the blow-down can particularly result in environmental problems. In some areas near large desalination plants equipped with copper-nickel or brass tubes, a change in algae growth has been noticed, indicating the negative influence of the blow-down on the local microbiological life in the seawater. This problem can be avoided by proper selection of the materials in contact with seawater or brine. Titanium and high grade stainless steel materials (e.g. nitrogen stabilized CrNi Mo 1810) can reduce the metal emission to virtually zero. The negative effect of large pH variations in the blow-down is becoming minor as acid dosing is used less frequently, and the plant controls are becoming more efficient and reliable than in the past.

3.7. Cost of Desalination Processes

There are many, parameters to be considered in calculating the specific water costs (Fig. 39). Data given in various publications [29, 30, 33, 34, 35] vary over a wide range of capital and operating costs. Figure 35 includes the complete desalination plant within its boundaries, but excludes the seawater intake, the power production section, water storage, spares and replacements.
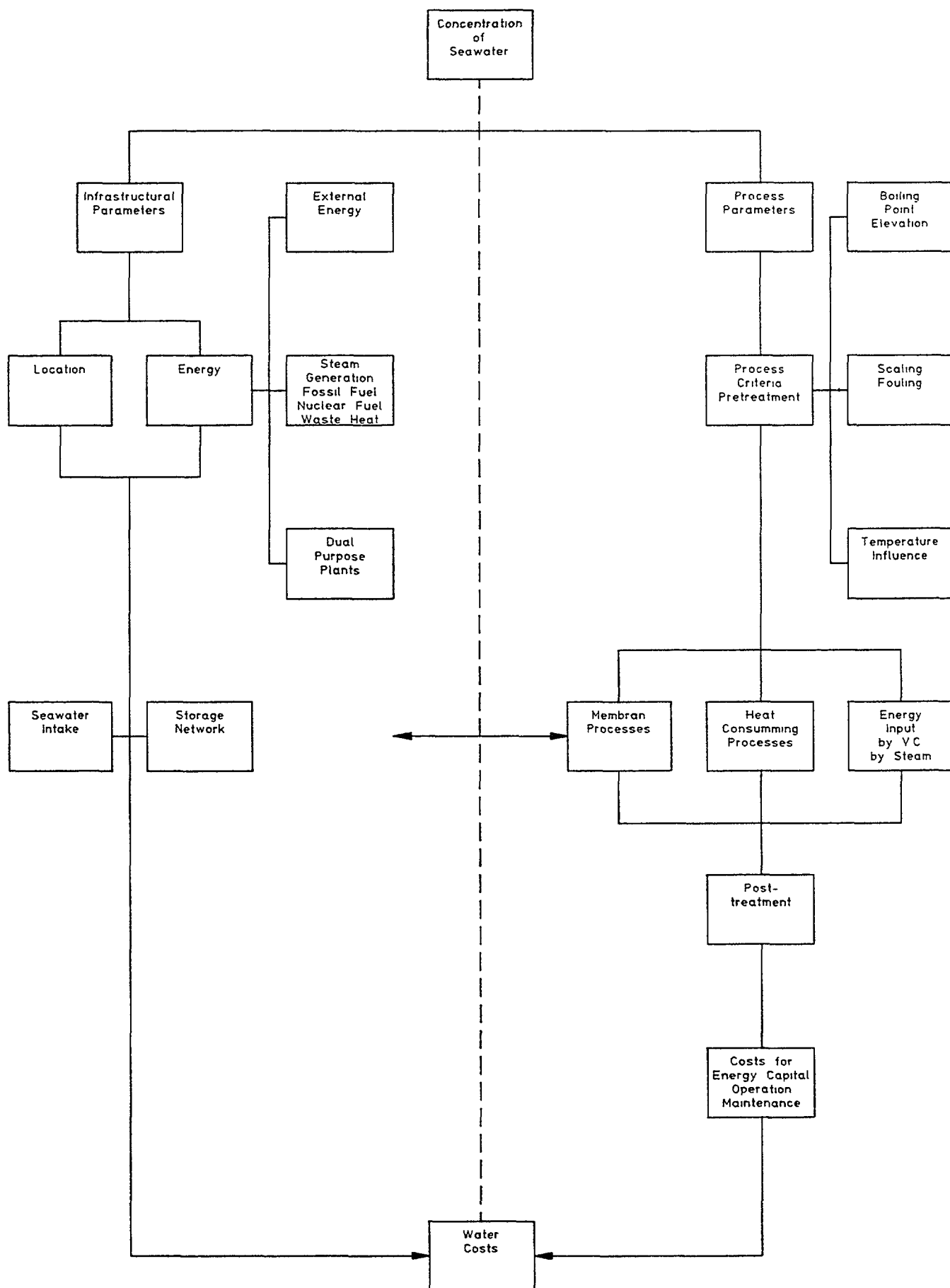
Fig. 39. Water cost parameters (seawater desalination).

Therefore, the values quoted can only provide a basic indication. For example, the RO process is the cheapest based on initial capital costs, but during the lifetime of the plant, the membranes have to be changed several times. A complete membrane change may cost 10-20% of the initial investment. The normal lifetime of a membrane is 3 to 5 years, therefore typically 40% has to be added to the initial investment cost taking into account a plant lifetime of 15 years, and this does not include the normal spare parts.

The cost for the seawater intake is also a very significant sub-component directly to the desalination process. As the cost of the intake is directly dependant on the location of the desalination process, a case by case evaluation is required to obtain realistic costs. The following example may indicate the complexity and the need for a comprehensive cost evaluation.

RO plant within its boundaries	1000 US\$/m^3/d
Replacement membranes (15 years lifetime of plant)	400 US\$/m^3/d
Seawater intake	600 US\$/m^3/d
Power Production by Diesel Generator	1800 US\$/m^3/d
Storage and Water transfer Station	250 US\$/m^3/d
Specific initial investment costs for a turnkey plant	4050 US\$/m^3/d

This example explains the large variation in the data given in [35]. Without an exact explanation of what is included, data taken from literature can be most misleading. The example also indicates the relative significance of the each of the various sub-components. The cost for the desalination process is only 25% of the cost of the "turn key" project.

3.8. Criteria and Optimization

3.8.1. Technical Criteria for Comparison between Processes

This section discusses a number of important technical considerations that should be involved in the selection of a desalination process [37].

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3.8.1.1. Purity of the Product

Any one of the distillation processes can produce comparatively pure water. Manufacturers typically submit bids containing warranties that the TDS will be less than 25 ppm and, in some bids, less that 10 ppm. The Reverse Osmosis (RO) membrane process, on the other hand, will give up to ten times higher TDS than the distillation processes from a seawater source in a single stage, as shown in Table below. In addition TDS increases constantly from start up to the end of life (3 to 5 years) for RO. Electrodialysis (ED) can attain over 99% of salt rejection in a single stage, but cannot remove non-ionized impurities and colloids.

Desalination by freezing results in almost pure ice crystals, but the adhering brine, that is not removed by rinsing, contributes impurities to the product. Contaminants are rejected regardless of ionic charge. Because of the low temperature of operation, many volatile impurities remain behind in the reject stream.

Product Water Quality Using a Single-Stage RO Process

Plant	Drop (Kuwait)	Helgoland W. Germany	Jeddah Saudi Arabia
Operation Start	Feb. 1985	July 1988	May 1989
Capacity (m³/day)	1000	960	56 800
Supply Quality (ppm as TDS)	48 000	35 000	43 300
Product Quality (ppm as TDS)	260 (after two years)	45 (start up)	120 (start up)
Conversion (%)	32	35	35
Operating Pres. (MPa)	6.5	6.0	5.7

3.8.1.2. State of Development of the Processes

Distillation processes are fully developed and have been in successful commercial use for a number of years. The membrane processes, RO and ED, have processed brackish waters in sizable modules for over 10 years. A few large RO plants have recently been built as outlined in the previous table. The application of seawater ED is currently limited to small capacity apparatus. Freezing desalination, while yielding excellent results according to paper studies, shows little success in pilot plant

equipment, and has yet to be installed in a moderately large commercial plant.

Improvements continue to be made in all these processes. In distillation, the emphasis is largely on the reliability of components and the control of corrosion. In membrane processes, the present effort centers on membrane reliability, new membranes, and on membrane sizing, which is a method of upgrading deteriorated membranes based on established textile sizing procedures.

3.8.1.3. Insensitivity to Feedwater Conditions

Although the "minimum theoretical work" of distillation is roughly proportional to feed concentration, the total energy consumption is almost the same for seawater or very dilute brackish water. The membrane processes, on the other hand, experience a sharp increase in energy demand as the feedwater concentration rises. For RO, the pump pressure required by a brackish feedwater is 1.8 to 2.9 MPa, and for seawater 5.6 to 7.0 MPa. The ion migration and other problems with ED are even more serious. Not only does the ED ion transport current increase with dissolved salt concentration, but a high salinity concentrate stream increases back-diffusion of solute, to a large extent negating the desalting action of the electric current. In addition, very high salinities short-circuit the current through the flow ports, thereby "burning" the edges of the membranes and the electrodes. In freezing desalination, increased salinity of the feed lowers the freezing point of the brine, thereby increasing the energy consumption. In addition, a high-salinity feedwater will yield a less pure product water than a feed of low salinity.

3.8.1.4. Discussion of Pretreatment Requirements

Large objects must be eliminated from any feedwater stream. To this end, ocean surface intakes are equipped with trash racks and screens. An alternative is the construction of sea wells, which strain the seawater through the naturally occurring sand of the seashore. These wells remove not only kelp and marine organisms, but also fine suspended matter that cannot be tolerated by RO membranes. In contrast, distillation plants are indifferent to moderate amounts of silt. If the silt loading is excessive however, its removal by means of hydrocyclones is adequate for distillation plants. For both RO and some distillation plants, it is mandatory to

chlorinate the feed, preferably by shock chlorination, a treatment that
destroys microorganisms and, in the case of open intakes, also the
shellfish which could lodge in the tubes of distillation plants, either
blocking the flow or inducing erosion by generating eddies downstream from
the obstruction. In general, this concern is minimal in those horizontal
tube plants, where the brine is sprayed on the outside of the tubes,
because deposits on the exterior of the tube do little harm, and are easily
removed.

The formation of scale can be a serious obstacle to the successful
operation of a desalination plant. Scale deposits impose a barrier to the
transfer of heat in a thermal process, coat and even pierce membranes in a
membrane plant, and obstruct flow passages and "freeze" valves in any kind
of plant. One of the most common scale formers is calcium carbonate
($CaCO_3$), which deposits when carbon dioxide (CO_2) is released from the
feed by boiling or by CO_2 transfer across a membrane, as described below:

$$Ca(HCO_3)_2 \text{ ---- } CO_2 + H_2O + CaCO_3$$
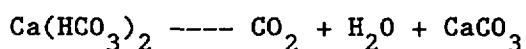
One of the oldest methods for the prevention of scale is the
acidification of the feed with a mineral acid. This technique, however,
requires the storage and handling of a potentially dangerous substance and,
if not carefully controlled, may induce rapid corrosion of metallic plant
components. Scale control additives have been tested for the prevention
of carbonate scaling with varying degrees of success. For RO plants, the
transfer of CO_2 across the membrane makes the use of acid in combination
with additives the best method at present. For distillation processes that
operate below 120°C, high-temperature additives show promise. Multistage
and multi-effect plants, at temperatures not exceeding 90°C, have
successfuly used sodium polyphosphate for a number of years.

Even plants using acid for the prevention of carbonate scale require
sodium hexametaphosphate (SHMP) or one of the newer additives, to prevent
the deposition of calcium sulfate, a common problem in brackish water and
all seawater.

RO, in general, requires thorough pretreatment to avoid deposits that
might decrease the product flux or, in extreme cases, could completely
destroy the membranes. However newly developed membranes are much less
sensitive, as discussed earlier.

Reports indicate that ED with reverse polarity can operate safely for extended periods without acids or additives. This is equally true for the freezing process. Silica, which deposits damaging scale from some feedwaters in other membrane processes, is reported to do no harm in ED plants with reverse polarity.

3.8.1.5. Necessary Skill of Operators

At present, no operating experience is available for commercial-scale freezing desalination plants. Reverse polarity ED, Low-Temperature Multi-Effect distillation, and Low-Temperature Vapor Compression require very little operator attention or skill. High-temperature distillation requires careful attention to scale control and corrosion prevention methods. The most demanding process has been RO, for which operators had to be trained in all the pretreatment steps, but the newer RO membranes are less sensitive, reducing the demands of the operators.

3.8.1.6. Maintenance Requirements

In every well-operated plant, even those which inject acid into the feed stream, scale and other contaminants will deposit slowly. When the heat transfer drops below a predetermined value in distillation plant or when the product flux or purity drops to a preset value in a membrane plant, cleaning is initiated as outlined below:

- In distillation plants, inhibiting acid is circulated through the system. This can be done without shutdown, but with no water production. A high-temperature system will require cleaning at intervals of 3 to 12 months, provided no serious maloperation has occurred. A low-temperature plant must be cleaned at intervals of 6 months to 2 years. In an MSF plant, the scaling rate can be substantially reduced by circulating sponge balls through the tubes during plant operation, a process that involves an increase in investment.

- For an RO system, a detergent/suspending-agent solution is circulated through the feed side of the plant. If the elements are loaded with scale to the point that the cleaning process is ineffective, the elements must be removed from their pressure vesseles and soaked in a tank of cleaning solution. Should this

fail to solve the problem, the membrane elements must be discarded and replaced by new ones.

- Although polarity reversal is quite effective in eliminating scale formation in ED, either deposits on the membranes or other problems may require maintenance. Prior to shutdown, the trouble spots are located by measurement of inter-cell potential drop. Then the stack is disassembled and dirty membranes are cleaned by manual scrubbing. Membranes showing burns of fractures are replaced. Defective electrodes are removed for replating.

3.8.1.7. Stability Under Design and Partial Load Conditions

Two possible sources of instability are the vapor compressor in a VC plant and the control equipment in any desalination plant. It is safe to assume that a reliable manufacturer of vapor compression equipment will design a compressor to operate in the stable range. The balance of this or any other system can become unstable if the control system exhibits positive feedback characteristics. The most annoying (and perhaps damaging) is the improper control of flow in a circulating loop, results in surging, but this is seldom a problem in a well-designed control system.

3.8.1.8. Flexibility of the Process

The purchaser of a desalination plant will ask two questions:
- Can I achieve more than the rated output if needed?
- To what degree can I cut back on the plant production?

As for the first question, it must be remembered that the supplier is not obligated to provide overcapacity beyond the contracted value. However, it is possible to increase the output of an ED cell simply by increasing the current through the cell, making certain not to exceed the maximum specified by the manufacturer. For an RO plant, an increase in applied pressure, if permitted by the pumps, will yield a greater product flow, but at the expense of shortened useful membrane life, increased energy consumption and the risk of reduced product quality. The output of a VC plant can be increased only if the compressor motor and the compressor itself have been overdesigned. A higher output from a thermal distillation plant requires an increase in prime steam temperature and flow, preferably with an increase in brine recirculation rate. A higher steam temperature increases the danger of scale formation in the brine heater, even if the

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pumps permit an increase in recirculation rate. In summary, a 10 percent increase is possible for MSF, 25 percent for MED; a substantial production increase in the other processes is questionable.

The answer to the second question depends on the desalination process. For ED, unlimited turndown is possible, accompanied by an improvement in product purity, but an increase in specific energy consumption. Alternatively, an ED plant can be turned on and off as needed, with no harmful effects. For RO, on the other hand, a decreased feed pressure cuts down product flow but is detrimental to product purity. In addition, there are definite limits to minimum and maximum flow through RO elements. Turndown of a VC plant lowers the energy efficiency and, even more seriously, may lead to instability of the compressor. MSF can tolerate, in general, a turndown of about 40 percent, below which the operation becomes unstable or ceases to function entirely. Multi-Effect Distillation (MED) output can be reduced substantially without instability or energy penalty, except for the wasted power of the recirculating pumps. It has been demonstrated that the multi-effect evaporator design can readily accept a 40 to 45 percent turndown, which is achieved rapidly in response to changes in the steam supply.

3.8.1.9. Reliability of the Process

One of the factors effecting the reliability of any process is the operators skill and experience, and for that the need for better training of the operators and use of automated systems is essential. The reliability of each of the three broad categories of commercial desalination processes is evaluated below.

Distillation Processes

Serious problems have been encountered in multi-stage flash MSF plants, particularly those operating with pH control of scale. Operator intention or defective instrumentation has been responsible for wide swings in pH.

Insufficient dosage of acid permits scale deposition, and excess acid leads to catastrophic corrosion of tubes and evaporator shells. Even a well-operated plant is difficult to control since the target pH is on the knee of the pH-vs-dosage curve. One alternative for good scale control with moderate corrosion is the continuous injection of scale control additives.

Another source of difficulty is the chlorination required as biocide. The chlorine reacts with the bromides in seawater, liberating bromine, which severely corrodes the venting system.

Successful removal of both scale and marine organisms from heat exchange tubing has been achieved by circulating sponge ball through the plant (the Taprogge process), but at considerable increase in complexity and need for continuous attention.

Further corrosion problems are introduced by hydrogen sulfide (H_2S), which results from organics present in some seawater sources. Shutdowns for the repair of corrosion damage are frequent and become increasingly so with time.

Greater reliability is exhibited by the low-temperature distillation (MED) plants. Although still faced with the problems of marine growth, they suffer less from corrosion, and scale formation is easily controlled. In contrast with the MSF plants, these low-temperature systems have been reported to operate from 6 months to 2 years before a short interruption for on-line cleaning is necessary. For the MED plants that operate at lower temperatures, an organic coating applied to the chamber interior provides long-term protection of the carbon steel. Multi-effect plants with aluminum-alloy heat-transfer tubing experience a uniform tube corrosion rate of about $12.7\mu m$ per year, and show no sign of crevice corrosion or stress corrosion cracking, even in the presence of considerable amounts of H_2S. Thus, almost no operating time is lost for retubing or for the patching of vessel shells.

The RO Process

For the RO process, reliability is dependent on the type of feed. In general, plants supplied with brackish well water have an excellent on-stream factor if properly operated and serviced. Seawater plants have experienced a number of interruptions; however, the seawater application is relatively new, and its problems are expected to be gradually resolved. At the other extreme, a high degree of reliability cannot be predicted at this time for the processing of surface waters or wastewaters by RO unless very thorough pretreatment is provided.

The ED Process

In ED, the early problems of scaling and attack on the electrodes have been overcome by the introduction of reversing polarity. Recent plants

using reverse polarity ED for the desalination of brackish water are performing well, and exhibit a satisfactory on-stream factor. It should be emphasized again that ED is not currently used for seawater desalination on a large scale, and that its reliable application to wastewater requires careful attention to the control of bacteria, and membrane contaminants such as iron in solution.

3.8.2. Economic Criteria

The most useful cost evaluated in feasibility studies is that of the desalted water (e.g. expressed as US$/m^3 product water). This cost is obtained by dividing the sum of all the expenses related to the production of desalted water by the total amount of desalted water (where proper levelizing and/or capitalizing are done according to a predetermined discount rate). However, some other criteria have to be considered:

1.   The total investment and specific investment per unit capacity (e.g. expressed as US$/m^3 per day etc.).
2.   The value of the specific energy consumed by each unit product.
3.   The value of other cost components.

These are influenced by the major cost components, and uncertainty of the assumptions used. Assumptions such as the life-time of the plant, interest rate, duration of construction, future price of energy etc. might change considerably with time. Thus, sensitivity studies have to be carried out taking into consideration risks and possible future improvements.

3.8.3. Summary of Technical Criteria

Figure 40 summarizes the evaluation discussed in the preceding subsections. Under each criterion, a number has been assigned to represent the rating of each process as follows: 3— a highly satisfactoy process; 2 —a process that is only fair in meeting a particular criterion; 1 — a process that does not perform well or one that is troublesome; 0—a criterion that has not yet been demonstrated for the particular process.

The sum of the ratings for each process provides a rough basis for selection by the prospective purchaser. It has been assumed that each of the technical considerations is weighted equally. Under some

circumstances, the purchaser of a desalination plant may be justified in attaching greater importance to one or more of these criteria, leading to a different ranking of the processes than the one shown here. The reader should note that a zero rating does not indicate a failure but, instead, that the process has not yet advanced beyond the pilot plant stage. In addition, commercial ED has not been constructed for seawater desalination with a capacity larger than 1000 m^3/day. Freezing and seawater ED may be considered for future development.

It is apparent that a process may have a high rating for some applications and yet be a questionable choice for others. In general, the highest overall rating is shown for seawater desalination by multi-effect distillation in low-temperature plants of the horizontal tube type.

In some applications, the use of a process of slightly inferior numerical rating but lower overall cost may be justified.

3.8.4. Optimization

In selecting the required design parameters of a plant, some are determined by known physical & chemical etc. constraints. With the others, there is a certain degree of freedom, which allows continuous or arbitrary determination. To achieve the best results such determination is arrived at via optimization, in most cases according to economic criteria. For single-purpose plants the cost of the product is usually the dependent variable which should be minimized by the optimized design. In dual-purpose plants there might be several possible optimizations depending on the customers of the two products. One conventional method is to design a dual-purpose plant to achieve minimum cost for the second product (e.g. the desalted water), using conventional costing for the primary product (e.g. electricity).

The number of parameters to be determined by optimization is quite large, each plant and process having its own specific aspects. However, some are common to all seawater desalination processes:

a)   —   The ratio between the feed seawater and the desalted product water.

b)   —   The temperature range at which the separation takes place.

c)   —   The dimensions of the separation elements (e.g. the diameter and

length of the heat transfer tubes in evaporation processes, the
size of membranes in RO or ED processes etc).

d) – The number of effects, stages or passes in the various processes.

e) – The velocities of the fluid in each element.

f) – The most important parameter to be optimized in each process
element is the flux ϕ (ie. the heat transferred per unit area
W/m^2 – in heat exchange equipment or the flow rate of desalted
water per membrane unit area – $m^3/day/m^2$ – in RO elements).

All these parameters are also limited by physical or chemical
constraints, but the optimal value of each usually differs from the extreme
value.

The designer of a plant may wish to reduce the optimal capital
investment which is a function of area, by using a larger temperature
difference in the case of thermal processes, or pressure difference in the
case of RO, at the expense of energy cost. Various detailed methods are
available in the literature for optimization.

4. RECENT EXPERIENCE AND STUDIES
COUPLING NUCLEAR PLANTS WITH DESALINATION PLANTS

In principle, the energy produced by thermal power units can drive desalination processes in three different ways:

a)   Mechanical, and/or electrical energy for processes that are based on mechanical work: Reverse Osmosis, Vapour Compression and most of the Freezing Processes.

b)   Heat for evaporation (distillation) processes and for Freezing by absorption.

c)   Electricity for Electrodialysis.

Also, all desalination processes need mechanical work for pumping, and electricity for auxiliaries and services.

Obviously, one nuclear unit can energize several processes via different forms of energy.

4.1.   Water Cooled Reactors (WCR)

Almost 90% of the nuclear power plants now operating in the world, are water cooled reactors (WCR). Almost all those which are now under construction also fall into this category.

Advanced water cooled reactors are now being designed and developed for the next generation of plants to be built after the year 2000. Hence reviewing and analyzing the potential of such units for seawater desalination is important.

Five types of WCR exist:
1)   PWR   – Pressurized Light Water Reactor.
2)   BWR   – Boiling Light Water Reactor.
3)   PHWR – Pressurized Heavy Water Reactor.
4)   LWGR – Light Water (cooled), Graphite (moderated) Reactor.
5)   Water Pool Type Reactor.

The following subsections deal with specific aspects of Water Cooled Reactors coupled to seawater desalination plants.

4.1.1.   Mechanical Energy Supply From WCR

4.1.1.1. Direct Mechanical Energy

It is possible in principle to drive the main compressors of the MVC (Mechanical Vapour Compression) or Freezing processes, and the high-pressure pumps of RO (Reverse Osmosis) process by steam turbines, taking the steam from an adjacent WCR that is either (a) single purpose for desalination only or (b) dual purpose, for electricity and desalination.

(a)   In the first case many small steam turbines operating with high pressure steam must be used, because the size of a turbine is determined by the largest compressor or pump suitable for the desalination process. Thus, for example, if a compressor is used to produce 3800 m^3/day of desalted water, consuming 7 kW(e).h/m^3, then a small WCR generating an equivalent of 200 MWe would be coupled to about 160 parallel compressor units. In addition, about 20 MWe would be needed for pumping. This arrangement has advantages over electricity driven desalination plants due to eliminating AC generator and electric motor inefficiencies. On the other hand, many small turbines and steam lines are more expensive (per power unit) and less efficient. Also, the ready availability in the market place of suitable turbines is not known, especially since they are operated by "nuclear" steam which has higher moisture content. Although the possibility has not yet been studied, it seems that the disadvantages weigh more, in particular for RO and Freezing desalination. Condensing the exhaust steam from the turbine can be used economically to preheat feedwater of desalination processes. Avoiding the risk of radioactive contamination by the steam coming from the WCR in such arrangements may be expensive.

b)   A dual purpose arrangement, where part of the steam drives the compressors/pumps of the desalination units, suffers most of the disadvantages, but is more flexible in the following three respects:

−   The steam turbines inlet (or even outlet) pressures can be selected more freely.

−   The amount of desalted water can be varied over a wide range.

−   The size of WCR selected need not be based on water needs.

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In view of the above mentioned drawbacks, and the risk of having radioactive traces in the steam from WCR (unlike steam from GCR and LMR) mechanical coupling appears to be the least promising.

4.1.1.2. Mechanical Work via Electrical Energy

Such an arrangement can be carried out with or without nuclear energy associated with the grid. However, coupling a WCR and seawater desalination units has the following advantages, provided it is feasible to build the power unit close to the sea:

1) The same seawater can be used as coolant for the power unit and as feed for the desalination plant so that investment in the intake system (all or at least a major part of it) and part of the pretreatment and pumping energy is saved.

2) Electrical transmission losses are saved.

3) The large number of desalination units are independent (except for common electricity and seawater supply) and have a high load factor which contribute to increase the power unit load factor, thus reducing the cost of generated electricity.

4) Skilled manpower is available in the power unit and can save a significant part of the labor expenses.

5) Common facilities contribute additional savings such as for workshop, warehouse, tools, hoisting, roads, communication etc.

6) For Vapour Compression desalination, where the feed seawater is used first for cooling the power unit, the preheating of this feed is another saving. This is relevant only if the power unit condenser tubes are not made of copper alloys or if the desalination heat transfer surfaces are not made of aluminium, since these materials are not compatible. For RO, such preheating is an advantage, but membrane lifetime must be kept reasonable.

The possibility of leakage in the power unit condenser, resulting in contamination of either the motive steam cycle by salts, or the saline feed water by radioactive carry-over traces, is discussed in the next section. (This possibility is much more probable at the high pressures and temperatures which are discussed in the next section). A simple solution is to maintain the seawater in the condenser at a pressure higher than that of the condensing steam, and to monitor the qualities of the condensate and coolant at their outlets from the condenser. This solution is acceptable only for PWR and PHWR, not for BWR, as the latter introduces primary coolant too close to the desalted water, which may not be sufficiently safe.

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Process	Purity of the Product	State of Development	Insensitivity To Dissolved Solids of Feed	Pretreatment Requirements	Necessary Skill of Operators	Maintenance Requirement	Stability Under Design Conditions	Flexibility	Reliability Of the Processes	Sum of Ratings
Multistage flash distillation (seawater only)[a]	3	3	3	2	2	1	3	1	2	20
Multi-effect distillation (seawater only)										
Vertical tube, high temp.[a]	3	2	3	1	2	1	3	3	2	20
Horizontal tube, low tem.[a,b]	3	2	3	3	3	2	3	3	2	24
Vapor compression distillation[c]	3	3	2	2	2	2	3	2	3	22
Reverse Osmosis										
Seawater	2	2	2	2	2	3	3	3	2	21
Brackish well water	2	3	1	2	2	3	3	3	3	22
Surface or wastewater	2	2	1	1	1	1	3	3	1	15
Freezing desalination[d]	1	0	3	3	0	0	0	0	0	7
Electrodialysis										
Seawater	Not currently constructed for seawater desalination with a capacity larger than 1000 m³/day									
Brackish water or Wastewater	2	3	2	2	3	2	3	3	3	23

Ratings - 3 = highly satisfactory process
2 = Fair
1 = Low quality or troublesome
0 = Performance not demonstrated

Notes:
(a) Not competitive for brackish water
(b) Technically superior to membrane processes for some wastewaters
(c) Large units sold predominantly for wastewater concentration
(d) Pilot plant tested on seawater and some industrial concentration processes to date

Fig. 40. Summary of technical criteria.

The desalination units can be backed by the grid against shut-downs of the power unit. This power-water combination depends neither on the type of the reactor nor on whether the electricity is used solely for water desalination or partly for sale as electricity. Such coupling is relatively simple and is not associated with particular problems. The advantages are relatively small but can decrease the desalted water cost by up to about 10-15% compared to units that get their energy from the grid. This value is based on the assumption that the cost of an equivalent kWhe from the WCR is equal to that from the grid. Otherwise, the cost of the desalted water has to be adjusted accordingly.

An economical WCR is usually considered to generate 600-1400 MWe. If all the electricity is used for desalination, huge amounts of desalted water can be produced.

Assuming around 5 kW(e).h/m^{3}for large RO units, the maximum capacity of a single purpose plant is:

$$\frac{600,000 \text{ kWe}}{5 kW(e).h/m^3} = 120\ 000 \text{ m}^3/h = 2.9 \times 10^6 m^3/day = 900 \times 10^6 m^3/year$$

For MVC, assuming 7.5 kW(e).h/m^3, the maximum capacity of a 600 MWe WCR will be 600 x $10^6 m^3$/year. While less than RO in quantity, better quality and possibly cheaper water is obtained.

4.1.2 Heat Supply From WCR

According to reference [37], the following are the three most promising seawater desalting processes.

1) Low Temperature Horizontal Tube Multieffect distillation (LT-HTME), in a dual-purpose plant.

2) Vapour Compression distillation (VC).

3) Reverse Osmosis (RO).

VC and RO, utilizing heat from the WCR, were briefly discussed in the previous section 4.1.1.1. In the present section, the most promising process (LT-HTME, dual purpose) and the most widespread process (MSF), as well as other evaporation processes heated by the WCR, will be described and discussed.

Possible Steam Couplings

In order to maximize the economy of a project, energy waste should be avoided. Therefore, the steam from WCR should be utilized so that all the pressure difference between the condition at which it is generated (e.g. 7 MPa for PWR) and the condition at which it is supplied to the evaporation process is converted to mechanical energy. There are four typical pressures for process steam, which are of special interest:

Case 1: 0.2-0.37 MPa (condensing temperatures 120°C-140°C) for MSF and MED (Multi-Effect Distillation). In these evaporation processes the maximum brine temperature should not exceed 121°C (brine recycle plants) and 135°C (once through plants) to avoid scale problems.

Case 2: 30-40 kPa (condensing temperatures 69°-76°C) for LT-HTME (Low Temperature Horizontal Tube Multi-Effect Distillation) with aluminum tubes. Maximum temperatures should not exceed 72°C for the brine and 70°C for the aluminum.

Case 3: 17-18.6 kPa i.e. 5"-5.5" Hg abs.; (condensing temperatures 56.5°C-58.5°C). These temperatures are determined by the available large condensing turbines, which cannot operate at higher exhaust pressures. This suits all thermal evaporation processes, although there is a certain penalty with some processes. LT-HTMED evaporation seems to have the lowest penalty.

Case 4: 4-8 kPa i.e. 1.2"-2.5" Hg (abs) (condensing temperatures 30°C-42°C) which is the conventional range of condensing turbines. A special version of MSF was adapted to these conditions for sites where the seawater is cold, 20°C or lower, but number of stages is reduced.

Cases 1 and 2 are determined by the desalination process to which the steam cycle of the power unit has to be adjusted technically and economically to the extent possible, while in cases 3 and 4 the desalination process has to be adjusted to the power unit to a large extent, though there are a few minor changes in the power unit as compared to a single purpose plant.

4.1.2.1. Case 1: Highest Permissible Brine Temperature

The conditions of Case 1 are suitable for most of MSF and high temperature MED processes. However, it poses a problem of matching the heat conditions of the heat source and the desalting processes.
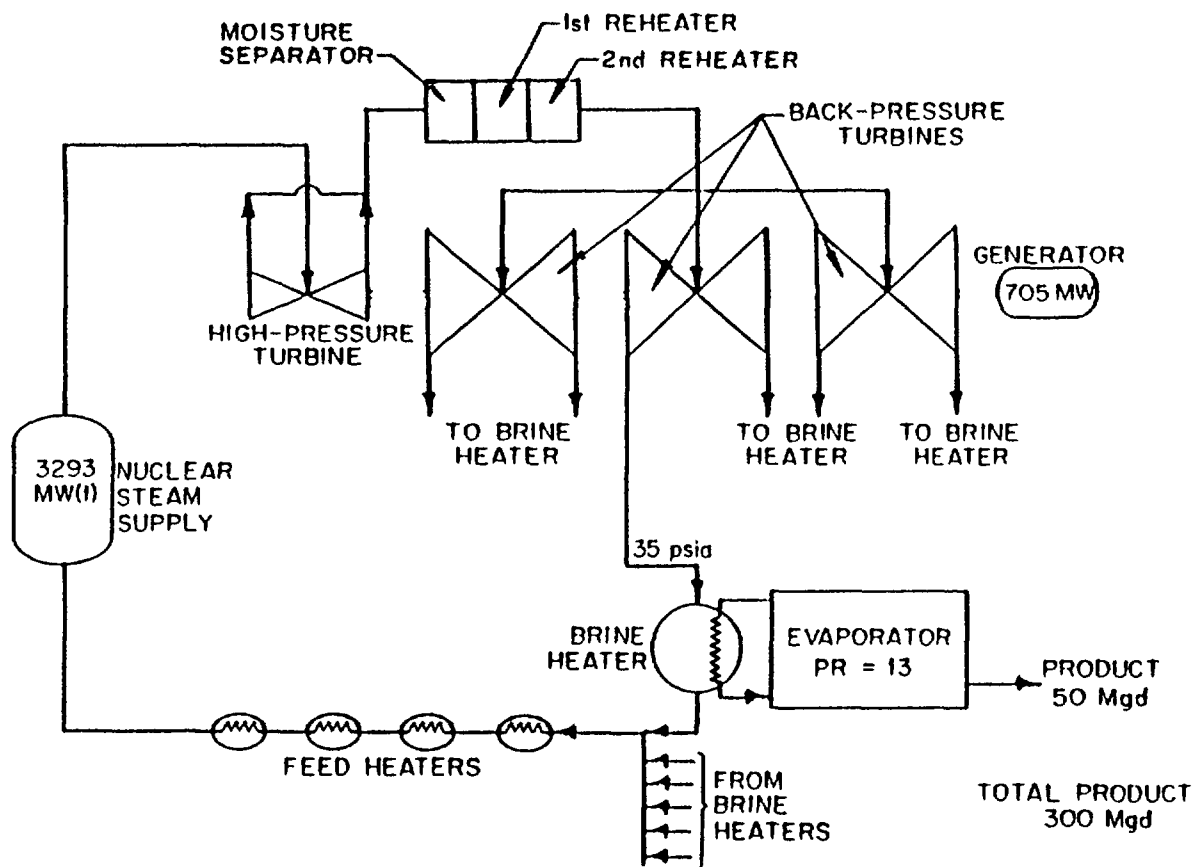
Fig. 41. Schematic of full-scale dual-purpose plant with multiple back pressure turbines.

The ideal arrangement is to obtain a large amount of heat from a dual purpose plant, by condensing all the steam from the exhaust of the power unit turbine and by releasing its latent heat to the desalting process. This could be practical if the existing and available turbines were designed to operate at an exit or extraction steam pressure of 0.2-0.37 MPa. Suitable extraction condensation turbines extracting the steam partially at 0.2-0.37 MPa and having the final pass out at 3 to 40 kPa are already used in many dual purpose fossil fired plants and this experience can be used also for turbines in WCR plants.

A possible alternative is to take off some steam after partial expansion. If a large amount of desalted water is needed, so that all the available steam from the power unit is used, then several relatively small back-pressure steam turbines connected in parallel, and designed to operate at 2 bar to 3 bar exhaust pressure, may replace the original large condensing turbine (Fig. 41). This solution depends on the availability of such back pressure turbines and their sizes. The smaller the available turbine - the lower is its efficiency, the more expensive is the investment and installation and the more complicated is the system. The viability of

this solution is, therefore, questionable, in particular when considering medium or large WCR for power generation. Such units are so far recognized to supply cheaper electricity. However, this arrangement maximizes the amount of desalted water by heat.

WCR have lower thermodynamic efficiency than conventional fossil fuel units, HTR or LMFBR. Therefore, they produce more exhaust heat per MWe generated. A typical single purpose WCR of 600 MWe discharges about 1150MWth at ambient temperature. If the steam expands in the turbines to a pressure of, say, 0.25 MPa, the heat discharged by its condensation is approximately 1400MWth and the electricity generated is about 350 MWe. The amount of desalted water, with a GOR (Gain Output Ratio) of 12 is about 6 24 000 m^3/day). The ratio of water to electricity supplied by the station is high, as the desalination process consumes 25 to 100 MWe (for pumping mainly); 25-40 MWe if MED is used, 65-100 MWe if MSF is used. The ratio is 80-110 m^3/h/MWe respectively.

Another solution is simpler but not more economical i.e to use a large condensing turbine for power generation and divert part of the steam to one or a few parallelly connected smaller back-pressure turbine(s) that operate with on exhaust pressure of 0.2-0.3 MPa. The steam can be diverted either from the prime steam line or from the cross-over line between the high- and low-pressure turbines, according to the availability of adequately sizable and efficient back pressure turbines. This solution yields considerably less water than that discussed earlier, with a ratio of water to power produced below 20 m^3/h/MWe.

A third possibility is more simple, feasible and economical i.e to extract the steam from an existing extraction pipe between stages of the low pressure turbine. This arrangement has one limitation i.e the amount of steam is relatively small, so that only low water production is possible, i.e. up to about 5000 m^3/day (=1.3 mgd) from a large nuclear WCR power unit of 1200 MWe. The water/power ratio is < 0.18 m^3/h/MWe. This possibility, however, may suffer from sensitivity to off-design conditions and load following.

Adequacy of types of WCR to Case 1

Compared to fossil power plants, Gas Cooled Reactors and Liquid Metal Cooled Reactors, WCR are characterized by the following features:

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1) Relatively low thermodynamic efficiency resulting from: (a) low steam temperature and pressure, and (b) wet steam, the expansion of which involves more energy losses. Thus more heat is released per KWe produced.

2) The pressure in the steam cycle is lower than that of the primary reactor coolant, thus leakages may carry radioactive traces to the power/water interface.

The BWR is less attractive for thermal desalination, as the primary reactor coolant – the motive steam – reaches the condenser, i.e. the heat source for the power/water interface.

PWR and PHWR are safer as they have an additional barrier fluid between the reactor coolant and the desalination plant motive steam i.e the steam generator fluid. Therefore, they are preferrable.

The graphite moderated WCR is questionable for desalination in view of the Chernobyl accident.

A different type of WCR for desalination is the low pressure, small reactor that is designed for relatively low temperature (< 130°C) heat supply. This heat can be used for various low temperature industrial applications, district heating or desalination. A small amount of electricity can also be generated.

Typical WCR of this type are "Thermos" [39], "CAS 2G" and "CAS 3G", developed by the French company "Technicatome". These WCR were designed to have an output of 100 and 200 MWth ("Thermos"), 250 MWth (CAS 2G) and 420 MWth (CAS 3G). Two "Thermos" units are designed for 40 000–80 000 m^3/day of desalted water. GOR (Gain Output Ratio) is 10.2–10.8, provided all the primary heat is used as thermal energy for the desalination plant. Electricity for driving the reactor systems and the desalination plant pumps is supplied by another source. However, it is possible to generate electricity by the primary heat of "Thermos" using "Freon"-driven turbines probably reducing the water output. (No details have been published about "CAS" reactors).

The "Thermos" reactors are cooled by 0.9–1.0 MPa pressurized water at a maximum temperature of 137–140°C. The primary coolant is cooled by a secondary cycle of pressurized water having pressure >1.1 MPa and maximum temperature around 128°C.

Various small reactors have been built and operated in the USSR for several years to supply heat and power. Examples are given in table 1 below [38]:-

TABLE 1. SMALL NUCLEAR POWER PLANTS BUILT IN THE USSR

Plant	Reactor Type	Reactor Power, MW(th)	Unit Power el/thermal, MW	Number of units	Sitting & date of start-up
TES-3	PWR	11	1.5/-	1	Obninsk, 1961
ARBUS	organic-organic	5	0.75/-	1	Dimitrovgrad, 1963
VK-50	BWR	250	50/-	1	Dimitrovgrad, 1965
Bilibino NHPP	water-graphite, channel	62	12/17.5-29	4	Bilibino, 1973-1976

Other USSR reactors are the ABW type (48 and 100 MW(th), 38°C water, and AST30B reactor (30, 70°C inlet water and 144°C outlet). These reactors have inherent safety features and are designed for factory fabrication and module shipment.

Water-graphite reactors which have been developed in the USSR are the ATU-2 reactor (125 MW(th).h), providing steam at 6.7 MPa, and a similar RKM type based on kenetic micro modules. Studies of the latter have been completed in the range of 20 to 300 MW(th).

Another reactor that has been studied is the 50 MW(th) RUTA reactor which is a natural circulation pool type reactor with 60°C pool water at core inlet and 95°C at outlet.

Similar investigations have also been done with regards to other small reactors, and are briefly described as follows.

- The Integrated PWR (IPWR) [40] is used to drive the Otto Hahn ship. It could be operated to generate either low pressure steam of 0.8 MPa (180°C) or medium pressure steam of 4.7 MPa (270°C). In the first case the scheme referred to single purpose plants, 3 sizes were considered 38 MW(th), 138 MW(th) and 220 MW(th) with water production

capacity of 14 000, 50 000 and 80 000 m^3/day respectively, while 2.3, 7.5 and 10.5 MWe are generated for local needs. In the second case (medium pressure steam) less water is produced - 10 000, 40 000 and 80 000 m^3/day respectively but additional electricity of 6.7, 19.5 and 38.5 MW(e) respectively can be produced for sale. The GOR is about 10.5.

- A similar approach was adopted when the Consolidated Nuclear Steam Generator (CNSG) was considered as a heat source. The CNSG is a 313 MWth PWR reactor for propelling a 6 00 000 ton tanker [41].

In all these concepts, the desalination plant was of the MSF type. Such desalination plants require an input steam temperature of betweem 120 and 140°C. Multi-Effect Distillation at elevated temperatures would have given better results. As a result of such temperatures, pressurized water as a coolant has to be employed. Therefore, the water reactors that have been considered for water desalination are either PWR or deep pool reactors.

The Thermal Coupling

The thermal coupling consists of heat transfer system between the steam or hot water from the nuclear unit and the saline water of the desalination unit.

The requirement is to eliminate the possiblity of radioactive traces penetration into the desalination system. Thus, at least two "barriers" between the primary coolant and the saline water are required plus the "pressure-reversal". Where pressurized water is the primary coolant, the steam generator is the first barrier (i.e at normal operation without leakages the secondary cycle is "clean"). Where MSF desalination is used, the brine heater, (acting as the steam condenser or water-water heat exchanger for "Thermos") serves as the second barrier. In order to have the "pressure-reversal" the brine at the brine-heater should be maintained at a sufficiently higher pressure than the heating fluid - steam or water, so that the direction of a leakage in the brine water, if it leaks, will be from the desalination system, not into it. Thus, the probability of radioactive contamination of the desalted water is extremely low. It may happen only when both barriers leak and the "reversal-pressure" ceases to exist simultaneously. Even then, there should be instrumentation that monitors radioactivity in the desalination plant, and if a dangerous situation starts, actuates means that (1) divert the effluents away from the mains, (2) notify the operators and (3) stop the process.

Fig. 42. Pressurized water isolation loop.
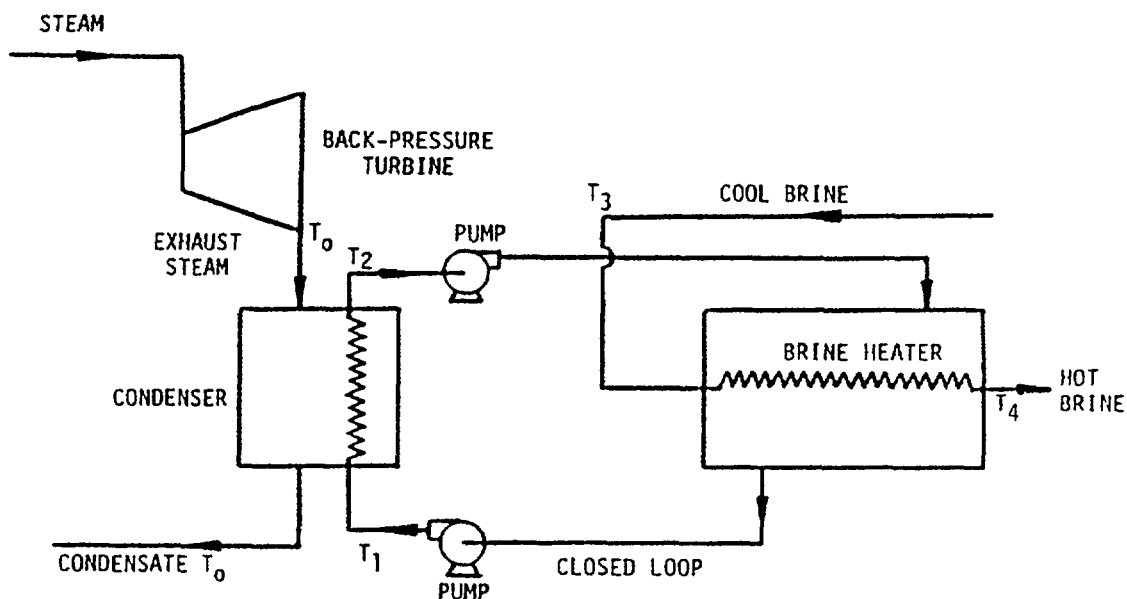
T_0 = TEMPERATURE OF EXHAUST STEAM
T_1 = LOW TEMPERATURE IN CLOSED LOOP
T_2 = HIGH TEMPERATURE IN CLOSED LOOP
T_3 = BRINE TEMPERATURE PRIOR TO ENTERING THE BRINE HEATER
T_4 = BRINE TEMPERATURE AT EXIT FROM THE BRINE HEATER

The "pressure reversal" may cause saline water ingress into the secondary coolant, by a single leakage in the brine heater, resulting in prohibitive quality of this coolant and corrosion of the equipment. This may be solved by essential instrumentation monitoring the salinity of the secondary coolant and actuating the same means, as mentioned above, in case of a leak.

A more stringent provision against radioactive contamination, which helps also against salination of the secondary coolant, is the "isolation loop" (Fig. 42). This system consists of a closed loop placed between the nuclear steam and the water plant. In this system the exhaust steam is condensed and the heat is transferred to a medium within the loop which is then used to heat the brine. Two heat transfer media have been considered for use within the loop namely pressurized water or boiling water. An analysis by ORNL [42] shows that if boiling water is used the loop does not seem to accomplish much. If pressurized water is used, the loop pressure can be kept at a higher pressure than the exhaust steam or the brine by operational control. If leaks develop in either the condenser or the brine heater the result would be leakage of water from the isolation loop into

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the nuclear steam or the desalination water plant. Since the quality of the loop water is controllable, neither of these contingencies would cause difficulty.

The pressurized water loop is, however, an expensive alternative. The capital and operating costs of isolating loops are obvious costs, including equipment, and energy for pumping of large amounts of water, as well as expensive heat transfer surfaces. Also, there is an additional cost attributable to the loop - the turbine must be operated at a higher exhaust pressure and temperature and/or the desalination process must operate at a lower temperature in order to supply the thermal potential necessary to cause the heat to flow through the loop. This results in a loss of electrical and/or water capacity. This loss of capacity constitutes an additional cost.

Case 1 is suitable for MSF, MED and combinations of these two processes, as well as for combination of either of these two with Vapour Compression as a topping unit. The latter combination, where the compressor may be driven by steam turbine or electric motor, has a potential for high water to power ratio.

However, for MED, which unlike MSF does not have a brine heater, the thermal coupling has to be implemented by an isolation loop using either high quality water in a closed loop, or saline water recirculation in an open loop, ("flash-loop") which has been described in the following sub-section.

4.1.2.2. Case 2: Medium Brine Temperature

The conditions of Case 2 are suitable for making use of most of the low-cost evaporators with aluminum heat transfer surfaces.

This case differs from Case 1 in several essential aspects:
1) Larger steam turbines of about 300 MW(e) are available that are capable of operating at the exhaust pressure of 30-40 kPa. Such turbines are designed to operate with dry cooling tower heat rejection.
2) MED with aluminum heat transfer surfaces can be used. This process operates at an optional temperature drop of 2.3 to $3^{\circ}C$ per effect, so that about 15 effects can be incorporated between the condensation temperature of $72^{\circ}C$ ($\pm 3^{\circ}C$) and ambient temperature. The GOR

obtained ranges between 10 to 12.2, that is about the same as in Case 1, with a large saving in energy (the steam expansion between 0.2-0.3 MPa and 30-40 kPa is gained) and with some gain in pumping.

3) The conditions in the brine heater, i.e., the thermal coupling, are much milder than in Case 1. The temperatures are lower and the corrosion rate is much slower. The pressures, forces and stresses are smaller as well as the driving forces for leakage.

Another possible solution for the problem of availability of large turbines that can operate at this range of back pressures is to remove the last stage of expansion from a conventional nuclear condensing turbine, i.e. to order such turbine without the last row of blades. This solution is not recommended, but is feasible. It was implemented successfuly in Ashdod, Israel for a dual purpose plant of 50 MW(e) and 17400 m^3/day. This plant was intended to simulate a dual purpose PWR with LT-HTME evaporation process.

The water production, for an identical WCR as in Case 1 is about the same, if Low-Temperature Multi-Effect distillation with aluminum heat transfer elements is employed.

Other evaporation processes can also be employed within Case 2 but the performance ratio might be lower.

Thermal coupling

Thermal coupling considerations are qualitatively the same as in Case 1. Lower desalination system pressures make isolation more difficult.

For MED as built by IDE, the coupling is arranged so that the pressurized saline water stream is recirculated through the power unit condenser as coolant, gains a few degrees in temperature while absorbing the heat of condensation from the steam, then flows to a chamber where it flashes about 0.5-1% of its mass as low pressure steam. This steam condenses in the hottest effect, supplying the heat and becoming desalted water. The main stream of coolant is cooled down by its flashing and is pumped back to the condenser by the recirculation pump. A relatively small part of it is extracted as blow-down (about 1-2%). Preheated seawater is added as make-up to balance the mass. Thus the salinity of the recirculation is about 1.5 times that of the seawater.

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Proper piping (bypasses, valves etc.) and control system design, together with adequate procedures, enable operation of the power unit to continue even when the desalination plant does not function, and at partial loads, transients, start-up and shut-down. Such a design has been recently prepared by IDE Ltd. for identical conditions of dual purpose nuclear plant, with back pressure steam at 37.3 kPa (11"Hg). The reactor was not WCR, but MHTGR, designed by GA, but the coupling is exactly identical. (The only difference in this respect between WCR and HTGR is that in the latter the pressure reversal takes place in the steam generator so that this coupling system is not a must but an option - exhaust steam can be delivered directly into the MED plant).

Although it was stated above that an isolation loop is a questionable solution for Case 1 due to a large economic impact, and even less viable for Case 2, it has some specific advantages for Case 2, provided the heat transfer medium is flashing, rather than pressurized, desalted water. This way, the cost of equipment, energy and exergy of this loop is reduced, compared to pressurized water isolation loop. On the other hand, the coupling is safer, simpler and more reliable than the first coupling with flashing saline water. A comparative detailed analysis of the two couplings is recommended.

The possibility of a water-pool reactor has been considered for Case 1. A deep pool is needed for elevated temperatures. For the range of pressures and temperatures of Case 2 the requirement for the pool to be deep is removed. Atmospheric water below $100^{o}C$ can be used. The idea has been suggested several times in the past e.g [43].

Recently, Atomic Energy of Canada Ltd. started developing a small unpressurized pool type reactor, 2-20 MW(th), supplying heat at $65^{o}C$-$85^{o}C$. This is the "Slowpoke" energy system which is suitable for Case 2 regarding the equilibrium temperatures. If no electricity is generated, a 10 MW(th) "Slowpoke" unit can desalt up to 4 500 m^3/day, more probably up to 3 800 m^3/day. AECL claims only 2 900 m^3/day [44].

The coupling of the Slowpoke system consists of three water loops - primary, secondary and tertiary coolants with liquid-liquid heat exchangers. The possibility of having saline water as the tertiary coolant has yet to be explored.

4.1.2.3. Case 3:   Low Brine Temperature

From the point of view of availability of large steam turbines, Case 3 is the only one where there is no problem of producing large amounts of desalted water, with minimum penalty on the power unit, if any, and with maximum flexibility, simplicity, reliability and safety. Under the conditions of case 3 the existing turbines can operate at exhaust steam pressures allowed by their manufacturers: 17 kPa (5" Hga) for General Electric turbines, 18.6 kPa (5.5" Hga) for Westinghouse turbines and 23.7-27.1 kPa (7"-8" Hga) for European manufactured turbines. All exhaust steam can be used as the heat source for desalination by large WCR's. On the other hand, due to the lower temperature at which this heat is supplied to the desalination process, the optimal performance ratio is low compared to Cases 1 and 2. Assuming $26^{\circ}C$ seawater temperature and $56.5^{\circ}C$ steam condensing temperature (5" Hga), the GOR of MSF will only be about 3.5 – 4.5. For MED with aluminum heat transfer surfaces it could be between 5.5 and 6.4. For 5.5" Hga condensing pressure it may rise to about 4.8 for MSF and to 6-7 for LT-MED with aluminum. For 7" Hga, the GOR may be 5-5.9 for MSF, 7.5-8.5 for MED.

Thus, for example, a single purpose nuclear unit of 945 MW(e) with exhaust steam pressure of 8.5 kPa (2.5" Hga) will generate only 880 MW(e) when operating at 18.6 kPa (5.5" Hga). About 1830 MW(th) can be used for desalination. With LT-MED about 320 000 to 420 000 m^3/day can be obtained as desalted water (=85 to 110 mgd).

The conditions of Case 3 enable all kinds of WCR to be used as heat source, although the BWR is less preferable, since the steam is the primary coolant.

The above mentioned "Slowpoke" energy system as a possible heat source for Case 2 can also be used in Case 3 for single purpose water plant. Improving load factor by off-peak water production plus electricity, and where needed space heating, are all being studied by the Slowpoke designers.

The possible thermal couplings are the same as described for Case 2. For MSF, the steam condenser serves as brine heater. Maintaining "pressure reversal" at these temperatures is extremely easy. The probability of leakage at temperatures lower than in Cases 1 and 2, with much milder pressures and stresses, is smaller. The only difference between

non-nuclear heat source and nuclear heat source (WCR) is the need for careful monitoring of the brine and product for radioactive traces.

For MED, the saline-water flash loop described for Case 2 is probably the best solution. The degree of safety for Case 3 is higher than for Case 2 due to the lower temperatures and pressures, and the rate of fouling and scaling in the condenser is lower. Thus, the alternative coupling i.e the isolation loop, becomes less attractive for Case 3.

For the possibility of using Slowpoke as heat source with electricity generation - the latter may probably be implemented by organic fluid Rankine cycle which will serve as additional barrier, which may in turn enable optional simpler couplings.

4.1.2.4.   Case 4:   Cold Brine Temperature

Where cold seawater is available for WCR power unit, it is possible to desalt relatively small amounts of water with the power unit operating just as a single purpose plant, except supplying electricity for pumping and venting to the desalination plant. The latter consist of single flash stage or a few flash stages, up to 3 according to the publications of Nord-Aqua (Helsinki) who were developing this process [45]. The GOR is as low as 0.5 to 2 and the quantities that can be desalted are about 6% to 50% (more probably 10% to 20%) those of Case 3.

Since only flash distillation is being considered, the coupling is identical to that described in Case 3 for MSF.

4.1.3.   Hybrid Systems

To increase, where necessary, the desalted water output, it is possible and often advantageous to divert part, or all, the electricity generated by a dual purpose plant to operate MVC or RO units in addition to the thermal processes. It is also possible in principle to use part or all the mechanical energy of the turbine to drive a MVC unit, as shown in Fig. 43.

The additional advantages of such systems are that, the more the energy is diverted from the grid to high-availability energy consumers like MVC and RO units, the higher is the capacity factor of the power unit, which is good for the operation and economy of nuclear units in particular.
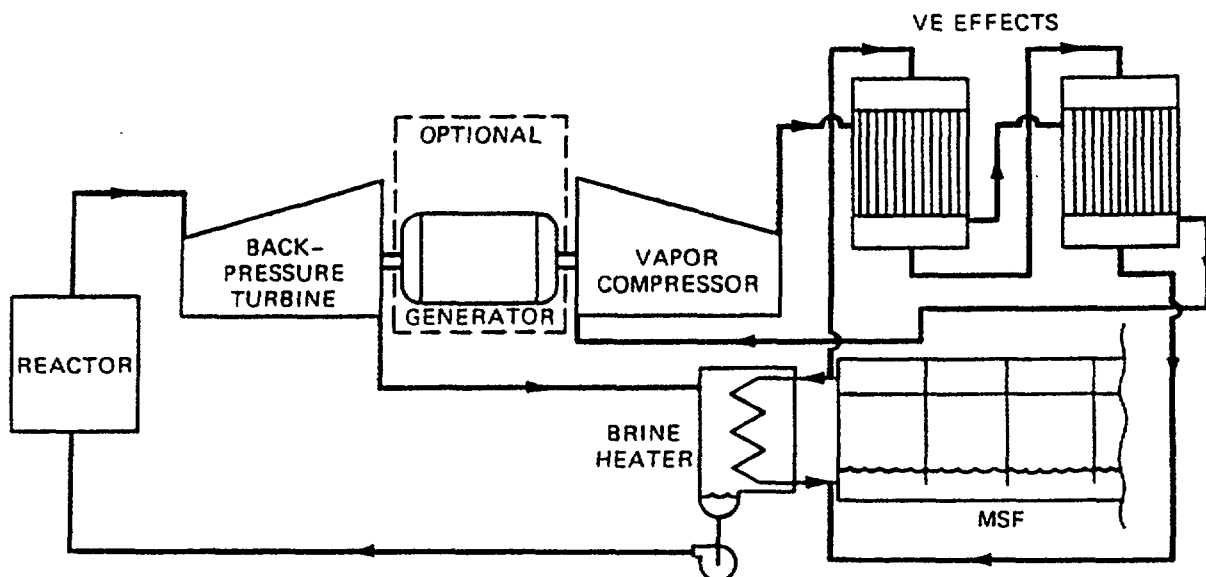
Fig. 43. MSF plant with vapour compression-VE topping.

Where RO units are operated, another advantage comes from mixing the high purity desalted water from the distillation process with the less pure product of RO. Water from an RO plant usually has marginal quality and tends to deteriorate gradually.

The couplings for hybrid systems with WCR are the same as described in sections 4.1.1.1, 4.1.1.2 and 4.1.2.

4.1.4   Operating Experience

No real experience has been gained so far with desalination energized by WCR. The only close to real experience known is the simulation of a full scale 17 400 m^3/day LT-HTME unit as coupled with a 50 MW(e) oil fired unit in Ashdod, Israel.

The Ashdod unit was designed to simulate the saline-water flash loop coupling of MED with a PWR. The size of the unit is the maximum considered practical for MED plant i.e 8.6 meters internal diameter. The plan for a full scale WCR dual purpose plant is to install several such units in parallel.

The Ashdod unit operated continuously for over a year as a demonstration plant and fulfilled the design requirements: capacity, product quality, availability and modes of operation. It was stopped in 1983 because of the high oil prices as it was too expensive to operate the

low-efficiency old 50 MW(e) unit. Occasionally it was operated for very short periods as a demonstration for potential customers. In 1985 it was operated for 3 months continuously to reduce a temporary severe water shortage. The thermal coupling in particular was very satisfactory from all points of view:

a) Start-up was smooth and fast. Once the vessel of the evaporator is evacuated of air - the evacuation time is determined by the size of the evacuation system - the plant is ready to absorb all the heat rejected from the power plant immediately. Water production starts within half an hour, once the mass of the evaporator heats up sufficiently.

b) Shut-down is practically immediate, when necessary. The procedure to change the mode of operation from dual purpose to single purpose (electricity only) is quite simple i.e seawater to the power unit condenser is pumped directly, bypassing the MED unit.

c) It is likewise easy and simple to change the mode of operation from single purpose to dual purpose, by opening and closing the appropriate valves according to the predetermined sequence.

d) It was found that operation at partial load and variable load was also easy and trouble free. The MED unit could follow the electric unit load between 100% and 35% of the capacity without any difficulties.

It is important to note that the flash loop in Ashdod is more sophisticated than the simplified description in this section. The optimum temperature gain of the recirculated saline coolant through the power unit condenser is $>5^{\circ}C$. Flashing it in the desalting plant to cool down by such a temperature drop is a waste of exergy. Therefore, the flashing takes place in two consecutive flash chambers, so that the steam generated in the hotter flash chamber has higher exergy that can be used to increase the product rate and/or to save heat transfer equipment. (In Ashdod it is used to save equipment). In some designs, the flashing is accomplished in three consecutive chambers and pressures.

Another conceptual design [46] for a specific dual purpose plant was prepared by the Israeli Electric Company with the Atomic Energy Commission and the manufacturers of LT-HTME evaporator - Israel Desalination Engineering Ltd. (IDE): In this design a PWR of 945.3 MW(e) (single purpose, condensing pressure 2.5" Hga) and of 880.2 MW(e) (dual purpose, condensing pressure 5.5" Hga) was considered, with a desalted water

capacity of 324 500 m^3/day at full load. The conceptual design consists of 8 parallel identical LT-MED systems, each one heated by a "flash loop" of 23 060 m^3/h recirculated brine about 1.54 times more concentrated than seawater. Each MED system consists of 3 multi-effect evaporators, each of which is heated by a flash chamber. The recirculation steam is flashed in 3 consecutive stages, cooling down by 2.8°C per stage.

A complementary study [47] relating to the same plant was accomplished by engineers from Westinghouse and IDE as to the conditions for partial loads of either the PWR and/or the desalination plant. The quantitative relationships between these loads, the flow rates of the steam to the turbine and the make-up water to the flash-loop, the thermal load on the condenser, the condensing pressure and the size of the condenser have been investigated. In addition, the economical characteristics of this plant were calculated.

Note: The two studies [46, 47] are considered "experience" as they referred to a specific plant for which a few sufficiently detailed alternatives of conceptual designs have been prepared. (On the other hand, general possibilities that do not refer to a specific plant at a given site were discussed in sections 4.1.1.-4.1.4).

4.1.5.   Cost Analysis

4.1.5.1. Single Purpose Plants

The procedure for calculating the cost of single purpose plants is relatively simple, and is based on the principle that the cost of a unit product is the sum of all the expenses during the history of the plant per net product, with proper capitalization according to an agreed interest and amortization rate. Accurate cost analyses are dependent on the specific project. Large differences between cost analysis are expected due to differences in technology, special requirements, capacities, local conditions etc. A very long list of specific data, in addition to a very long list of unknown important parameters which have to be assumed, are necessary to start such prospective project cost analysis.

An example of such a study was made [47] for the case of a relatively small nuclear reactor supplying its energy solely for desalination. Five

different desalting systems were investigated; (1): a thermal desalting plant using all of the thermal energy produced by the reactor; (2): a Reverse Osmosis (RO) system using all of the electrical power produced by an electrical plant connected to the reactor; and (3), (4), & (5): three various hybrid MED or MSF with RO desalting systems connected to a small nuclear power plant applying a back-pressure turbine. By applying a 365 MWt nuclear reactor, water production rates in the range of 200 000 to 530 000 m^3/day were obtained at costs ranging between 45 to 50 cents/m^3, (1977 prices). The hybrid plants show considerably lower costs than the single process plants.

Of special interest is the economics of the "Slowpoke" energy system used for desalination. According to the developers [44] of this system, the cost of heat is projected to be about US$ 0.01/kW(th).h.

Assuming a low-temperature Horizontal Tube Multi-Effect Distillation plant with a high GOR of 12, the heat component of the cost is approximately equal to US$ 0.54/m^3.

This is more than twice the cost of heat from large dual-purpose plants but the size has advantages. It should be emphasized that the above mentioned cost of the heat is based on a low real discount rate of 5% per year excluding inflation, whereas in some cases higher discount rates are used.

The following is a rough estimate of desalted water cost from a 20MW(th) "Slowpoke" energy system supplying heat to a 7 600 m^3/day MED evaporator:

Heat	US$ 0.54/m^3
Electricity	US$ 0.08/m^3 [1.6 kweh/ton, US$ 0.05/kweh]
Capital Costs	US$ 0.27/m^3 [US$ 1200/(m^3/day)]
Operation & Maintenance	US$ 0.14/m^3
Total	US$ 1.03/m^3

The water cost increase to about US$ 1.3/m^3 if 8% year real discount rate is assumed. These costs pertain to 3 800-7 600 m^3/day plants; if "Slowpoke" energy systems of considerably high capacities, corresponding to

about 38 000 − 76 000 m^3/day are developed the costs may decrease meaningfully.

4.1.5.2. Dual Purpose Plants

One of the major advantages of a dual purpose plant compared with two seperate single purpose plants is the more efficient use of the thermal energy. The economic benefit of this higher efficiency is reflected in the combined production costs of the electricity and fresh water.

Clearly the unit costs assigned to the two products must account for the total costs of the dual purpose plant. The actual allocation of the total costs between the two products is a fundamental problem in the economic evaluation. Various methods have been proposed [34] and these fall into two groups:

- apportioning methods
- credit methods.

The apportioning method divides the total plant costs between the two products in a certain ratio. A suitable ratio can be selected according to various criteria. Such methods include, for example, a comparison of the dual purpose plant with alternative single purpose plants to establish a ratio of water to electricity costs. Whilst the application of such apportioning methods is fairly straightforward, it is difficult to ensure that the ratio employed is truly representative. In practice, the ratio can be somewhat arbitary in relation to the actual dual purpose plant. Problems likely to be encountered include:

- Difficulties in accurately defining the costs of equivalent single purpose plants. This is particularly true when the heat source is nuclear.
- Implications of unrealistic marketing conditions for either of the single outputs.
- Difficulties in selecting suitable, terminating points of the alternative plants being considered.

The credit method of cost allocation selects a pre−determined value for one of the products based on the cost of that product from an alternative source. This alternative can be a single purpose desalination

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or power plant (either existing or conceptual) and it effectively describes an upper limit to the value of either water or electricity. Using that value as the cost of one of the products of the dual-purpose plant, the cost of the second product can be determined. In effect, the second product is credited with all of the economic benefits associated with the plant being dual-purpose.

For a dual-purpose desalination plant in which electricity generation dominates, the power credit method is appropriate. This is likely to be the case when a large NSSS is used as the heat source. In this situation, it is reasonbale to assume an electricity cost equivalent to that of a single-purpose electricity generation station. The net electrical output from this single-purpose plant will clearly be greater than that from the dual-purpose plant if it is assumed to have a NSSS of the same thermal rating.

The power credit costing method using the generation cost of a power-only station of larger net output (method E of Ref. [34]) is therefore considered appropriate for the type of dual purpose plant being discussed. This method was also adopted in a later IAEA guide on the costing of water [35].

As said previously in section 4.1.5.1., the actual costs of any particular project depends on numerous factors specific to that project. As an indication of possible costs, the following figures relate roughly to a typical dual-purpose plant arrangement:

NSSS:	PWR, 2800 MW(th)
Power Generated:	880 MW(e) gross from condensing turbine
Power Output:	860 MW(e) net
Water Output:	420 000 m^3/day
Capacity Factor:	75% (power and water)
Unit cost of power:	U.S. cents 5.0/kW(e).h
Capital cost for water:	US$ 0.36/m^3
Energy cost:	US$ 0.24/m^3
Operation and maintenance:	US$ 0.07/m^3
Total cost of fresh water:	U.S. $ 0.67/m^3

Note – Typical plant costs at 1988 price levels assumed, 30 years plant life, discount rate 8% per annum.

- Inflation not included.
- Cost apportioned using power credit method for single purpose plant
  having same thermal rating.

The effects of escalation in plant costs, due to general inflation and specific escalation rate have also to be considered.

The following costs were calculated in 1976 for a PWR with LT-MED [48]:

Capital costs: US$ 0.16/m^3

Energy costs: US$ 0.10/m^3

Operation & maintenance: US$ 0.036/m^3

Total water cost: US$ 0.296/m^3

The costs of a pressurized water isolation loop were also calculated and optimized by ORNL [42].

4.2.   Liquid Metal Cooled Reactors

4.2.1. BN-350 (USSR)

Exploiting natural resources in the arid regions of West Kasachstan in the USSR became possible due to the solution of water supply problems and the development of electric power supply. In a relatively short time the Mangyshlak complex, which is a multi-purpose energetic enterprise, was founded, providing industry and population of this region with heat, electric energy and water. The complex includes the largest Distillate Production Plant (DPP) in the USSR, a thermal electric station using gas and fuel-oil, and a Fast Breeder Reactor (BN-350) [4].

FBR-BN-350, the first in the USSR, was the most powerful industrial breeder reactor in the world at the time of start-up on July 16, 1973. The tasks assigned to this reactor were: (a) acquisition of operating experience necessary for the application of an industrial sodium cooled FBR in large nuclear power installations, (b) study and estimation of the costs of using a nuclear reactor for seawater desalination [50, 51]. These tasks have been accomplished with the results of more than 15-years operation of BN-350. The benefits of large capacity sodium cooled FBR applications have been proven, and the characteristics of joint operation of BN-350 and desalination installations have been studied. The combination of the reactor with desalination units yielded high thermal efficiency [52].

4.2.1.1. Status of Technology and Experience

BN-350 was put into operation in July 1973 and is still operating to date. Its operation is accomplished according to the standards and regulations applicable to nuclear power plants in the USSR. The reactor design, its ability to self-control, and the reliability of the control, management, and protection systems, all provide good nuclear safety characteristics. Prolonged operating experience of the BN-350 reactor with the desalination units demonstrated high efficiency and reliability, proving this to be a good solution to water supply problems for population and industry [53].

Technical Description of Coupling The Shevchenko complex comprises a nuclear power plant BN-350, and a seawater Distillate Production Plant (DPP). It is the first and for the time being the only demonstration plant in the world for seawater desalintion using a nuclear reactor [53]. Steam-generators of the BN-350 FBR, and boiler units of drum type "E-220" supply steam to several turbines of different types. Steam from the BN-350 unit at 4.5 MPa and 723° K is directed to the backpressure turbines "P-50-45" and to the condensing turbine "K-100-45". Steam from the fossil fuel boilers of the thermal electric units at 9.0 MPa and 808°K enters the turbine "PT-60-90/13". It is also possible to reduce the steam pressure for the fossil fuel boilers, through a reduction cooling down unit, to that being generated by the BN-350 steam generators, to enable it supply the desired steam conditions to the backpressure and condensing turbines.

Exhaust steam from the turbines "PT-60-90/13" and "K-100-45" enters the condenser, where it is condensed and deaerated. The condensate, after purification, is returned to the steam cycle. Steam from the turbines "P-50-45" and "PT-60-90/13" is directed towards the desalination units (DPP) and the industrial enterprises of the town. Steam is supplied from the steam turbines to the DPP via a double-pipe system: an operating steam line and a spare steam line. All desalination units are connected to these steam lines. While developing the project of the complex, other variants of heat supply to the desalination installations were considered. For example: (a) a supply of hot water from the heat exchangers, (mounted in immediate proximity to the backpressure turbines and heated by steam from these turbines) to the heating chamber of the first evaporator; (b) secondary steam, generated from hot water in single- or multi-stage

evaporators, mounted near the heating chamber of the first apparatus. These variants have been tested during the operation of a pilot plant in Shevchenko [49]. While analysing the design of heat supply to the desalination system, the advantage of hot water loops was taken into consideration, as they provide additional barriers against the possibility of radioactive penetration into the desalted water. Steam condensate after the backpressure turbines returns from the desalination units to the cycle after being cooled and purified at the water pretreatment installation. Desalted water is used for making up losses in the steam cycle of the thermal electric units and BN-350. This distillate enters the stationary deaerators after purification in the pretreatment installations [49].

Seawater enters the "K-100-45" turbine condensers, and the "PT-60-90/13" desalination units condensers, from the onshore pumping station connected with the sea via a pipe-line, the head of which is 3000 m from the shore. The cooling water from the turbine and desalination unit condensers, and the brine from the desalination units, are discharged into a natural canal having an outlet into the sea 15 km from the water intake pipe-line.

Special Requirements for Coupling. More than 15-years experience of commercial operation of the Shevchenko desalination installations in conjunction with the atomic thermal power station brought out a number of special requirements for similar desalination installations, operating in such a complex [49, 53, 54, 55, 56].

The main ones are:
- High operating reliability for a long time;
- Ability and flexibility of the desalination complex for quick increase or decrease in the consumption of thermal energy;
- High and stable distillate quality without dependence on the external effects or on the thermal energy consumption of the desalination installations (e.g. because of the pressure change of the operating steam, vaccum in the last stage of the desalination installation etc.).

4.2.1.2. Operating Experience

The Shevchenko complex is the largest center of the commercial thermal desalination in the USSR. This is the main scientific-testing facility,

providing ground for the development and improvements of the desalination engineering, testing of new theoretical and scientific ideas in the field of desalination and technology of production of artificial potable water. It also enables the sanitary-hygienic estimation of potable water by persistent observations of physiological effect on the human organism from prolonged use.

The work on the development and improvements of different seawater desalination processes (such as 7-stage MSF [57], Electrodialysis, Ion Exchange, single stage LTV with Mechanical Vapour Compression [58]) was started in 1961 at the Mangyshlak peninsula. The first pilot plant consisted of a 100 m^3/day three-effect LTV unit [56]. Tests of different types of desalination installations under similar conditions, showed that for water supply to the developing town it is expedient to use Multi-Effect LTV distillation units. The experience accumulated on these installations and the results obtained provided the initial data for design of a large evaporation pilot plant.

The starting-up of a 4-stage 3600 m^3/day installation took place in November 1963 [59]. This installation, together with a 7500 m^3/day (PWPS-7.5) station of artificial potable water preparation, was the only source of potable water supply of the region. In 1967 a 13 000 m^3/day 5-effect LTV unit [24] was put into operation in order to meet the requirements of the developing industrial region of the Mangyshlak peninsula for fresh water, and PWPS-7.5 was redesigned into PWPS-28, the output of which extended to 28 000 m^3/day.

Presently, the operation of the following three types of desalination installations is being examined in the desalination complex:

a) 5-effect LTV forward-feed installation with natural circulation.
b) 10-effect LTV forward-feed installation with forced circulation.
c) 34-stage MSF installation.

There are 12 operating desalination units at the desalination complex in Shevchenko (see Table 2) with a total capacity of 140 000 m^3/day. All these desalination units produce fresh water for current needs, make-up water for steam generators (of the thermal electric stations and BN-350) and for making-up the system of hot water-supply for the town and industrial enterprises.

TABLE 2. DESALINATION INSTALLATIONS IN THE TOWN OF SHEVCHENKO

Installation description	Installation type	Year of putting into operation	Design output, m^3/day	Specific heat consumption kW(th).h/m^3 distil
OPIU	4-effect LTV forward feed	1963	3 600	230
PIU	5-effect LTV forward feed	1967	13 200	160
DOU-1	5-effect LTV forward feed modernized	1969	14 400	150
DOU-2	5-effect LTV forward feed modernized	1970	14 400	150
DOU-3	10-effect LTV forward feed with forced circulation and horizontal pumps	1971	1 440	91
DOU-4*	34-stage MSF three-loops	1972	15 100	87
DOU-5	10-effect LTV forward feed with forced circulation and horizontal pumps	1973	14 400	91
DOU-6	10-effect LTV forward feed with forced circulation and horizontal pumps	1974	14 400	91
DOU-7	10-effect LTV forward feed with forced circulation, modernized with horizontal pumps	1980	14 600	87
DOU-8	The same	1982	14 600	87
DOU-9	The same	1985	14 600	87
DOU-10	The same	1987	14 600	87
DOU-11	The same	1989	14 600	87
DOU-12	10-effect LTV forward feed with forced circulation, modernized with vertical pumps	Being manufactured and mounted 1991	16 800	87
DOU-13	16-effect HTME	Being designed, start-up in 1993	16 800	49

* Brought out of operation in 1988 because of material aging and physical wear.

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The first four installations represent desalination plants of the first generation in the USSR. "DOU-3" through "DOU-I2" may be characterized as modern desalination plants of the second generation in the USSR. These were distinguished by lower thermal energy consumption, by the possibility of their application for different feed and product waters, by preparation of potable water from the sea, and by production of pure distillate for boiler unit making-up and mineralized waste water treatment.

The experience of constructing and operating the desalination units of the first and second generation, the systematic investigations and the studies of various ideas in the field of seawater desalination in the USSR resulted in new distillation developments with HTME (Horizontal-Tube thin-film Multi-Effect evaporators). A large-scale experimental apparatus of this type, comprising the rebuilt unit "DOU-I" [4], has been commercially tested since 1985 on a 240 m^3/day test pilot installation. The water-chemical regime design of the 16 800 m^3/day, 16 effect HTME (Horizontal Tube Multi-Effect) desalination unit "DOU-I3" is optimized. Experiments are aimed at confirming initial data, and obtaining further improvements to the technique from engineering.

The distillate at the desalination units in Shevchenko, is characterized by the following parameters, obtained from the average performance during 1989.

```
Total salinity, ppm ............................. 3
Hardness, ppm-eq ................................ 0.0073
Alkalinity, ppm-eq .............................. 0.0187
Sodium, ppm ..................................... 0.16
Chlorides, ppm .................................. 0.15
Total iron, ppm ................................. 0.014
Copper, ppm ..................................... 0.0096
Silicic acid. ppm ............................... 0.019
pH-value ........................................ 7.41
```

Part of the distillate is used for potable water preparation. The USSR sanitary service has set the optimal level of potable water salinity for Shevchenko in the range of 300-400 ppm, on the basis of the conducted investigations. The required water quality is prepared by specially developed technology, which consists of distillate cooling by seawater in tubular heat exchangers, stabilization by filteration through marble aggregate at the desalination plant and further at the stations of potable water preparation, absorption on wood activated carbon, enrichment with calcium hydro-carbonate by means of injection of carbon dioxide and filtering through marble aggregate, then mixing with deep-well mineralized

water and subsequent conditioning of the mixture under the conditions of filtration, stabilisation and disinfection. Systematic operational control of the potable water quality directly at PPV and at the piping of the town, as well as constant control by sanitary means, accomplish full compliance with the artificial potable water quality requirements of USSR GOST (Government Standard) 2874-82 "Potable water".

Up to July 1973 the Shevchenko desalination units were heated by the thermal station, working on natural gas and fuel oil. After the start-up of BN-350 FBR all desalination units and part of industrial enterprises in Shevchenko were supplied with steam, from its steam generators. Only during planned outages of BN-350, steam supply to these units is accomplished from a fossil fuel thermal station.

BN-350 operates with the output of 750 MW(th) having the following important parameters [52]:

```
Electric power, MW .............................. up to 125
Sodium temperature, °C:
   at the reactor inlet ......................... 283
   at the reactor outlet ........................ 425
Superheated steam:
   pressure, MPa ................................ 4.5
   capacity, t/h ................................ 1050
Steam, being delivered for desalination:
   pressure, MPa ................................ 0.5
   temperature, °C .............................. 220
Output of DDP distillate, guaranteed
   by the reactor, m³/day ....................... up to 100 000
Annual average reactor downtime for
   performing reloads and scheduled-preventive
   maintenance, days ............................ 50
```

The only serious defect during the whole operating period of BN-350, which influenced the atomic power station capacity, was the repeated leakage of steam generators at the intermediate third reactor loop. The main cause of this was the poor quality of manufacturing and welds at the end of heat transfer tubes. All steam generators were repaired. The reactor operated from start-up until 1977, with an availability of 85%, followed by 88%, (7 700 operating hours per year) at its design output. The rated burnup of the reactor fuel, equal to 5%, was exceeded. According to conditions for 1983, this value was equal to 5.8%, and was limited by the permissible dimensions of shape change of the fuel assemblies hexahedral cladding. In general the design rating of the newly developed non-standard equipment was exceeded. The BN-350 is very safe. During operation, there was not a single case of sodium leakage from the first

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loop; only two leaks in the second loop (in the sampling and oxide indication systems) needed to be fixed [50].

The reactor is also used for experiments on physics, physical metallurgy and sodium engineering. Runs in these fields and other experimental work are carried out on BN-350 without detriment to the planned tasks on the production of electrical energy and distillate, the main task of the complex [50].

The long operating experience of the BN-350 FBR dual-purpose complex, with its demonstrated high efficiency and reliability, has shown the technical and economic feasibility of nuclear energy for seawater desalination in the remote regions deprived of fresh water and natural sources for energy production. From this experience, with all its negative and positive points, the development of desalination stations associated with thermal reactors of different output of distillate from some thousand to several hundred of thousand cubic meters of distillate per day, have been planned in the USSR.

4.2.1.3. Cost Analysis

The erection of the Shevchenko dual-purpose complex was preceded by a technical-economical comparison of different possible variants of water provision for this industrial region. The variants of water supply with the pipelines and channels from the Volga, Urals and Amu-Darja rivers were considered. The supply could be both from each river separately and from any two rivers together. Besides, Caspian seawater could be desalted locally by Electrodialysis, Ion Exchange, LTV and MSF distillation. The variants of a nuclear power station and imported fossil fuel were also analysed as alternative energy sources.

According to the study results, the best variant for the Mangyshlak peninsula, turned out to be erection of a large complex based on one nuclear reactor and LTV evaporators. Taking into account the predictions of costs for the 1970s, it was decided to use steam from backpressure turbines at 0.45-0.5 MPa pressure as the heat source for the desalination installation, and to use five stages for the desalination units. Later in the 70s, when costs increased more than expected, it was decided to increase the desalination plant capacity in Shevchenko by installing more energetically efficient 10-stage desalination units with forced circulation (DOU-3 through DOU-12, see Table 2). A certain contribution to the

increase in efficiency and economy was made by an automatic control system, created on the basis of a micro-ZVM-1300 in the mid 70s. The annual average technical-economical data for 1989 for each of the 10-effect units, being the main producer of distillate at DDP in Shevchenko, are characterised by the following:

```
Capacity, m³/day ........................................ 14 700
Heat specific consumption, kW(th).h/m³ ................... 86
Electric energy specific consumption, kW(e).h/m³ ........ 4.5
Seawater flow rate for desalination, m³/h ............... 850
Seawater concentration ratio ............................ 3.6
Cooling water flow rate, m³/h ........................... 2260
Maintenance personnel, per .............................. 2
Cost of distillate (excluding interest), rub USSR/m³ .... 0.48
```

The distillate is used for steam generator making-up in the TES and BN-350 reactors, heat-supply system and hot-water supply for the population and industry and preparation of potable water in accordance with the USSR Standard 2874-82 for "Potable water". Distillate is brought up to the standards required by GOST "Potable water" at the stations of potable water preparation (SPPR) Nos. 28, 35 and 40, with a total capacity of more than 100 000 m³/day. The cost of potable water, in the water-supply system of the town, amounts to 0.68 rub (USSR)/m³.

At present in the USSR, HTME desalination units are operated which are characterized by 1.5-1.7 times lower energy requirements (heat and electric energy), and lower capital investments compared to the older units. HTME desalination units of 16800 m³/day [23] will be used in the following 10 years for DDP capacity increase in Shevchenko (DOU-13 and the next one) and for replacement of DOU-I through DOU-6. Such a new installation is characterized by the following design technical-economical data:

```
Capacity, m³/day ........................................ 16 800
Number of effects ....................................... 16
Steam consumption at a pressure of 0.4 MPa, t/h ... 44.4
Steam consumption at a pressure of 1.3 MPa
  (for vacuum creation and maintenance). t/h ....... 3.4
Heat specific consumption, kW(th).h/m³ ............. 49
Specific power of simultaneously operating
  electric receivers, kW(e).h/m³/day ............... 0.053
Seawater flow rate, m³/h ........................... up to 1950
  including for desalination, m³/h ................. 1350
Seawater concentration ratio ....................... 2.07
Quantity of maintenance personnel, per ............. 2
Specific building area, m²/m³/day .................. 0.063
Cost of distillate (predicted)
  (excluding interest), rub USSR/m³ ............... 0.30-0.35
```

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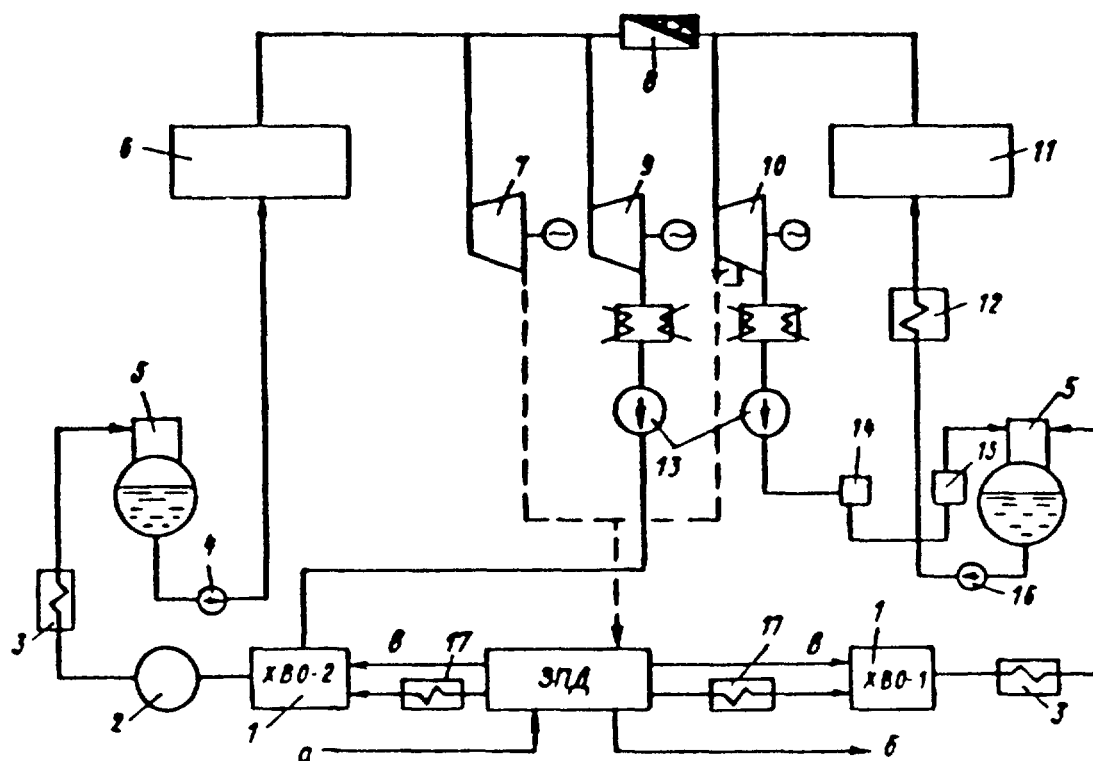
Fig. 44. The principle process diagram of the energetic complex.
(1) water preparation units; (2) vacuum deaerators; (3) desalted water preheaters; (4) feeding electric pumps; (5) thermal deaerators of 0.7 MPa; (6) steam generators BN-350; (7) back-pressure turbines P-50-45; (8) reduction-cooling unit 100/45; (9) condensation turbine K-100-45; (10) turbines DT-60-90/13; (11) steam generators of thermal electric station; (12) high pressure preheaters; (13) condensate electric pumps; (14) condensate treatment; (15) low-pressure preheaters; (16) feeding electric pumps; (17) heating steam condensate coolers; a — seawater; b — disposal brine; c — distillate.

4.2.2. 4S Liquid Metal Cooled Reactor (Japan)

4.2.2.1. General

CRIEPI (Central Research Institute of Electric Power Industry) of Japan has initiated a conceptual design study, whose purpose is to prevent desertification in the world [60]. This focus on agricultural applications is unique among current studies of desalination. Nevertheless, this study may also be applied to the production of potable water from the sea on a very large scale.

The selected desalination process is Reverse Osmosis (RO), and the water production rate is to be 3 000 000 m^3/day. Energy for the desalination plant is supplied by a group of Liquid-Metal-Cooled Fast Reactor modules; each having an output of about 50 MW(e) in the form of electricity or shaft power from steam turbines.

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This study is currently under way, and has not yet been completed. Therefore, only an outline of the preliminary design of the reactor module and the desalination plant is given here.

4.2.2.2. Reactor

The Liquid Metal Cooled Fast Reactor (LMCR) has been selected for this study for the following reasons:

(1) Electromagnetic pumps can be utilized in place of mechanical pumps, since the coolant has a high electrical conductivity.

(2) The core of a LMCR has a high internal conversion ratio, making it possible to maintain burnup over long periods without refueling. A core without need of refueling for 10 years can be built based on this feature. As a result, periodic refueling would be eliminated.

(3) The burning rate in the core can be controlled from outside of the reactor vessel, taking advantage of the long mean free path of fast neutrons. This feature enables us to eliminate the control rod driving mechanism which is usually inside the reactor vessel, greatly reducing the maintenance burden.

(4) The safety facilities of LMCRs (decay heat removal system) can be constructed with passive components only. The safety function can be guaranteed without maintenance.

(5) The reactivity coefficient can be made negative in a core with high neutron leakage. As a result, factors producing positive reactivity insertion are completely removed in any accident, making it possible to terminate by physical characteristics only.

A reactor concept was established along with major specifications as shown in Table 3, based on the above features. The preliminary reactor design is characterized by its compactness, safety and simplicity, as shown in Table 4, and is named 4S (Super-Safe, Small and Simple). The reactor concept is shown in Fig. 45.

The reactor is of modular type with a thermal output of 125MWth. The core consists of 19 fuel sub-assemblies with U–Pu–10% Zr based metal fuel pins as shown in fig. 46. The core life is forecast to be 10 years without refueling. The burning of the core is controlled by displacement of a reflector installed outside the reactor vessel.

An electromagnetic pump is used as a primary pump, and is located in the reactor vessel without cooling. The pressure drop around the entire

TABLE 3. MAJOR DESIGN SPECIFICATIONS

ITEM	SPECIFICATION
Thermal Output	125 MW_{th}
Gross Electrical Output	50 MW_e
Fuel Material	U-Pu-10%Zr
Core Lifetime	10 Years
Reflector	
Limiting System	Synchronous Motor
Driving System	Linear Motor
Primary Pump	
Type and Location	EMP inside R/V
Primary Head	0.1 MPa
Heat Exchanger (IHX)	Vertical
Reactor Vessel Diameter	
Major Part	1100 mm
Upper Part	1700 mm

TABLE 4. CHARACTERISTICS OF THE REACTOR

SUPER SAFE

1. Low Pressure Drop Core (40kPa)
2. Negative Coolant Feedback Coefficient
   $(-6.0 \times 10^{-6} \Delta K/K/°C)$
3. Low Linear Power Rating (190W/cm)
4. Reflector Limiting Mechanism
   Using Synchronous Motor
5. Reactor Vessel Air Cooling
6. Elimination of Moving Parts in Vessel
7. Top Dome Type Containment

SUPER SIMPLE WITH LOW MAINTENANCE

1. Elimination of Fuel Handling System
2. Elimination of Control Rod Driving Mechanism
3. Elimination of Mechanical Pump
4. Elimination of Upper Core Structure
5. Elimination of Internal Piping
6. Elimination of Anti-Striping Structure
7. Elimination of Redan and Stand-Pipe

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INTERMEDIATE HEAT EXCHANGER

REFLECTOR

CORE

ELECTROMAGNETIC PUMP
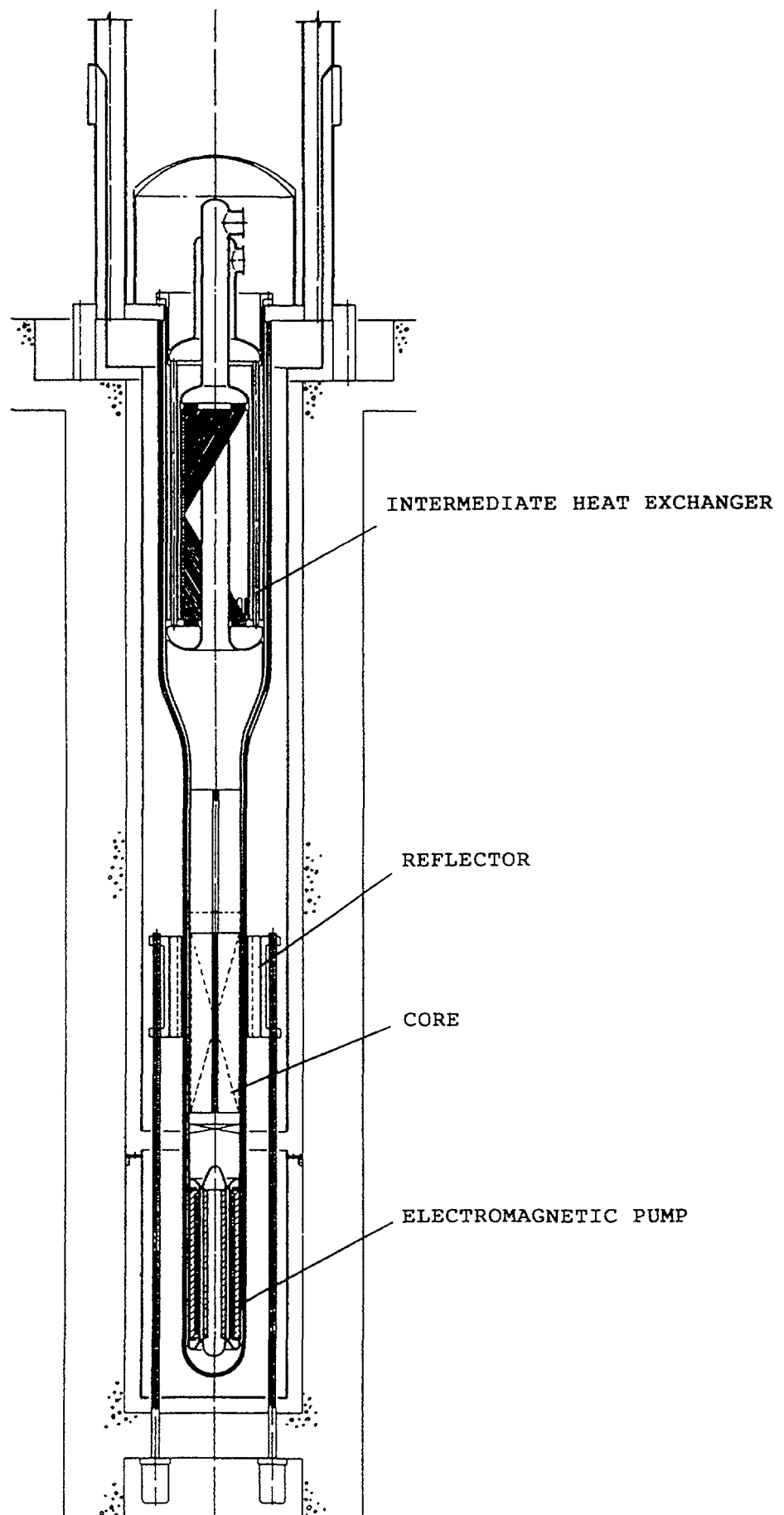
Fig. 45. The '4S' reactor concept.
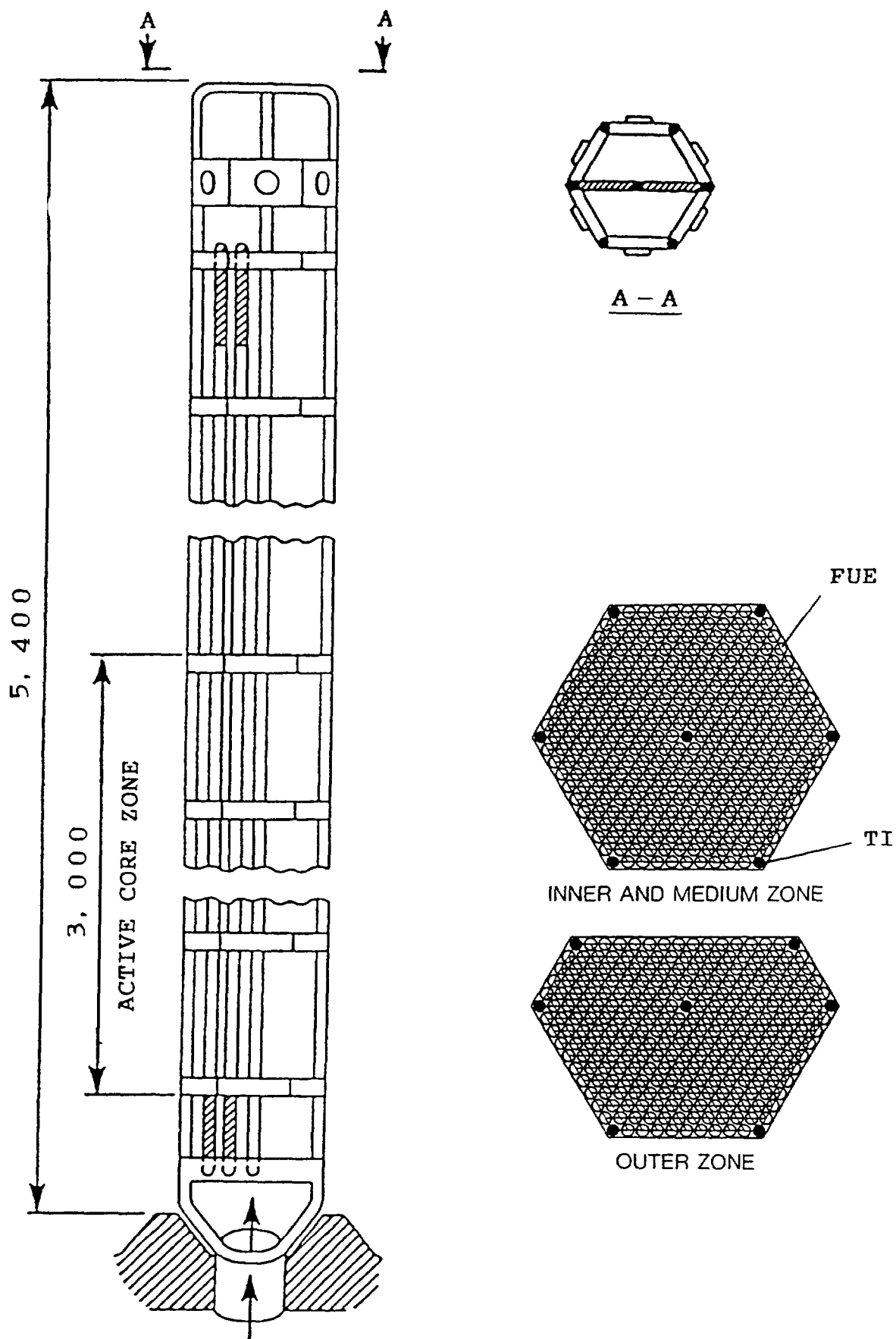
Fig. 46. Fuel sub-assembly.

TABLE 5. REACTIVITY COEFFICIENTS

Doppler	$T\dfrac{dK}{dT}$	-2.4×10^{-3}
Coolant Density	$\dfrac{\Delta K/K}{°C}$	-6.0×10^{-6}
Whole Core Void	$\Delta K/K$	-1.9×10^{-2} (BOL) -6.0×10^{-4} (EOL)
Fuel Axial Expansion	$\dfrac{\Delta K/K}{°C}$	-9.9×10^{-6}
Core Support Radial Expansion	$\dfrac{\Delta K/K}{°C}$	-1.5×10^{-5}

primary loop is kept small (approximately 0.1 MPa) by applying a low pressure drop core with a wide fuel pin pitch.

An intermediate heat exchanger (IHX) is installed in the reactor vessel. The IHX consists of 250 helically-wound heat transfer tubes.

The reactivity feedback coefficient of the core is one of the most significant factors for safety. As shown in Table 5, negative reactivity is inserted when the temperature rises. This eliminates problems of safety even during transients without scram.

4.2.2.3. Desalination Plant

The Reverse Osmosis (RO) process was selected for desalination plant because of low energy consumption, simplicity of operation, low maintenance, short start-up period and ease of partial capacity operation, as described in sub-section 3.3.4 of this report.

The plant, which is now at the preliminary design stage, has a total capacity of 3 000 000 m^3/day and consists of two units; the capacity of each being 1 500 000 m^3/day. This is about 4 times larger than the largest existing MSF plant, and about 26 times larger than the largest existing RO plant.

Seawater is obtained from a surface intake, which includes trash racks, traveling screens, and screen wash pumps. From the intake, seawater

Fig. 47. General arrangement.

① SEA WATER INTAKE HOUSE
② DUAL MEDIA FILTER (Under ground)
③ CLEAR WELL (Under ground)
④ R.O. BUILDING
⑤ PRODUCT WATER BUFFER TANK
⑥ PRODUCT WATER PUMP HOUSE
⑦ DRAIN PUMP
⑧ CHLORINATION HOUSE
⑨ WORK SHOP & STORAGE BUILDING
⑩ OFFICE BUILDING
⑪ GATE HOUSE
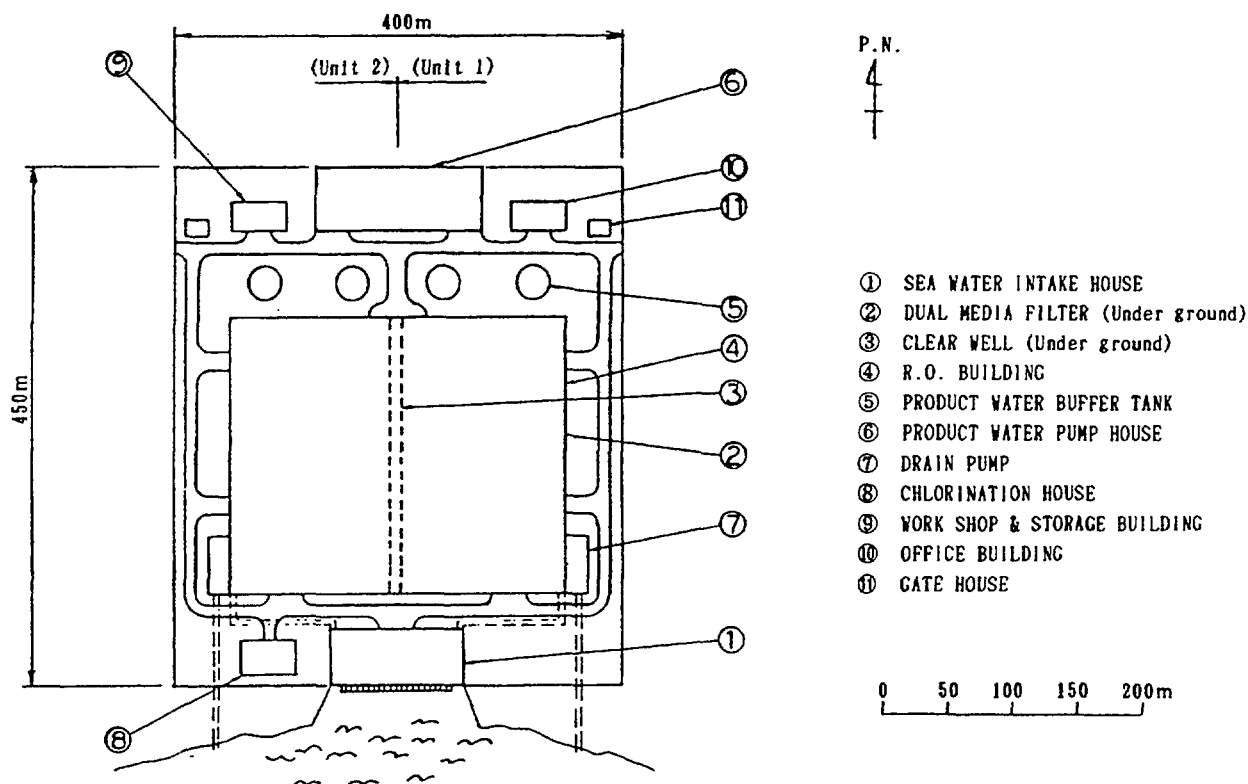
flows into dual media filters, and then into a clear well by gravity. Filtered seawater is pressurized by high pressure pumps and is led to the membrane modules. The reject brine from the membrane modules is expanded through energy recovery turbines to decrease the power consumption needed to operate the high pressure pumps. Figure 47 shows the general arrangement. The RO building is located above the pretreatment system in order to minimize the land area required.

The pretreatment processes expected to be used for this plant are chlorine injection in the intake, coagulant addition before the dual media filters, and sulfuric acid addition before the clear well. Dechlorination and cartridge filters will not be fitted. Figure 48 shows the process flow diagram. Equipment is listed in Table 6 for one unit.

Energy consumption per unit is 265 MW(e) or 4.23 kW(e).h/m^3 of product water, excluding the energy required for product water delivery pumps.

4.2.2.4. Coupling of Desalination Plant with the Reactor

Most of the energy required for the RO process is in the form of shaft power for high pressure pumps. Therefore, there are two choices of

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TRASH RACK   DUAL MEDIA FILTER   FILTERED WATER PUMP   RO MODULE   PRODUCT WATER PUMP

TRAVELING SCREEN   CLEAR WELL   HIGH PRESSURE PUMP   PRODUCT WATER
                                              & RECOVERY TURBINE   BUFFER TANK

TO SEA
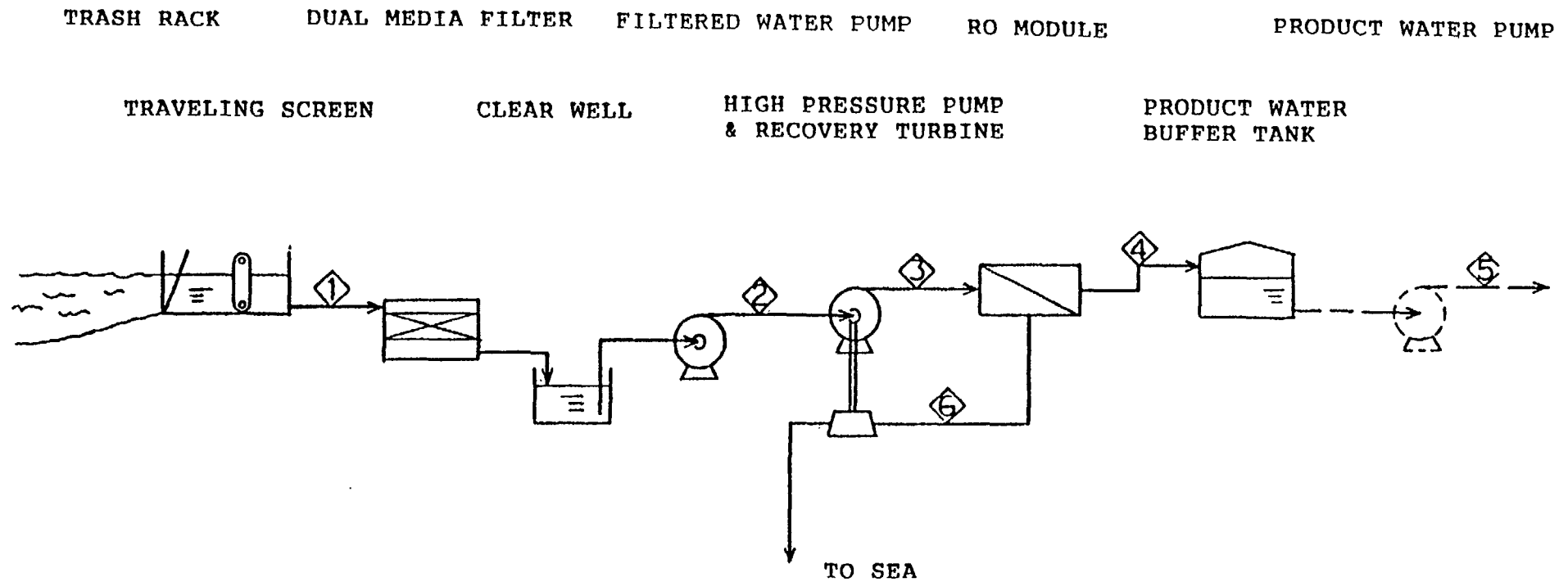
LINE NO	1	2	3	4	5	6
FLOWRATE m^3/h	125000	125000	125000	62500	62500	62500
PRESSURE MPa	0.3	0.4	8.0	0.2	OPEN	7.9
ppm as TDS	40000	40000	40000	<500	<500	>79500

for one unit ($1500000m^3$/day)

Fig. 48. Process flow diagram.

TABLE 6 EQUIPMENT LIST FOR ONE UNIT

No	ITEM	Q'ty	CAPACITY(each) and TYPE
1	RO MODULE	7500	$50000m^3$/day x 30blocks
2	FILTERED WATER PUMP	15	$8334m^3$/h x 30m, 844kW, Vertical
3	HIGH PRESSURE PUMP	30	$4167m^3$/h x 827m, 12314kW, Vertical
4	RECOVERY TURBINE	30	$2083m^3$/h, -4056kW
5	SCREEN WASH PUMP	10	$471m^3$/h x 60m, 115kW, Vertical
6	CHEMICAL CLEANING PUMP	5	$4167m^3$/h x 30m, 434kW, Horizontal
7	TRAVELING SCREEN	10	$12500m^3$/h, 60kW, $4m^W$x $6m^H$
8	DUAL MEDIA FILTER	80	$1563m^3$/h, Gravity Siphone, $24m^L$x$12m^W$
9	CLEAR WELL	1	$20000m^3$(for 2 Units), $240m^L$x$10m^W$x$10m^D$
10	PRODUCT WATER BUFFER TANK	2	$15625m^3$, $30m^D$x$25m^H$
11	CHEMICAL CLEANING TANK	5	$72m^3$, $5m^D$x $5m^H$
12	DRAIN PUMP	2	$9375m^3$/h x 15m, 475kW, Vertical
13	PANEL and OTHERS	-	2500kW

TOTAL ENERGY COMSUMPTION (No.2,3,4,5,7 and 13)   264650kW
SPECIFIC ENERGY COMSUMPTION   4.23 kWh/m^3

coupling. One is: all reactor power is converted into electricity, a part of which is then used for electric motors to drive high pressure pumps. This choice has advantages of great freedom in the location of the desalination plant, and ease in output control of desalination and electricity. The other option is: a part of the reactor output is converted into electricity, and the rest is used directly to drive high pressure pumps using steam turbines. In this choice, the desalination plant must adjoin the reactor, but energy loss can be avoided in the process of energy conversion from mechanical to electrical and from electrical to mechanical, and, at the same time, costs of generators and electric motors can be saved. On the other hand, the smaller steam turbines are less efficient and more expensive. The desalination plant described in Section 4.2.2.3 is based on the former choice. However, the final choice of coupling method will be made after analysis of costs and electricity demand, taking the site location into account.

4.2.2.5. Cost Analysis

Cost analysis is currently under way. It is recognized that to achieve the goal of large scale water production for agricultural purposes,very low water costs must be achieved.

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4.3. High Temperature Gas Cooled Reactors

4.3.1. Southern California Desalination Study (USA) [61]

The coastal plain of Southern California has scant water resources. Less than 40% of the water consumed by the region's 14 million individuals is indigenous to the area. The balance is transported long distances via aqueduct systems which, in breadth and daring, rank among the world's modern engineering marvels. This water supply is never without threat. Drought cycles historically occur in random patterns and can persist for long periods. Earthquakes could disrupt the flow of aqueduct water to the region. Interstate and intrastate competition for available water resources bring additional uncertainty to future supplies.

Southern California's rapid population growth is projected to continue well into the next century, resulting in ever increasing demand for water despite continuing conservation efforts. New sources of water will be needed, but are increasingly more difficult to acquire. The growth in the region's population is also bringing with it an ever increasing demand for electrical power. Although the Southwest is currently enjoying a surplus of electrical generating capacity, this surplus is projected to disappear by the year 2000, by which time substantial new sources of power will be required.

For the above reasons, the Metropolitan Water District of Southern California (MWD) (a water utility), in conjunction with the U.S. Department of Energy (DOE), initiated a study to evaluate the technical and economic viability of using the Modular High Temperature Gas-Cooled Reactor (MHTGR) for desalination. The MHTGR was viewed as being particularly appropriate for such an application for the following reasons:

o   The small plant size (compared with current reactor concepts) and modular configuration are more compatible with process energy applications such as desalination

o   In cogeneration applications, the impact on electrical production is reduced relative to WCRs by using the MHTGR, due to the high initial steam conditions (17.2 MPa, 540°C)

o   The small unit size (350 MW(th)), and passive safety characteristics of the MHTGR, provide a technical basis for siting near to water distribution systems

Some basic ground rules for the study were established at the outset. First, the plant was to be based where possible on the reference four-module MHTGR currently under development by the DOE. Second, the study was to consider only desalination technologies that were either currently commercially available or were expected to become commercially available by the mid-1990s. Finally, the plant was not to be developed for a specific site, but instead a set of generic site characteristics encompassing possible sites in the Southern California area was to be considered.

The study scope included an assessment of future needs for new water and power additions; specifying the requirements for a plant which would meet a reasonable fraction of the projected need; selecting a desalination process for use with the MHTGR: developing a conceptual plant design and cost estimate; investigating the safety and institutional issues associated with the plant, and developing a project plan.

4.3.1.1. Technical Description

The MHTGR Desalination Plant that was defined as a result of the Southern California study consists of four 350-MW(th) reactor modules, two 273-MW(e) (gross) steam turbine energy conversion systems, and eight 50 000 m^3/day Low-Temperature Horizontal-Tube Multi-Effect distillation (LT-MTME) desalination trains. The net water output of the plant is approximately 146 000 TCM per year (400 000 m^3/day) and the net electrical power output is 466 MW(e). Relatively few modifications to the reference MHTGR are required for the desalination application. A detailed description of the MHTGR concept is provided in Ref. [62] and, therefore, details of the reactor, the nuclear island and the basic turbine plant design are not repeated here in the interest of brevity. Rather, this discussion focuses on the selection of the desalination process and the coupling of the desalination process to the MHTGR.

4.3.1.1.1. Process Selection

A fundamental ground rule stipulated by MWD for the selection of candidate processes was that they must be endorsed by an established vendor as being commercially available at present or by 1995. This eliminated advanced desalination concepts which may eventually prove successful, but at this stage are not fairly comparable with demonstrated processes. Of

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the remaining, the most commonly-used desalination processes are Multistage Flash (MSF) distillation, Multieffect Distillation (MED), Electrodialysis, and Reverse Osmosis (RO). Of the more common desalination processes, only MSF and MED were found at the time of the study to be suitable for use in a dual-purpose power/desalting plant based upon projected economics.

A single purpose (desalination only) plant was not considered due to:
- The need for electricity in the Southern California area
- The high cost/value of electricity in Southern California
- The size and high temperature characteristics of the MHTGR as an energy source

In the course of the evaluation, two specific MED designs were evaluated as well as a MSF design. The two MED designs included a Vertical Tube Evaporator (VTE) and a Low-Temperature Horizontal Tube Multi-Effect distillation (LT-HTME) process.

The selection criterion was simply to choose the process that had the lowest levelized water cost, provided that other factors did not result in any overriding negative findings. These other factors included:

- Product water quantity
- Number and size of existing commercial units
- Operating experience to date
- Long-term supplier availability
- Potential for process improvement

On the basis of the evaluation, the LT-HTME process was selected as the reference concept to be coupled with the MHTGR. The specific design is one proposed by Israel Desalination Engineering (IDE) that utilizes aluminum tubing for the heat transfer surface.

4.3.1.1.2. LT-HTME Optimization for Coupling with the MHTGR

Following initial comparisons which showed LT-HTME to have a significant cost advantage over the other processes, further efforts to optimize the LT-HTME process were expanded in cooperation with the vendor (IDE).

Steam Delivery System. Two different methods were proposed for supplying heat to the LT-HTME process. These are referred to as Scheme 1

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COGENERATION PLANT
PRINCIPLE FLOW DIAGRAM
SCHEME NO 1

COGENERATION PLANT
PRINCIPLE FLOW DIAGRAM
SCHEME NO 2

Fig. 49. Alternate schemes for delivering heat to the LT-MED process. (Note: steam bypass for turbine and sea-water bypass for desalination trains not shown for clarity.)

and Scheme 2 and are illustrated in Fig. 49. In Scheme 1, turbine exhaust steam is condensed in a conventional condenser becoming boiler feedwater. The latent heat of condensation is transferred to a circulating saline water stream. This cooling water, which is heated in the condenser by approximately $5.5^{\circ}C$, is fed to flash chambers to produce steam energy for the desalination units. In this scheme, the condensate of the steam from the flash chambers is pure distillate and adds to the product water. Makeup flow and blowdown streams are provided to maintain the circulating water salinity within the maximum desired salt concentration.

In Scheme 2, the turbine exhaust steam is fed directly to the first effect of the desalination units. This process is thermodynamically more efficient than Scheme 1, due to the fact that it receives thermal energy at a higher temperature and the thermal losses in the flash chamber are eliminated. In addition, pumping energy is lower than in Scheme 1 due to the elimination of the flash chamber-condenser circulation pumping. Nevertheless, the performance ratio with this scheme will be lower than that of a plant with the same number of effects operated using Scheme 1, because the condensate from the first effect must be returned to the turbine generator system rather than being mixed with the product water.

Among the advantages of Scheme 1 are the following: the interface between the water plant and the power plant is much simpler with Scheme 1. Scheme 2 requires very large steam ducts and valves between the turbine exhaust and the desalination trains whereas Scheme 1 does not. A turbine guarantee may not be possible with Scheme 2, particularly for a turbine operating at relatively high backpressure (over 5.0-in HgA). Scheme 1 offers greater flexibility in accommodating part-load operation and operation of the power plant without the water plant.

An advantage of Scheme 2 is that it requires one-third lower pumping power than Scheme 1. Another advantage of Scheme 2 is that the condenser and recirculating systems are eliminated, resulting in some cost savings.

A cost analysis was performed to determine the enocomic effects of these various differences. This analysis showed a slightly lower (2.1%) cost of water for Scheme 2 as compared to Scheme 1. However, this was judged insufficient to outweigh the disadvantages with Scheme 2 and so the Scheme 1 steam delivery system was selected.
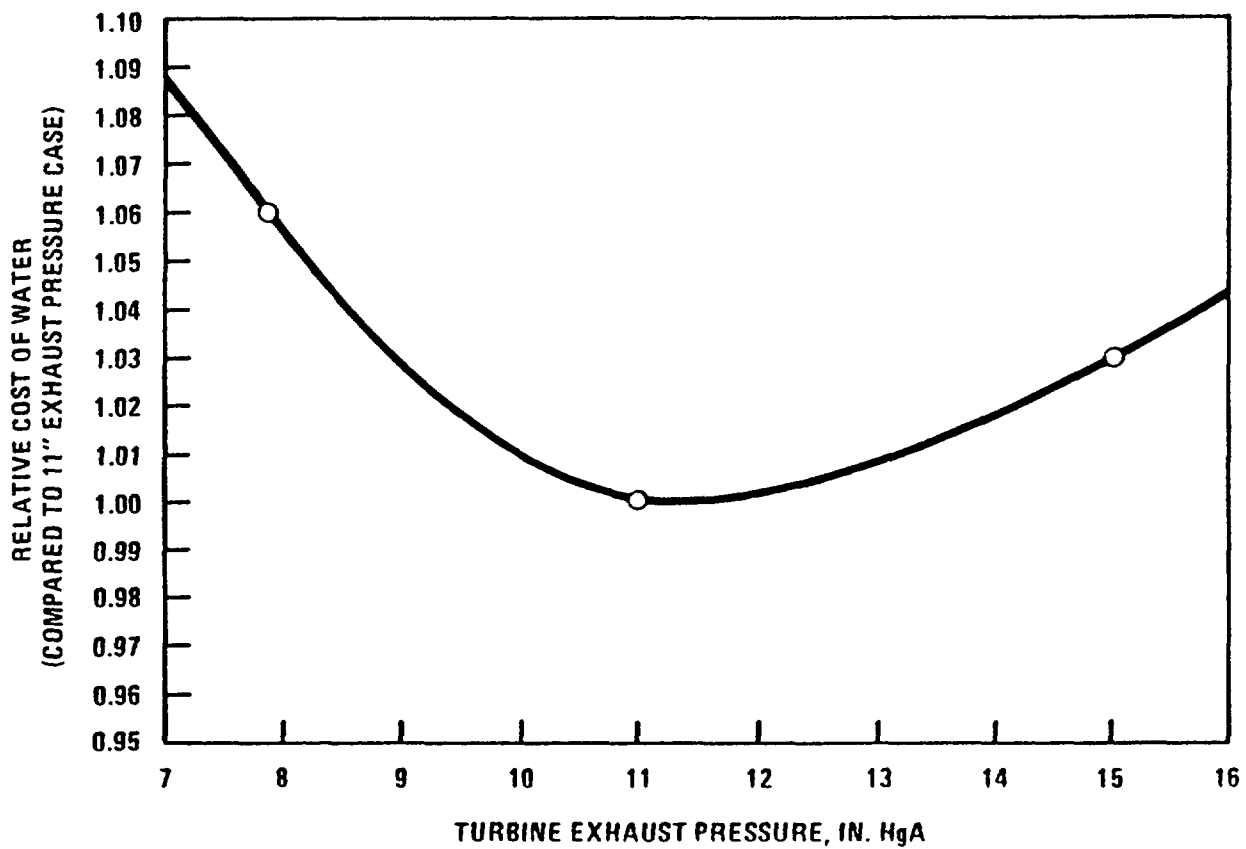
Fig. 50. Effect of turbine exhaust pressure on LT-MED water cost.
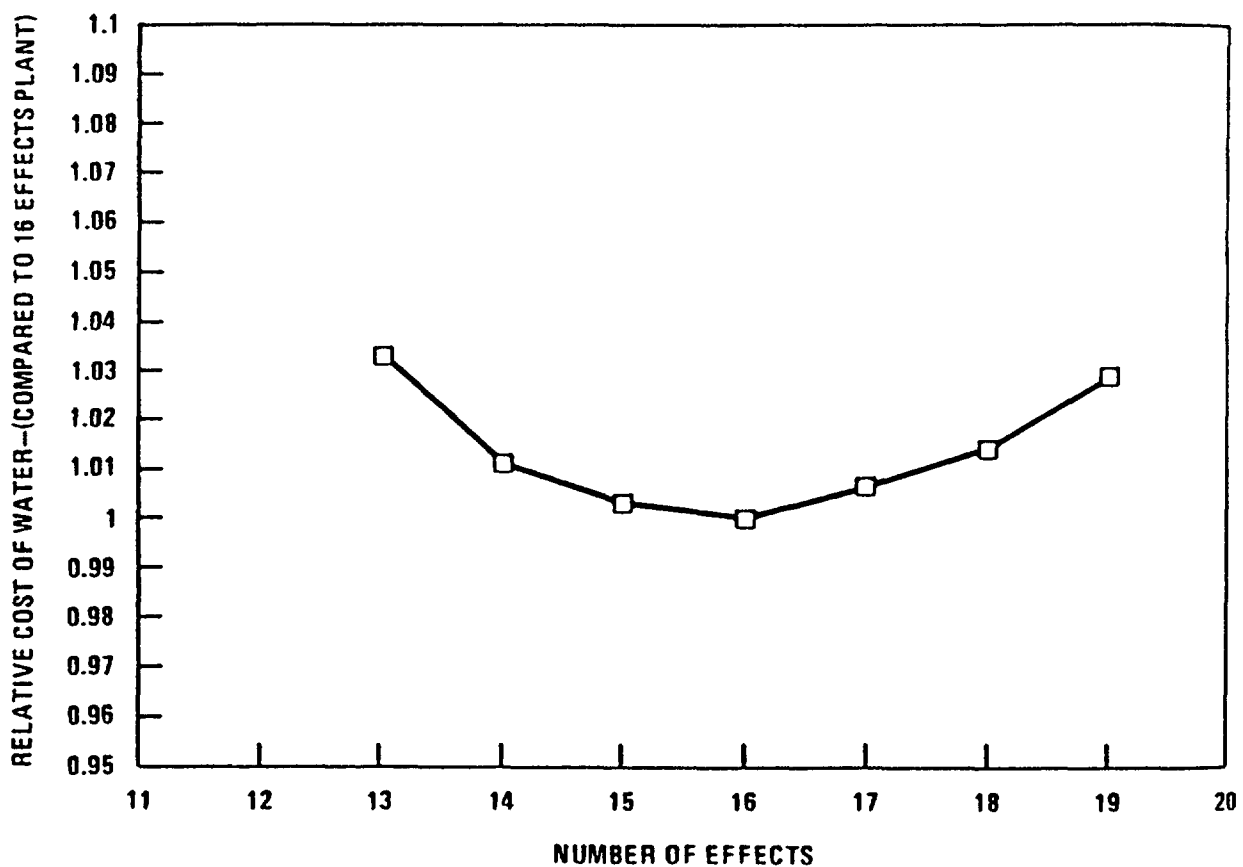
Fig. 51. Relative cost of water as a function of LT-MED number of effects.

Steam Pressure. A second parameter considered for LT-HTME was the turbine exhaust pressure. Three different pressures were considered: 27,37 and 51 kPa (8,11, and 15, in HgA). Using lower pressure steam lowers the cost of heat, but it also lowers water production, and increases capital cost per unit output. Conversely, using higher pressure steam raises heat cost and water production, but lowers capital cost per unit output. The net effect is shown in Fig. 50, which shows that a turbine exhaust pressure of 37 kPa (11-in. HgA) gives the lowest water cost. Thus, the turbine exhaust pressure for the LT-HTME process was specified to be 37 kPa (11-in. HgA).

Number of Effects. Another analysis was performed to determine the number of effects for Scheme 1 with 11-in. of turbine exhaust pressure. Fig. 51 shows the effect of product water costs due to varying the number of effects from 13-19. As can be seen, the lowest product water cost results from a plant with 16 effects, therefore a 16-effect process was selected.

4.3.1.1.3. Reference Desalination Plant Description

The reference MHTGR Desalination plant features resulting from the selection and optimization process are depicted in Figures 52 and 53, a summary of the major plant design parameters is given in Table 7.

TABLE 7. MHTGR DESALINATION PLANT — MAJOR DESIGN PARAMETERS

Reactor thermal power, MW(th)	1 400
Gross Generator output, MW(e)	546
Net electrical output, MW(e)	466
Fresh water production, m^3/day	400 000
Thermal power to water plant, MW(th)	873
Water plant performance ratio	5.3
Maximum brine temperature, ^{o}C	64
Intake seawater flow m^3/min	1262
Product water TDS, ppm	<30
Plant life, years	40
Water production availability, %	84
Power production availability, %	80

4.3.1.2.   Operating Experience

To date, there has been no direct operating experience in which the LT-MED desalination process has been coupled with a nuclear power plant. However, the accumulated experience with the LT-HTME process is

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Fig. 52. MHTGR desalination plant arrangement.

N

LEGEND

1	REACTOR BUILDING
2	MAIN STEAM & FEEDWATER PIPING
3	REACTOR AUXILIARY BUILDING
4	REACTOR SERVICE BUILDING
5	OPERATIONS CENTER
6	PERSONNEL SERVICES BUILDING
7	RADIOACTIVE WASTE MANAGEMENT BUILDING
8	NUCLEAR ISLAND COOLING WATER BUILDING
9	STANDBY POWER BUILDING
10	FUEL OIL STORAGE TANK & PUMP HOUSE
11	HELIUM SERVICES BUILDING
13	GUARD HOUSE
14	HELIUM STORAGE STRUCTURE
15	CLARIFIER
16	MAKEUP WATER TREATMENT & AUXILIARY BOILER BUILDING
17	MAINTENANCE BUILDING
18	CONDENSATE SURGE TANK
19	DEMINERALIZED WATER STORAGE TANK
20	UNIT TRANSFORMER
21	NI WAREHOUSE
22	HYDROGEN STORAGE AREA
23	TURBINE BUILDING
24	FILTERED WATER STORAGE TANK
25	SWITCHYARD
26	STARTUP AUXILIARY TRANSFORMER
27	UNIT AUXILIARY TRANSFORMER
29	FIRE WATER STORAGE TANK
30	FIRE PUMP HOUSE
31	ECA WAREHOUSE
32	REMOTE SHUTDOWN BUILDING
33	WASHDOWN BAY
34	CHILLED WATER BUILDING
35	ELECTRICAL EQUIPMENT AREA
36	SEAWATER INTAKE STRUCTURE
37	DESALINATION TRAIN
38	CIRCULATING WATER PUMPS
39	PUMP PIT
40	DISCHARGE SEAL WELL

50 0 50 100   200   300 FT

GRAPHIC SCALE

Fig. 53. MHTGR desalination plant — simplified flow diagram.

significant. Over 175 LT–HTME units have been placed in operation, although all are smaller than the proposed plant. The largest train built up to now is a prototype constructed by Israel Desalination Engineering (IDE) that has a capacity of 19 000 m^3/day.

The IDE unit is about half the size proposed within the Southern California Study. Of particular significance, however, is the fact that the prototype has been configured to closely represent coupling to a power plant.

A recent assessment of desalination technology by Black and Veatch for MWD Ref. [63] has indicated favourable operating experience with LT–HTME plants, with reported availabilities of over 98%. Most of these units were of relatively small size compared with the plant proposed for this study, but this nevertheless indicates good expected performance of LT–HTME plants in general.

4.3.1.3.   Cost Analysis

An economic evaluation was made of the MHTGR Desalination Plant to determine the capital cost and the corresponding product costs for water and electricity.

4.3.1.3.1. Economic Assumptions

An important consideration was the financial parameters assumed, which in turn depended upon assumptions regarding the ownership of the plant. In this section, a reference case is described in which the Water Production Plant (WPP) is owned by the water utility (MWD) and the remainder of the plant including the Nuclear Island (NI) and Energy Conversion Area (ECA) are owned by an Investor-Owned Utility (IOU). Other ownership options were also considered but are not included here for brevity. The ECA includes the turbine plant, turbine plant auxiliaries and structures not part of either the NI or WPP. The financial parameters for the reference case are provided in Table 8.

4.3.1.3.2. Capital Costs

Separate capital cost estimates were developed for a first-of-a-kind plant, a second-of-a-kind or "replica" plant, and a mature commercial plant

TABLE 8. DESALINATION PLANT — FINANCIAL PARAMETERS

	Metropolitan/ GOU Parameters	IOU Parameters
Capitalization		
Debt, %	100.00	50.00
Preferred stock, %	—	10.00
Common equity, %	—	40.00
Return on capitalization		
Debt, %/year	8.5	9.70
Preferred stock, %/year	—	9.00
Common equity	—	14.00
Average nominal cost of money, %/year	8.5	11.35
Inflation rate, %/year	5.5	5.5
Inflation-adjusted cost of money, %/year	2.84	5.55
Federal income tax rate, %	N/A	34.00
State income tax rate, %	N/A	9.30
Combined federal and state tax rate, %/year	N/A	40.14
Tax-adjusted cost of money, %/year	8.5	9.40
Real cost of money, %/year	2.84	3.70
Property tax rate, % of cap/year	N/A	1.12
Replacement rate, % of cap/year	0.50	0.50
Book life, year	30	30
Tax depreciation period, years	N/A	15
Tax depreciation method, %	N/A	150 Declining Method
Accounting method	Normalized	Normalized

designated the "nth-of-a-kind (NOAK)" plant. Capital costs developed for these three plants are summarized in Table 9. In developing the total plant capital cost, an on-site construction duration of approximately 44 months was projected.

TABLE 9. MHTGR DESALINATION PLANT — CAPITAL COST SUMMARY
(MILLIONS OF 1988 DOLLARS)

	First	Replica	NOAK
Land and land rights	100	100	100
Structures and improvements	145	142	138
Reactor plant equipment	337	299	270
Turbine plant equipment	134	133	132
Electric plant equipment	58	57	56
Water plant equipment	293	290	288
Miscellaneous equipment	15	15	14
Main condenser heat rejection	18	18	17
Seawater intake/discharge	35	35	34
Total direct	1135	1088	1050
Construction services	86	82	79
Home office support	98	69	54
Field office	31	30	29
Owner's cost	180	156	151
Total indirect	395	337	313
Contingency	291	271	256
Interest during construction	275	210	197
Total plant capital cost	2096	1906	1815

4.3.1.3.3. Operating Costs

The operating costs, including maintenance, for the MHTGR
Desalination Plant are projected in Table 10. The estimates include
provisions for a total plant staff of 344 persons.

4.3.1.3.4. Production Costs

The levelized water and power costs in constant 1988 dollars were
calculated by summing the present worth of the year-by-year revenue
requirements to pay operating costs, taxes, return on undepreciated capital
investment, and capital investment depreciation, and then dividing by the
equivalent quantity of product produced. All ownership cases necessitated
allocating costs between water production and power production. This was
accomplished by setting the power cost at the reference all-electric MHTGR
value and pricing the heat energy to the water plant to compensate for the

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TABLE 10. ANNUAL O & M COST ESTIMATES FOR ELECTRIC GENERATION PLANT
(JANUARY 1988 DOLLARS)

	Power Generation Costs (MUS$/year)
Onsite staff	10.7
Maintenance materials	
Fixed	2.5
Variable	0.9
Subtotal	3.4
Supplies and expenses	
Fixed	4.3
Variable	
Plant	0.4
Control rod and reflector disposal	1.3
Subtotal	6.0
Offsite technical support	2.3
Subtotal, power generation costs	
Fixed	19.8
Variable	2.6
Subtotal	22.4

	* A&G Costs (MUS$/Year)
Pensions and benefits	2.7
Nuclear regulatory fees	1.1
Insurance premiums	3.7
Other A & G	3.2
Subtotal	10.7

	Total O & M Costs (MUS$/Year)
Fixed	30.5
Variable	2.6
Total	33.1

* Administrative and General

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lost power generation due to raising the turbine exhaust pressure. Thus, no subsidies to water sales are paid by power sales and vice versa.

Levelized water costs were computed for both blended and unblended water products. Blend water at 1500 total dissolved solids (TDS) and $ 105 per thousand cubic meters (TCM) was stipulated to be available based on a survey of brackish aquifers in Southern California. This water was blended with the 30 TDS distilled water from the WPP to produce a greater amount of 500 TDS product water at a lower price.

The levelized product costs for the case of joint Metropolitan and investor-owned utility ownership (Case 2) are summarized below. All costs are in 1988 dollars:

	First	Replica	NOAK
Annualized capital cost, MUS$/yr	143.4	132.6	125.9
Annualized fuel cost, MUS$/yr	55.7	50.0	41.0
Annualized O&M cost, MUS$/yr	47.7	44.4	41.1
Annualized decommissioning cost, MUS$/yr	2.3	2.3	2.3
Total plant annual cost, MUS$/yr	249.2	229.3	210.3
Required power sales revenue, MUS$/yr	188.8	171.8	155.6
Levelized power cost, cents/kW(e).h	5.79	5.27	4.77
Required water sales revenue, MUS$/yr	60.4	57.6	54.7
Levelized water cost (without blending), US$/1000 m^3	489.7	467.0	443.5
Levelized water cost (with blending), US$/1000 m^3	366.4	351.0	335.6

The range of water costs represents a significant reduction from previous desalination experience for both single-purpose and dual-purpose plants. Previous desalted water costs were estimated in Ref. [63] to be in the range of US$ 973 to 1459/1000 m^3. The lower costs obtained in this study are primarily attributed to the low-temperature desalination technology, which permits the use of inexpensive tube materials and reduces the impact on power production in the MHTGR plant.

These costs do not include the cost of transporting the product water from the desalination plant boundary to the distribution point. Assuming a

Ø 9400 mm

Ø 5900 mm

25 000 mm

Mean Core Height 9430 mm

Ø 3000 mm

22 500 mm

1 Pebble Bed
2 Pressure Vessel
3 Fuel Discharge
4 Small Absorber Balls
5 Reflector Rod
6 Fuel Loading
7 Steam Generator: Pipe Assembly
8 Outer Shroud
9 Feed Line
10 Live Steam Line
11 Blower
12 Hot Gas Duct
13 Surface Cooler
14 Insulation
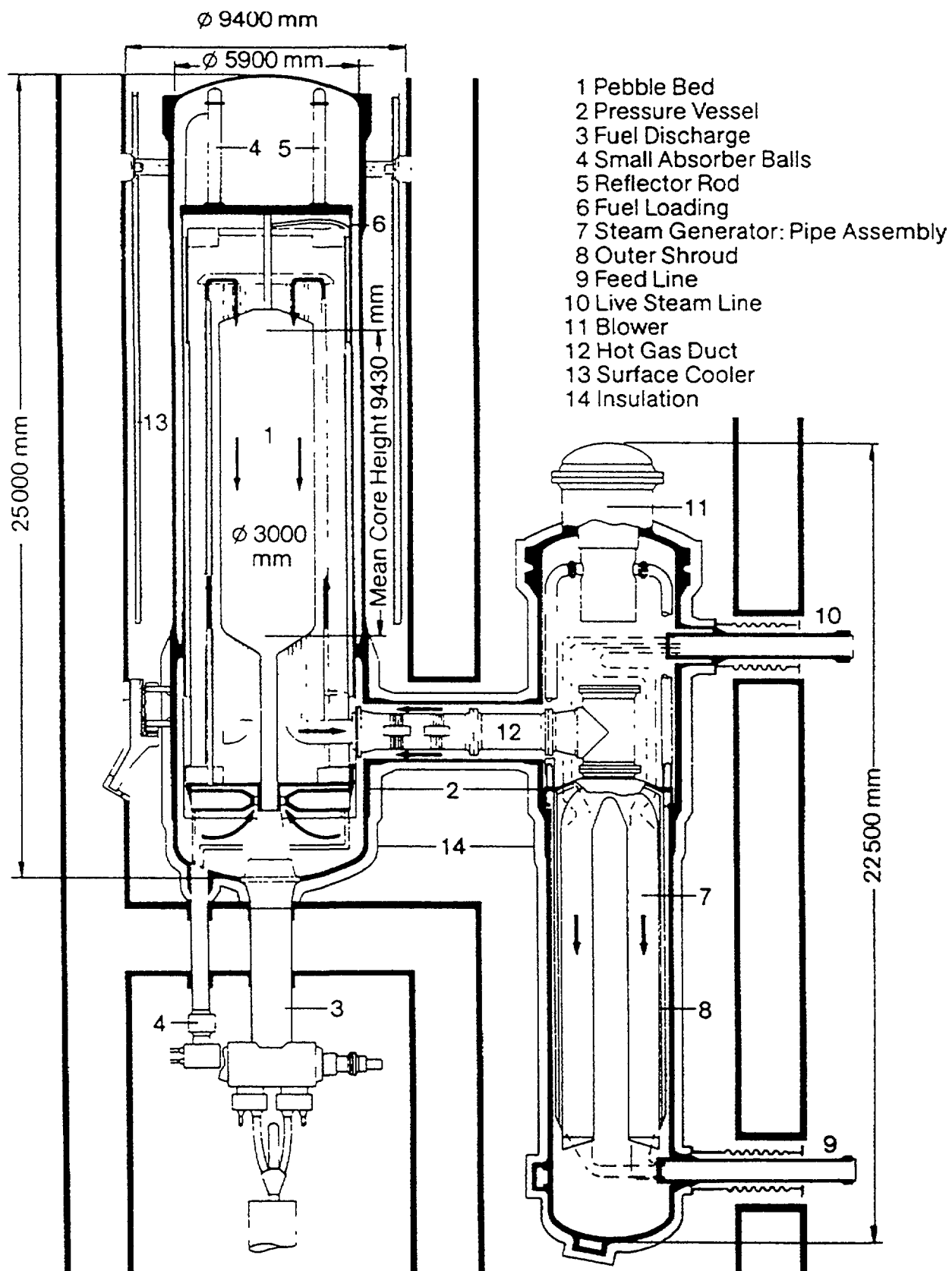
Fig. 54. Longitudinal section through reactor.

32 km pipeline and a 244 m lift, this cost is estimated to be about US$ 97/1000 m^3. The magnitude of this estimate indicates that the subject of where and how to inject the product water into the Metropolitan system should be examined carefully in order to minimize this cost.

4.3.2. HTR–Module for Seawater Desalination (FRG)

The technical feasibility and economics of mounting a Modular High Temperature Reactor (HTR–Module) power plant on a barge has been investigated in the report "Autarke Barge–montierte Energiestation mit Hochtemperaturreaktor–Modul" in July 1985 by Howaltswerke Deutsche Werft AG and Interatom GmbH. One application of such an energy station is seawater desalination by Reverse Osmosis [see Ref. 64].

The concept of a barge–mounted desalination plant with a low to medium power rating offers decisive advantages. The complete desalination plant can be manufactured in a shipyard and its main functions can be tested there. The barge is then used to ship the plant to its destination at any coast in the world. Once it has reached the site, the barge may pass through an inlet channel into a coastal basin where it is positioned on a foundation. The power plant now can be operated as a stationary plant.

4.3.2.1. Technical Description

The HTR–Module is a helium cooled pebble bed reactor and is constructed as an assembly of several modular subunits. Each subunit consists of a reactor with 200 MW(th) output and a steam generator in two separated steel pressure vessels (Figs. 54, 56). So a total power size of between 400 MW(th) (HTR-2 Module) and 1 600 MW(th) (HTR-8 Module) can be achieved.

Each HTR unit of a multi–modular plant can be operated independently. Each modular unit can be individually shut down, started up and connected to the overall plant once it has achieved the operating conditions. Thus, in the case of an outage of a single module, operation of the overall plant can be continued at a reduced power level.

A more detailed technical description of the HTR–Module and its excellent safety properties is given in several publications such as Ref. [64].

SEEWASSER 4,5% SALZGEHALT

VORGEWARMT AUS KONDENSATOR

38 °C 18000 n³/h

NATRIUMHYDRO-
GENSULFITDOSIER.
Z. ENTCHLORUNG

SCHWEFELSÄUREDOSIERUNG
ZUR
ENTKARBONISIERUNG

FILTRATION

18000
n³/h

ZWISCHENTANK

DRUCKPUMPEN
9+3

KERZENFILTER
30+10

SAMMLER

ABWASSER BEI
FILTERWECHSEL
MIT DIATOMIT

KONZENTRAT
JE STRASSE
77 n³/h

CHLORDOSIERUNG
ZUR ENTKEIMUNG

BRACKWASSER-
UMKEHROSMOSE
9 STR. JE60 MOD.

HOCHDRUCKPUMPEN
9+3 JE 380 KW

ZWISCHENTANK

SEEWASSERUMKEHR-
OSMOSE, 45 STRASSEN
JE 40 MODULE

PERMEAT
1470 ng/l
SALZGEHALT

PERMEAT
190ng/l
SALZGEHALT

PERMEAT
1470 ng/l
SALZGEHALT

ZWISCHENTANK

BEIMISCHPUMPEN
JE 30 KW

SAMMLER

CHLORIERUNG

HOCHDRUCKPUMPEN
9+6 DAVON 11 MIT
ELEKTROMOTOR

PUMPEN
9+6 JE 110 KW

AUFHARTUNGSFILTER
MIT DOLOMIT 10+1

TRINKWASSER 450 ng/l
SALZGEHALT, MAX.4300n³/h

KONZENTRAT AUS PELTON-
TURBINE ZURÜCK INS MEER

Fig. 55. Flow scheme of a reverse osmosis desalination plant with product water output of 100 000 m³/d.
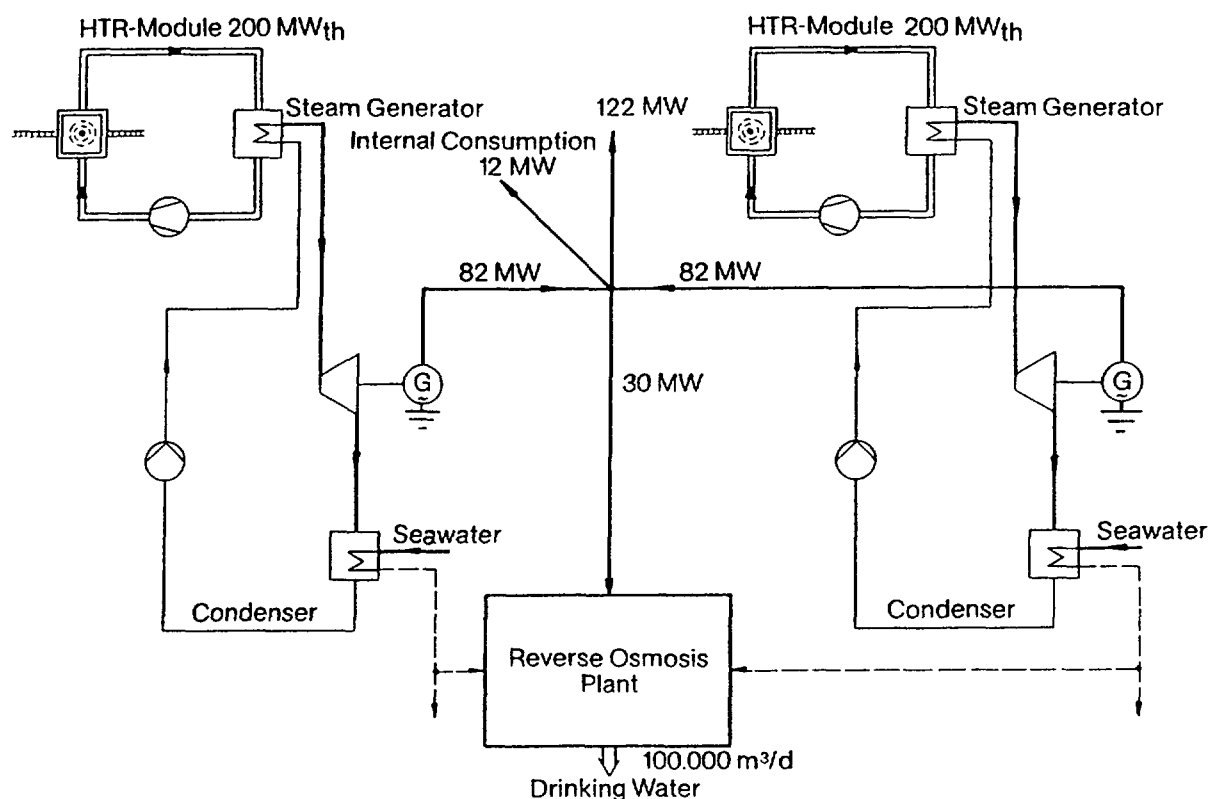
Fig. 56. Simplified flow scheme of a 2 module plant for cogeneration of electricity and drinking water.

Here a HTR-2 Module and HTR-4 Module power plants are considered with a net electricity production of 152 MW(e) and 304 MW(e) respectively.

The Reverse Osmosis desalination process has been selected because of its comparatively low energy consumption and its good operational features. The product water output of the RO plant connected with the HTR-Module is about 4 170 m3/h or 100 000 m3/day with a remaining salt content of 450 ppm. The electric power consumption is only 30 MW and the surplus electricity of 122 MW is sold to other energy consumers.

The rather high electricity consumption (7.2 kW(e).h/m3 product water) of this RO plant is a result of a high seawater salt content (4.5%)in the Arabian Gulf and conservative assumptions on plant design and available membrane technology. A pressure of 70 bars is maintained for the RO process.

A flow scheme of the desalination process is shown in Fig. 55. 18 000 m^3/h of preheated raw seawater with a temperature of 38°C and a salt content of 4.5% is chlorinated, and cleaned by diatomaceous filtration. After passing a storage tank, it is treated with sodium

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bisulfite (for dechlorination) and sulfuric acid (antiscaling), and then fed through cartrigde filters to the first stage of the Reverse Osmosis plant. This first stage consists of 45 trains with 40 RO modules each. The high-pressure energy of the brine stream is recovered by a turbine. After this first stage the salt content of the product water is reduced to 1 470 ppm and it is fed to a second RO stage consisting of 9 trains with 60 RO units each. The product water of the second stage contains salt with a concentration of 190 ppm, and is blended with brackish water received after the first RO stage, to maintain a final salt content of 450 ppm. Finally the product water is filtered with dolomitic material and chlorinated again.

The total consumption of chemicals for water treatment (H_2SO_4, $Na_2S_2O_5$, NaOCl) will amount to about 5 500 tons per year. The two RO stages will have to be cleaned about 4 or 6 times per year. For cleaning purposes an additional 250 tons of chemicals are required.

The RO desalination plant and the HTR-Module power plant are mounted together on one barge. The overall size of the barge would be:

	HTR – 2 Module	HTR–4 Module
Length	227.5 m	325.0 m
Beam	52.0 m	52.0 m
Height	54.1 m (total)	54.1 m
Draught	6.3 m	7.3 m
Weight	71 930 t	123 100 t

The reactor building with the nuclear steam generating system is located in the middle of the barge (see Fig. 57). For shielding reasons, the reactor and steam generator are surrounded by thick-walled concrete structures (primary cell). A crane positioned above the primary cell can move right across the entire width of the barge for maintenance and repair work.

The auxiliary building directly adjoins the reactor building, and accomodates the reactor auxiliary systems, offices and personnel rooms. Access to the reactor is through this building. The machine building with the two separate steam power plants, adjoins the reactor building on the opposite side. This is followed by the switchgear building, with the control room, and rooms for instrumentation and control systems. The desalination units are directly connected to the switchgear building.

Reactor Building

Crane

Machine Building

Switchgear Building

RO-Drinking Water Production

Auxiliary Building

RO Switchgear

2nd Step – Brackish Water
1st Step – Seawater

Workshop	Air Conditioning	Gas Purification Plant		Control Room Computer Room
	Offices			Electronic Cabinet
	Gate-way	Control Panel	Offices	Conduit Room Emergency Power Systems
Storage	Labors	He- and N₂ Systems		Starting Diesel
	Waste store		Main Cable Ducts	Pumps	Generator

Filtration   Carbonization Filter

Pumps

Reactor   Steam Generator

Fig 57 General arrangement of a HTR 2 module plant for electricity and drinking water production

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4.3.2.2. Status of Technology

Development work on the modular HTR started in 1979. The Safety
Analysis Report on the HTR-Module was submitted in April 1987 and provided
the basis for a site-independent licensing procedure in accordance with the
German Atomic Law. Since April 1990 the final statement of the German
Reactor Safety Commission (RSK) on HTR-Module concept is published and
gives a very positive judgement on HTR-Module safety features and
licensibility [65]. Today a HTR-Module power plant is ready to be
constructed and operated commercially. Barge mounting of the HTR-Module
could be shown to be technically feasible. Reverse Osmosis plants have
been in commercial operation for about 20 years.

4.3.2.3. Special Requirements for Coupling

There are two energy connections between the desalination plant and
the HTR-Module power plant. The main connection is the electric power line
and the other connection is the preheating of seawater intake by the
condenser of the power plant. The efficiency of the RO process is improved
by raising the water temperature.

Both energy connections are unproblematic with respect to safety and
operational flexibility of the total plant.

4.3.2.4 Cost Analysis

Water production costs have been calculated for a nth-of-a-kind (NOAK)
HTR-2 Module desalination plant on a barge. The input data are:

Total capital cost (1993):	1 658 - 2 142 million DM
Surplus electricity generation:	122 MW(e)
Water production:	100 000 m^3/day
Plant utilization:	7 000 - 8 000 h/a
Plant depreciation period:	20 a
Interest rate:	8 %/a
Inflation rate:	4 %/a
Construction period:	4 a
Plant staff:	100
Average salary (1993):	68 000 DM/a
Nuclear fuel cost (1993):	14.2 - 15.3 DM/MW(th).
Year of commissioning:	1,993
Annuity factor:	9.793 %

All costs are given in 1993 money. They can be shifted to other years by
4% per year inflation rate.

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The total capital costs are divided roughly into the following groups:

Organization, overhead   3 %
HTR-2 Module power plant   47 %
Barge   10 %
RO-plant   36 %
Transport, site   4 %

The annual costs (in 1993 million DM/a) of the total plant are calculated in case of 8 000 h/a utilization:

Capital amortization: 163 - 210
Nuclear fuel: 45.5 - 49.0
Operating staff, maintenance,
  insurance: 35 - 44
Membrane replacement, chemicals,
  filters: 24.8

total (in 1993 million DM/a):   268.3 - 327.8

Because of cogeneration of two products the water production cost can be calculated only if revenues from electricity sales are known. Here it is assumed that electricity is sold for a price equal to electricity generation cost of a single purpose HTR-2 Module power plant on a barge. This price was evaluated to 14.5 - 17.5 Pf/kW(e).h (1993 money).

This results in an annual electricity sales revenue of 141.1 - 171.6 million DM which has to be substracted from the total annual costs to obtain the required water sales revenue (costs in million DM, 1993 money):

Total annual costs: 268.3 - 327.8
Electricity sales revenue: 141.4 - 171.6
Required water sales revenue: 126.9 - 156.2

With these figures the following resulting water production costs are calculated:

Utilization h/a	Water costs (1993) DM/m^3
7 000	4.32 - 5.32
8 000	3.81 - 4.69

The water production costs (in 1993 money), of a HTR-4 Module plant on a barge are:

Utilization h/a	Water Costs (1993) DM/m^3
7 000	3.43 - 4.32
8 000	3.03 - 3.82

Expresed in 1985 money all water production costs are lower by 37%.

In 1984/85 when this study was performed, the currency exchange rate between US$ and DM was 3 DM/$. The nuclear fuel costs and RO membrane costs used here are based on this exchange rate.

4.4. Advantages and Disadvantages of Single Purpose vs Dual Purpose
Plants

In single purpose plants the energy source provides electricity
and/or thermal energy exclusively for the desalination process. Water is
the only product sold under normal conditions. In dual purpose plants, the
reactor is designed to provide a product other than water, normally
electricity.

4.4.1. Advantages of Dual Purpose Plants over Single Purpose Plants

1. The load factor of dual purpose plants is higher, because during an
   outage of the energy source the desalination plant can still be
   powered by the electricity grid and can maintain water production.
   During an outage of the desalination plant, the energy source (e.g.
   nuclear reactor) can still generate electricity for the grid. In
   single purpose plants any production is stopped if either
   desalination plant or energy source has an outage.

2. Where sufficient demand exists, operational flexibility of a dual
   purpose plant is higher, because e.g. more electricity can be
   generated during periods of low water consumption.

3. Economy of dual purpose plants is better, because more product
   (electricity) can be sold. In particular, if a nuclear reactor is
   used as energy source, a larger power size can be chosen, taking
   advantage of the reduced costs per unit of product in nuclear
   reactors of larger power size.

4. Dual purpose plants with electric coupling may not require a separate
   backup energy source.

4.4.2. Advantages of Single Purpose Plants over Dual Purpose Plants

1. Siting of single purpose plants is easier as a connection to an
   electricity grid is necessary.

2. Total plant investment costs of single purpose plants may be lower.

3. Smaller single purpose plants imply improved safety characteristics
   and perhaps eased licensing.

4. Potential reduction in construction and decommissioning time.

5. Simpler organizational requirements.

6. Reduced complexity in evaluating and allocating costs.

4.5. Important General Considerations

4.5.1. Blending Information

Many desalination processes, such as those involving distillation, provide water quality levels in excess of those needed for consumption. For example, the Low-Temperature Multi-Effect Distillation (LT-MED) process produces water at less than 30 ppm total dissolved solids (TDS), whereas > 300 ppm TDS would be a typical requirement for potable water. This suggests that, if a source of higher TDS water is available at appropriate cost, blending could be utilized either to reduce the net cost of the product water, to extend the amount of product water produced, or both. In evaluating the potential for blending, both local sources of brackish water and hybrid desalination processes might be considered.

If a local source of suitable brackish water exists, it is relatively a simple analysis to estimate the volume and cost of the blended product. However, it should be noted that water from typical distillation processes requires no further treatment prior to blending with the local supply. If contaminants in the brackish water lead to a requirement for further treatment, then the cost of that treatment must be taken into account.

Another potential source of high TDS water is a less efficient desalination process, such as Reverse Osmosis (RO). For example, a hybrid desalination process which combines RO and distillation to produce blended water with 500 ppm TDS is illustrated in Fig. 58. This has the potential for both increasing the total amount of water produced and lowering its cost. Raising the product water salinity requirement of the RO process to 1500 ppm (as opposed to 500 ppm required for an RO drinking water plant) results in less stringent requirements on the RO membranes and allows fewer membranes and/or a higher product recovery ratio to be used. This can substantially lower the cost of the RO water. Also, since RO production increases about 1.7% for each degree Fahrenheit increase in feedwater temperature, if warmer seawater such as that available from the cooling water discharged from the MED process is used, then less membrane area is required. This too, lowers the cost of the RO water. (There are, however, temperature limitations on the membranes which must not be exceeded). In
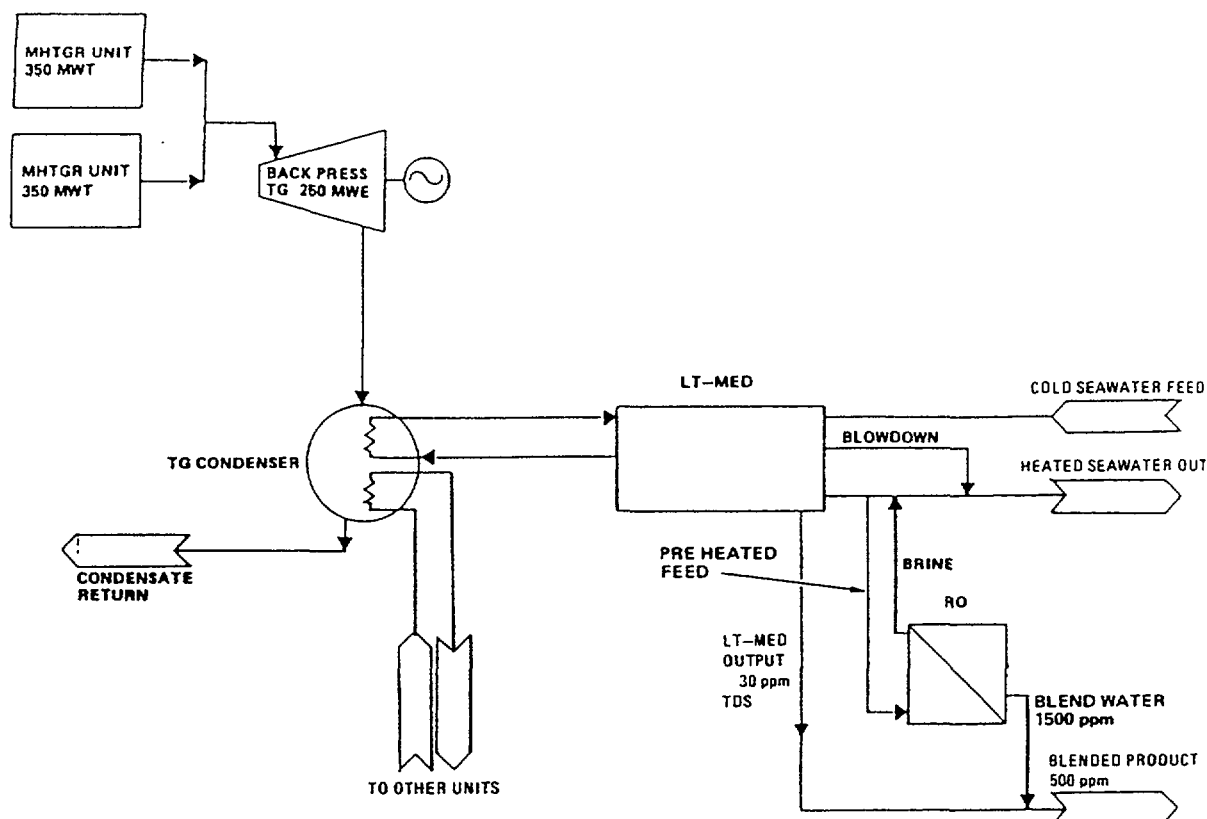
Fig. 58. Hybrid process combining RO and LT-MED to produce 500 ppm blended product water.

addition, some equipment and operating personnel can be shared for the two processes and nearly all of the maintenance personnel can be shared. The net effect is a lower specific operating and maintenance cost for the hybrid plant.

In a recent study addressing the potential for desalination in Southern California [61], both blending with locally available brackish water and hybrid desalination processes were evaluated. In that instance, it was determined that a source of 1500 ppm TDS water would likely be available at an approximate cost of US$105/1000 m^3. That compares with a reference product cost from the LT-MED process that was assumed for the comparative evaluation to be approximately US$527/1000 m^3.

The results of the assessment are summarized in Table 11.

The results of the Southern California evaluation clearly illustrate the potential benefits of blending. With a source of 1500 ppm TDS water assumed to be available locally, the blended product water cost is reduced by about 25%, and total water production is increased by 50%.

TABLE 11. POTENTIAL COST REDUCTION WITH BLENDING

Case	Base case LT-MED	Locally Available Brackish Blend Water	Seawater Hybrid RO/LT-MED
Water from LT-MED Process			
Quantity, m³/day	400 000	400 000	400 000
Salinity, ppm	30	30	30
Relative cost	1.00	1.00	1.00
Blend Water			
Quantity, m³/day	––	190 000	190 000
Salinity, ppm	––	1500	1500
Relative cost	––	0.20	1.09
Blended Product			
Quantity, m³/day	400 000	590 000	590 000
Salinity, ppm	30	500	500
Relative cost	1.0	0.75	1.03

Given the capital and operating costs provided by suppliers, however, the cost of the 1500 ppm TDS blend water from the RO process was found to be still quite high - approximately 9% higher than the 30 ppm TDS water produced by the LT-MED process alone. While water production is increased by 50%, the resulting product water cost was increased by about 3% over the reference value.

However, it should be noted, that the recent improvements in membrane processes are remarkable. For example, the product water quality was specified as high as 2500 ppm TDS in the Jeddah-1 RO plant, because it was intended to use this water as blending water with low TDS product water from the existing MSF plants. The quality obtained was only 120 ppm TDS as shown in a Table in section 3.8.1.1 of this report. In addition, the investment cost for an RO plant is estimated to be lower than that for an MSF or ME plant, as mentioned in the sub-section 3.3.4 of this report, thus current status for individual process should be used, when a hybrid process is considered.

4.5.2. Raw Water Source and Water Distribution Systems

A particular need of desalination facilities is to locate the plant as close as possible to both the source of raw salted water and to the point

at which the product water will be introduced within the distribution system. A related consideration is the special requirements of the seawater intake. These points are separately discussed as follows.

4.5.2.1. Location Relative to Raw Water Source

The cost of product water will normally be very sensitive to both the distance and elevation of the raw water source relative to the location of the desalination facility. This is due to the energy costs associated with pumping the water from the source to the plant. Key parameters that must be considered are the following:

Capital Cost of Raw Water Transport – The large volumes of raw salted water that must be circulated imply significant capital costs for the associated ducts, pumps, valves, etc. These costs increase proportionately with distance from the source.

Energy Costs – As energy costs increase, the incentives for location of the desalination plant near the raw water source increase correspondingly.

Process Efficiency – The amount of raw salted water that must be provided to the process for each unit of product water is also an important consideration. For Reverse Osmosis, typical ratios could be $2-3m^3$ of raw water for each m^3 of product water. Distillation processes would typically involve a somewhat higher ratio. For example, the LT-MED process selected in Ref. [61] had a ratio of about 4.5 : 1. Because the volume of raw water is much larger than that of product water, the location of the desalination facility near the raw water source is particularly important.

Discharge Location – In most instances, concentrated brine is simply returned to the source body of raw water. However, there may be special considerations arising from environmental concerns. For example, a long discharge pipeline with special diffusers may be required to avoid or mitigate damage to sensitive ocean areas. In some applications (e.g. desalination of brakish water from undergroud wells), the disposal site may be separate from the source. In these cases the capital and energy costs must equally be taken into account.

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4.5.2.2. Location Relative to Water Distribution System

The location of the desalination plant near the point of introduction of the product water into the distribution system is an important consideration. However, this parameter is usually less sensitive than that of the raw water source location for the following reasons:

- The volumes are much smaller
- Transport is in one direction only

There are additional considerations, however, that must be taken into account.

Chemical activity - In distillation processes, the product water has a very low solids content (e.g.: < 30 ppm total dissolved solids). Such water is chemically active and special pipe linings must be provided prior to blending with water of higher solids content. The length of such special piping is an economic consideration.

Water Quality - Water produced through desalination is of sufficient quality to be directly blended with already treated water. Control of the water quality must be maintained between the desalination facility and the point of use.

4.5.2.3. Seawater Intake Considerations

Desalination plants need up to 12 times the amount of water they are producing in the case of MSF and about 2,5 times the amount of water they are producing in the case of RO, MED, HTME and ME/VC processes. Seawater intake costs are in the range of 420 US$ to 1800 US$ per m^3/h of water pumped. These costs include intake pipes or channels, filtering system intake basins and seawater pumps with all auxiliary equipment. These costs demonstrate that the seawater intake is often the most expensive single component in the plant. Therefore, due attention has to be given to the design of the intake as well to the location of the plant.

The main problems in the seawater intake system are seaweed, mussel, shells, sand and contamination through hydrocarbons. In the case of seaweed, (a major problem in the eastern part of the mediterranean south coast for example) the intake piping has to be installed up to 15 m below the sea level to avoid suction of this matter. This results in intake

pipes up to 1,5 km long. Also in case of pollution through hydrocarbons the intake should be installed several meters below the lowest sea level (wave valley). Due to increasing worldwide pollution, simple onshore intakes with short channels are becoming less and less possible. Seawater intake is one of the vital components of the plant, so it should have a stand-by capacity.

Intake pipes may be installed on the ground of the seabed but also above the sea level with a vacuum based syphon system. The largest vacuum syphon, which is the best design for easy maintenance, built to the present times, has a capacity of 54 000 m^3/h and consists of 4 pipes each 2 m diameter and 600 m long. The syphon pipes are 1,5 m above sea level at high tides, and at low tides 4,5 m above sea level. (Desalination Plant Ghubrah in the Sultonate of Oman).

5. BASIS FOR NUCLEAR DESALINATION

5.1. Need for Water

It is difficult to find exact water consumption data for each country or even worldwide at present, or predictions for the future. Data are available only for a few areas in an exact way, while for some areas general estimates are available. For a major part of the world, including especially the less developed countries, no reliable data are presently available. Water consumption data cannot be concluded from the number of inhabitants within a certain area as it depends on a number of factors such as social standards, climate and the economic situation. Even, the correct figures for the number of inhabitants in some regions of the world are not available. However, it is known from daily reports in the news media that many areas in the world are facing a severe water crisis. From the water shortages point of view, the following three areas may be considered separately:

a) Mediterranean area and Middle East
b) Developing Countries
c) Developed Countries

a) Mediterranean area and Middle East
   Three quarters of the worldwide seawater desalination capacity is installed in these areas (see Figs. 60 a - e), and of this, nearly 40% is in Saudi Arabia. Despite this fact, practically all countries in these areas are facing a water problem, although the reasons for the shortage are different from area to area. About 12 000 000 m^3/day of potable water deficit can be predicted by the year 2000 within these areas, out of which about 10 000 000 m^3/day are needed in the mediterranean area.
   For example according to reference [66], Israel will face a deficit of 800 000 m^3/d by the year 2000. Syria will have a much bigger shortage. The Tripoli area in Libya, where potable water already costs more than 3 US$/$m^3$, will have a shortage of not less than 500 000 m^3/d by the year 2000. Other areas with a similar demand are Algiers, and Oran in Algeria. Other countries facing shortage of water in this area are Greece (Athens), Italy, France, Spain and Turkey. It
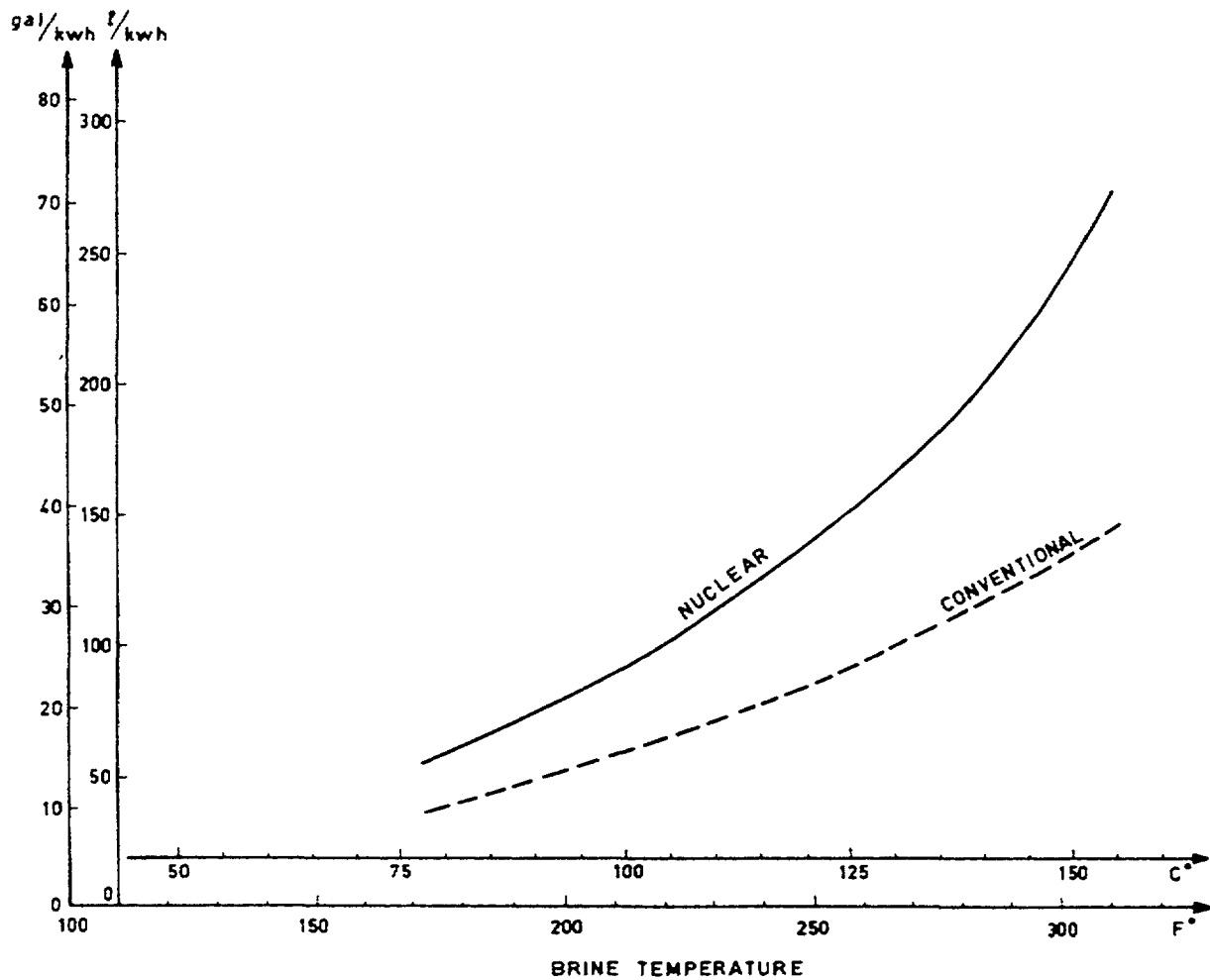
Fig. 59. Water/electricity ratio plotted against brine temperature before flashing (back pressure cycle).

can be concluded therefore that additional sources of potable water have to be developed for these areas.

b) Developing countries

It is practically impossible to obtain any concrete figures for water consumption in Developing Countries. However one can predict a major water deficit from various facts, which will become worse in the next decade. For example, the ground water table in Bejing (China) is actually dropping by 1 m per year. Serious water problems are also known in Pakistan (Karachi), India (Bombay and others areas), some islands in the Pacific, and many countries in Africa, as well as in South America (for example Chile). Most probably the water demand in this part of the world is even more important than in the Mediterranean area and the Middle East.

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Fig. 60a. Cumulative capacity of all land-based desalting plants capable of producing 100 m³/unit or more fresh water daily by contract year.

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Unit·Capacity (m3/d)

100-	2100	2551686= 21.3%
2100-	4100	1044191= 8.7%
4100-	6100	1221381= 10.2%
6100-	8100	28665C= 2.4%
8100-	10100	781952= 6.5%
10100-	12100	371039= 3.1%
12100-	14100	171198= 1.4%
14100-	16100	395394= 3.3%
16100-	18100	141820= 1.2%
18100-	20100	208328= 1.7%
20100-	22100	151760= 1.3%
22100-	24100	2016545= 16.8%
24100-	26100	97920= 0.8%
26100-	28100	952263= 7.9%
28100-	30100	
30100-	32100	405000= 3.4%
32100-	34100	1149500= 9.6%
34100-	36100	36000= 0.3%
36100-	38100	
38100-	40100	

0   1000000   2000000

Capacity (m3/d)

Percentages in relation to all unit-capacities

Fig. 60b. Capacity of all land-based desalting plants capable of producing 100 m³/unit or more fresh water daily by unit capacity.

Raw Water
SEA
BRACK
WASTE

7308735= 86.5%
1037284= 12.3%
100927= 1.2%

| 0 | 1000000 | 2000000 | 3000000 | 4000000 | 5000000 | 6000000 | 7000000 |

Capacity (m3/d)
Percentages in relation to all waters

Fig. 60c. Capacity of all land-based desalting plants capable of producing 4000 m³/unit or more fresh water daily by raw water quality.

Main Process
MSF
RO
ME
ED
HYBRI
VC

6835393= 80.9%
1202540= 14.2%
300019= 3.6%
84312= 1.0%
16355= 0.2%
8327= 0.1%

| 0 | 1000000 | 2000000 | 3000000 | 4000000 | 5000000 | 6000000 |

Capacity (m3/d)
Percentages in relation to all processes

Fig. 60d. Capacity of all land-based desalting plants capable of producing 4000 m³/unit or more fresh water daily by process.

Country

Country	Value	Percentage
Saudi Arabia SA	2818372=	33.4%
Kuwait KT	1284255=	15.2%
Arab Emirat.UAE	1198122=	14.2%
USA	547351=	6.5%
Libya LAR	360092=	4.3%
Qatar Q	280962=	3.3%
Bahrain BRN	261328=	3.1%
Iran IR	260794=	3.1%
USSR SU	227279=	2.7%
Hong Kong HK	181800=	2.2%
Italy I	161865=	1.9%
Neth. Antil. NA	112027=	1.3%
Oman OMA	105450=	1.2%
Spain E	94806=	1.1%
Iraq IRQ	89517=	1.1%
Algeria DZ	84642=	1.0%
Virgin Islands	70180=	0.8%
Holland NL	61400=	0.7%
Malta M	40265=	0.5%
Mexico MEX	32388=	0.4%
Australia AUS	29296=	0.3%
Germany DDR	22900=	0.3%
Israel IL	21132=	0.3%
Bahamas BS	18676=	0.2%
Greece GR	14500=	0.2%
Germany D	14300=	0.2%
South Africa ZA	14005=	0.2%
Japan J	14000=	0.2%
Antigua ANT	13622=	0.2%
GreatBritain GB	11620=	0.1%

0   1000000   2000000

Capacity [m3/d]

Percentages in relation to all countries
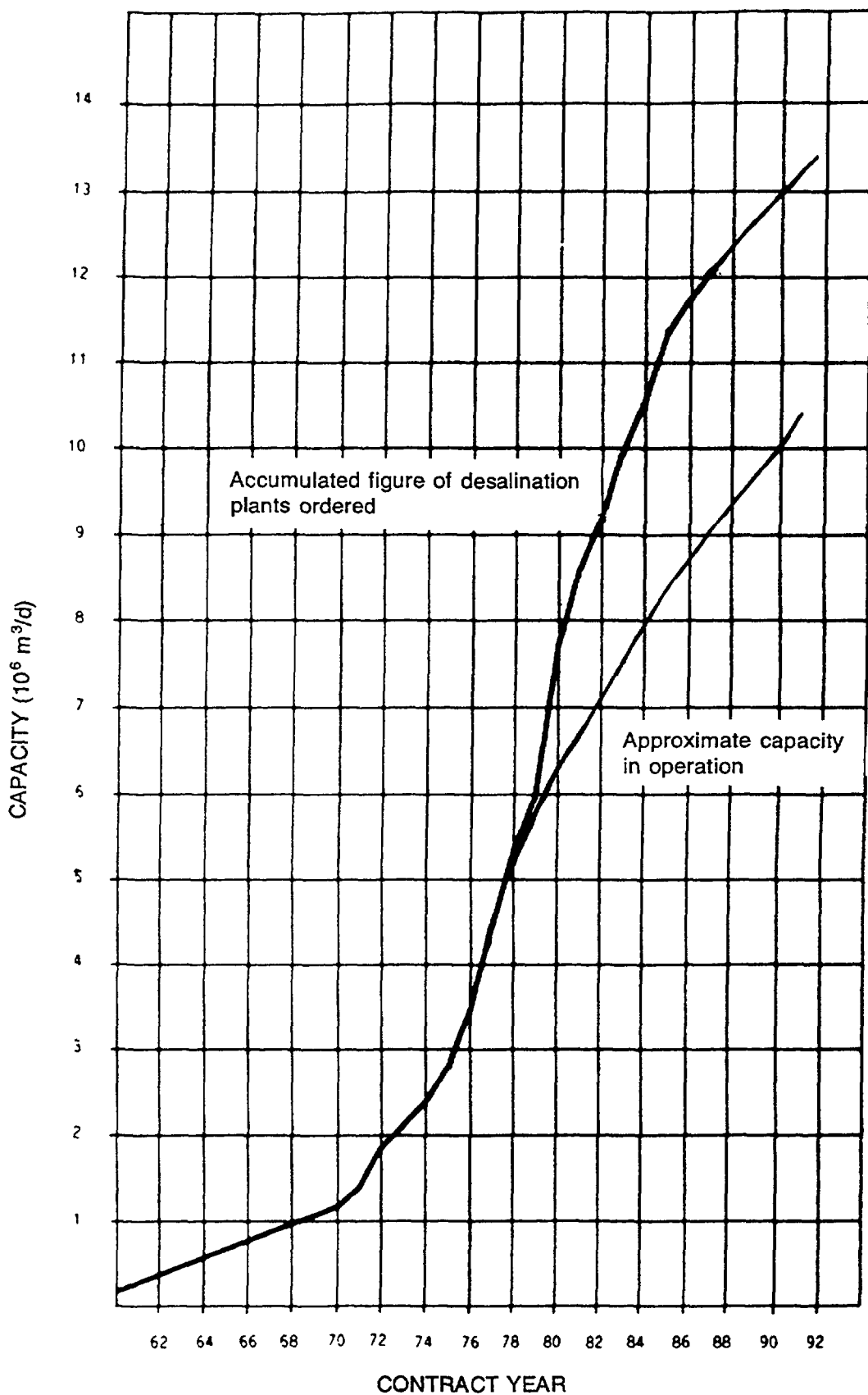
Fig. 60e. Capacity of all land-based desalting plants capable of producing 4000 m³/unit or more fresh water daily by country.

c) Developed Countries
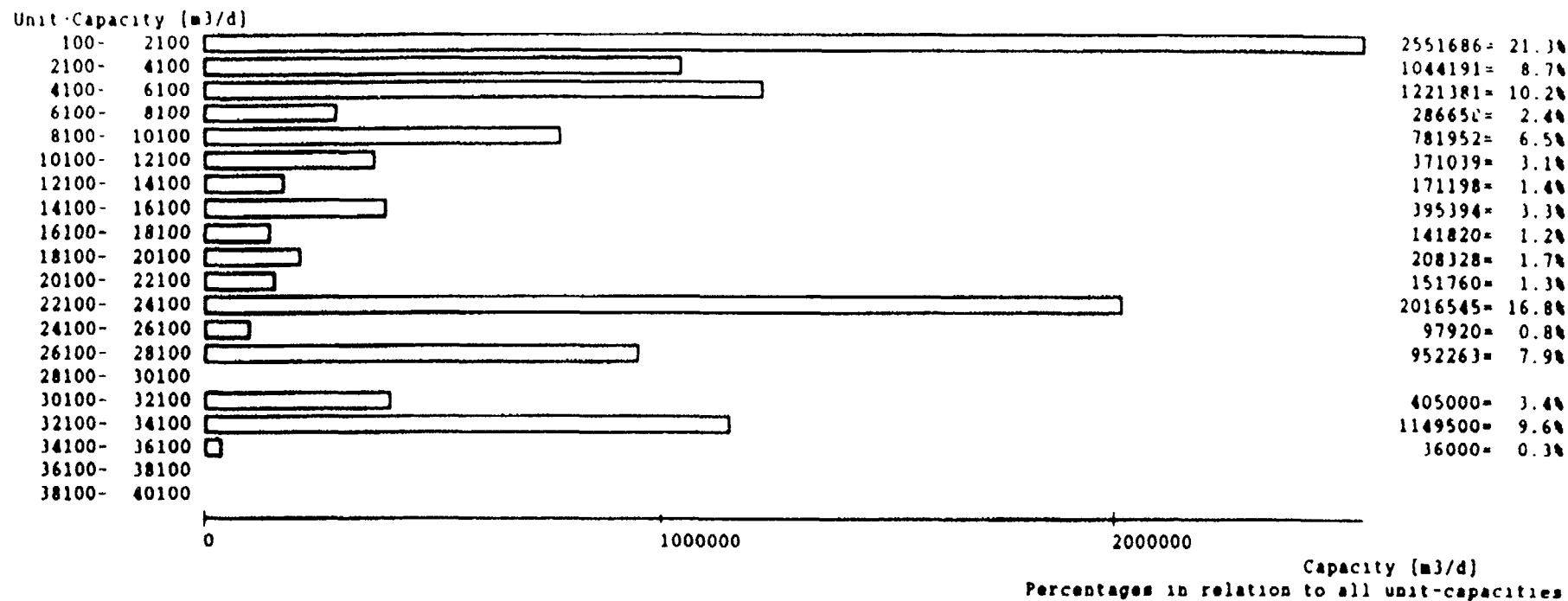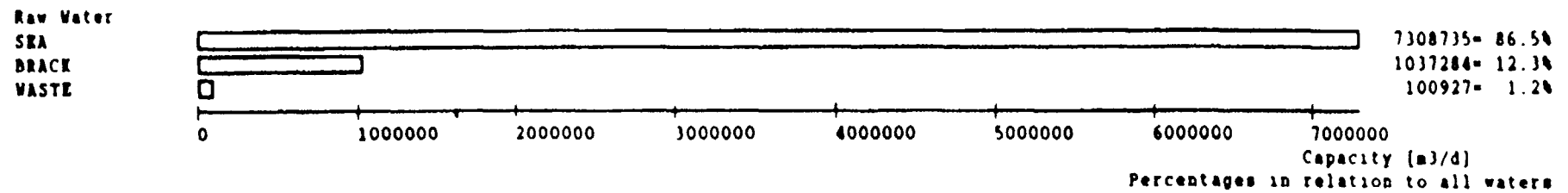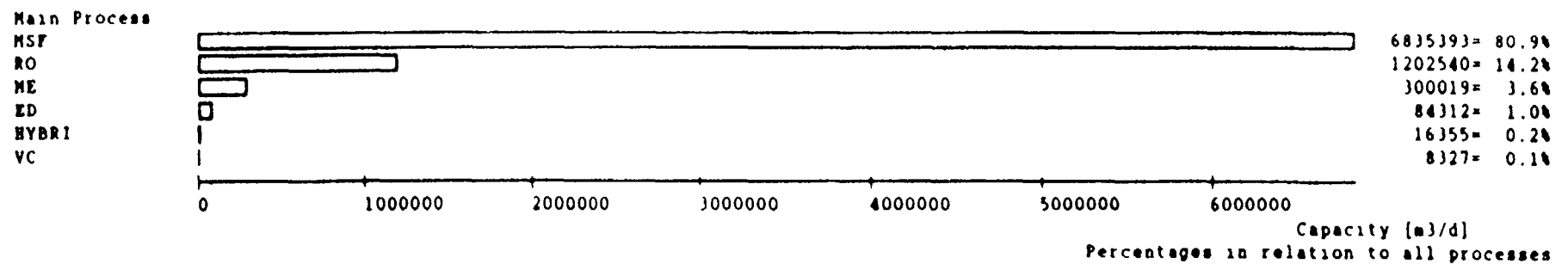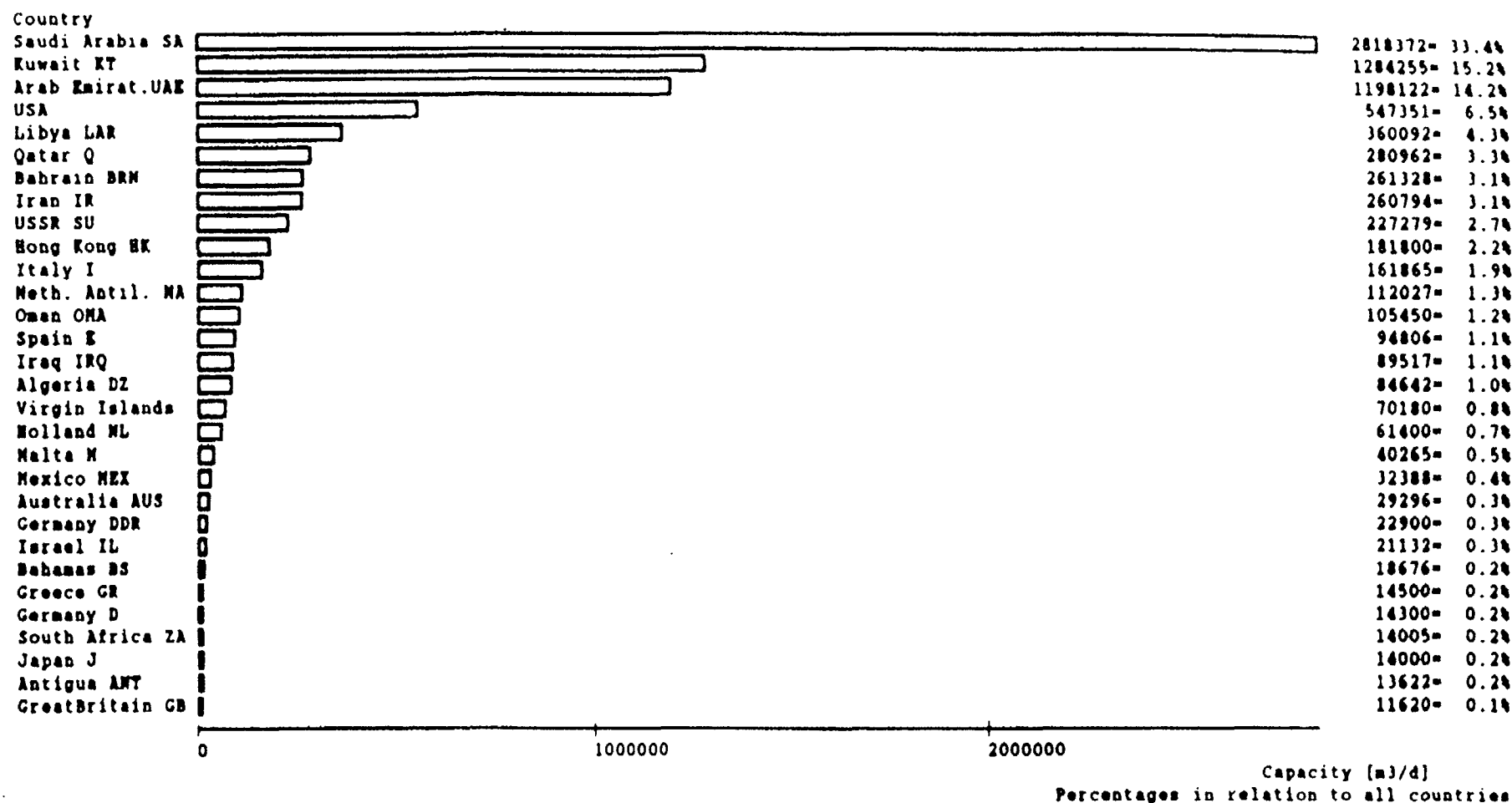
It has become difficult, in many developed countries, to keep the standard of living at the same level without finding new sources of water at acceptable cost. The water problem in these countries is man-made by contamination of well, springs and rivers or simply from over usage. Examples are California, parts of Florida, and even certain areas in the UK. Due to increased pollution of the conventional sources, water costs in some developed countries have reached a level where seawater desalination is becoming competitive. For example in Germany in some areas, water costs are greater than 1.20 US$/m^3, excluding distribution and waste water charges. Shortage of water has also been reported in many regions of the USSR.

The following general water consumption figures may assist in determining the water demand and shortage figures for different areas.

Minimum water to survive:	1-2 l/person/day
Minimum water to live and work:	4-6 l/person/day
Average consumption in Germany: (excluding industrial consumption)	150 l/person/day
Average consumption in Tripoli area: (including small businesses, lawn irrigation and losses, excluding industry)	250 l/person/day
Average consumption in tropical residential areas: (including small businesses, lawn irrigation and excluding industry)	350 l/person/day

5.2. Seawater Desalination vs Alternatives

Seawater Desalination can be considered as a source of drinking water but is only justified when economically superior to other alternatives, namely - (1) importing natural water from distant sources, (2) changing the uses of existing water, such as from agriculture to domestic or industrial, (3) reclamation of sewage-water, (4) desalination of higher-quality brackish-water. Each alternative has the following implications:

(1) Studies on the first alternative have been prepared for specific locations. As a general guideline, it was found that if the distance is around 1000 kilometers, seawater desalination is preferrable. It is also preferrable for small capacities and for locations which are sensitive to earthquakes.

(2) Changing the use of naturally available sweet water may involve other issues, such as unemployment, increased dependence on imports etc., in addition to economical aspects. An example is the case where

naturally available sweet water used up to date for agricultural
purposes is then used for drinking water, and the locally produced
vegetables and fruits then have to be imported due to lack of
irrigation water.

(3) Sewage water reclamation may involve difficulties of public acceptance
and/or limitation on uses such as irrigation only.

(4) Desalination of brackish water applies where sufficient amount of it
is available. (In some cases the quality of sewage water or brackish
water is inacceptable for treatment). Additional problems can occur
due to water table variations on land use, and seawater ingress.

5.3. Advantages and Disadvantages of Nuclear vs Fossil Desalination

The correct source of primary energy for seawater desalination must be
selected. Fossil fuel and nuclear can be considered as heat sources, while
others such as solar, geothermal, biomass and wind energies have limited
capacities. The advantages and disadvantages of nuclear vs fossil fuel are
discussed in detail as follows:

1. In very small heat consuming installations, the least expensive form
of heat in the foreseeable future will be from fossil-fuel-fired
boilers. However, in large installations, nuclear energy becomes
increasingly competitive because fuel cycle costs are considerably
lower for nuclear reactor plants than for fossil fuel plants. The
relatively high capital cost of nuclear plants, on a unit-cost basis,
thus becomes a less important factor. Further, the ratio of fuel
costs to total costs in a fossil plant is significantly higher than in
a nuclear plant. This will become increasingly true as supplies of
fossil fuel are depleted.

Figures 34a to 34h show that the cost of fuel or energy consumed in
different desalination processes is one of the major contributions to
total water cost, and amounts to about 34% to 58% [37].

The cost of product water as a function of plant size and type of fuel
is presented in Figure 34i [36].

It is apparent therefore, that the characteristics of a nuclear
desalination plant are a large investment cost, and a low proportional
fuel cost. The conventional fossil plant has the opposite features.

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However, the economic merit of nuclear desalination is strongly dependent on local circumstances, the prevailing market prices for both electricity and water, and a series of institutional factors (as discussed in section 6) that may strongly influence the economic assessment of the project.

2. The improvement of the load factor for dual-purpose plants benefits the nuclear more than the conventional plant.

3. Figure 59 [67] shows the variation of the water/electricity ratio versus brine temperature before flashing, in the case of a dual-purpose nuclear plant with a light water reactor delivering saturated steam at 7MPa (1000 lb/in^2), and also for the case of conventional one producing steam at 10MPa (1420 lb/in^2 520°C). The parameters of the steam raised by the light-water reactor are not high, so the same amount of heating steam supplies less electricity than in the case of the conventional plant, and this influences the price of fresh water thus produced.

4. In the case of a nuclear plant, the relative importance of the load factor on efficiency is more significant than that of the conventional fossil plant, and it would therefore seem that the pass-out condensing cycle would be more useful in this case.

5. Working with a by-pass line is less expensive in the case of a nuclear plant, because of the lower initial quality of the steam which is expanded uselessly in the reducing valve.

6. Nuclear plant economics do not vary to any great extent with geographic location. This factor is of importance for those regions or countries, which have a low availability of fossil fuels. Thus, nuclear desalination offers an additional degree of freedom in securing local energy requirements.

7. Air quality is deteriorated in the case of fossil powered desalination plants compared to nuclear. This is due to long term effects of increasing carbon dioxide level in the air (global warming) and acidification effects of nitrogen and sulfer dioxide (acid rain).

6. INSTITUTIONAL ISSUES

6.1. Safety Considerations

Two main safety aspects related to nuclear desalination have to be considered [64, 68, 32].
- Safe and simple operation of the nuclear reactors
- Protection of the product water against contamination
- Protection against misuse of fuel

The 3 aspects depend on the type of reactor, the desalination process and the type of coupling between them. Any safety related impact of the reactor on the desalination plant and vice versa has to be considered, as well as the safeguard of fuel.

Safety considerations for the operation of the nuclear desalination units will be almost the same as for nuclear electricity plants and/or nuclear heat generation plants. The fundamental point is, that no matter what type of desalination plant and interconnections are used, no occurances should lead to an uncontrolled situation in the nuclear reactor. This is not a difficult problem in principle, but must be considered carefully in detail design and licensing.

The design must ensure that no radioactive material from the reactor can reach the product water, types of interconnection to avoid water contamination were discussed earlier.

For example, the Reverse Osmosis or Electrodialysis or Vapour Compression processes are not a problem when coupled to a nuclear reactor because the interconnection is only equivalent to an electrical grid.

The situation is different in the case of distillation processes for seawater desalination, in particular if water reactors are used. The most efficient and economic coupling would be to use directly the steam from a backpressure or extraction turbine to heat the first stage of the distillation process. However, this steam may be contaminated and could penetrate to the cirulating brine of the desalination plant, if there is any leak in the heat exchanger tubes. This problem arises with Boiling Water Reactors in particular because the turbine is integrated with the

primary steam circuit. To assume that no radioactive material can reach the product water, an additional intermediate steam or water cycle may be necessary, such that the water/steam pressure is always higher on the desalination side.

For other reactor types (LMR or HTGR) it may be possible that an additional steam cycle is not necessary, and leak detection will be sufficient to protect the product water from contamination.

A separate issue is the safeguard of the nuclear fuel. Whilst the HTGR is believed to not present problems in this respect, other reactors produce fuel with burnup suitable for weapons. In the case of the Low Temperature Reactors it would be a solution to load the reactor with fuel required for 10-15 years, and operate the reactor under "Sealed Conditions". International agreements and inspection must insure that after this period the fuel is stored and/or reprocessed in conformity with international rules and policies.

6.2. Licensing/Regulatory Considerations

Licensing and regulatory interfaces will certainly have a major impact on the design, construction and operation of a nuclear desalination plant, and may have to be established with the following classes of authorities [61, 62].

- Regulators of nuclear facilities
- Regulators of water production facilities
- Public health officials
- Regulators of electricity production and distribution
- Siting and environmental regulators

Because of the larger number of authorities involved, licensing and operation of an integrated nuclear desalination facility may be more difficult than for separate power production and desalination plants. The need to locate the desalination plant both near the source of raw salted water and also near the water distribution system may further complicate the licensing effort.

Licensing in the reactor supplier countries will likely be required, while a suitable infrastructure to cover installation and operation in user

countries will need to be considered in detail, and could have a most significant impact on any project. To ease this problem, some form of future international coordination of licensing activities may become desirable.

In extreme cases, the difficulty of licensing an integrated facility may become an important input to the design selection process. For example, if economic factors are otherwise marginal, the selection of a process such as Reverse Osmosis, which uses energy input in the form of electricity, would allow separate siting of the nuclear and desalination plants.

In any specific project consideration, it is critical that all significant regulatory authorities be identified and that the associated criteria for licensing and operation be integrated into the early stages of project planning and design.

6.3. Environmental Aspects

The environmental aspects of nuclear desalination are concerned with any emissions of the nuclear reactor and the desalination plant. The environmental aspect of the desalination plant is independant of the heat or power source. In fact desalination can improve the environment considerably, if for example the water is used for irrigation purposes in dry or desert regions. The availability of fresh water is a very important environmental factor.

Fossil powered desalination plants release at least carbon dioxide and in more or less quantities other environmentally harmful substances. The deterioration of air quality on a global basis has become a subject of intense discussion in many parts of the world. In addition to the acidification effects of nitrogen and sulfur oxides (acid rain), the longterm effects of increasing carbon dioxide level in the air (global greenhouse warming) is causing concern.

The degree to which nuclear desalination can contribute to reduce environmental pollution depends on future development of nuclear desalting capacity and on the type of fossil fuel which is replaced by nuclear.

This situation is similar to that in the field of electricity generation, though energy consumption for seawater desalination is orders of magnitude lower. Each MW of nuclear thermal power avoids a CO_2

emission of about 3200 t per year, and a SO_2 emission up to about 50 t per year, if compared to combustion of coal (sulfur content 2%, without flue gas cleaning). Compared to oil or natural gas, the avoidable CO_2 emission is lower (about 2000-2900 t CO_2 per year), and the SO_2 emission may reach almost zero if desulfurized natural gas is used as fuel.

Thus, if the worldwide desalting capacity at the end of 1990, which is projected to be about 10 million m^3/day, in operation were to be powered by nuclear instead of fossil fuel, emissions of the following amounts could be avoided:-

$$20\ 000\ 000\ t\ CO_2$$
$$200\ 000\ t\ SO_2$$
$$60\ 000\ t\ NO_x$$
$$16\ 000\ t\ HC.$$

This is not much compared to emissions from the total worldwide electricity generation capacity, especially if one takes into account that a 100% market penetration by nuclear desalination plants is unrealistic.

A significant environmental improvement by nuclear desalination can only be achieved in those regions where a large desalination capacity is concentrated. A global effect would be noticeable only if desalination capacity increased drastically in the future.

The transport, treatment and disposal of radioactive wastes depends on the type of reactor, and no additional complications are caused by desalination applications.

6.4. Public Acceptance

Obtaining public acceptance could be a significant hurdle to overcome in the use of nuclear reactors for desalination, depending on country. Public opinion regarding nuclear power has declined since the events at Three Mile Island and Chernobyl. However, increasing public awareness of the adverse environmental effects of using fossil fuels, including poor air quality, acid rain, and the Greenhouse Effect, may help to overcome this hurdle. Also, increasing public awareness of the basic need for new indiginous sources of fresh water and electric power in different countries may contribute to greater public acceptance.

6.5. Organizational Aspects

A nuclear desalination plant poses particular organizational challenges as such an endeavor combines two activities that are normally carried out by separate entities. Specifically, the management and operation of a nuclear energy facility, most likely involving significant power production, is normally the function of a utility that is experienced in the generation and distribution of electricity and/or steam and heat. Conversely, the production, treatment and distribution of potable water are more commonly the provinces of a separate water utility.

For such an enterprise to be successful, equitable and workable arrangements must be developed among the participating parties for ownership and financing, management of the project during construction, and operation of the plant throughout its useful lifetime.

6.5.1. Ownership

The basic concerns of a combined facility for power production and desalination are further compounded by the fact that a number of scenarios might be envisioned for ownership and operation, including:
- Entire plant owned by one or more water utilities with surplus electricity sold on a competitive basis to electric utilities in the region.
- Entire plant owned by one or more electric utilities with water sold on a competitive basis to water utilities in the region.

- Water plant owned by one or more water utilities and the power plant owned by one or more electric utilities with negotiated allocation of costs to water and electricity.

- All or part of the plant owned by a third party (potentially including utility investors) that would sell water and/or electricity to utilities at competitive rates. (This latter scenario is consistent with recent trends in the U.S. electric utility industry.)

In the development of a specific project, detailed consideration should be given to the various ownership and financing options that may be practical. For each of these options, an analysis must be made of the particular contributions, liabilities, and benefits that will be associated with each participating party.

6.5.2. Project Management

In multiparty ownership scenarios, such as those assumed for a desalination plant, management during construction poses a particularly difficult challenge. Prior experience has shown it to be essential that a strong centralized project management team be developed with both the authority and the responsibility to effectively manage construction activities. Conversely, provisions must be made to adequately represent the interests of all organizations that have a financial stake in the plant. Whatever specific arrangements are developed, careful attention needs to be given to this area prior to construction commitment.

6.5.3. Plant Operation

Similar to management of the construction phase, the responsibility and authority of the respective parties need to be carefully defined for operating the plant once it is completed. Reflecting the multiparty ownership scenarios described above, there are several corresponding options that might be evaluated for plant operation.

In any operating scenario, it is essential that the operational philosophy be carefully developed and that it be documented in corresponding agreements which bind the participating parties. For example, priorities must be developed for allocation of available energy between the water and power products in partial outages. An example is the case in which a fault in the turbine interrupts the production of electricity, while water production may be continued using a bypass system. Should the plant be immediately shut down to restore the fault and reestablish electricity production or should priority be given to continuing the production of water until some agreed-to point? Details such as these must be carefully worked out among the participating organizations to avoid misunderstanding and conflict.

A related consideration in multiparty ownership is performance warranties. For example, the organization that is producing electricity would expect the desalination plant to accept a given amount of energy at the agreed price. Conversely, the operator of the desalination plant is dependent upon the availability of steam as input to the process. The responsibilities and liabilities of the parties for the production of their respective products and/or the use of the energy must be carefully defined

in advance and contingencies must be developed for problems that may be expected to arise.

In summary, operating relationships and operating agreements must be carefully worked out in advance of committing the plant to construction. Provisions must be made to resolve conflicts, including those which are not foreseen in the initial deployment agreements.

6.6. Financing Requirements

The total cost and the financing of any plan to fight the draught including Nuclear Desalination has to be considered in context with the costs and resulting financing requirements of overhauling old distribution systems, new distribution systems, interim water, storage and complementary water conservation schemes.

The required investment for 10 000 000 m^3/day installed capacity in the Mediterranean Area would be in the range of US$ 30 000 000 000 (see Fig. 35 and Ref. 32 in 1990 dollars) based on a single-purpose arrangement. Assuming that the additional worldwide figure is in the same range, and assuming that the additional costs for infrastructural works and complementary conservation schemes will be at least in the same range, a total investment of about US$ 120 billion has to be financed in the countries where water is not a question of quality of life but an absolute need. Installations required to maintain a certain standard of life (e.g. California and Spain) are not included in the above.

A major constraint in financing any plant will be that the majority of systems have to be installed in countries already in a critical monetary/economical situation. Even considering that some countries will be able to pay for their own needs, in addition to providing some financial help for their neighbours, still, a substantial amount will have to be found for many other countries.

As water to support life is a most fundamental need, a way may be found to overcome the financial problem. Additionally, the development and demonstration costs for large systems cannot be bourne by a few countries alone. It is also necessary to prepare for after the year 2000, when even more and cheaper water will be required. It might be necessary to set up a fund or funds to distribute the burden of investment as well as the

financial/technical burden of R&D, on many shoulders. It may be
investigated how, and under which form, an effective international
financing body can be created.

The following may be considered:

- Necessity for a Long Term Perspective
   The economic, technological and environmental issues, involved in the
   development and establishment of a viable scheme to fight the draught
   in all countries where the need for water is a question of life,
   necessitate a long-term continuous and sustained financing programme.

- Multi Source financing
   Financing Nuclear Desalination Schemes as well as the necessary and
   complementary R & D could be based on a multi-source approach
   involving;

   a)   International organizations
   b)   Public or governmental bodies
   c)   Private enterprises
   d)   The international banking community

   More detailed study of the financing aspect may be carried out in
follow-up to this report.

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LIST OF ABBREVIATIONS

AGM	Advisory Group Meeting
APS	Atomic Power Station
BWR	Boiling Water Reactor
CA	Cellulose Acetate
CM	Consultants' Meeting
DPP	Distillate Production Plant
ED	Electrodialysis
FBR	Fast Breeder Reactor
GCR	Gas Cooled Reactor
GOR	Gain Output Ratio
GOST	Government Standard (USSR)
GOU	Government-Owned Utility
HTME	Horizontal Tube Multi-Effect Distillation
HTGR	High-Temperature Gas-Cooled Reactor
HTR	High-Temperature Gas-Cooled Reactor
IDE	Israel Desalination Engineering Ltd.
IOU	Investor-Owned Utility
LMR	Liquid-Metal Cooled-Reactor
LT-HTME	Low-Temperature Horizontal-Tube Multi-Effect Distillation
LTV	Long-Tube Vaporization
MED	Multi-Effect Distillation
MHTGR	Modular High-Temperature Gas-Cooled Reactor
MSF	Multi-Stage Flash Distillation
MVC	Mechanical Vapour Compression
NCG	Non-Condensable Gas
NOAK	nth-of-a-kind
NSSS	Nuclear Steam Supply System
PWR	Pressurized Water Reactor

OSW	Office of Saline Water (USA)
OWRT	Office of Water Research and Development (USA)
RO	Reverse Osmosis
TCM	Thousands of Cubic Meters
TDS	Total Dissolved Solids
TVC	Thermal Vapour Compression
UOP	Name of a USA-company
VC	Vapour Compression
VTE	Vertical-Tube Evaporator
WCR	Water Cooled Reactor
WHO	World Health Organization

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